Exoplanets with The James Webb Space Telescope

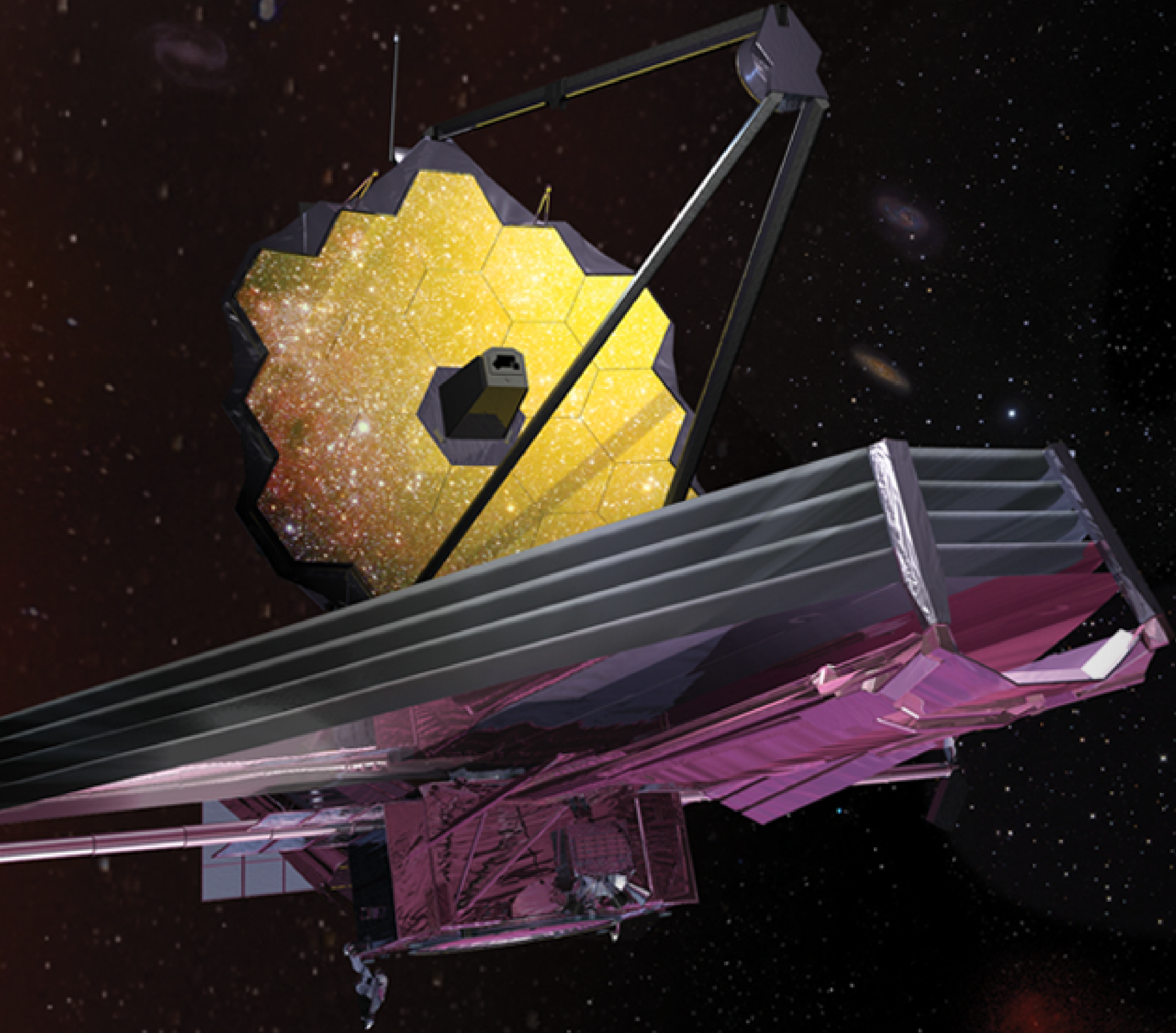
Benjamin Pope,

University of Queensland

Who Am I?

- From Jannali, NSW
- Honours/Masters in physics at University of Sydney
- DPhil in Astrophysics at Balliol College, Oxford
- NASA Sagan Fellow at New York University
- Lecturer in Astrophysics at the University of Queensland

JWST First Images

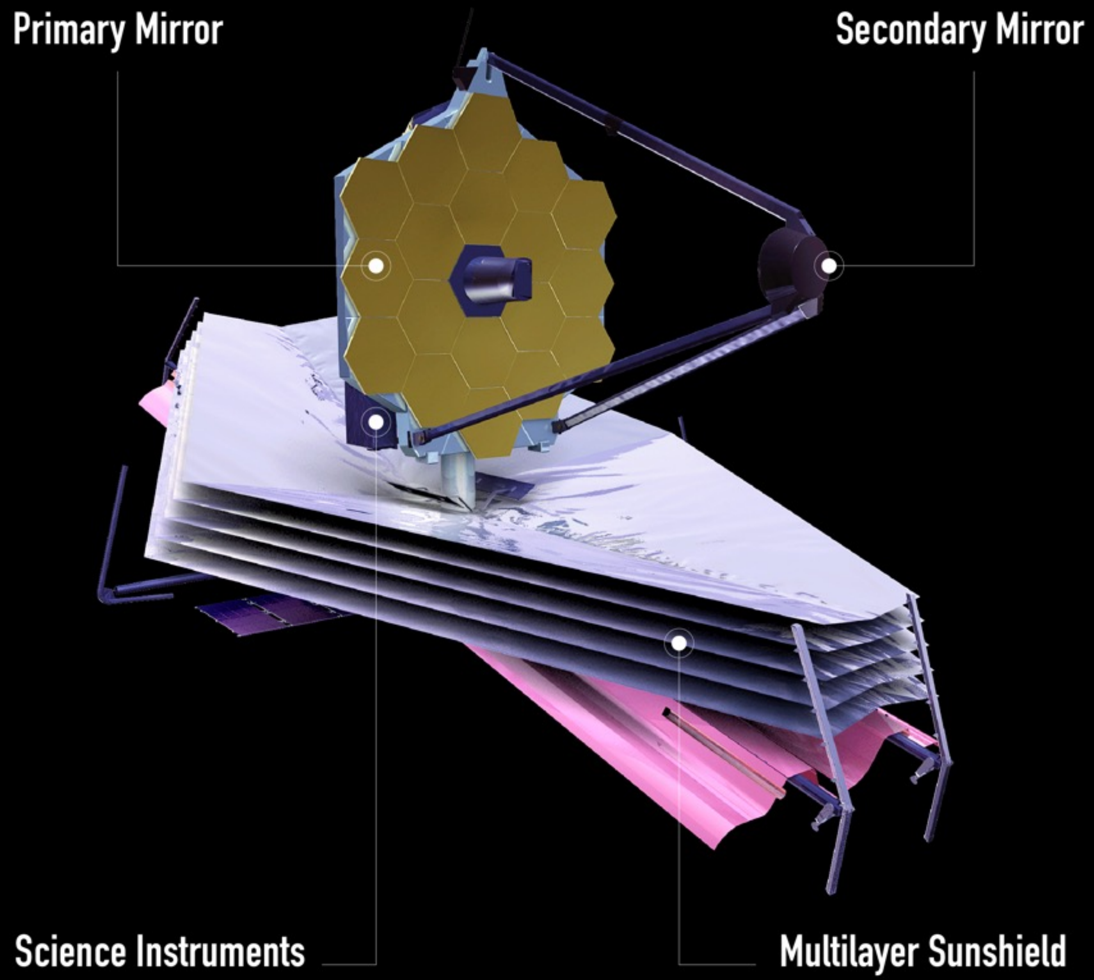


National Aeronautics and
Space Administration

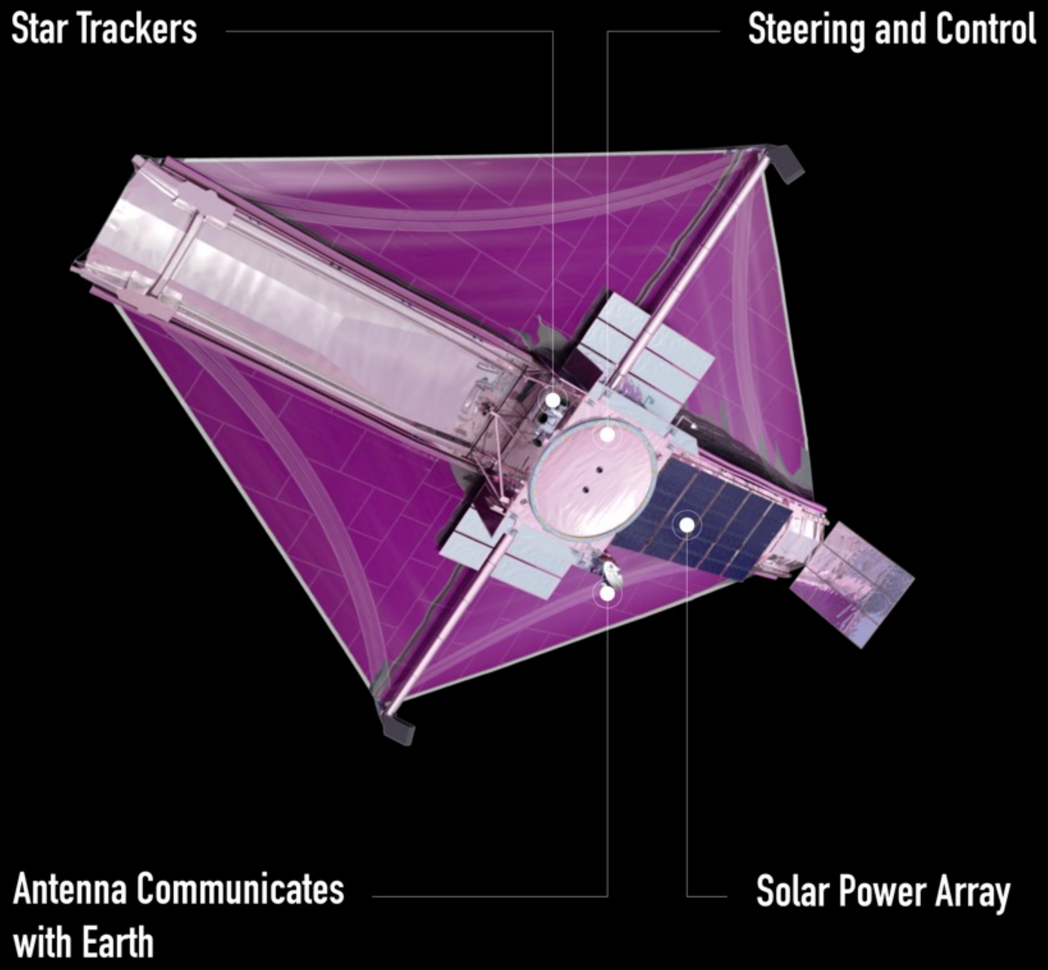
Webb's First Look at the Universe

Lift Off!

