# Today's Topics

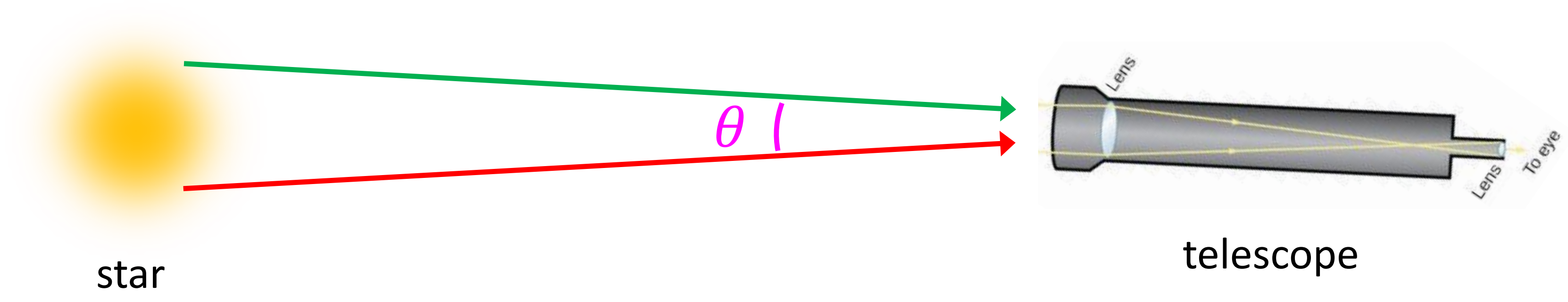
Monday, September 30, 2019 (Week 5, lecture 13) – Chapter 6.

1. Adaptive optics
2. Interferometry
3. CCD cameras
4. Telescopes by wavelength

# Review: Angular Resolution

**Angular resolution** (or resolving power) $\boldsymbol{\theta_{min}}$

The minimum angle that a telescope can see, i.e. it’s the “angular pixel” size.



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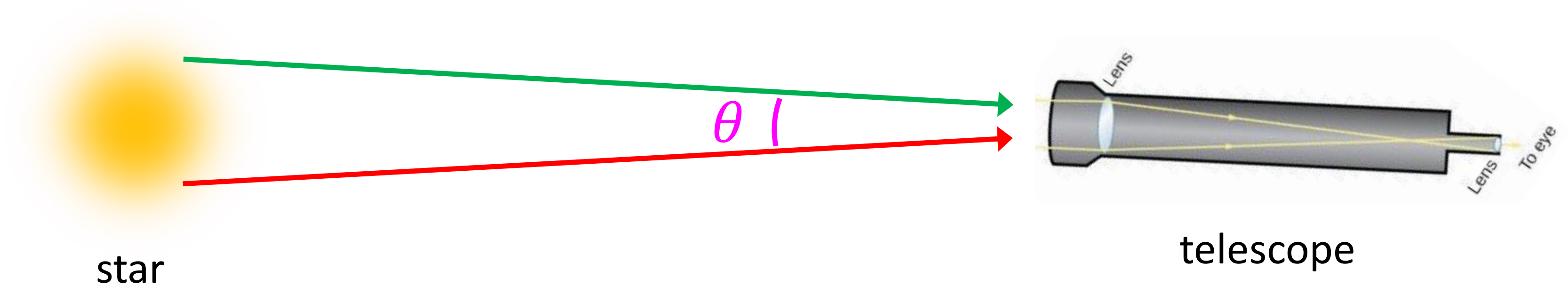

radians

wavelength in meters

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

- ➢ Typically, a telescope "tries" to reduce $\theta_{min}$
- ➢ Bigger diameter D decreases $\theta_{min}$
- ➢ Shorter wavelength $\lambda$ decreases $\theta_{min}$

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**Key point**

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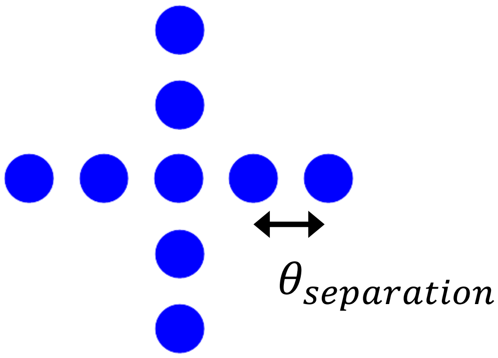

Stars in “plus” pattern

Telescope image for $\theta_{separation} \gg \theta_{min}$

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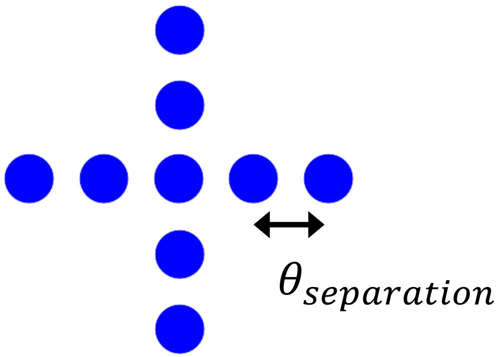

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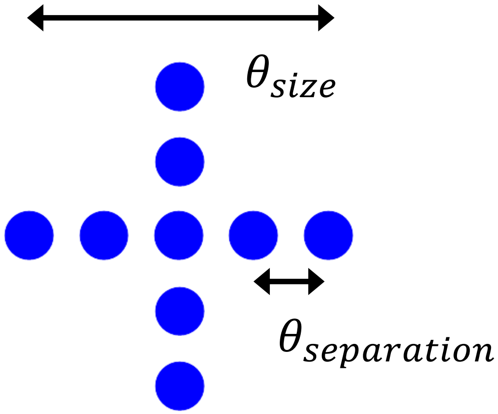

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Telescope image for $\theta_{separation} < \theta_{min} < \theta_{size}$

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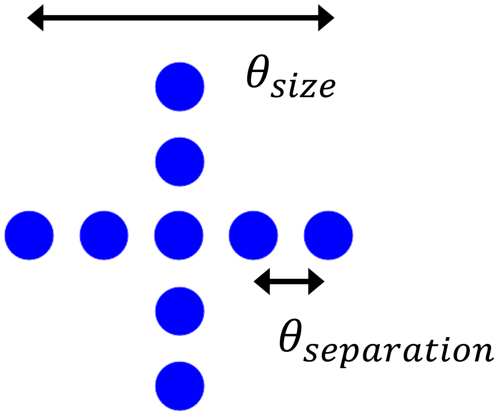

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Telescope image for $\theta_{separation} \ll \theta_{min} \sim \theta_{size}$

# Atmospheric Turbulence

[Recall: Gemini Telescope has an angular resolution of $\theta_{min} \backsimeq 0.016''$]

