

# Exoplanets with The James Webb Space Telescope

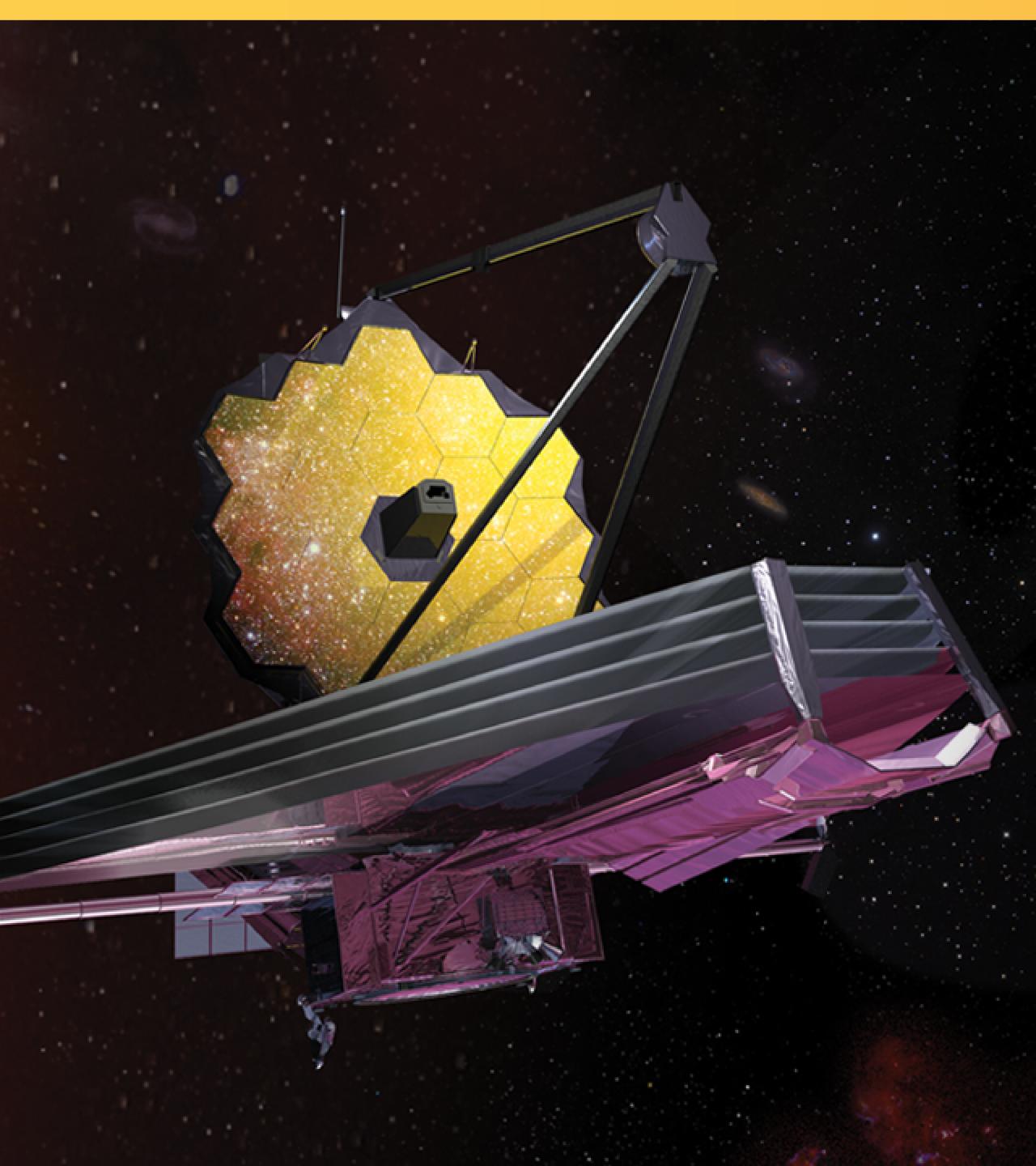
Benjamin Pope,  
University of Queensland

# Who Am I?

- From Jannali
- 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



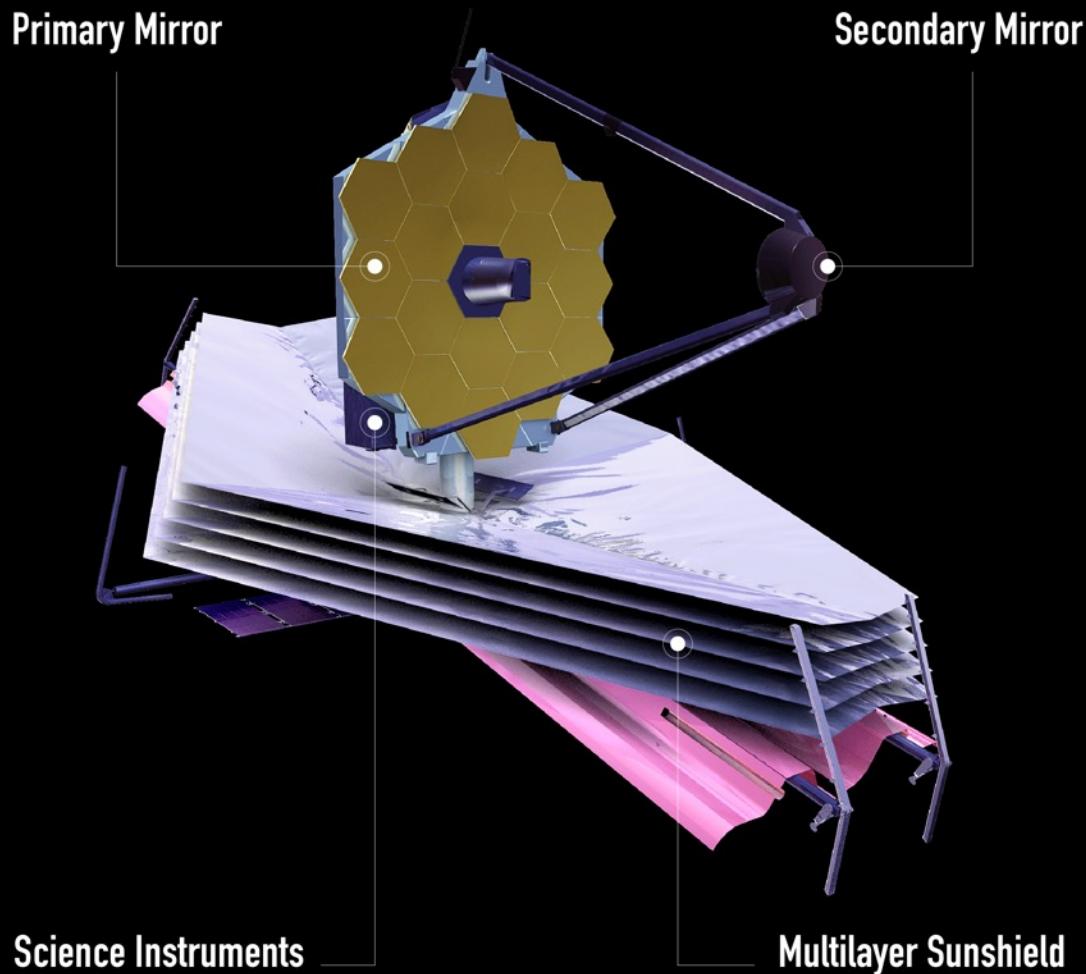
# Webb's First Look at the Universe



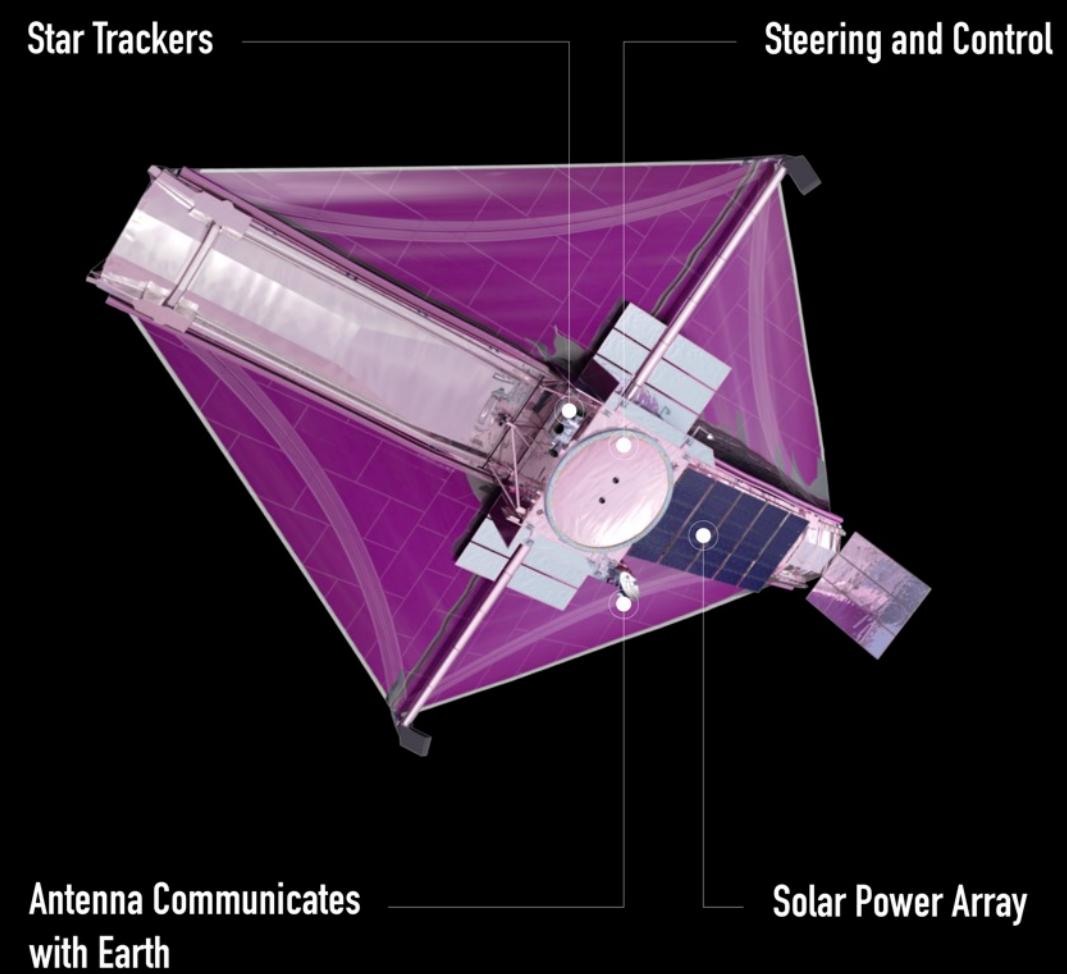
# Lift Off!