Observing Side

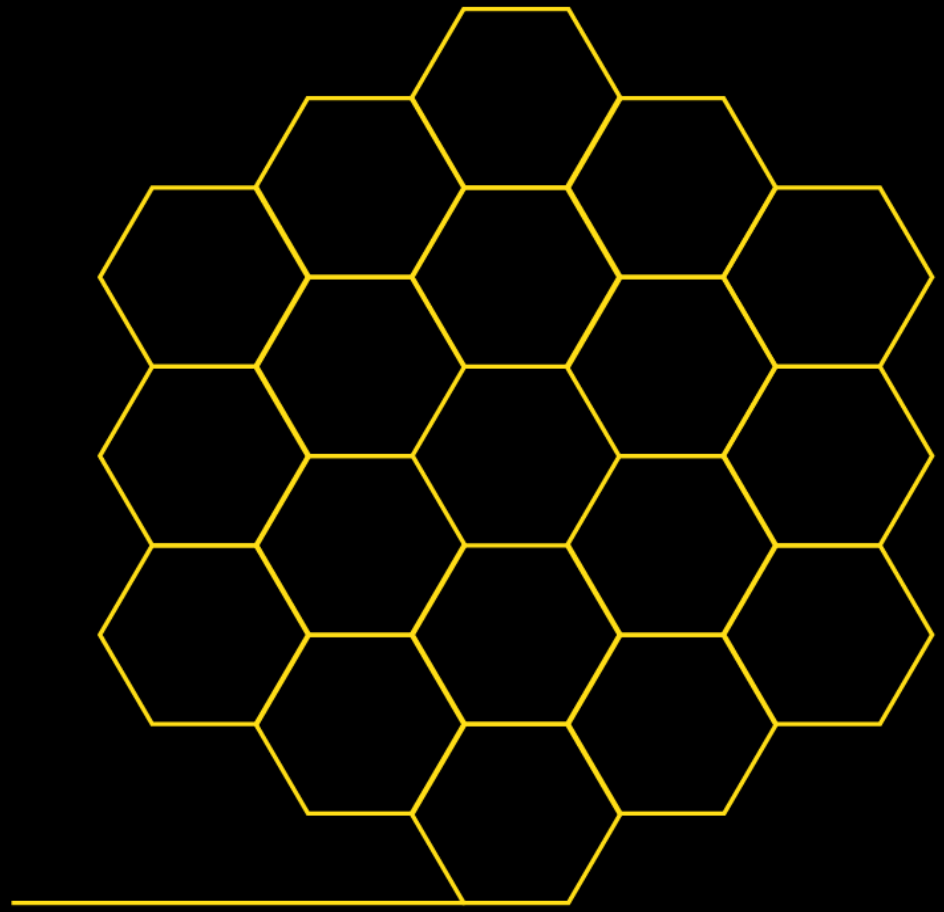


Sun-Facing Side



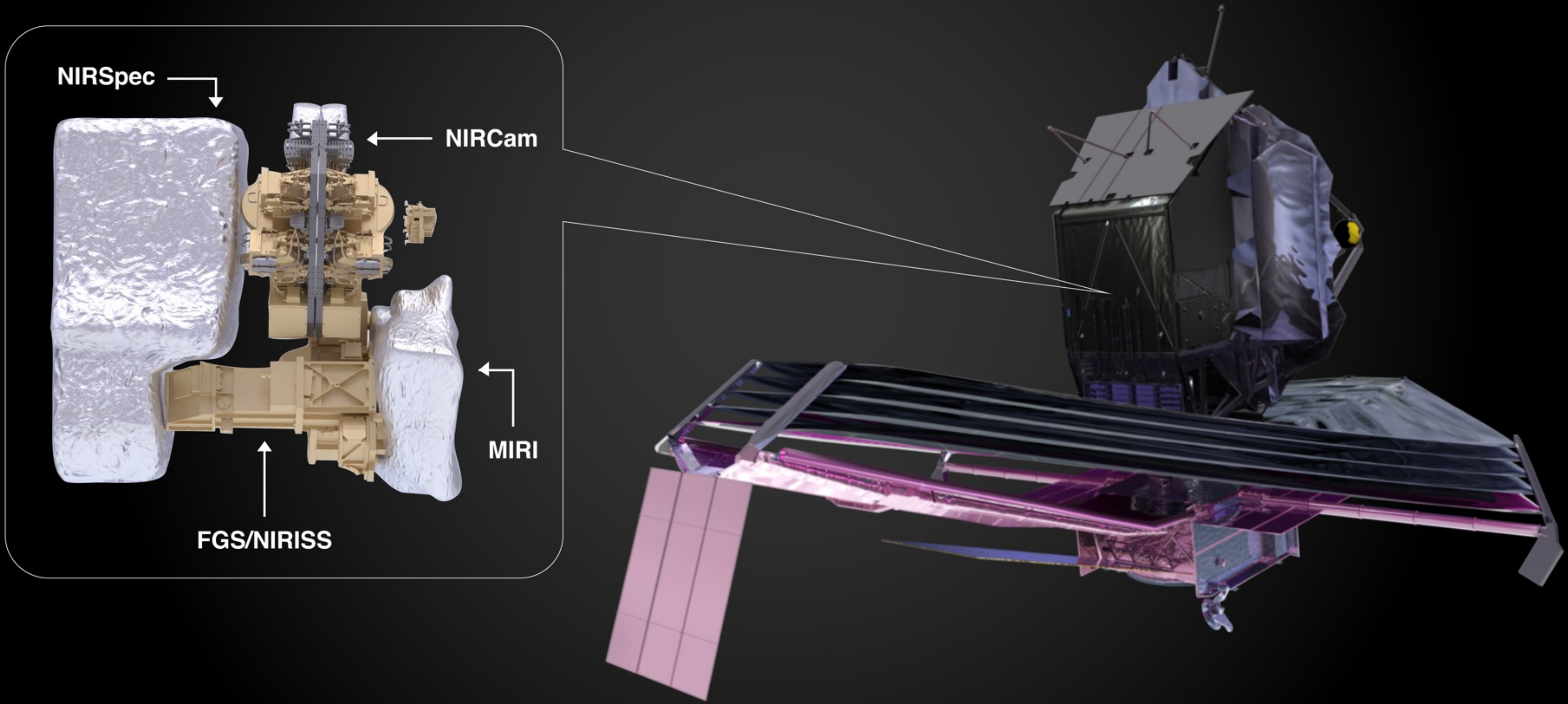
Capturing Faint, Infrared Light

Hubble's PRIMARY MIRROR

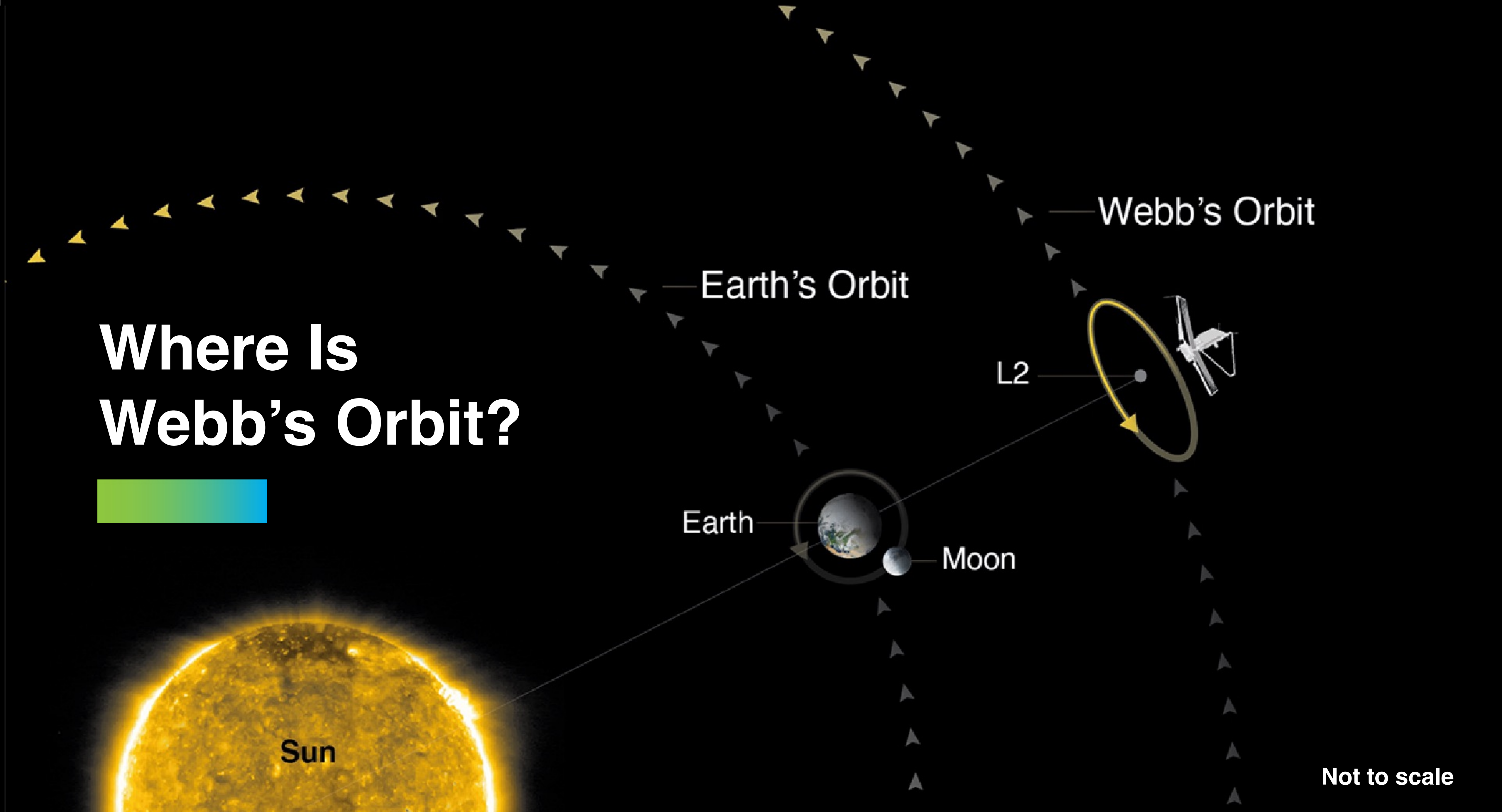


Webb's PRIMARY MIRROR

Webb’s Science Instruments



Where Is Webb's Orbit?

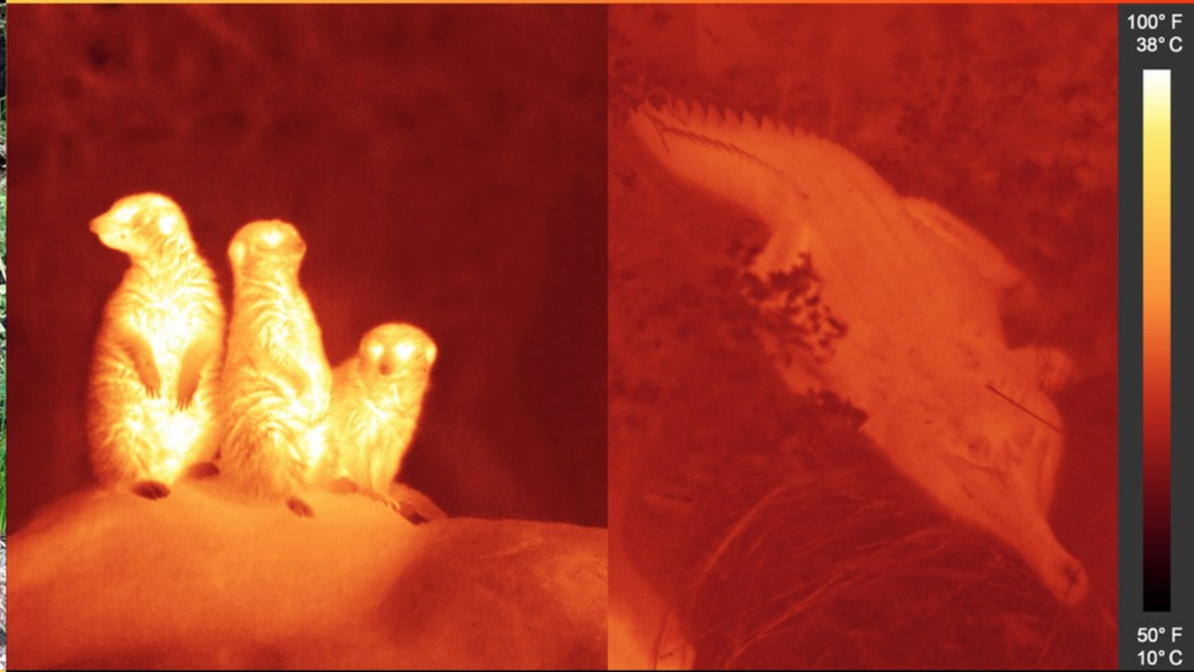


Why Study Infrared Light?

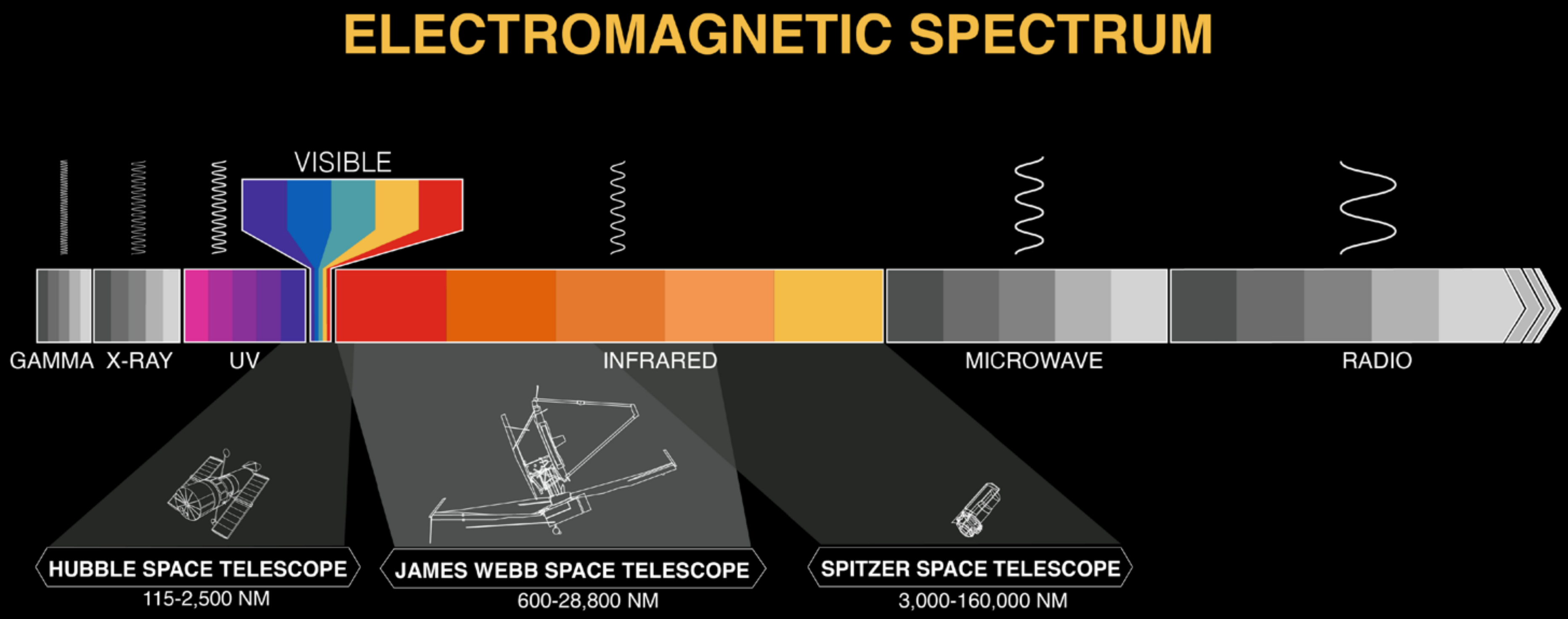
Visible vs. Infrared Light

Meerkats

Freshwater crocodile



Webb's Specialization in Infrared Light



Webb Can Peer Through *and* Examine Dust

Visible Light (ESO)