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Atmospheric turbulence limits optical angular resolution to $0.5''$

(0.5 arcseconds)

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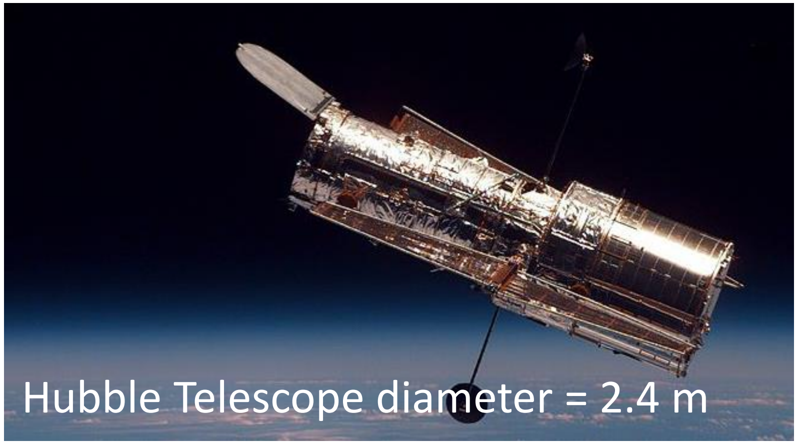
**Solution #1**

- 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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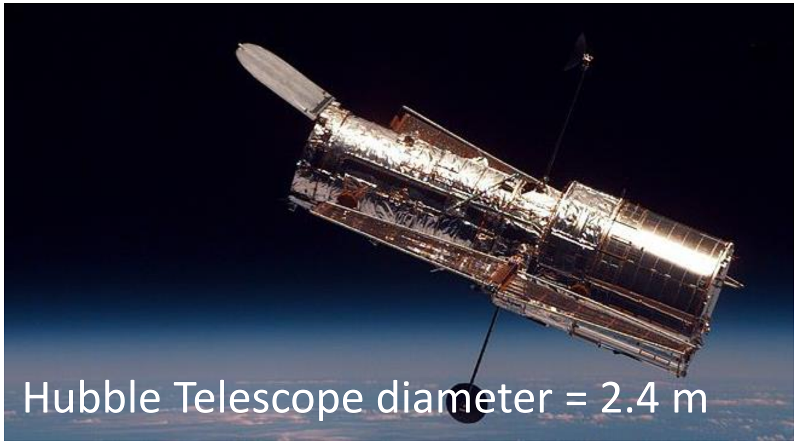

Hubble Telescope diameter = 2.4 m

[OpenStax, NASA]

**Solution #2**

- Adapted 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.
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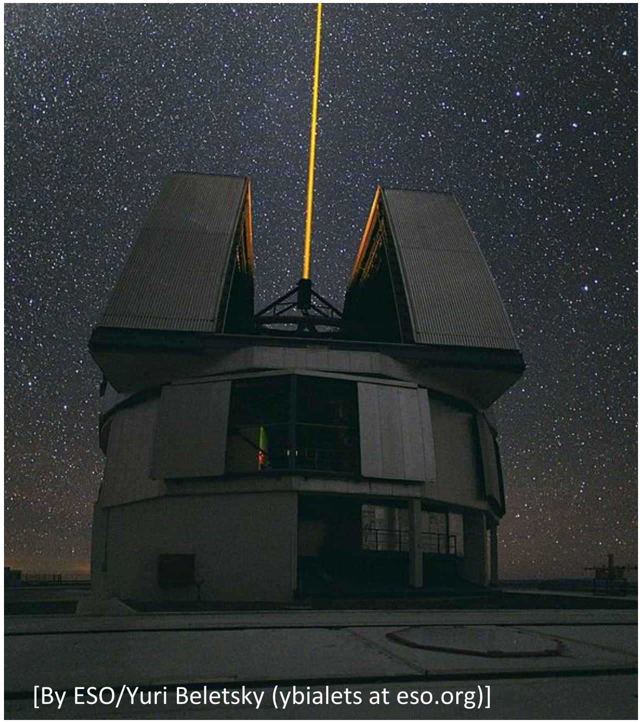
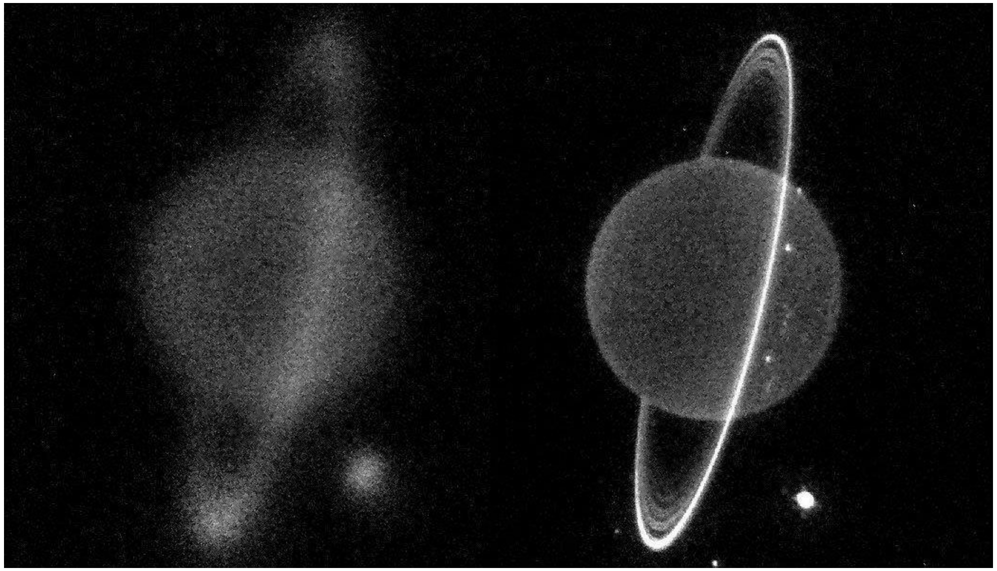


[By ESO/Yuri Beletsky (ybialets at eso.org)]