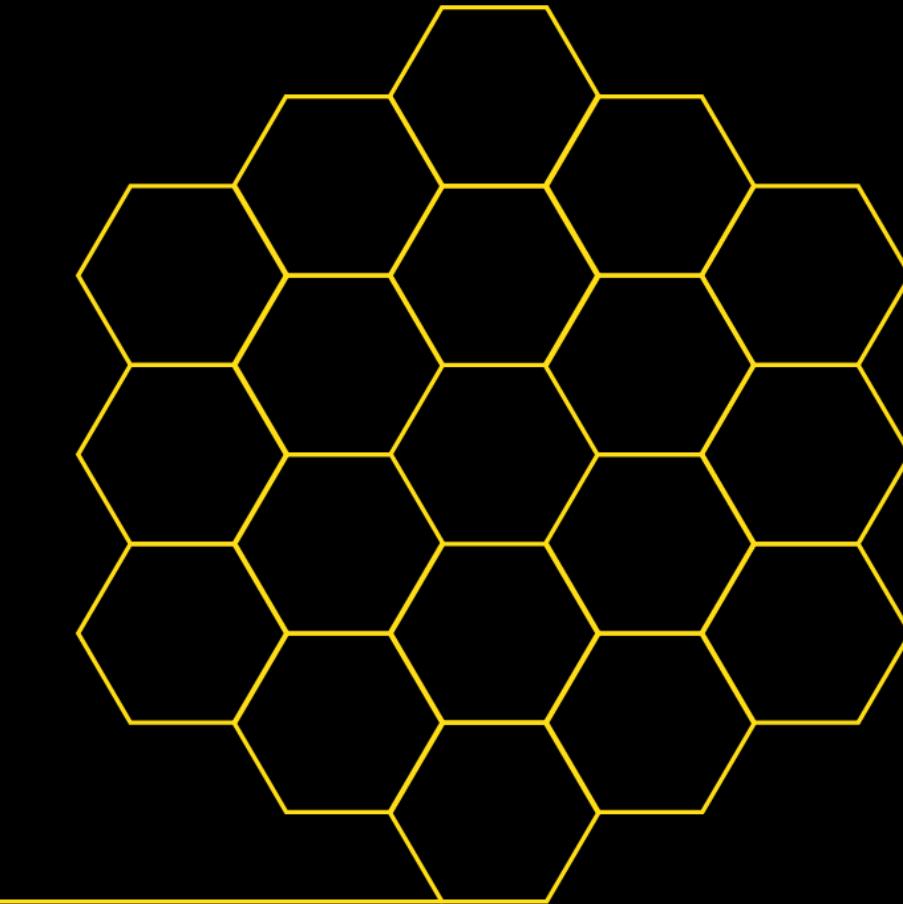
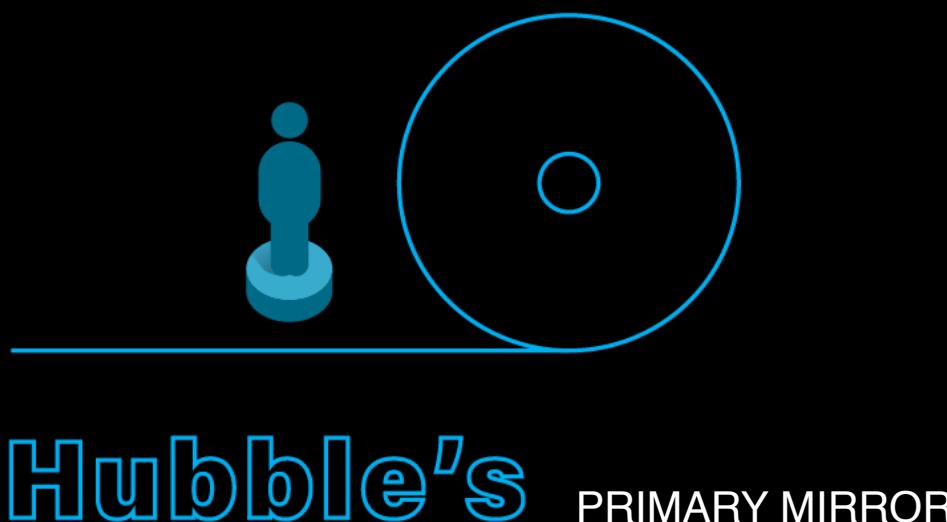
# Observing Side