Near-Infrared Light (ESO)

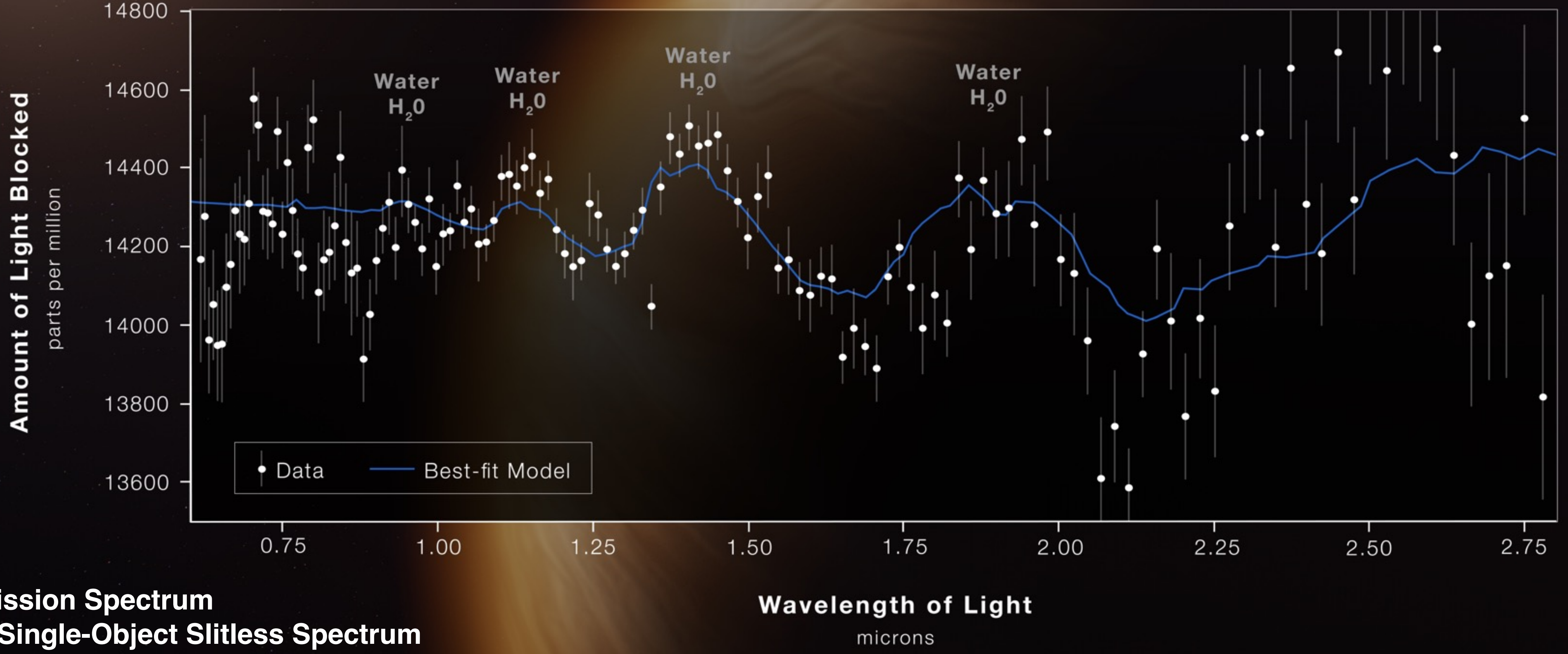
Mid-Infrared Light (Spitzer)

The Big Reveal: Webb’s First Observations

Webb's First Deep Field
SMACS 0723

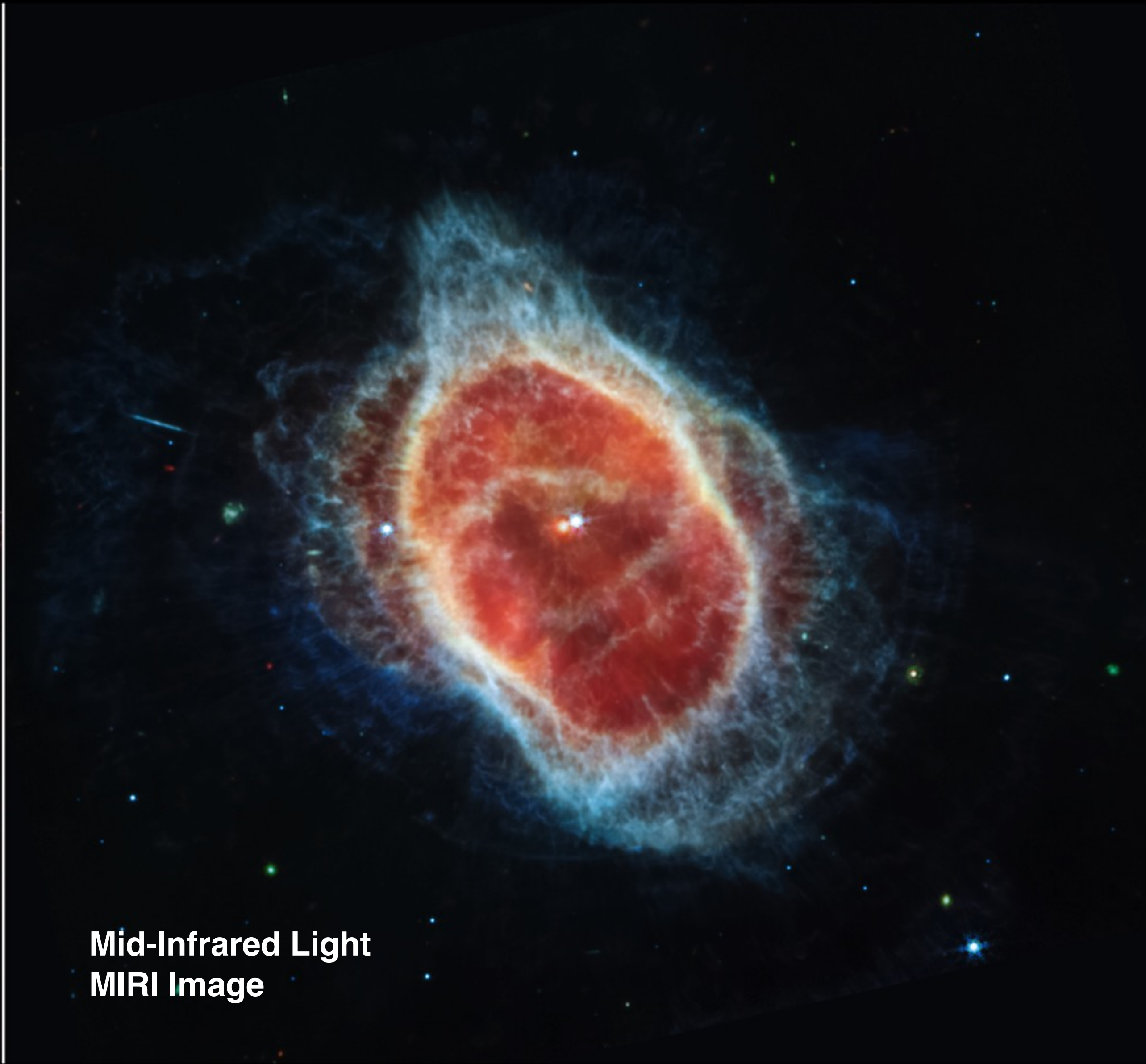
Near-Infrared Light
NIRCam Image

Exoplanet | WASP-96 b



Transmission Spectrum
NIRISS Single-Object Slitless Spectrum

Planetary Nebula | Southern Ring Nebula



Interacting Galaxies
Stephan’s Quintet

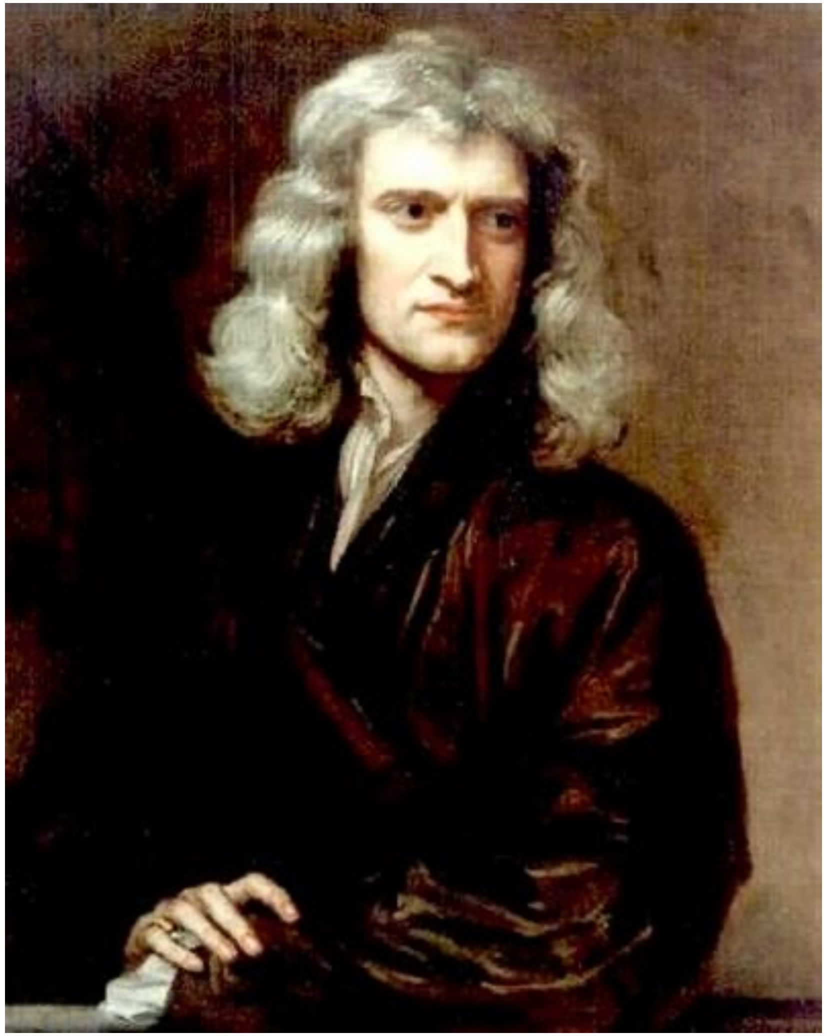
Near- and Mid-Infrared Light
Combined NIRCam and MIRI Image

Star-Forming Region I Carina Nebula

Aperture Masking Interferometry

Newton Describes The Seeing Problem

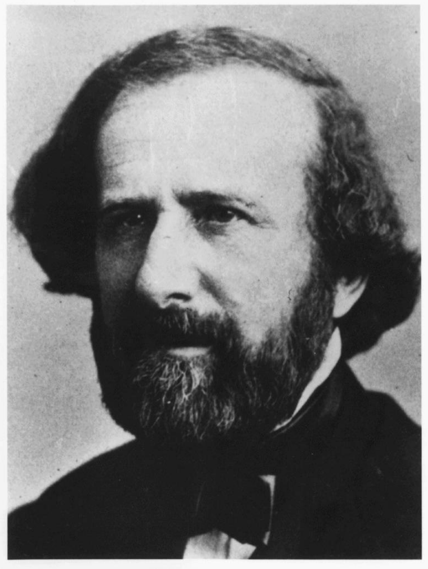
Isaac Newton



Opticks, 1704

"If the theory of telescopes could at length be fully brought into practice, yet there would be bounds beyond which telescopes could not perform. For the Air through which we look upon the stars, is in perpetual Tremor, as may be seen by the tremulous motion of shadows cast from high towers, and by the twinkling of the fix'd Stars … those many trembling points, confusedly and insensibly mixed with one another … thereby cause the star to appear broader than it is … Long telescopes may cause objects to appear brighter and larger than short ones do, but they cannot be so formed as to take away that confusion of the Rays which arises from the Tremors of the Atmosphere. The only remedy is a most serene and quiet air, such as may be found on the tops of the highest mountains above the grosser clouds"

1867 – Fizeau suggests Stellar Interferometry



PRIX BORDIN.

QUESTION PROPOSÉE EN 1865 POUR 1867.

(Commissaires : MM. Duhamel, Pouillet, Regnault, Bertrand, Edmond Becquerel, Fizeau rapporteur.)

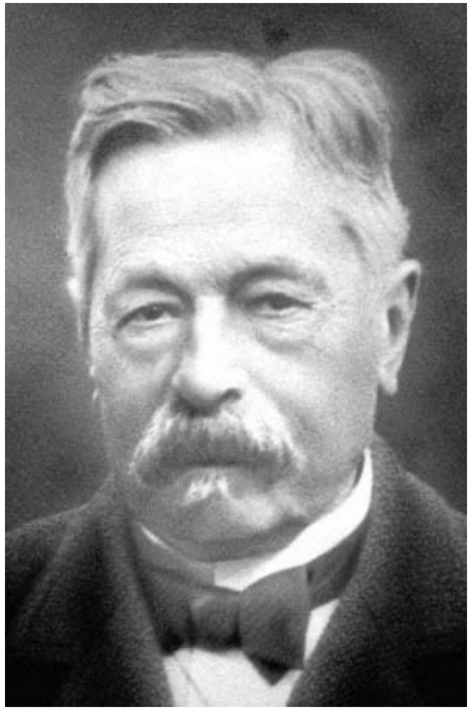
Rapport sur le Concours de l'année 1867.