## 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."

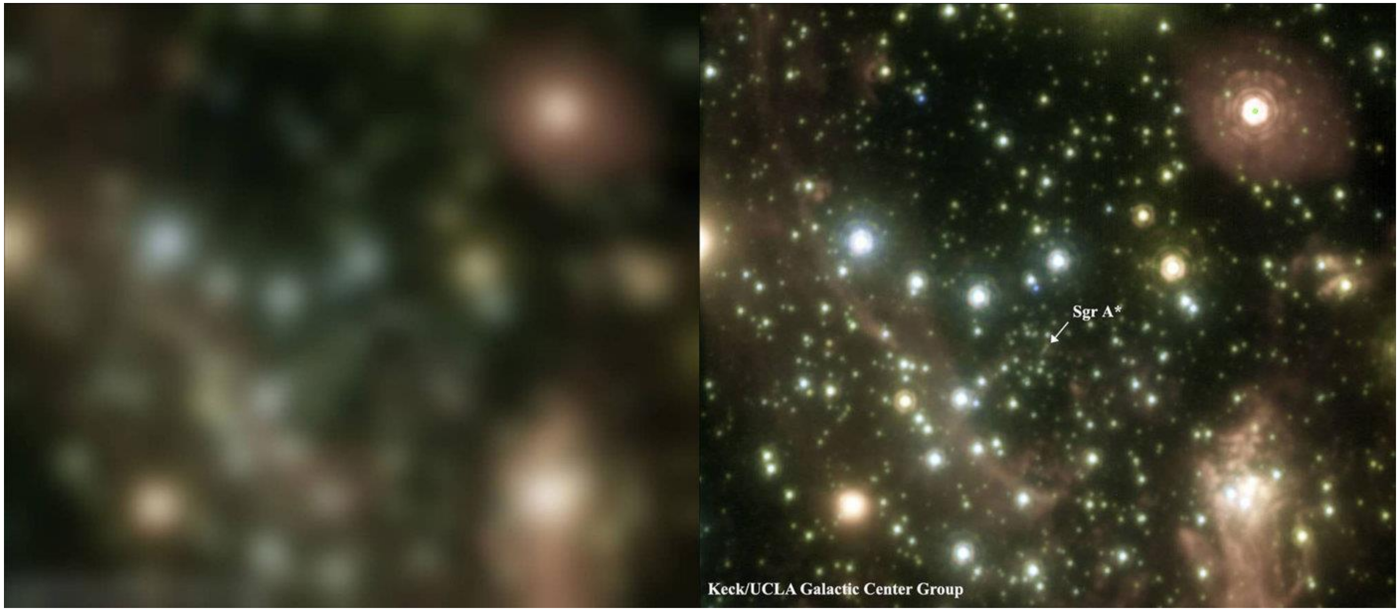
# Adaptive Optics Images



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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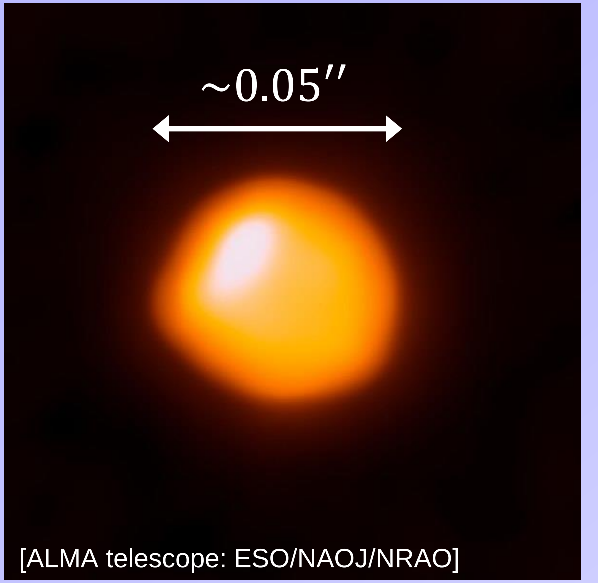
## Present

[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.

# Image of Betelgeuse



[ALMA telescope: ESO/NAOJ/NRAO]

λ = 0.89 mm, f = 338 GHz

(mm-wave)
(microwave)

Constellation: **Orion**

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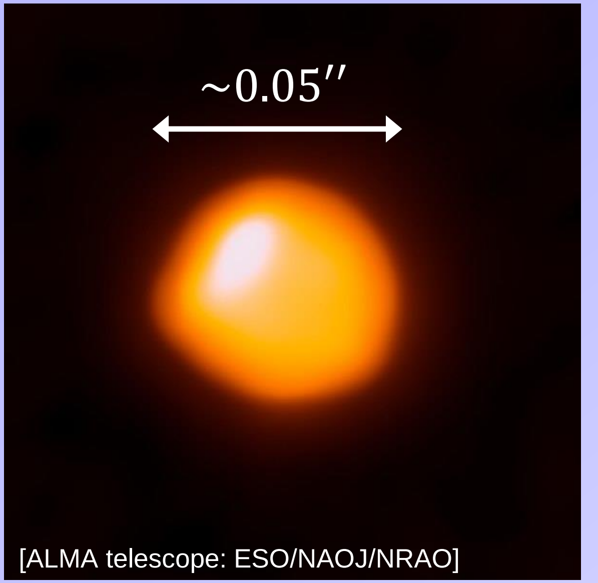

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The white "hot" feature is about 1/5 of the size of the star, i.e. $0.01''$.

→ Angular resolution must be better than $0.01''$.

*(5 times better than Gemini telescope)*

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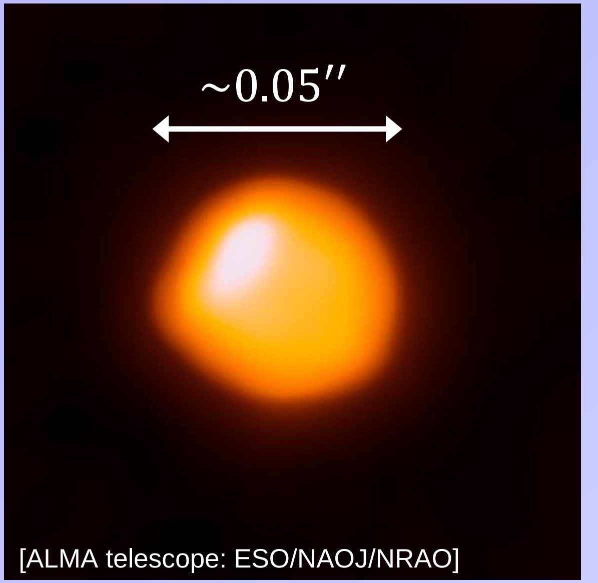

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**Answer:** Interferometric array of telescopes.