# Sun-Facing Side

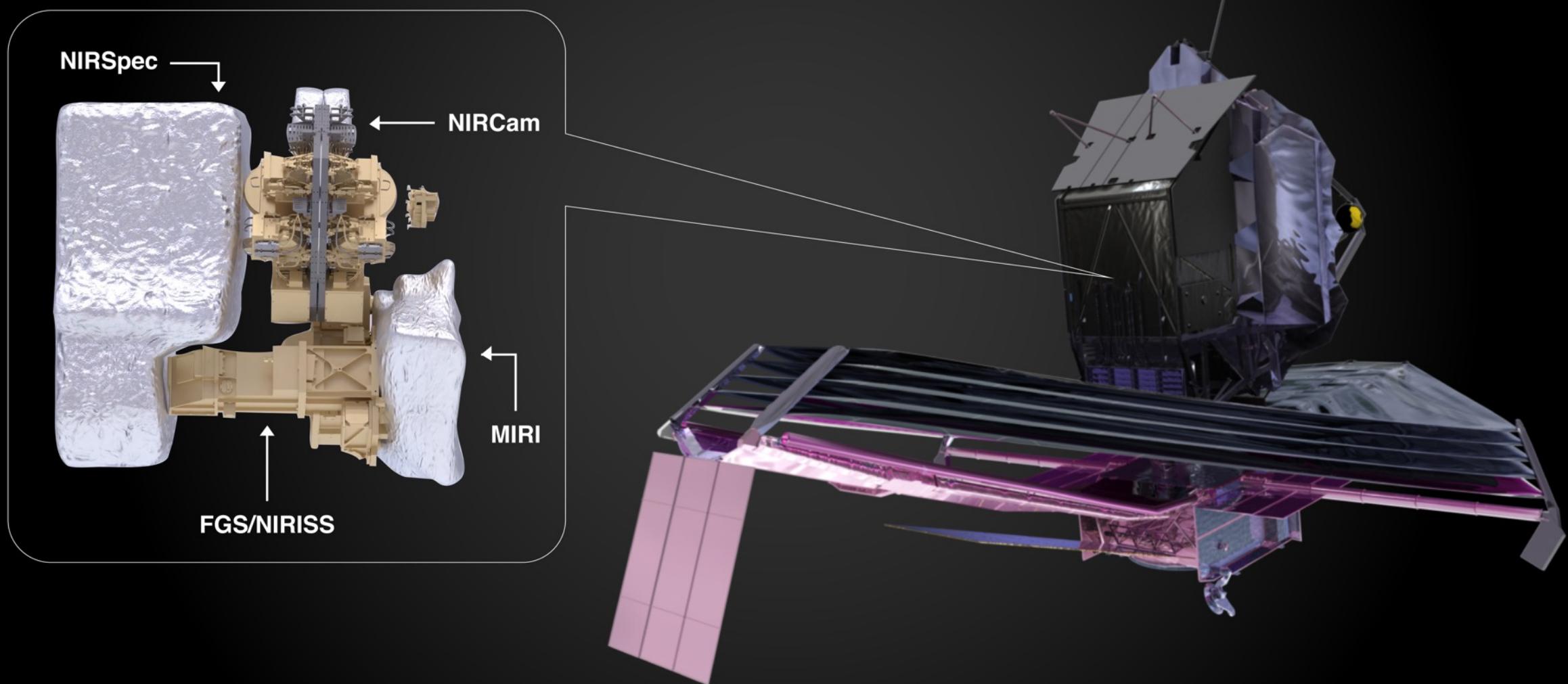


# Capturing Faint, Infrared Light

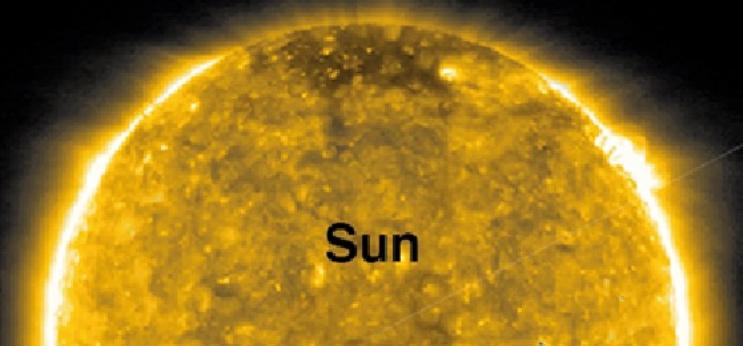


Webb's  
PRIMARY MIRROR

# Webb's Science Instruments



# Where Is Webb's Orbit?



Earth's Orbit

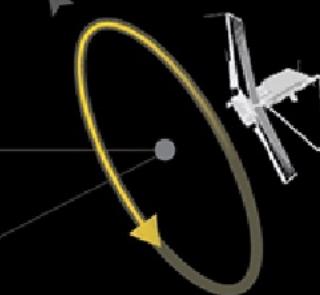
Earth

Moon

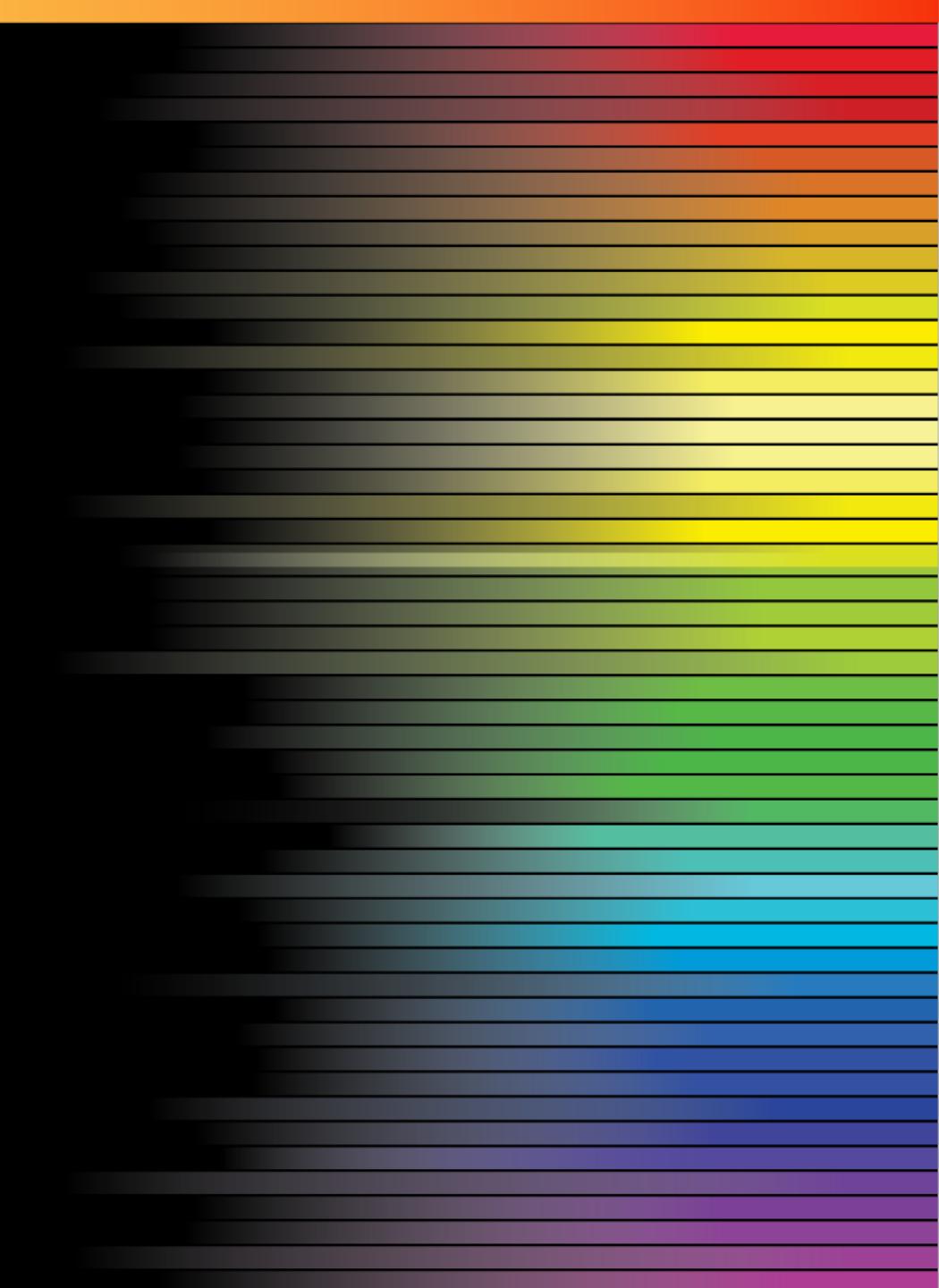
Webb's Orbit

L2

Not to scale



# Why Study Infrared Light?



# Visible vs. Infrared Light



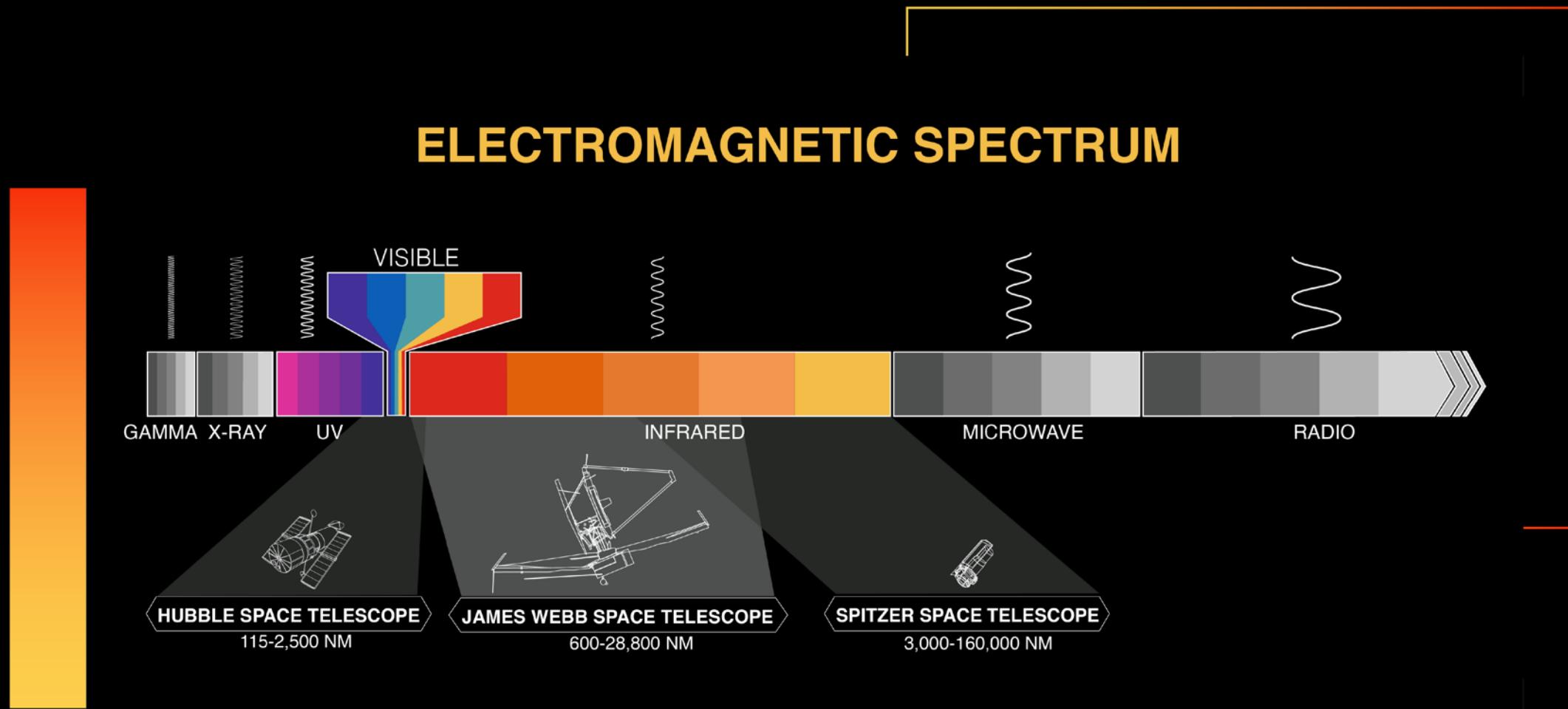
Meerkats



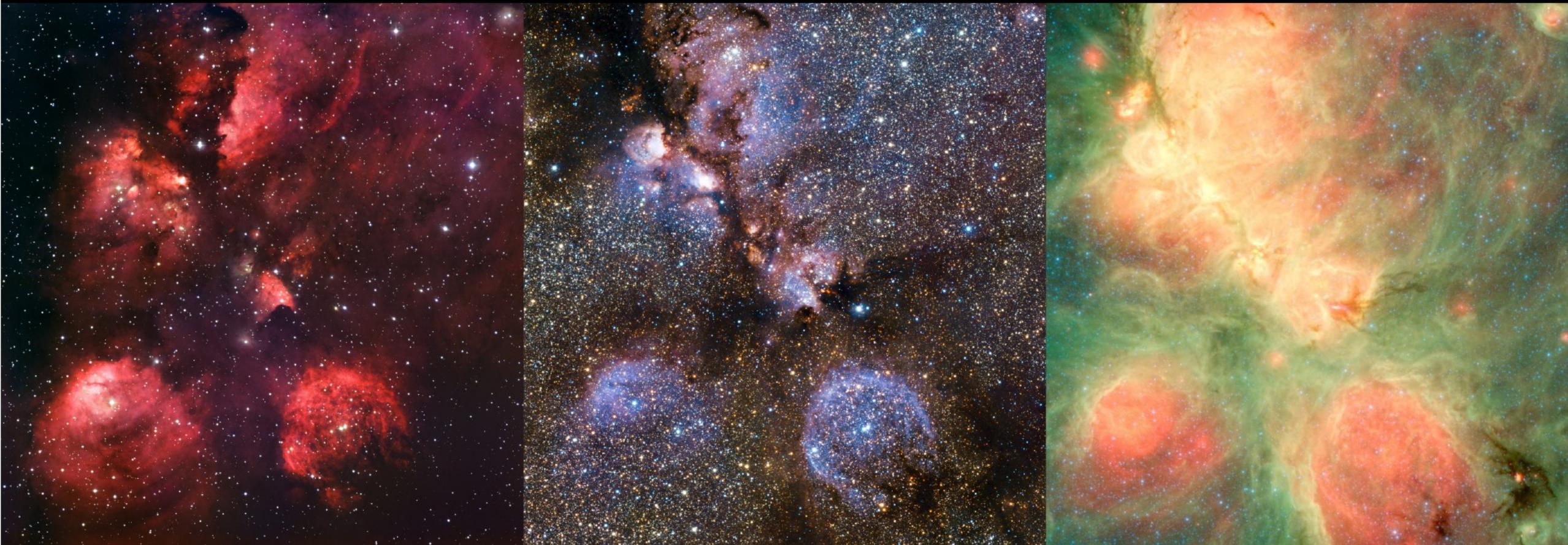
Freshwater crocodile