« *Le prix sera décerné au savant qui aura exécuté ou proposé une expérience*
» *décisive permettant de trancher définitivement la question déjà plusieurs fois*
» *étudiée de la direction des vibrations de l'éther dans les rayons polarisés.* »

Il existe en effet pour la plupart des phénomènes d'interférence, tels que les franges d'Yung, celles des miroirs de Fresnel et celles qui donnent lieu à la scintillation des étoiles d'après Arago, une relation remarquable et nécessaire entre la dimension des franges et celle de la source lumineuse, en sorte que des franges d'une ténuité extrême ne peuvent prendre naissance que lorsque la source de lumière n'a plus que des dimensions angulaires presque insensibles; d'où, pour le dire en passant, il est peut-être permis d'espérer qu'en s'appuyant sur ce principe et en formant par exemple, au moyen de deux larges fentes très-écartées, des franges d'interférence au foyer des grands instruments destinés à observer les étoiles, il deviendra possible d'obtenir quelques données nouvelles sur les diamètres angulaires de ces astres.

Slide courtesy Peter Lawson

Edouard Stephan (1837-1923)



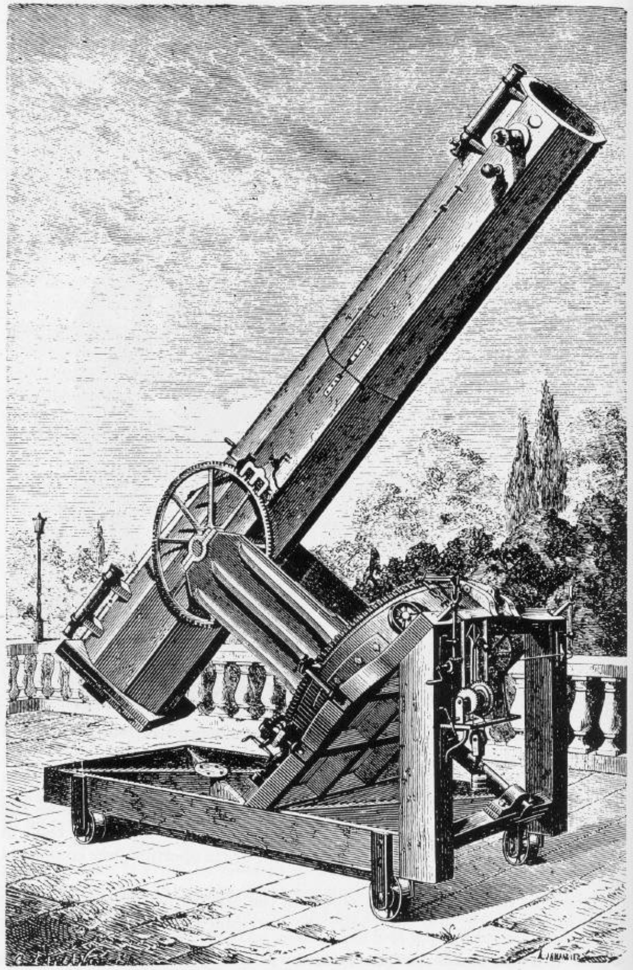


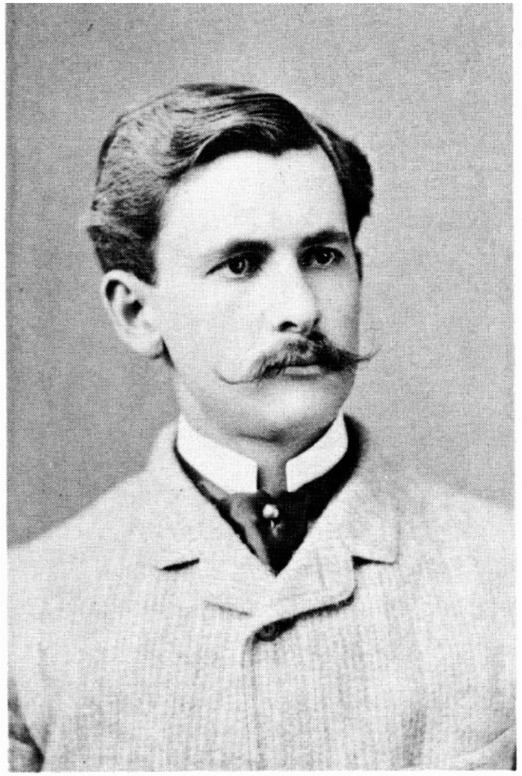
Fig. 5.8. Foucault's largest (80 cm) silver-on-glass reflector, completed in 1862 (reproduced from King [5.2])

1874 E. Stephan uses the Foucault refractor at the Marseilles Observatory to observe most stars down to 4th magnitude.

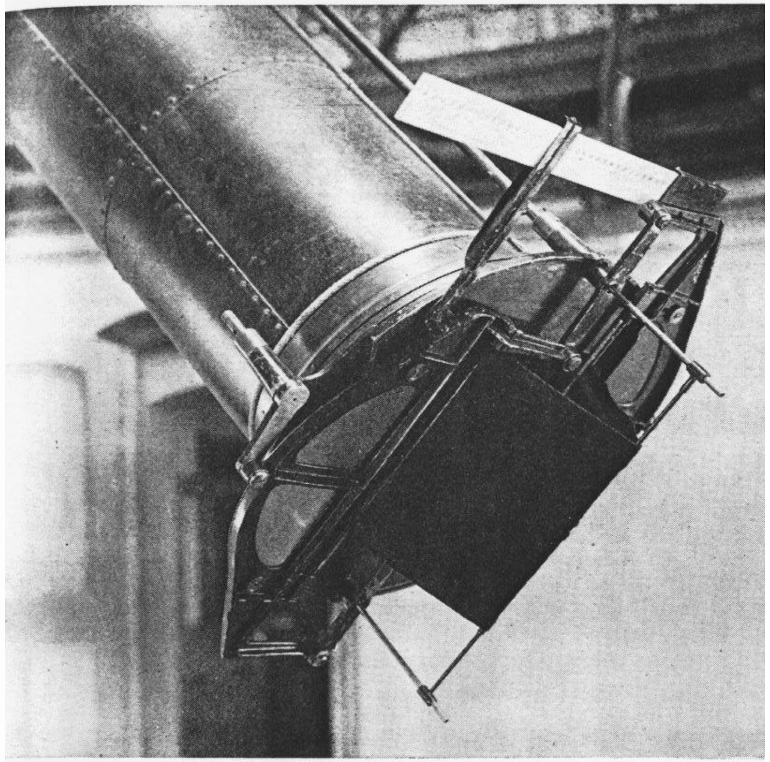
- 65 cm baseline.
- Correctly concludes stars must have diameters much smaller than 0.158 arcseconds.

Slide courtesy Peter Lawson

Michelson and the Moons of Jupiter (1891)

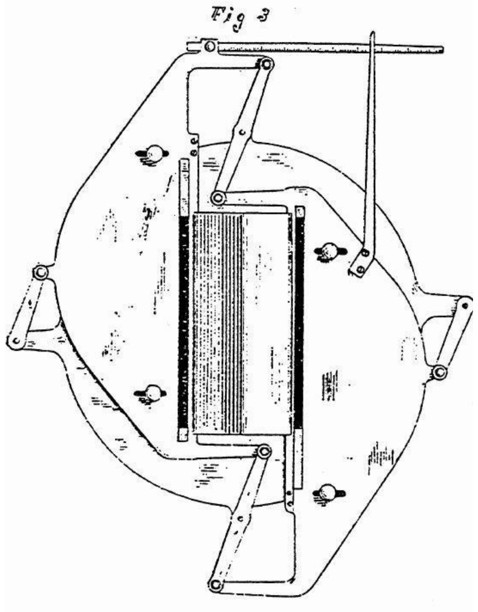


Michelson in 1887, at the time of the Michelson-Morley experiment
(COURTESY CLARK UNIVERSITY ARCHIVES)



Interferometric mask used on the 12-inch refractor at Lick Observatory to measur the angular diameters of the Jovian satellites. The rod adjacent to the telescop tube is turned by the observer, which in turn rotates a lever connecting the two slits immediately exterior to the pictured objective shroud. Photograph courtesy University of California at Santa Cruz Library.

12-inch refractor at Lick



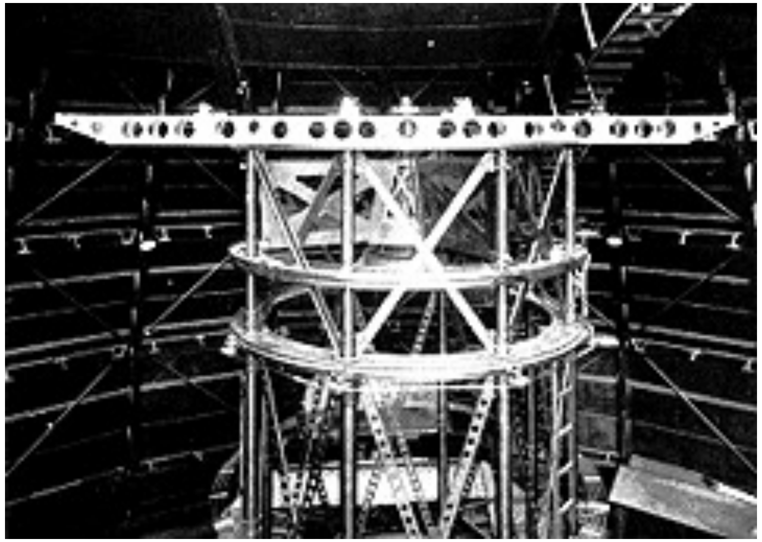
With this apparatus the satellites of Jupiter were measure ith results as given in the following table :—

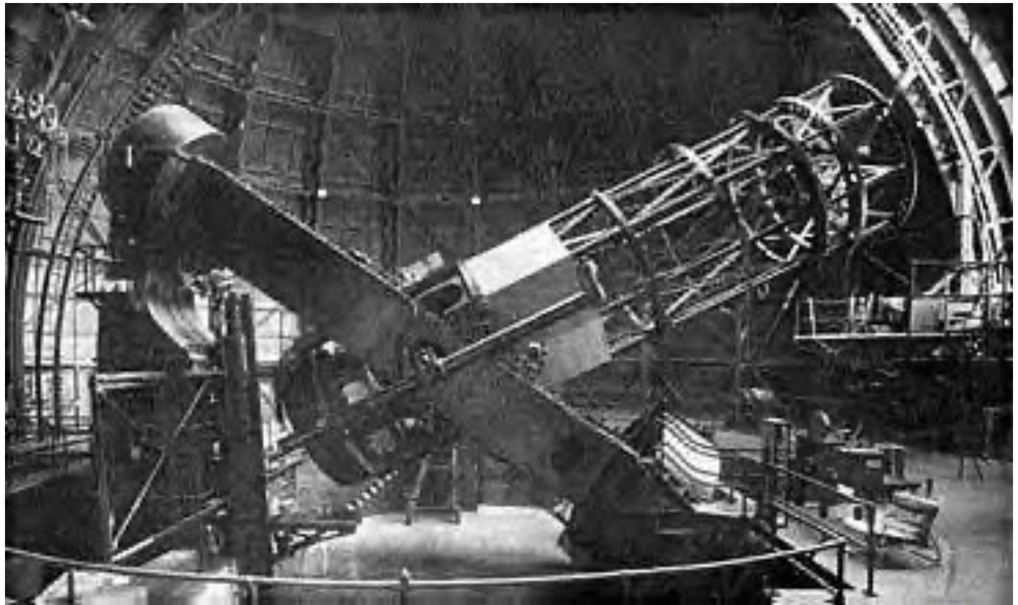
TABLE I.