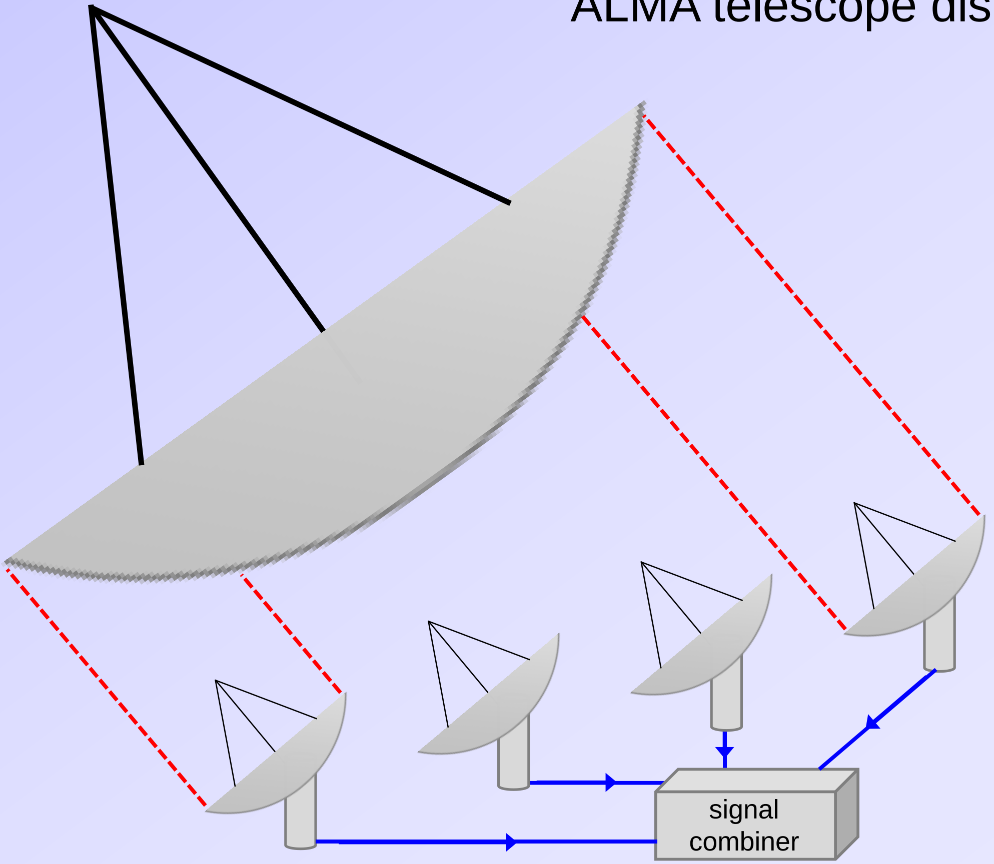
# Telescope Interferometry

[ALMA: Ajay Suresh, Atacama-52]

ALMA telescope dish

## Basic Idea

- You **combine** the signal **waves** from multiple telescopes.
- Important: the signal waves must stay **in-sync**.



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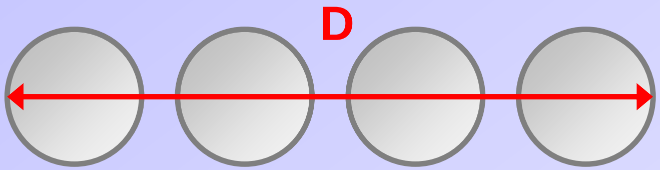
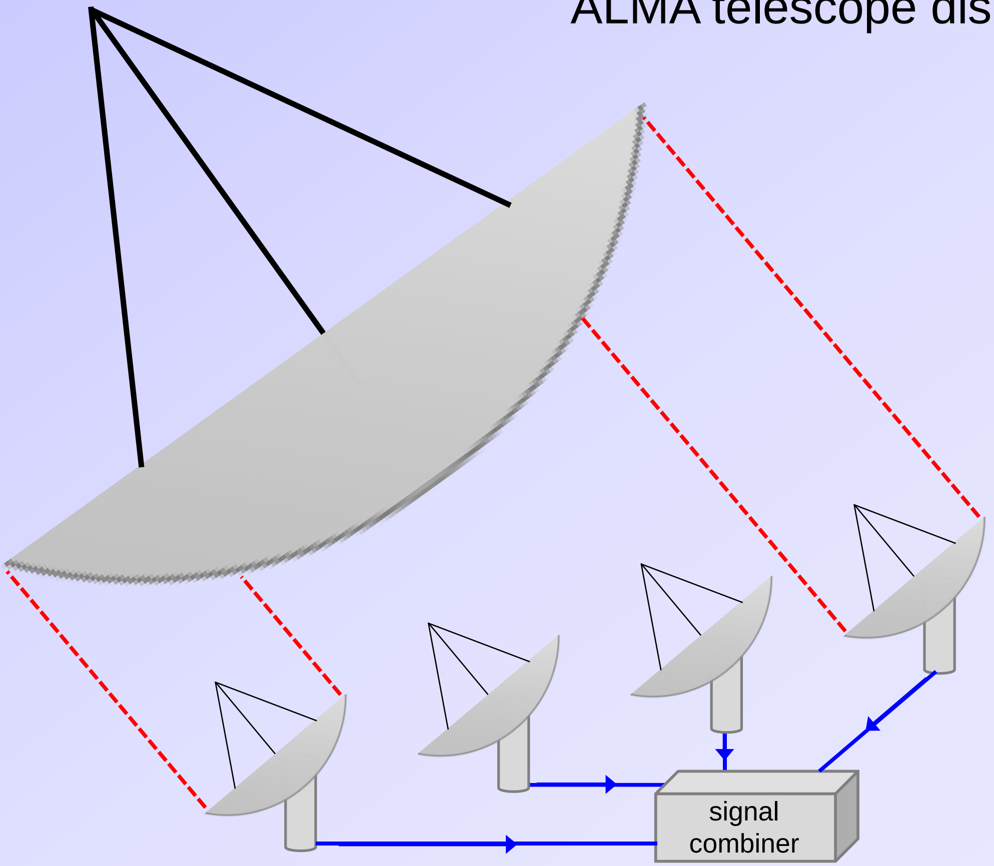
[ALMA: Ajay Suresh, Atacama-52]

ALMA telescope dish

- It is like having pieces of a much **larger mirror**.
- Gets around the aperture limit by making a **giant composite mirror**.
- The **aperture is now the "span"** of the mirrors (D).



- The **collection power** is the combined area of these individual mirror.



# ALMA radio telescope array

- Wavelength: $\lambda$ = 0.3 – 9.6 mm.
- 66 dishes with 7-12 m diameters.
- Dish separation up to 16 km.
- Atacama plateau, Chile.
- Multinational collaboration.
- $1.5 billion USD.