# 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

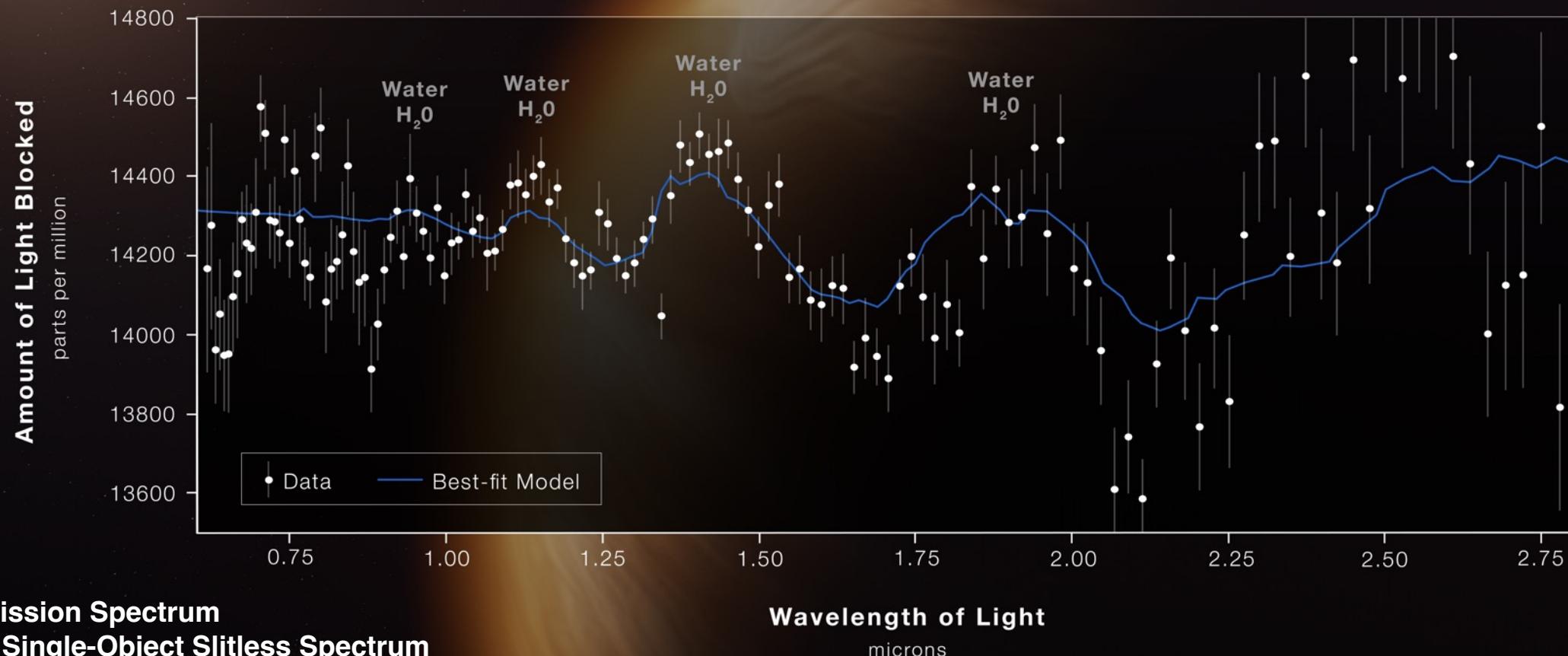


# Webb's First Deep Field SMACS 0723

Near-Infrared Light  
NIRCam Image

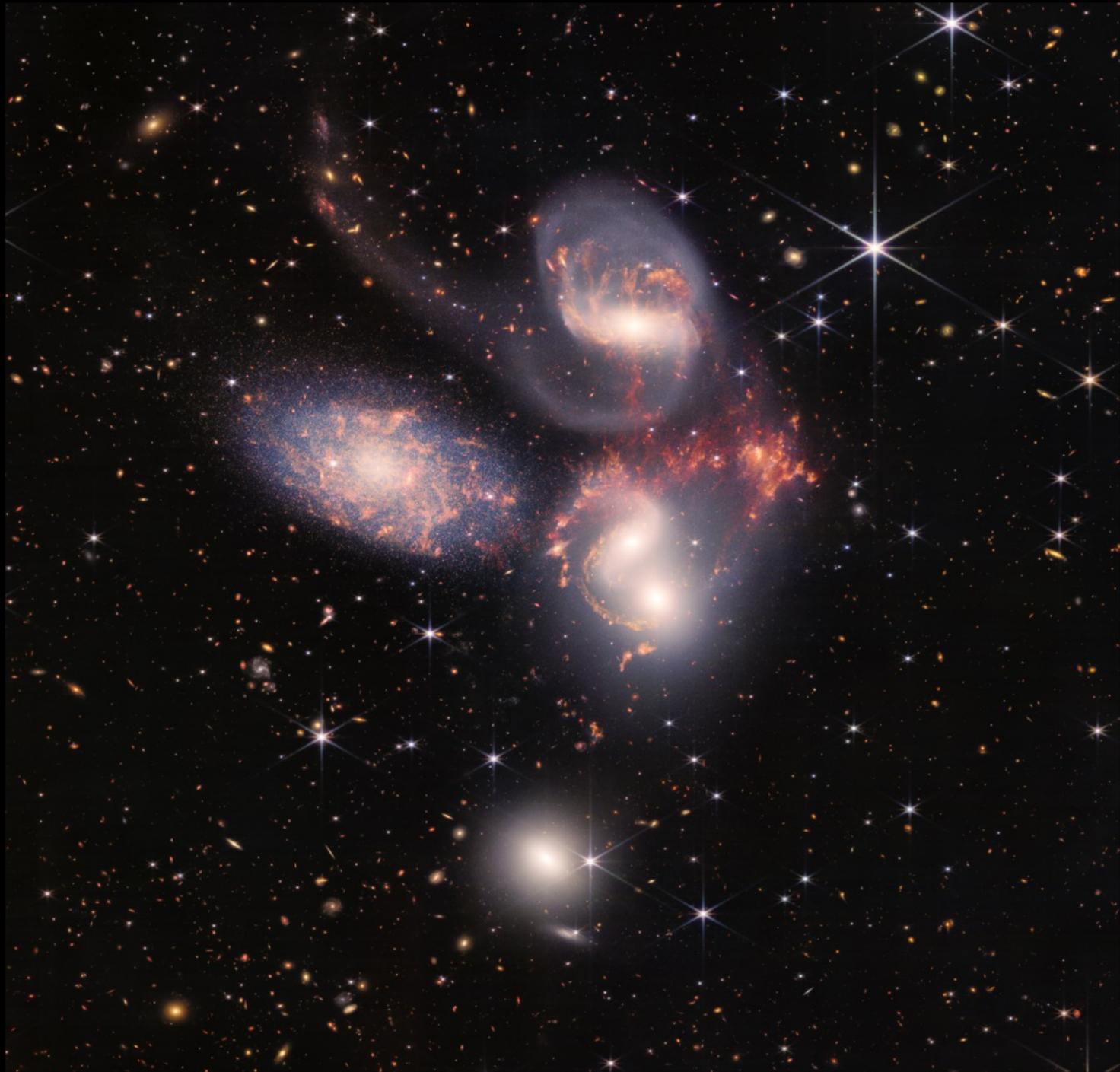


# Exoplanet | WASP-96 b



# Interacting Galaxies Stephan's Quintet

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



# Star-Forming Region I Carina Nebula



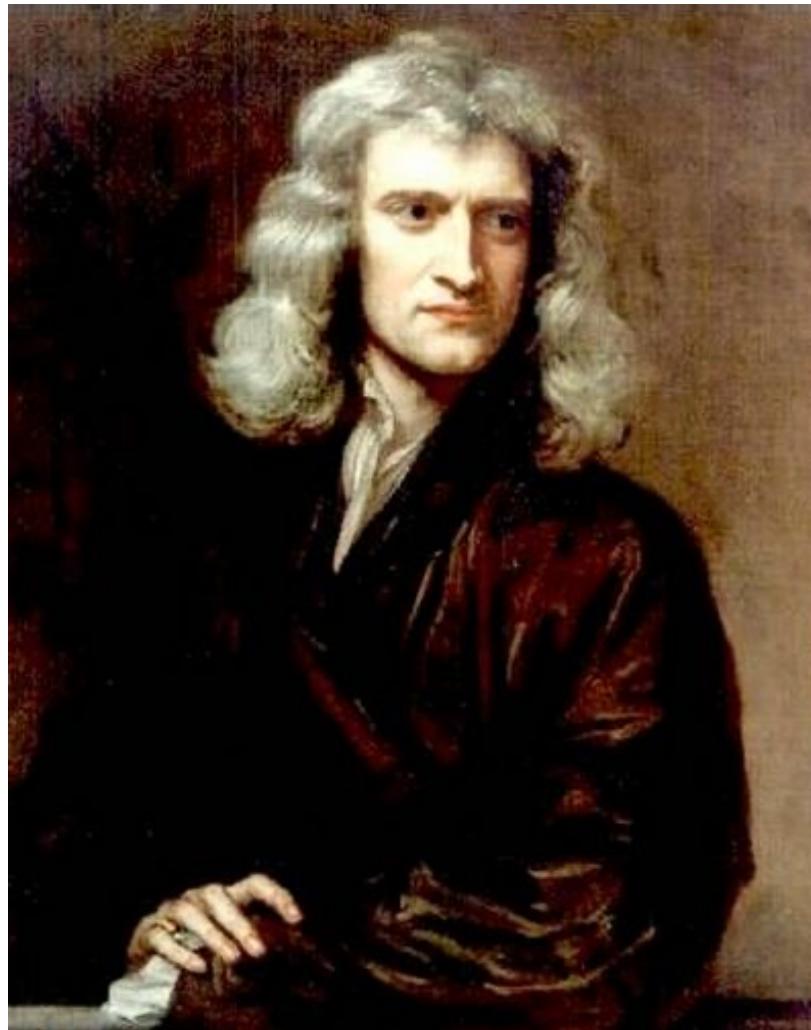
Near-Infrared Light  
NIRCam Image

# Aperture Masking Interferometry

# Newton Describes The Seeing Problem

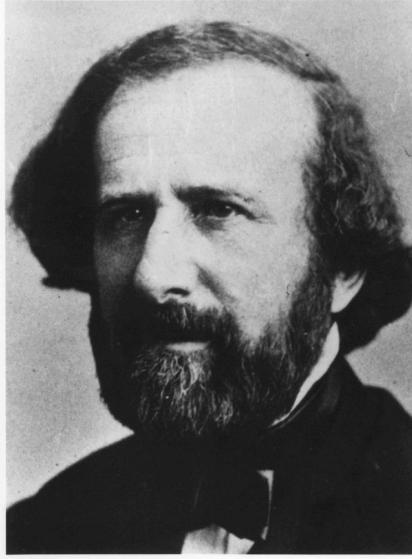