No. of Satellites.	I.	II.	III.	IV.	Seeing.
August 2 ...	1"29 ...	1"19 ...	1"88 ...	1"68 ...	Poor.
August 3 ...	1·29 ...	— ...	1·59 ...	1·68 ...	Poor.
August 6 ...	1·30 ...	1·21 ..	1·69 ...	1·56 ...	Poor.
August 7 ...	1·30 ...	1·18 ...	1·77 ...	1·71 ...	Good.
Mean...	1·29	1·19	1·73	1·66	

Slide courtesy
Peter Lawson

Michelson and the Mt Wilson 100-inch

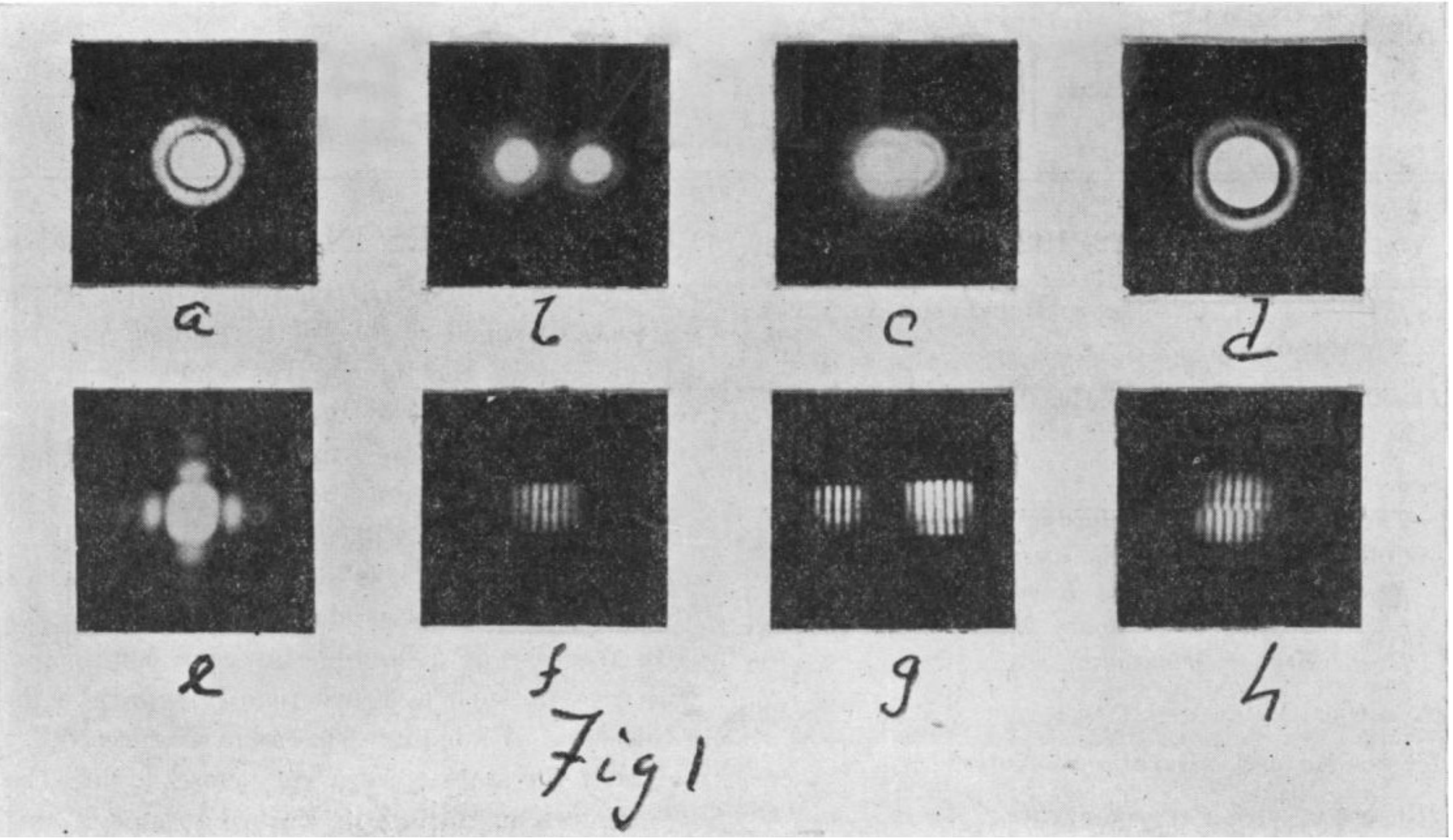




Albert Michelson

- Red Giant Stars
  - **Angular Diameters**
  - **Betelgeuse + others**

Interference and Visibility

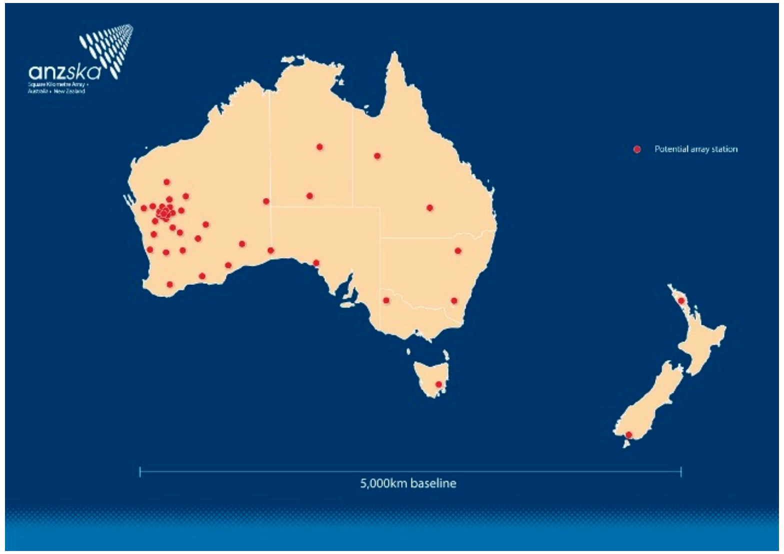


Why Interferometry?

A telescope has a resolution limit given by the ratio of its wavelength to its diameter

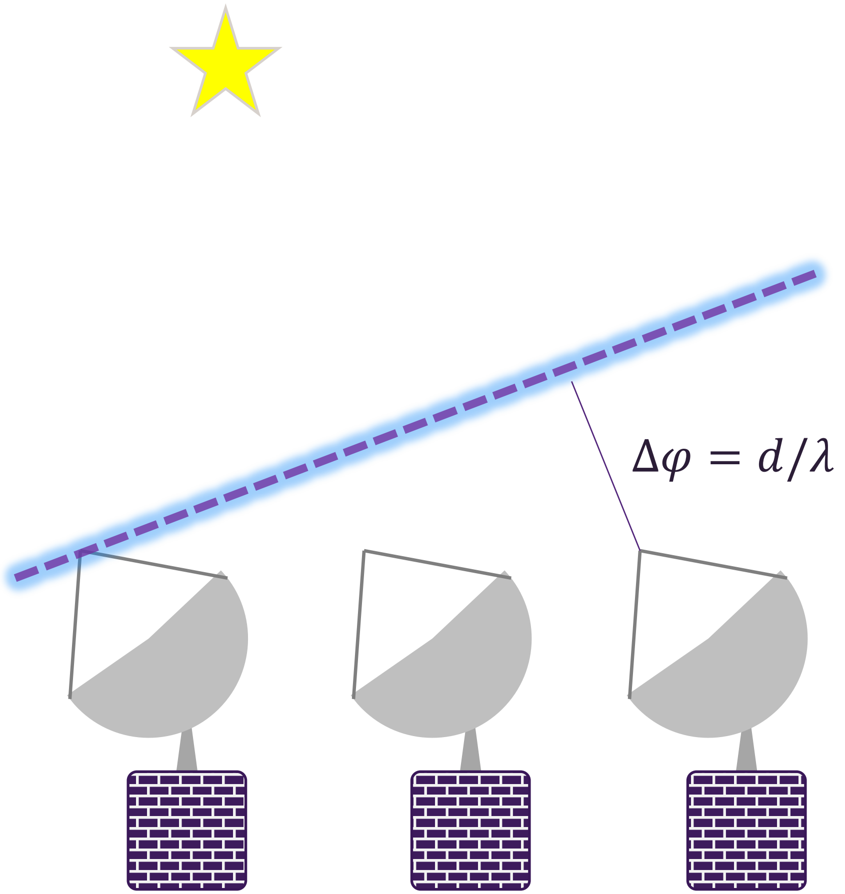
By interfering light from telescopes placed far apart, you get the resolution equivalent to a single telescope as wide as the spacing!

This is how most major radio observatories work – like the upcoming Square Kilometer Array (Australian SKA Pathfinder pictured below)



Interferometry: Phase

The phase delay between two receivers relates to the position of the astrophysical object

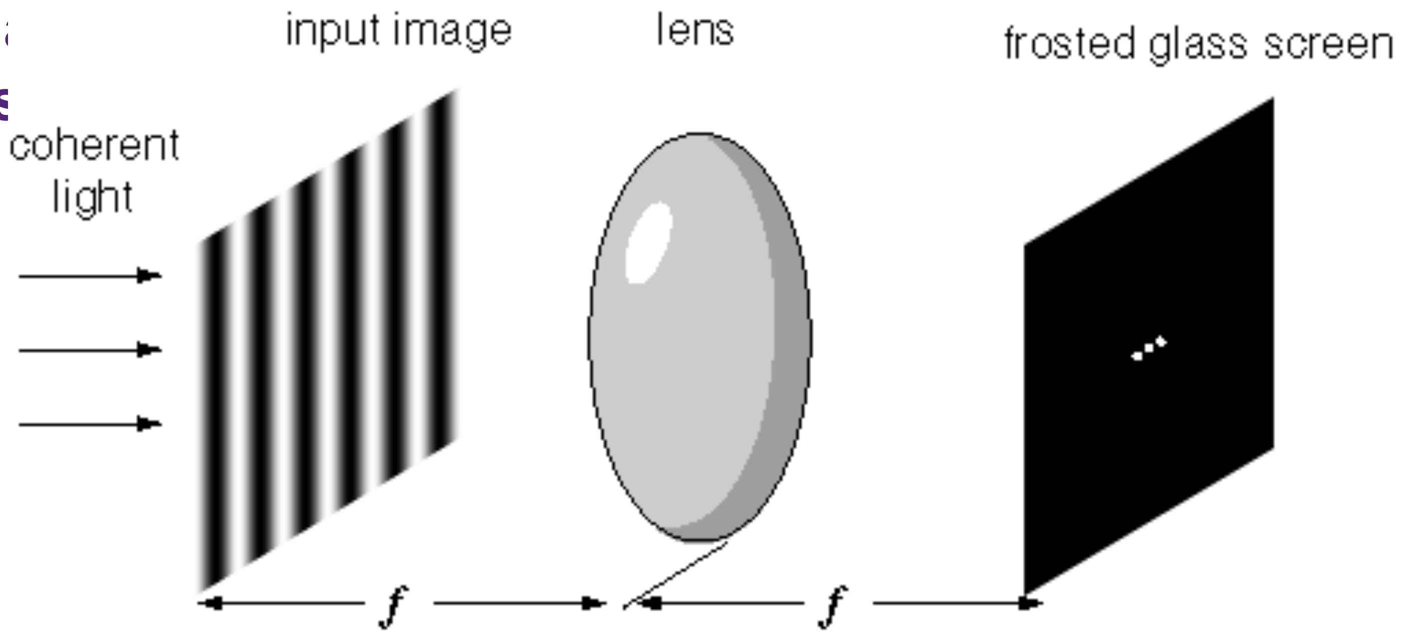


Fourier Transforms

A Fourier transform is just what a lens does to an image

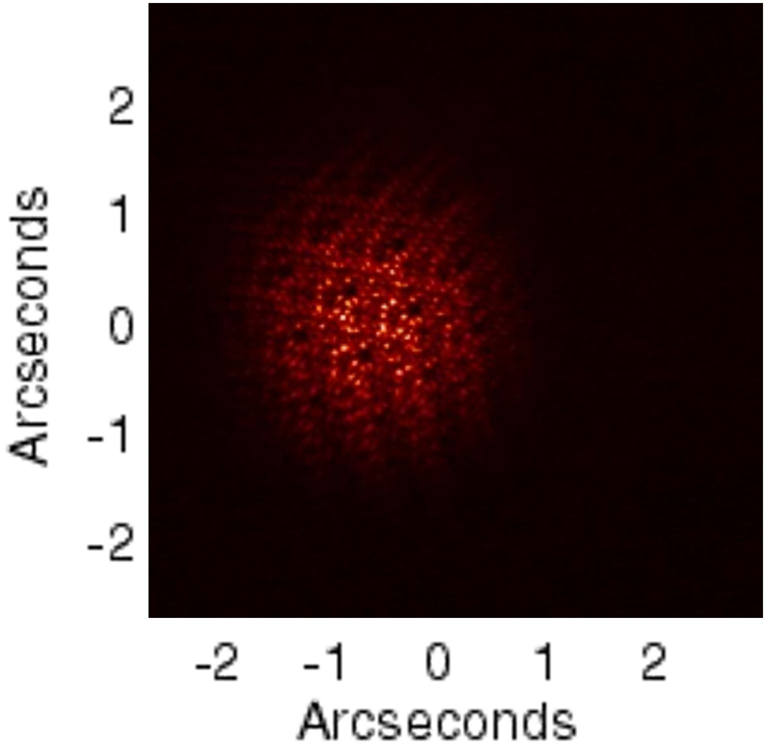
Or an ear to sound!

Splits up an im… …on of the fringes on the s…



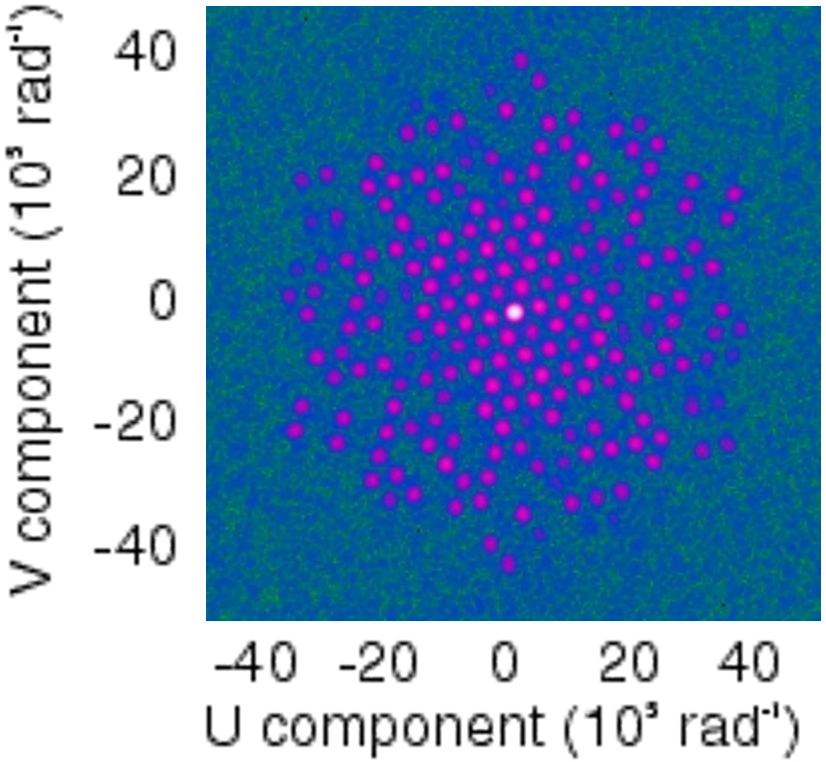
Fast Fourier Transform: Doing that on a Computer!