[Ariel Marinkovic – ALMA (ESO/NAOJ/NRAO)]

# Large Binocular Telescope

[jpl.nasa.gov]

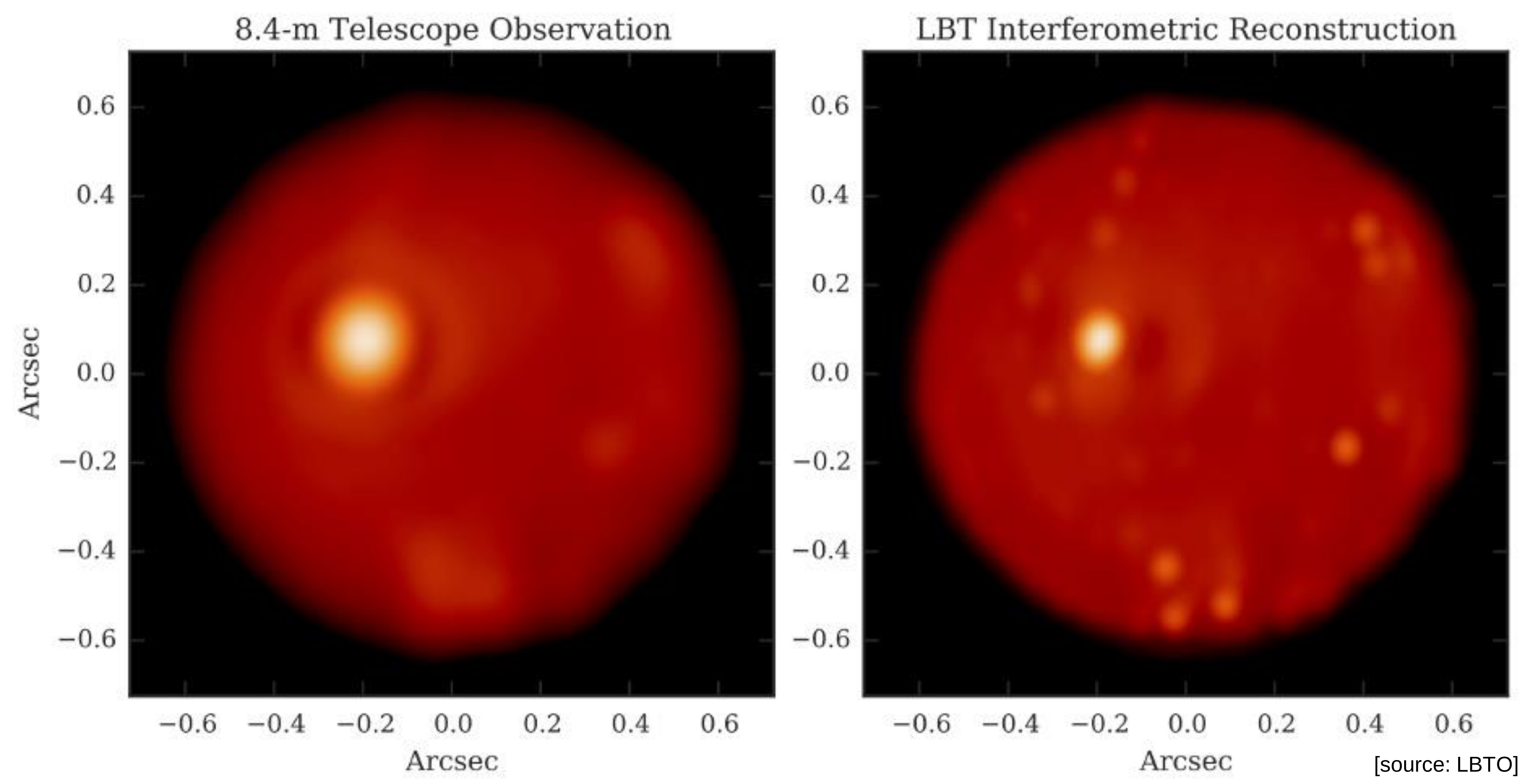
# Large Binocular Telescope

- Two 8.4 m mirrors
- Produces images with the resolution of a 23 m telescope (interferometer).
- Angular resolution $\theta_{min} \backsimeq 0.02'' = 20\,mas$ for a wavelength of $\lambda$ = 2.2 µm.
- In Arizona at an altitude of 3200 m (10,500 ft).

[jpl.nasa.gov]

# Large Binocular Telescope

Volcanos on Io (moon of Jupiter) observed at λ = 3-5 μm (infrared)



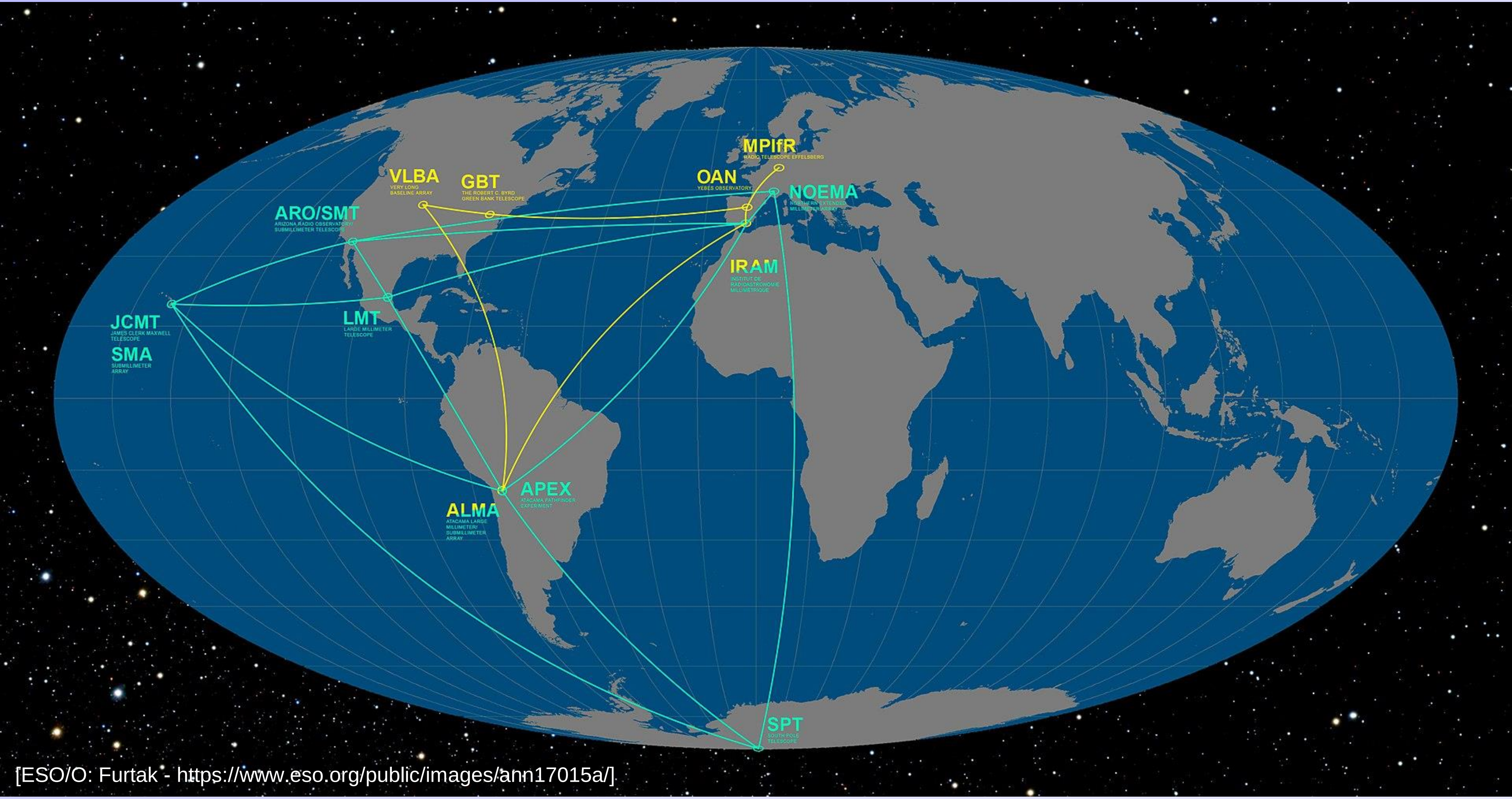
[source: LBTO]