Isaac Newton

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



Slide courtesy  
Peter Lawson

## PRIX BORDIN.

### QUESTION PROPOSÉE EN 1865 POUR 1867.

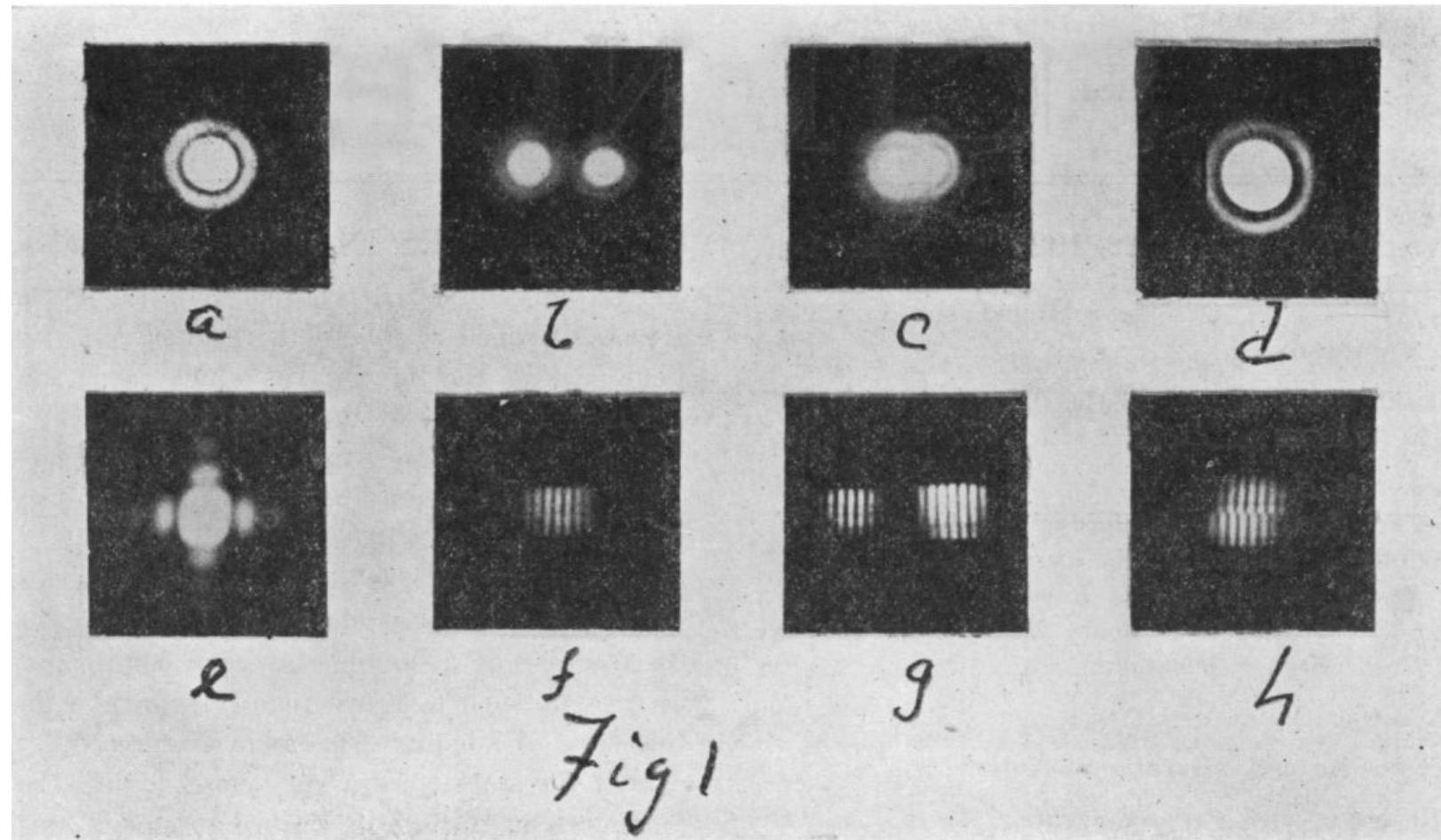
(Commissaires : MM. Duhamel, Pouillet, Regnault, Bertrand,  
Edmond Becquerel, Fizeau rapporteur.)

### 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.

# Interference and Visibility



# Why Interferometry?

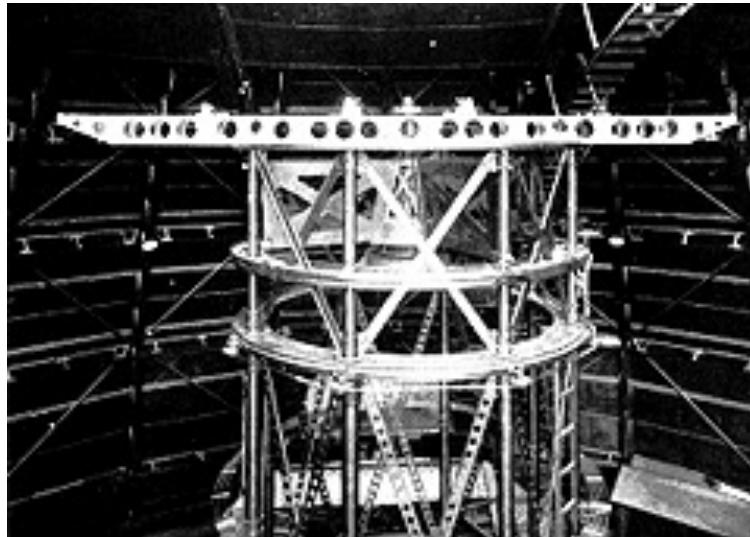
A telescope has a resolution limit given by the ratio of its wavelength to its diameter