Image



FFT

Fourier Transform



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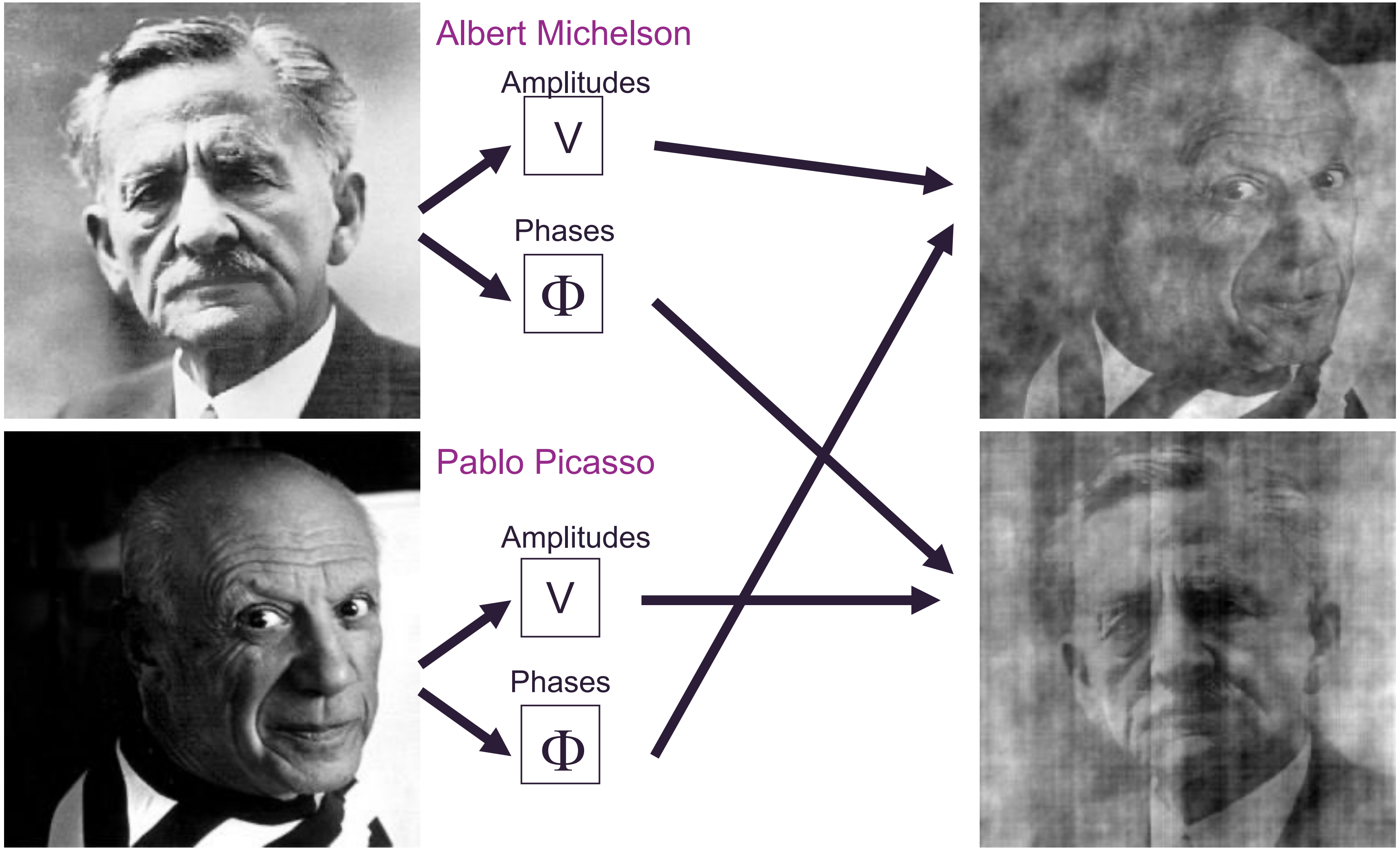
AUSTRALIA

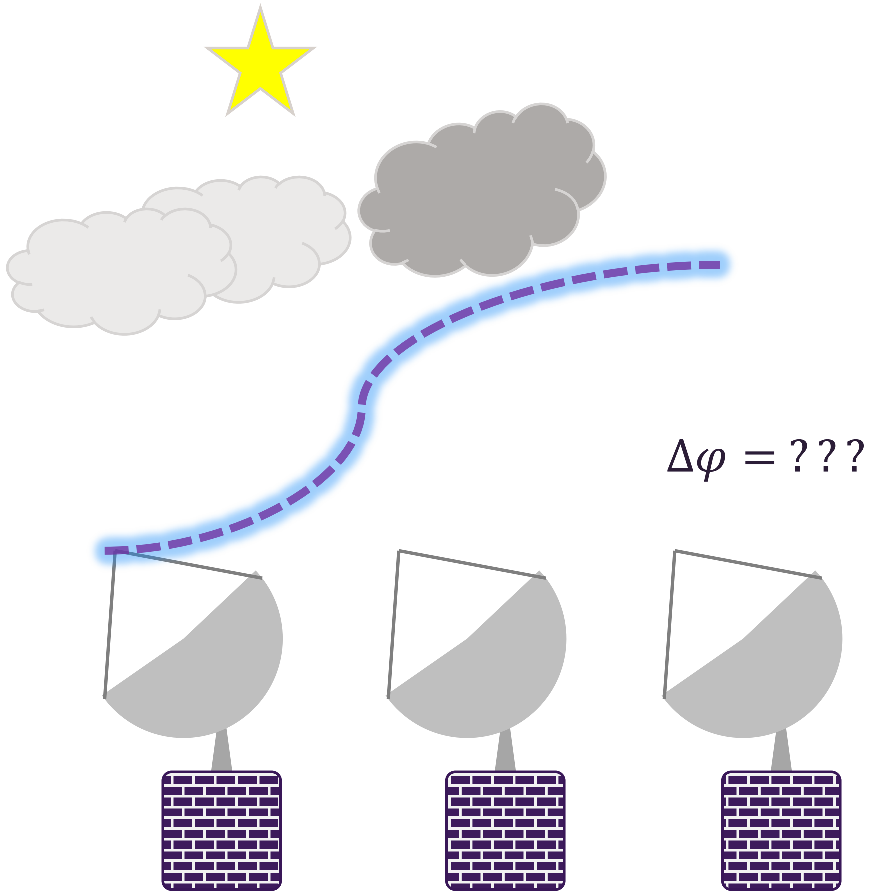
Fourier Amplitudes and Phases



Interferometry: Phase

The phase delay between two receivers relates to the position of the astrophysical object

If the atmosphere disrupts the wavefront, this information is corrupted by errors!



Closure Phase

True phases are encoded on baselines, Φ_{ij}, but errors are on the wavefront and hit each detector separately

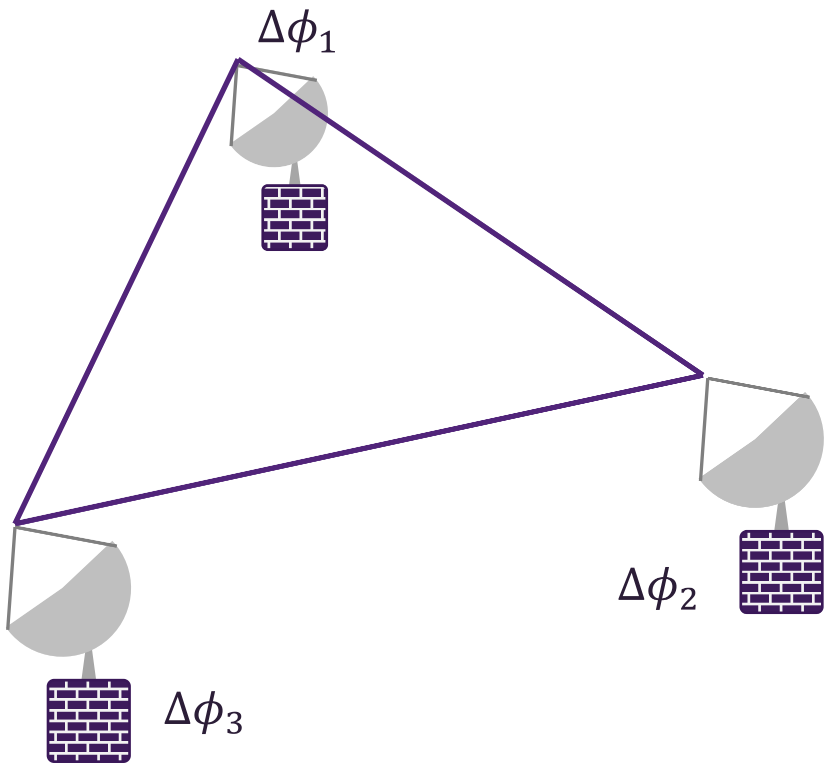
If we add up measured phases ϕ_{ij} around a loop, errors cancel out:

If $\phi_{ij} = \Phi_{ij} + (\Delta\phi_i - \Delta\phi_j)$, then the closure phase

$$\phi_{123} \equiv \phi_{12} + \phi_{23} + \phi_{31}$$

is immune to error:

$$\phi_{123} = \varphi_{12} + \varphi_{23} + \varphi_{31} + 0$$
$$= \Phi_{123}!$$

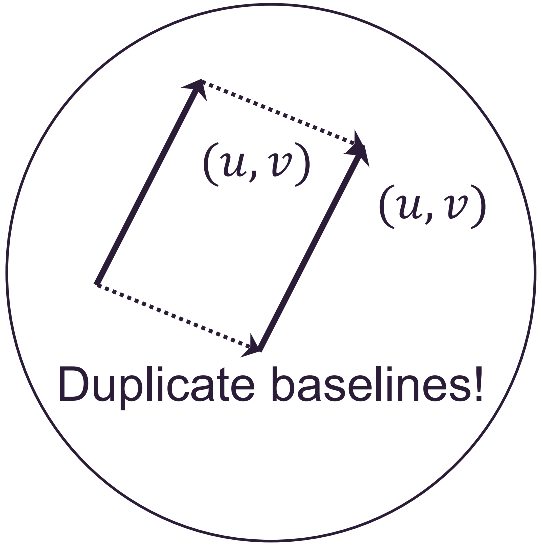


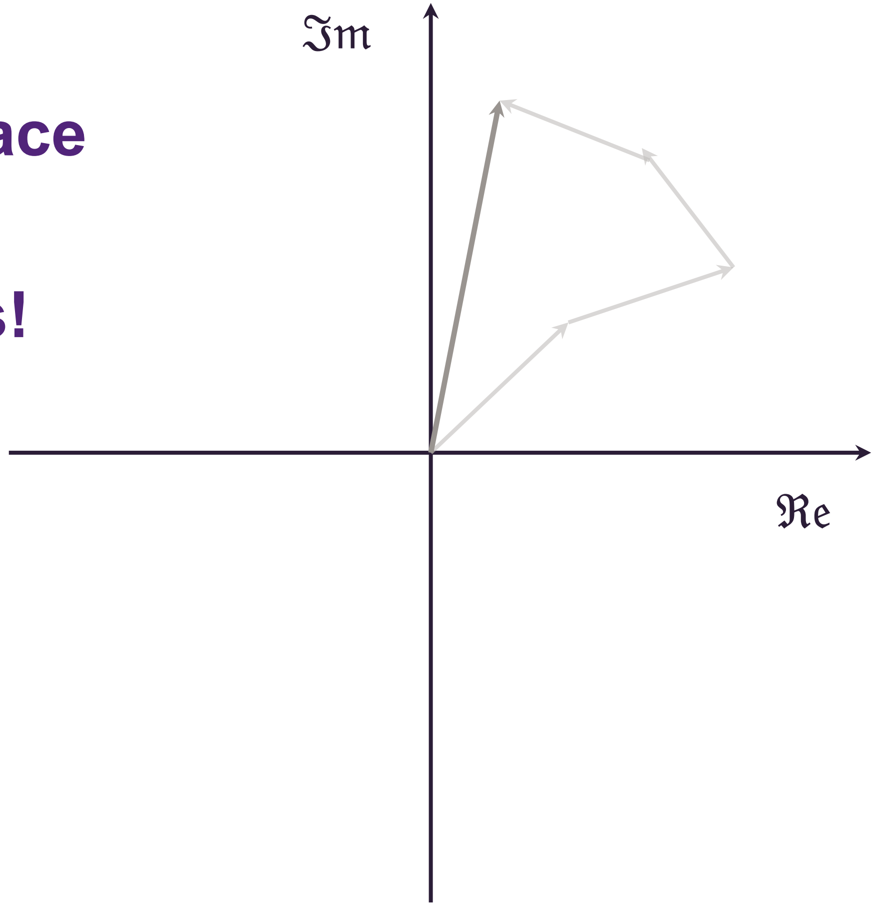
Redundant Baselines

Multiple pairs of points sample each (u, v) baseline.