(simulated)

(reconstructed from data)

# Event Horizon Telescope

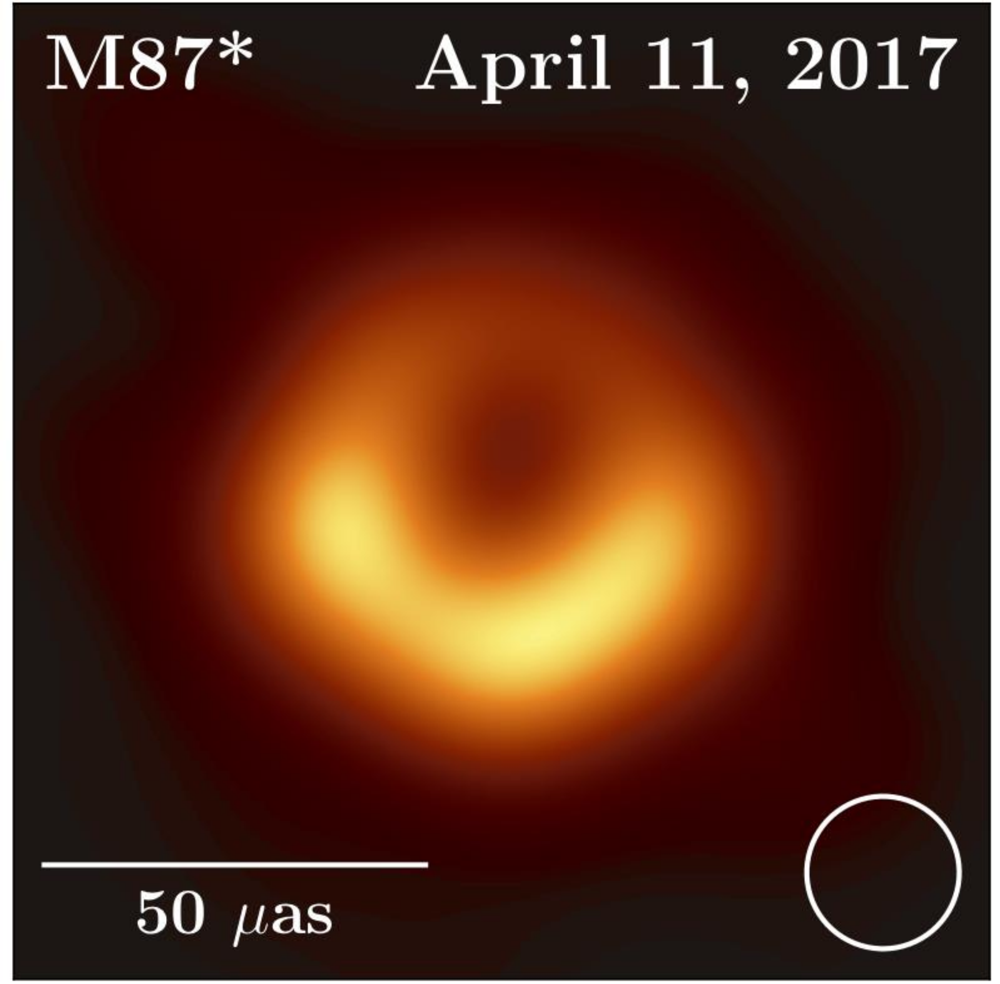
- Network of 8 radio telescopes spread over entire planet.
- Wavelength: $\lambda \sim 1$ mm.



[ESO/O: Furtak - https://www.eso.org/public/images/ann17015a/]

# Event Horizon Telescope

Super massive black hole at center of M87 galaxy



distance = 53 Mly

λ = 1.3 mm

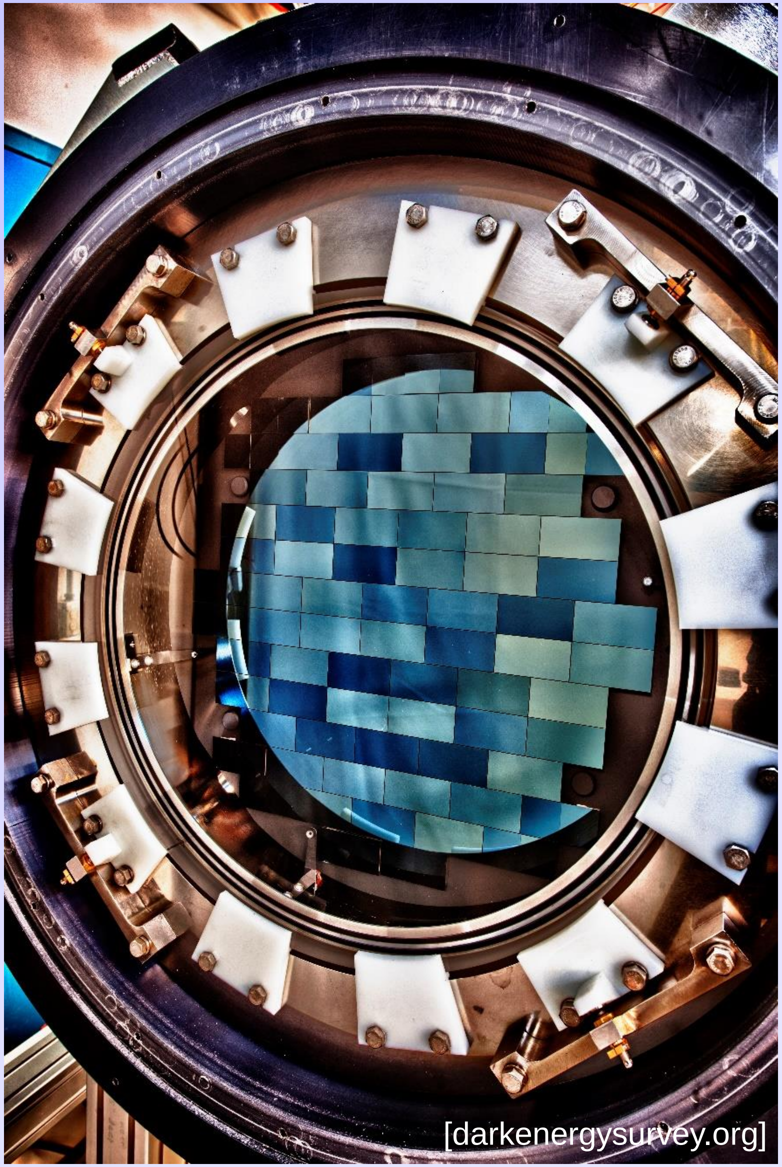
[aasnova.org, EHT collaboration (2019)]