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

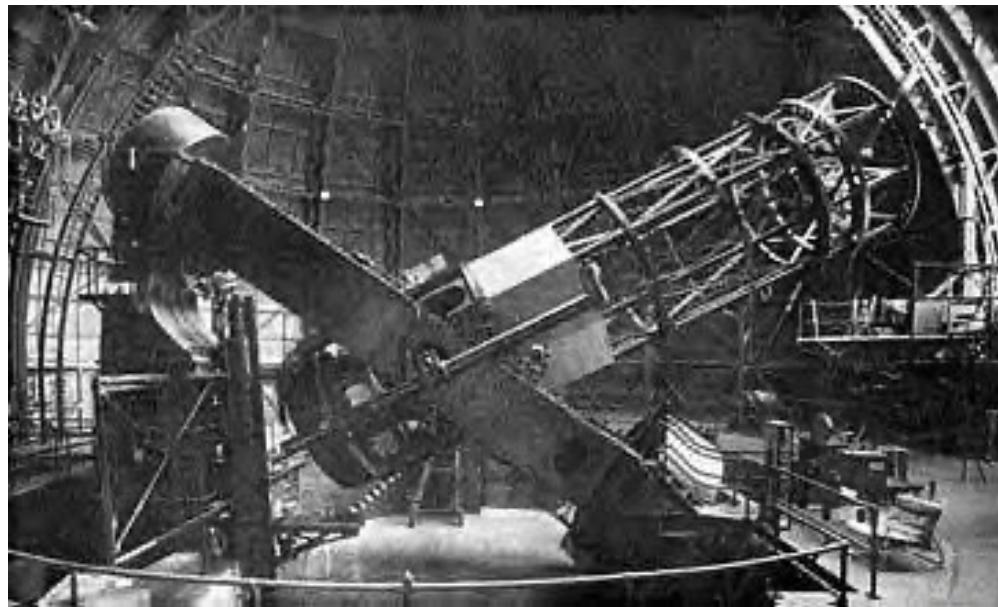
This is how most major radio observatories work – like the upcoming Square Kilometer Array (Australian SKA Pathfinder pictured below)



# Michelson and the Mt Wilson 100-inch



*Albert Michelson*



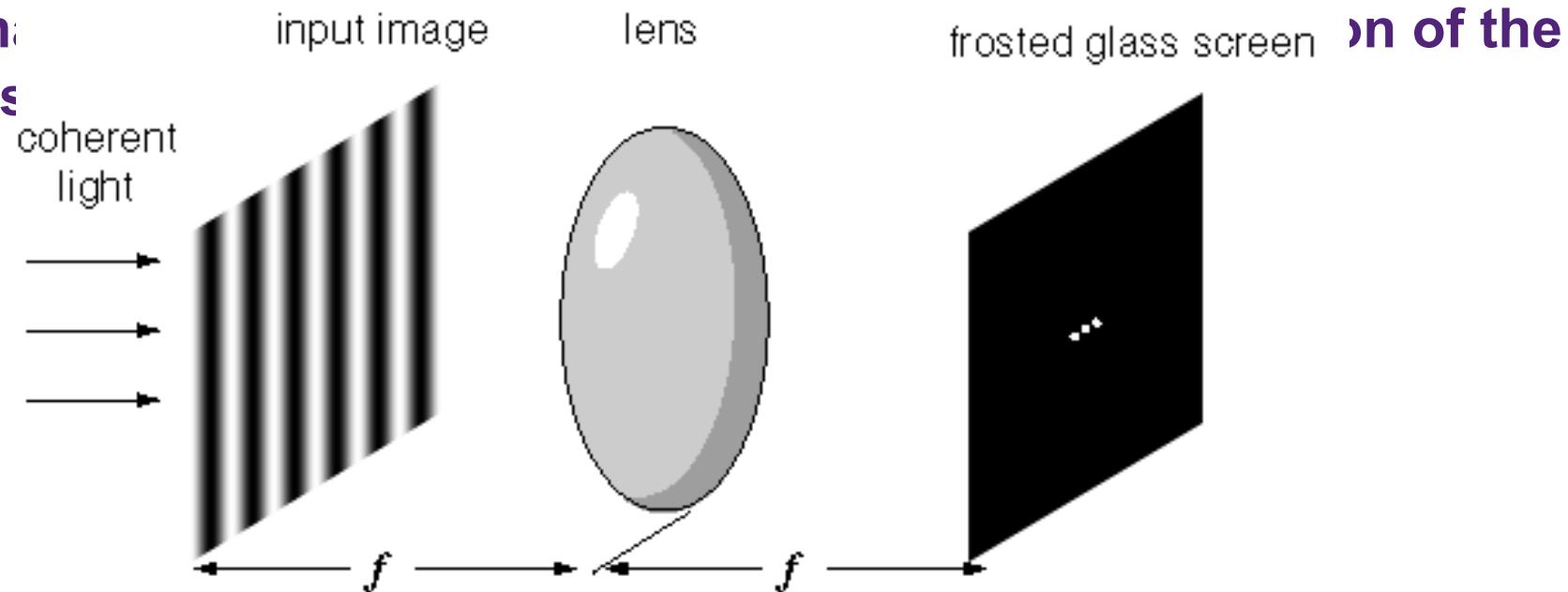
- Red Giant Stars
  - Angular Diameters
  - Betelgeuse + others

# Fourier Transforms

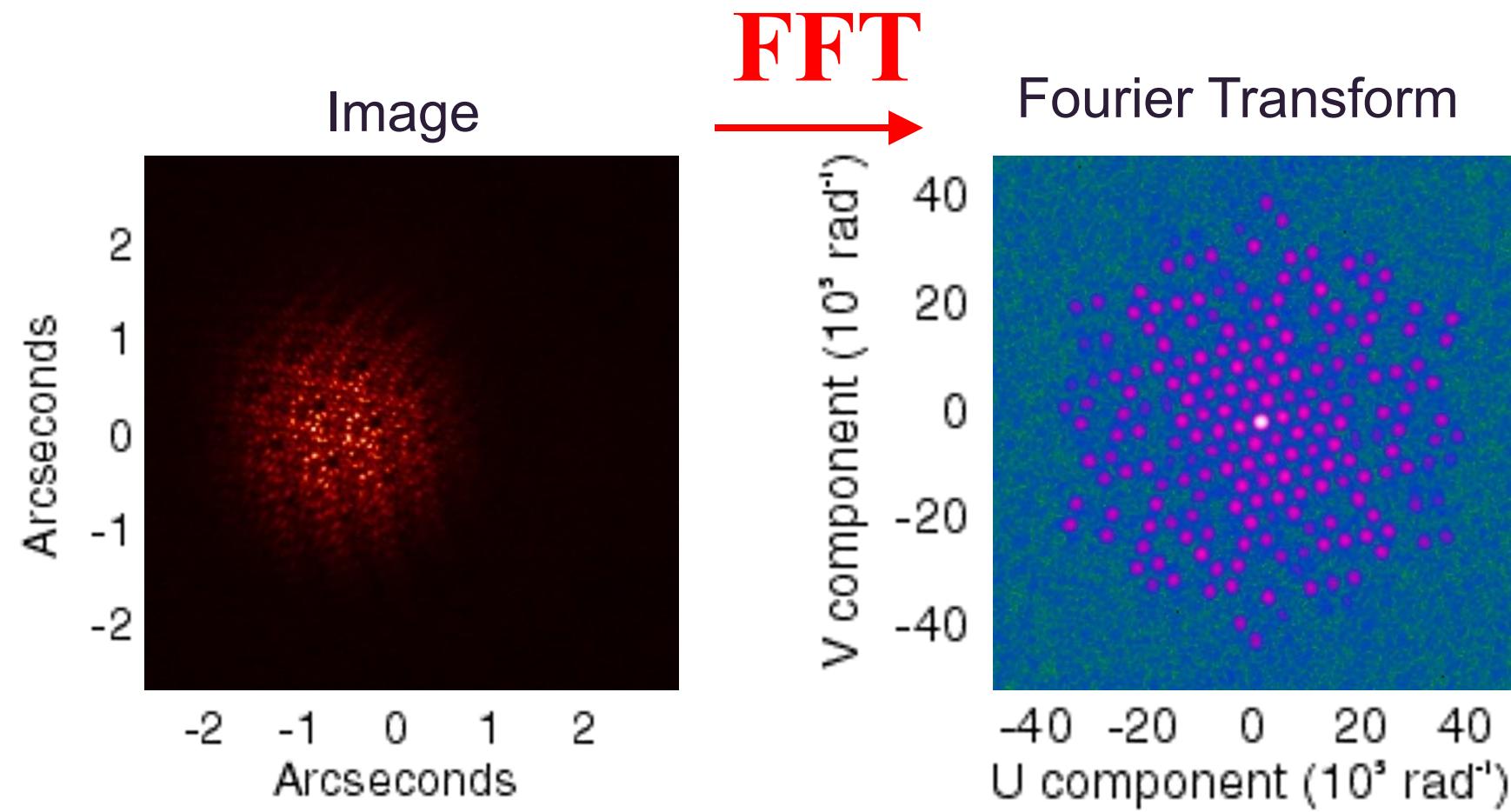
A Fourier transform is just what a lens does to an image

Or an ear to sound!