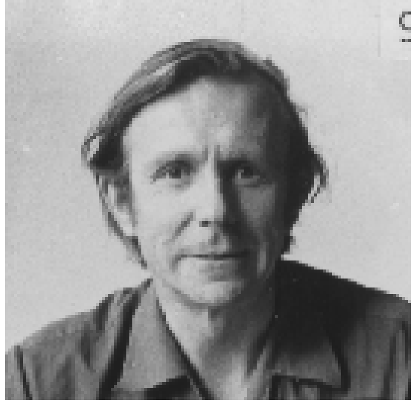
Random walk in the phasor space corrupts image

Closure phase no longer works!

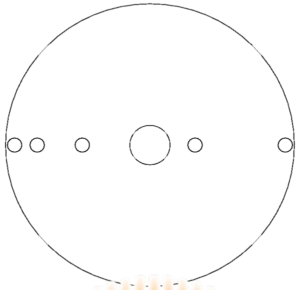


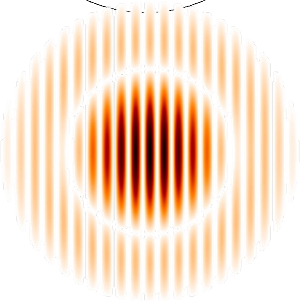


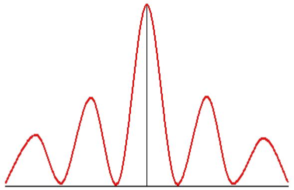
The Modern Renaissance of Masking (1986)



John Baldwin







1st optical Closure Phase

Bob Frater

WHT – La Palma

AAT – Siding Springs

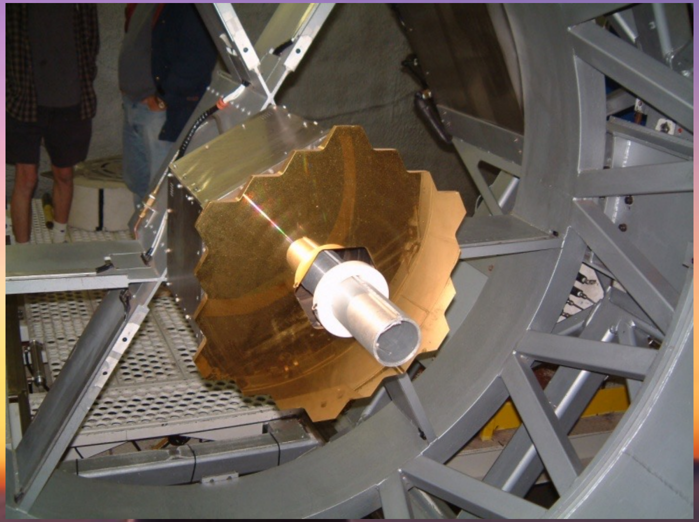
Non-Redundant Masking

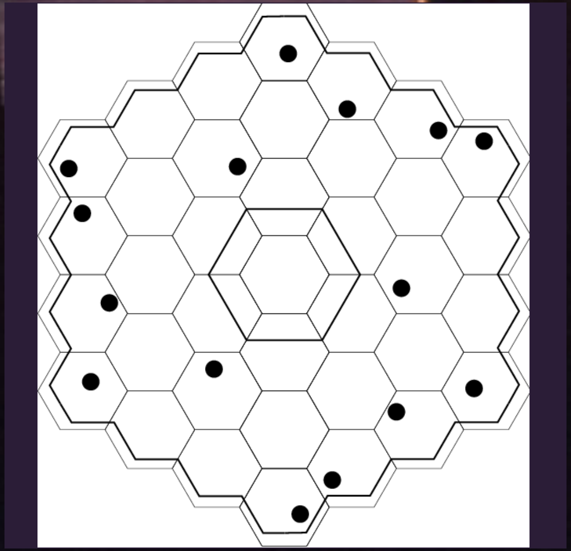
Aperture masks used on NIRC2 (image courtesy of Peter Tuthill).

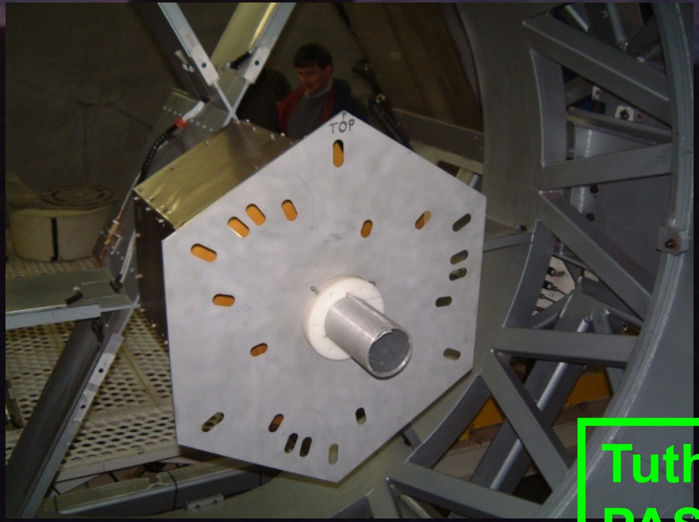
If we put a mask on the telescope aperture and let through only one copy of each baseline, we overcome this problem

Non-redundant masking gives us good amplitude measurements – and also lets us recover some phase information

Masking the Keck

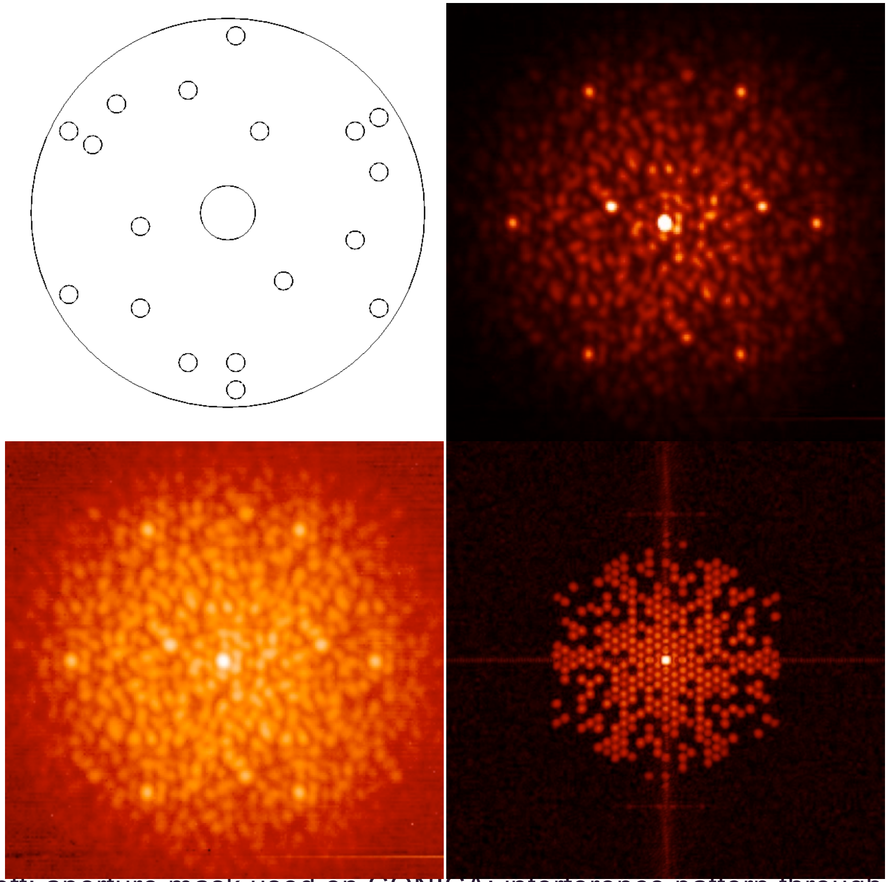






Tuthill et al, PASP 2000

What does NRM Data Look Like?



Clockwise from top left: aperture mask used on CONICA; interference pattern through same mask (linear scale); interference pattern (log scale); power spectrum.

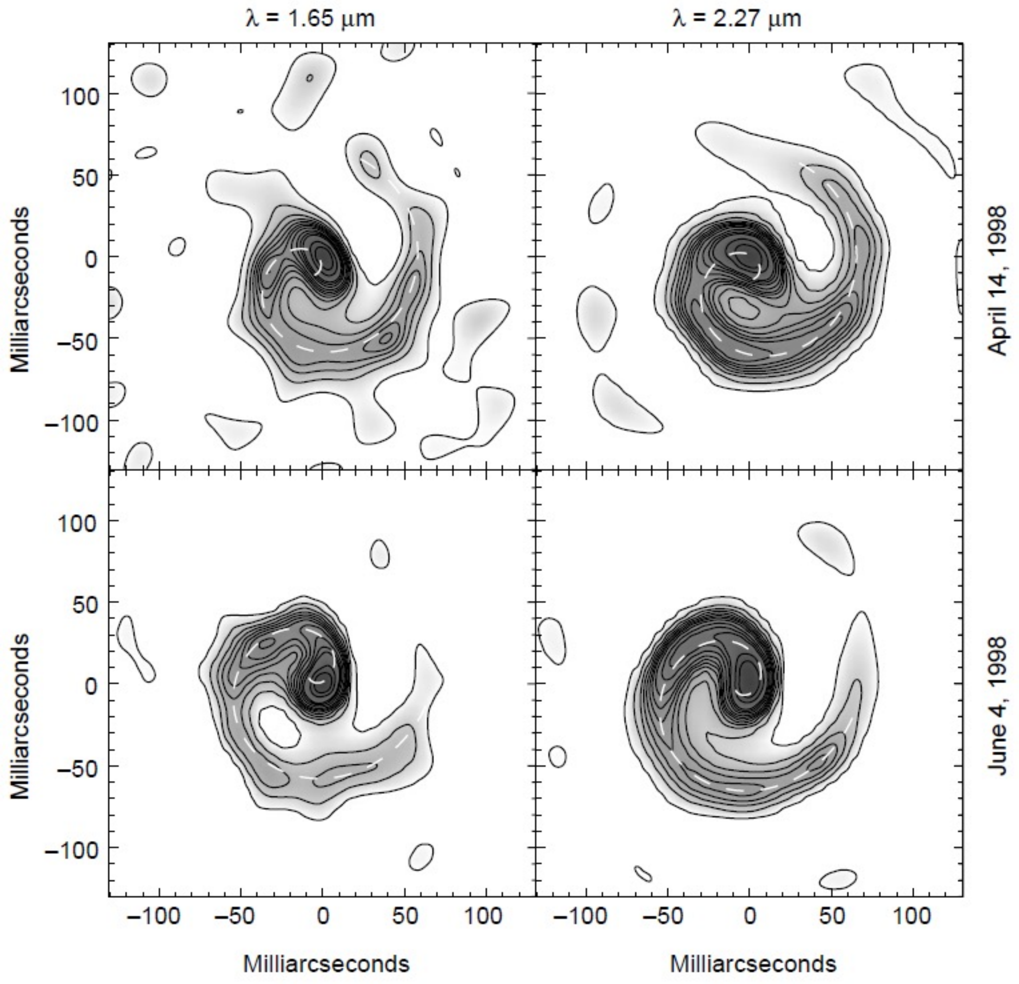
Each dot in the power spectrum (mod-squared Fourier transform) represents the power at some fringe spatial frequency.

Complementary to this is a phase diagram specifying the phase at each frequency.

These yield the 'complex visibilities'

(u, v) **coverage is not complete – NRM leaves gaps where no baseline can be found**

Wolf-Rayet 'Pinwheel' Nebulae



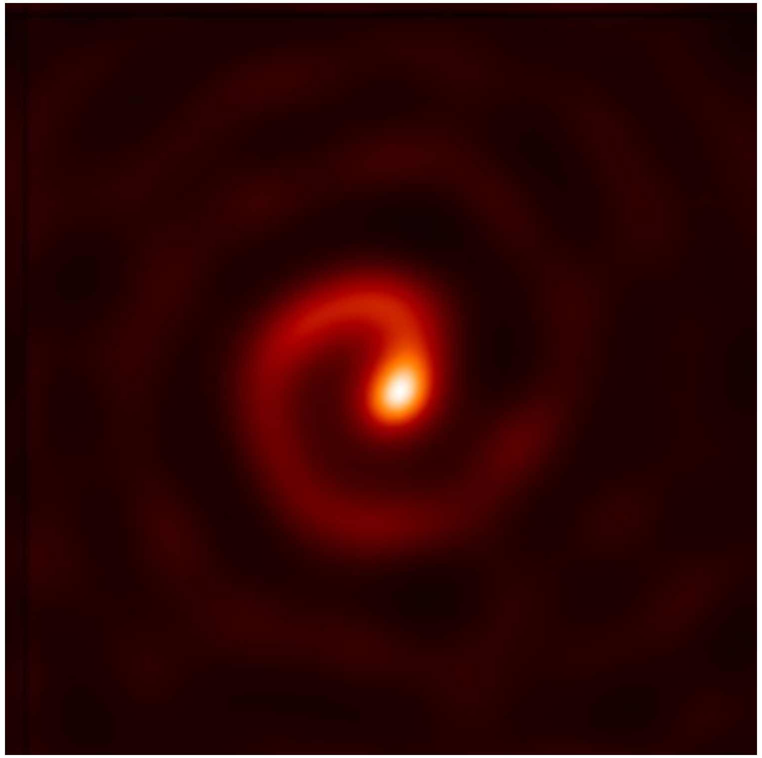
Wolf-Rayet stars are the last stage of the evolution of the most massive stars $(M > 20M_{Sun}\ !)$