Theoretical angular resolution of EHT: $\theta_{min} \sim 25\ \mu as = 0.000025''$

# CCD Cameras

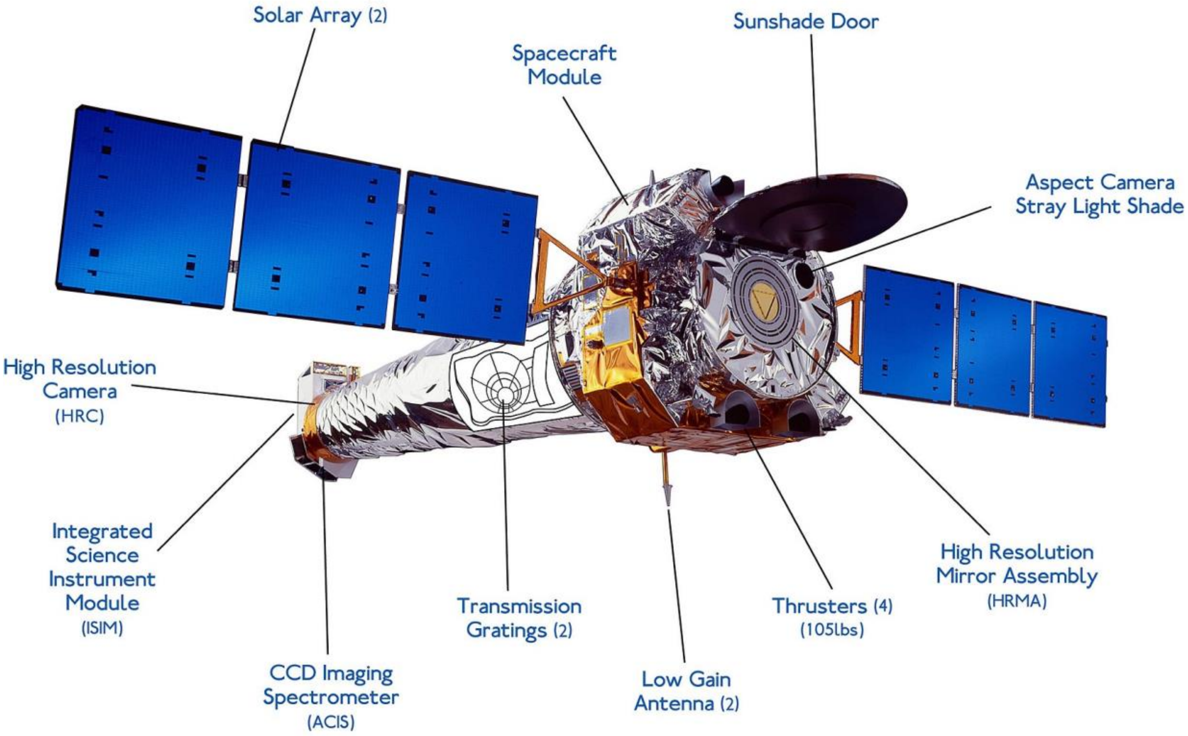
- CCD = Charge Coupled Device
- Standard digital camera sensor
- Wavelength

  → can cover X-ray to IR.
- **Efficiency:** 30-90% of photons detected (human eye ~ 20% in dark).
- Data is stored on a computer for later analysis (often made public).
- Often combined with a **spectrometer**.
- Does not work microwaves and radio-waves (antenna sensor).

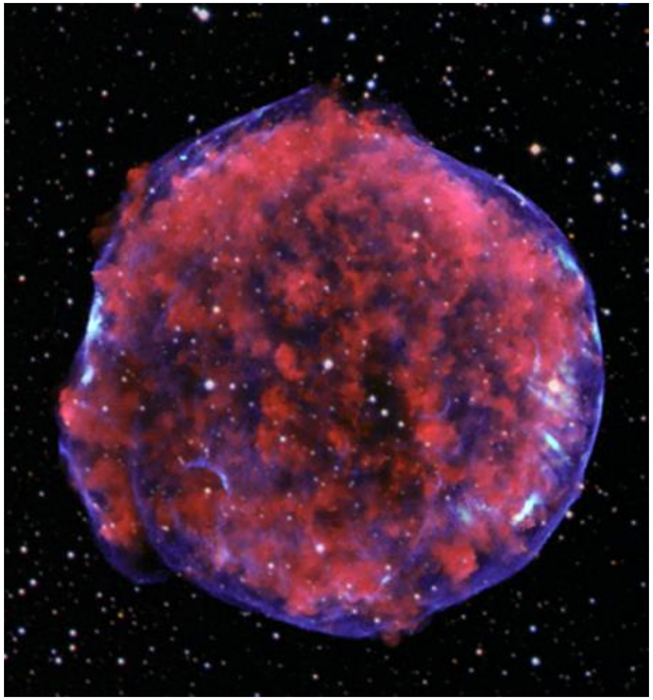

[darkenergysurvey.org]