Splits up an image  
fringes on the screen



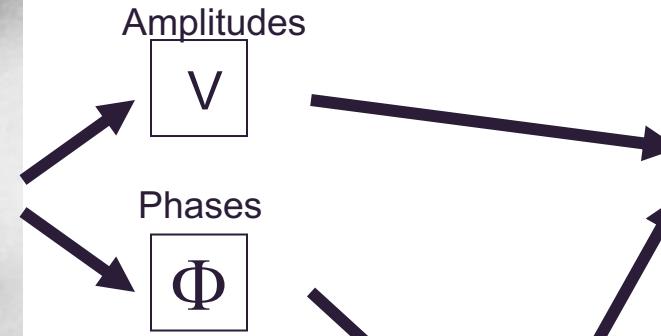
# Fast Fourier Transform: Doing that on a Computer!



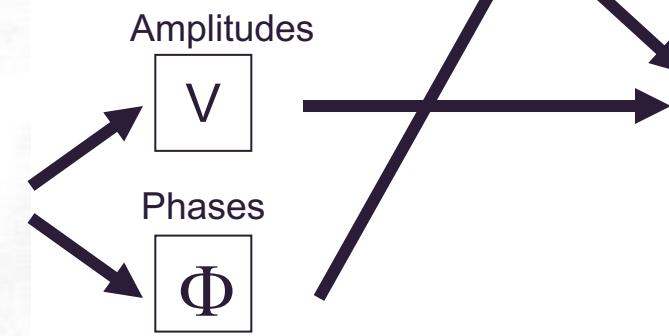
# Fourier Amplitudes and Phases



Albert Michelson

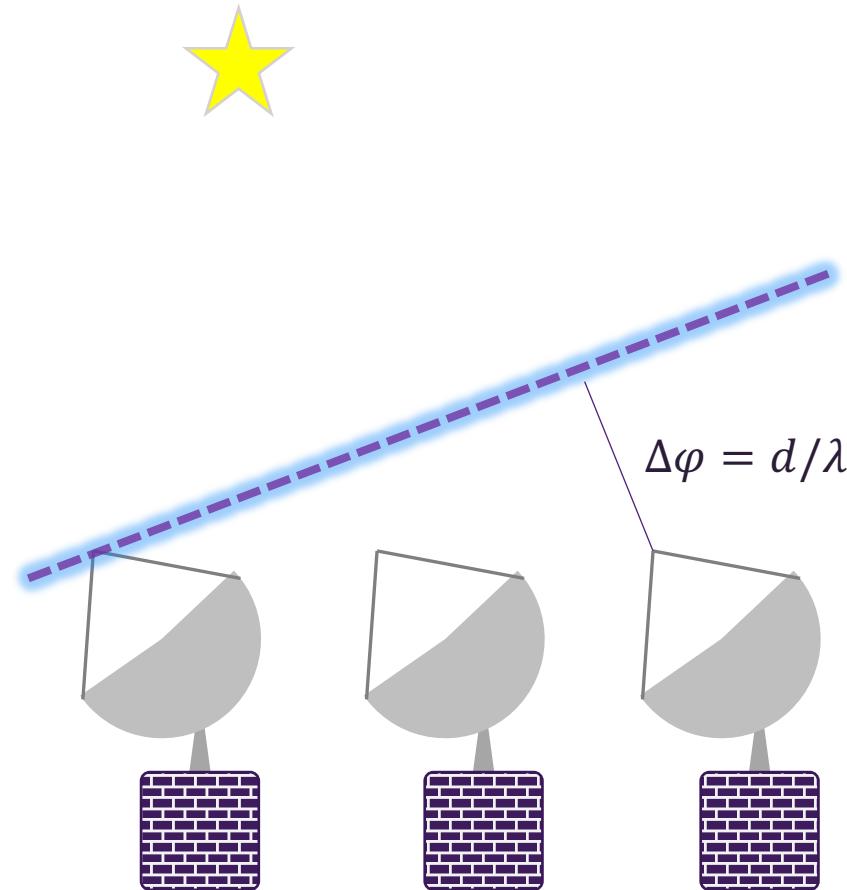


Pablo Picasso



# Interferometry: Phase

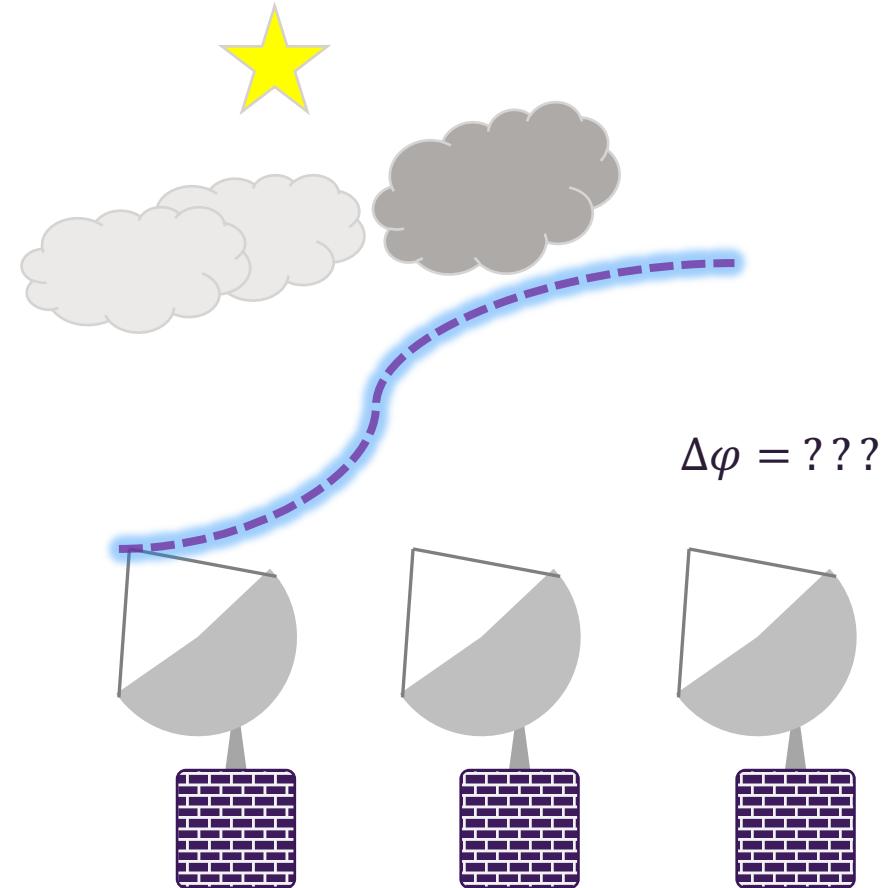
The phase delay  
between two receivers  
relates to the position of  
the astrophysical object



# 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,  $\Phi_{ij}$ , but errors are on the wavefront and hit each detector separately**

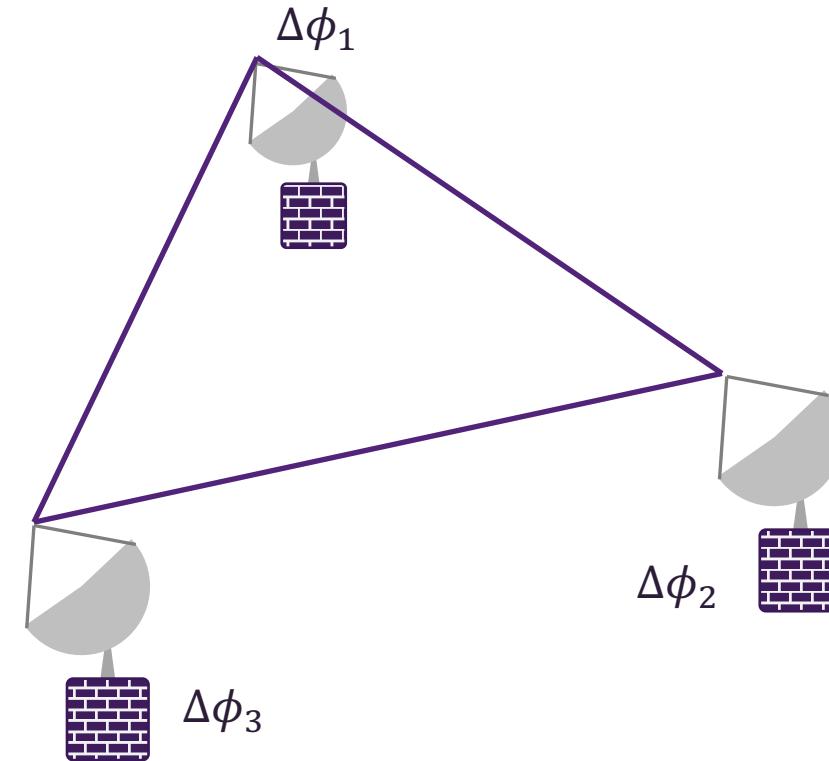
**If we add up measured phases  $\phi_{ij}$  around a loop, errors cancel out:**

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:

$$\begin{aligned}\phi_{123} &= \varphi_{12} + \varphi_{23} + \varphi_{31} + 0 \\ &= \Phi_{123}!\end{aligned}$$