This WR binary WR 104 shows IR excess – dust

With near-IR NRM imaging Peter Tuthill and colleagues found this to be a spiral

Jet of dust being formed along the axis between binary stars

Wolf-Rayet ‘Pinwheel’ Nebulae



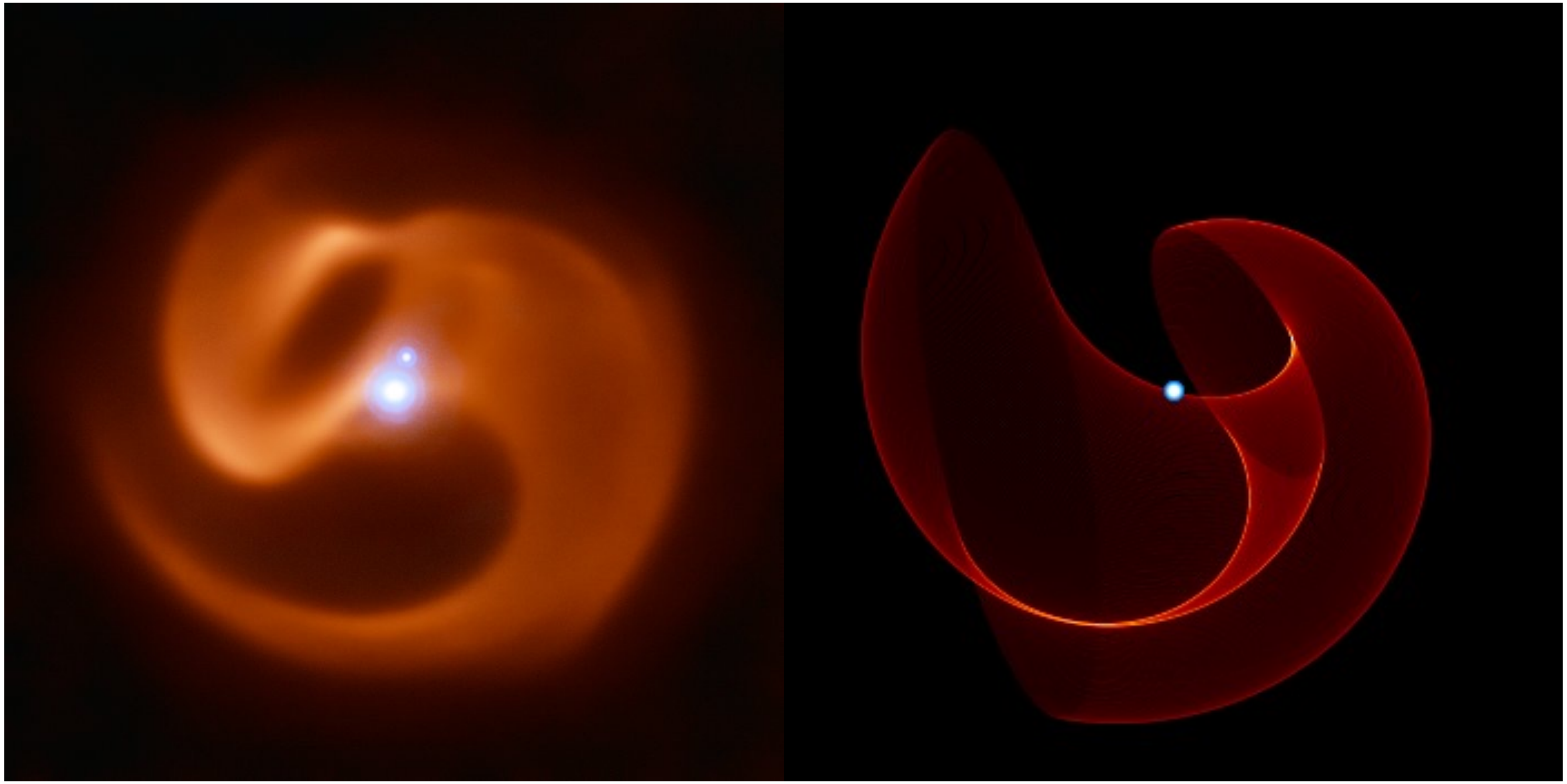
You can see these rotate as time goes by!

WR stars are believed to be the progenitors of some supernovae and gamma ray bursts

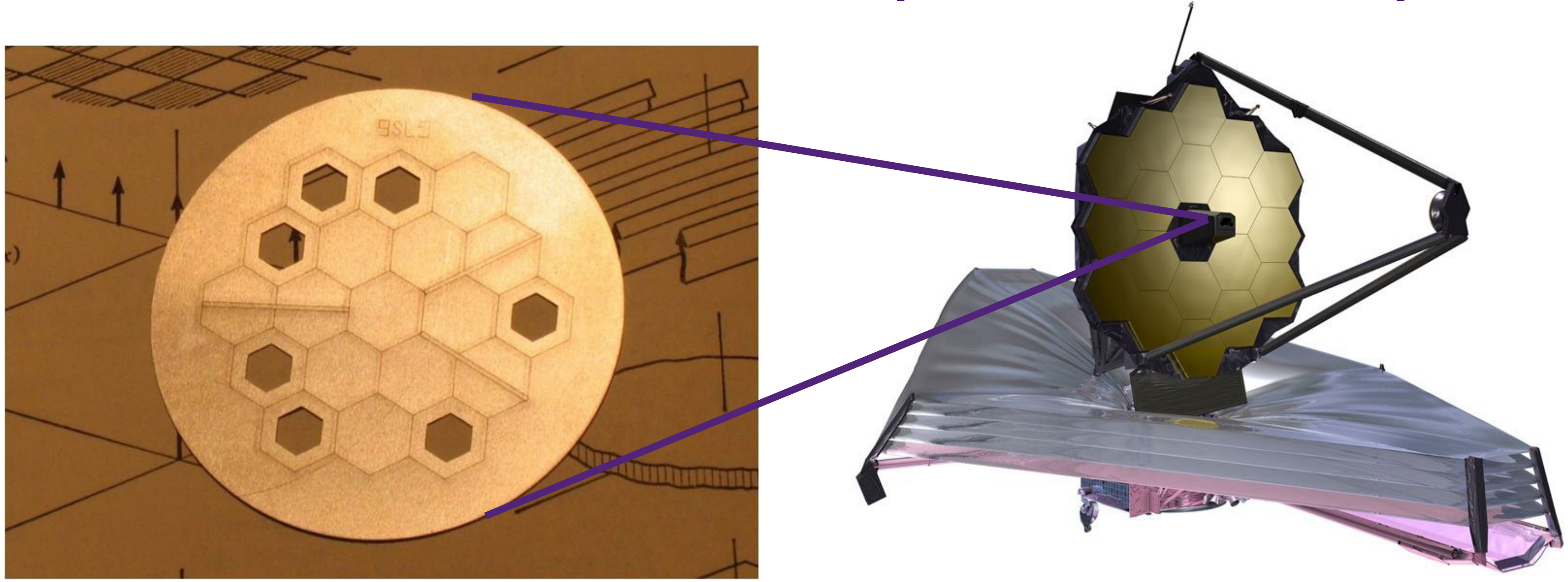
From the shape of this spiral, it looks like we’re staring down the barrel!

Wolf-Rayet 140 with JWST

Apep: Dance of Dragons

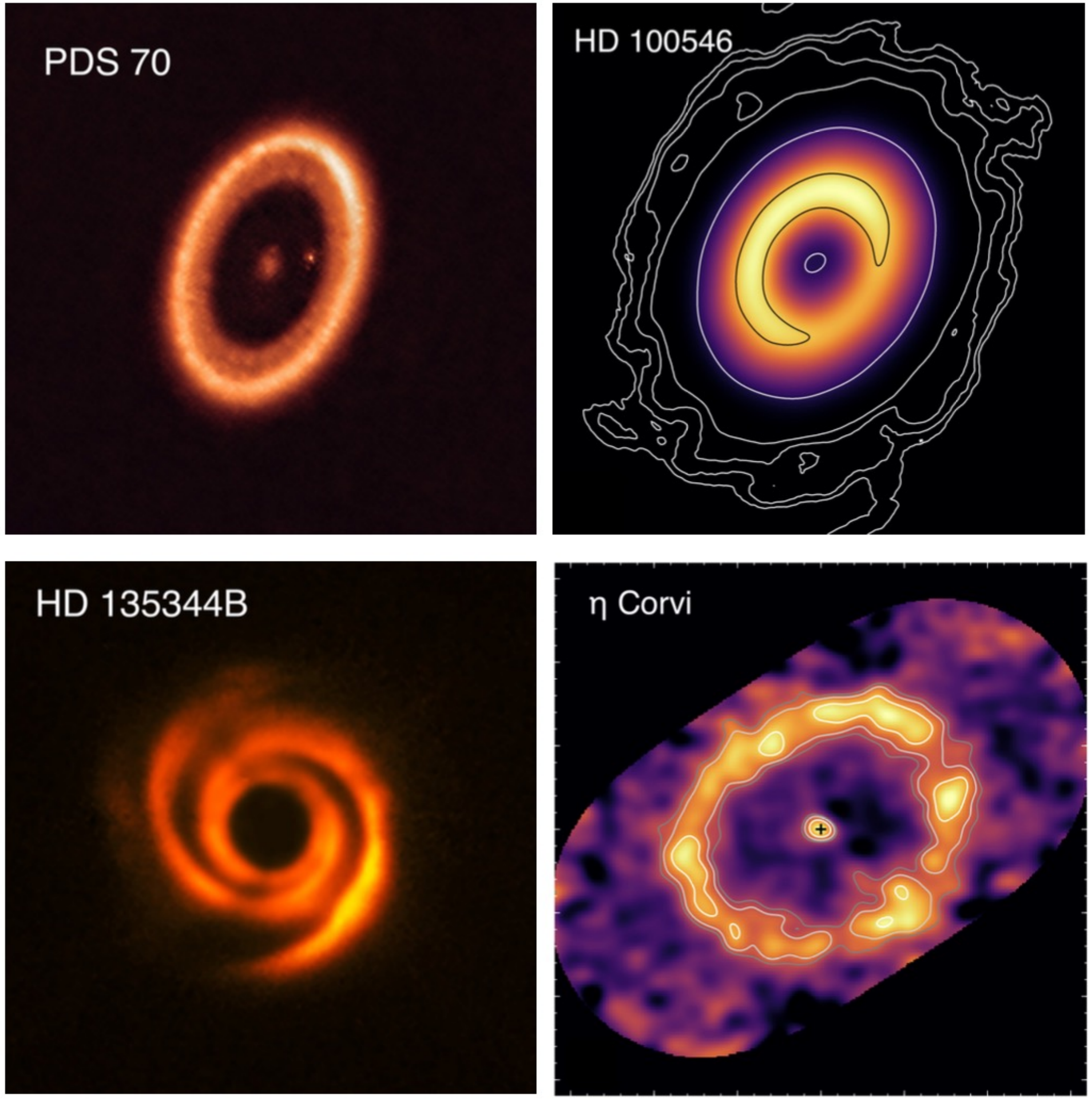


Aberrations on James Webb Space Telescope

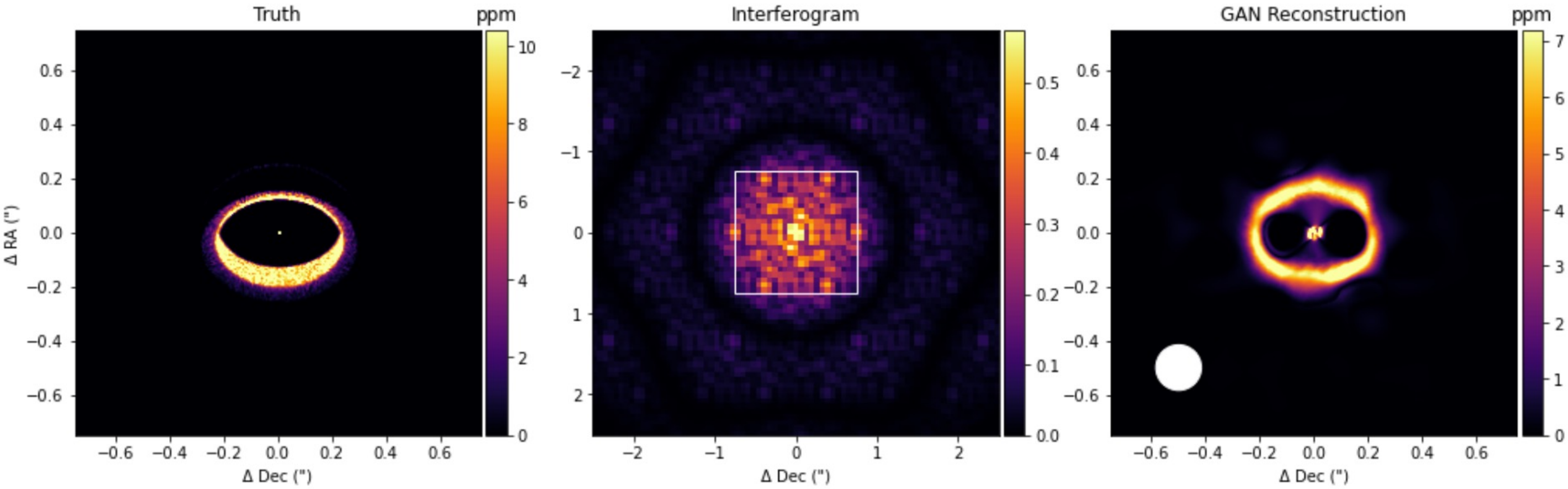


You can use a mask in reverse – to work out what the phase errors are, given an image

Our Observations



Using Machine Learning to Enhance AMI



Questions!