*CCD array for Dark Energy Survey camera*

# Chandra X-ray Telescope

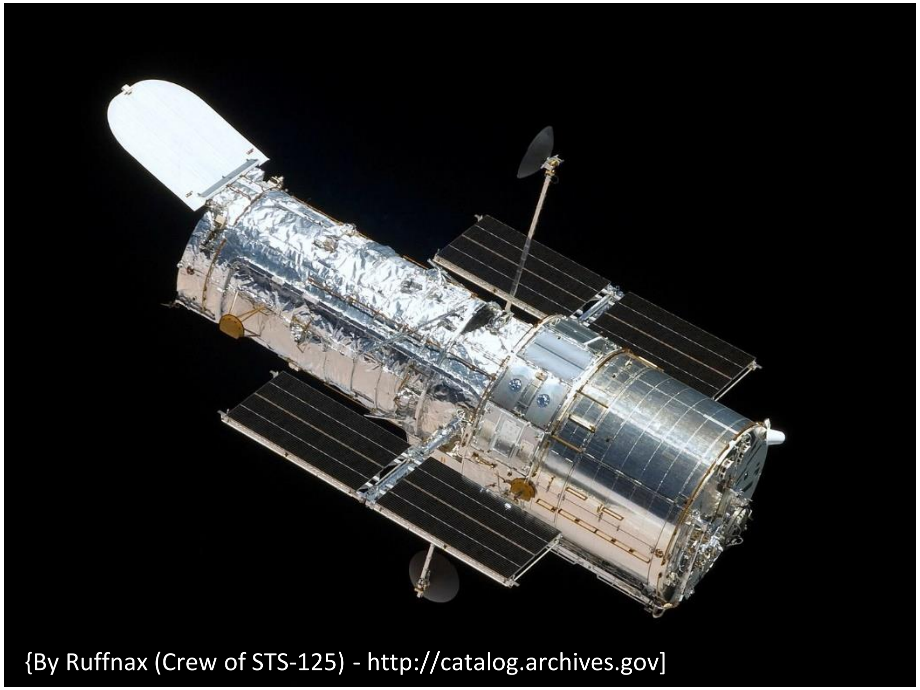


[NASA/CXC/NGST - http://chandra.harvard.edu]



Tycho’s supernova in X-ray (red & blue)
Stars are optical.

# Hubble Space Telescope



{By Ruffnax (Crew of STS-125) - http://catalog.archives.gov]

“pillars of creation” in the Eagle Nebula

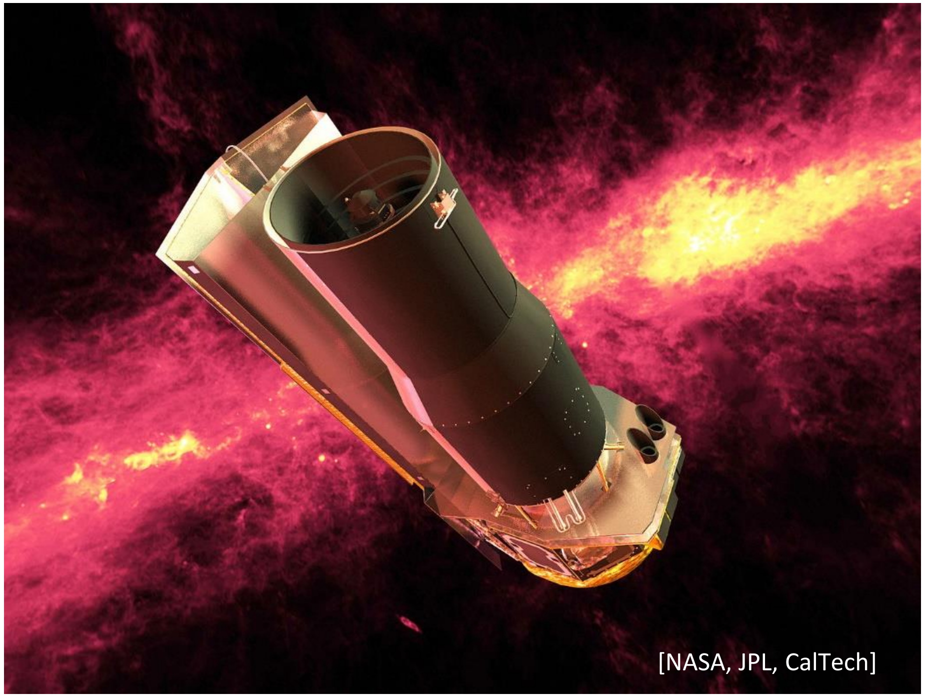
(Serpens constellation, northern hemisphere)

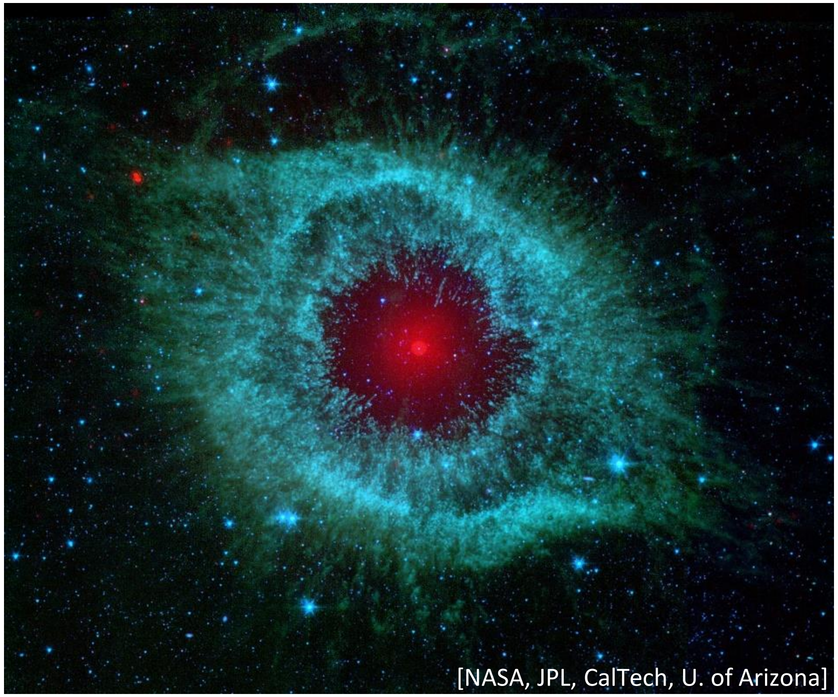
Wavelengths: near-IR, visible, ultraviolet.

Main mirror diameter: D = 2.4 m

Angular resolution: $\theta_{min} \sim 0.05'' = 50\ mas$

# Spitzer Telescope


[NASA, JPL, CalTech]


[NASA, JPL, CalTech, U. of Arizona]

Wavelengths: mid-infrared to far-infrared.

Main mirror diameter: D = 0.85 m

Angular resolution: $\theta_{min} \sim 1''$ at 3.6 µm
$\theta_{min} \sim 48''$ at 160 µm

Helix Nebula: constellation Aquarius.
→ distance = 600 ly.

blue = 3.6 - 4.5 µm, green = 5.8 - 8 µm, red = 24 µm