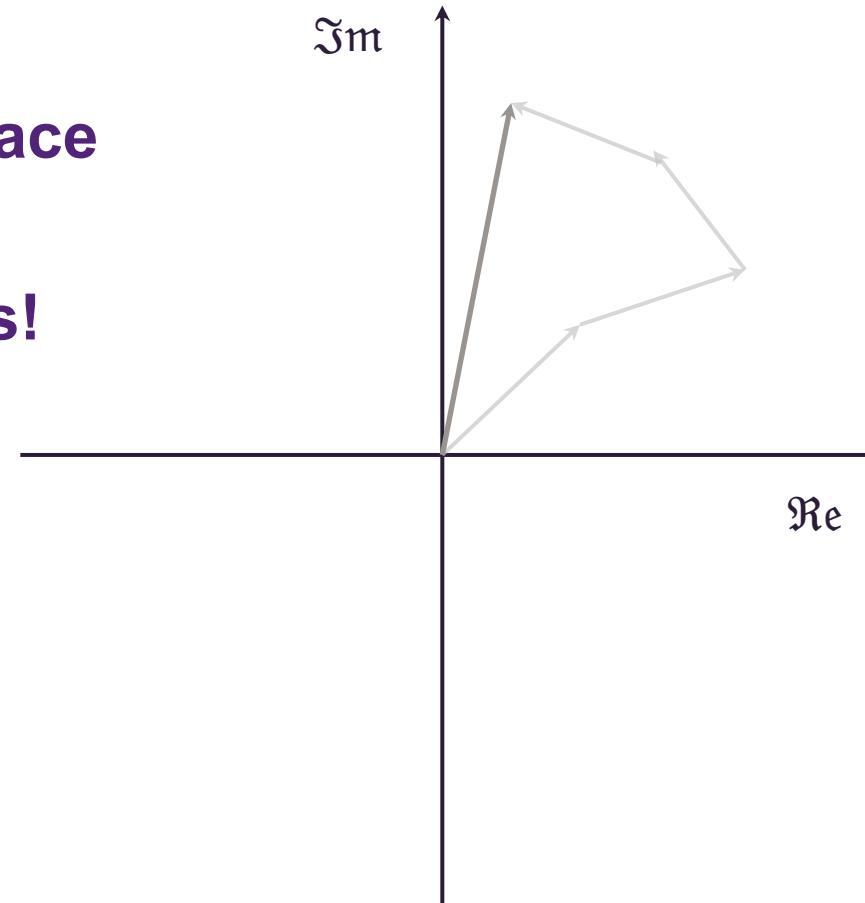
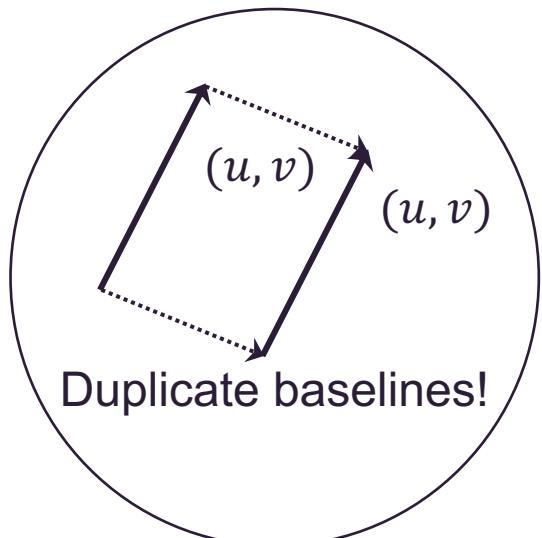


# Redundant Baselines

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

**Random walk in the phasor space corrupts image**

**Closure phase no longer works!**



# Non-Redundant Masking

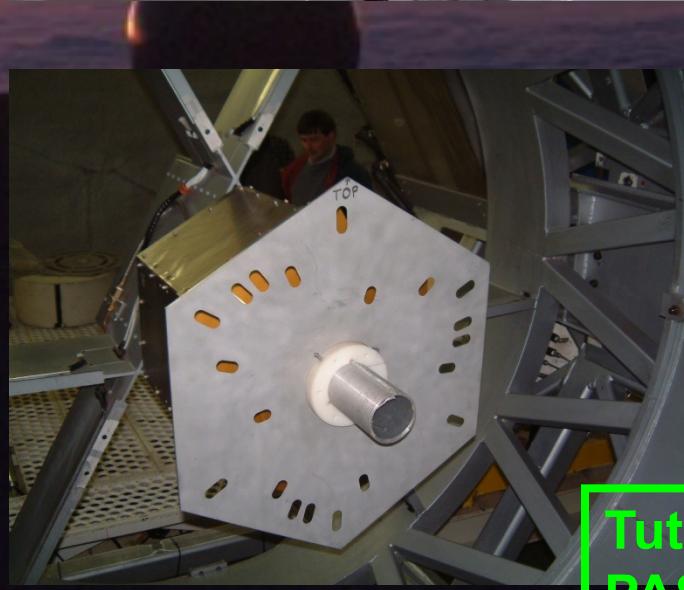
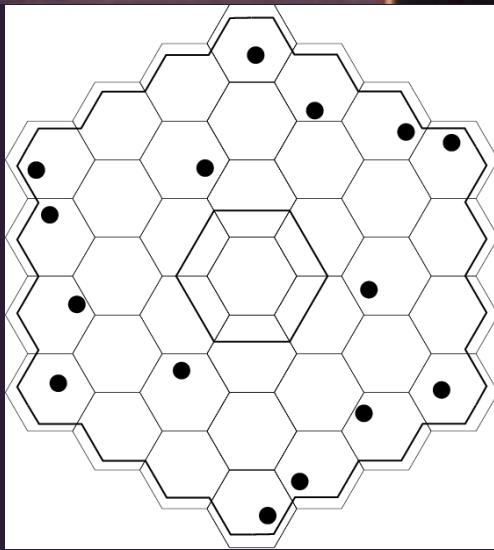
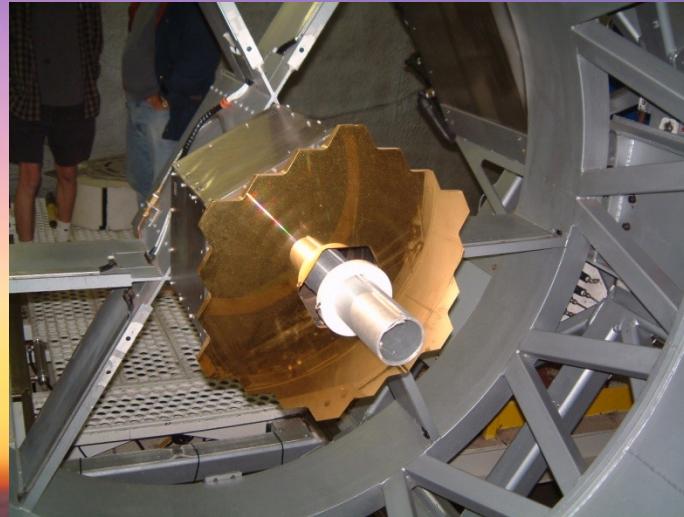


Aperture masks used on NIRCam 2 (image courtesy of Peter Tuthill).

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

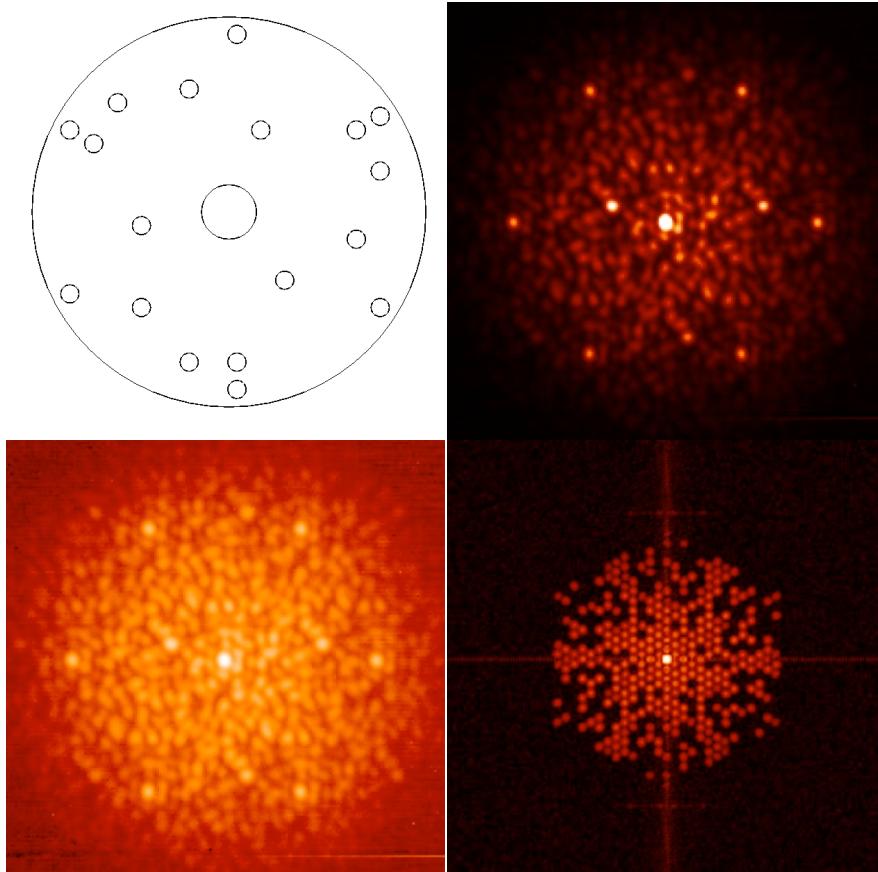
**Non-redundant masking gives us good amplitude measurements – and also lets us recover some phase information**

# 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.

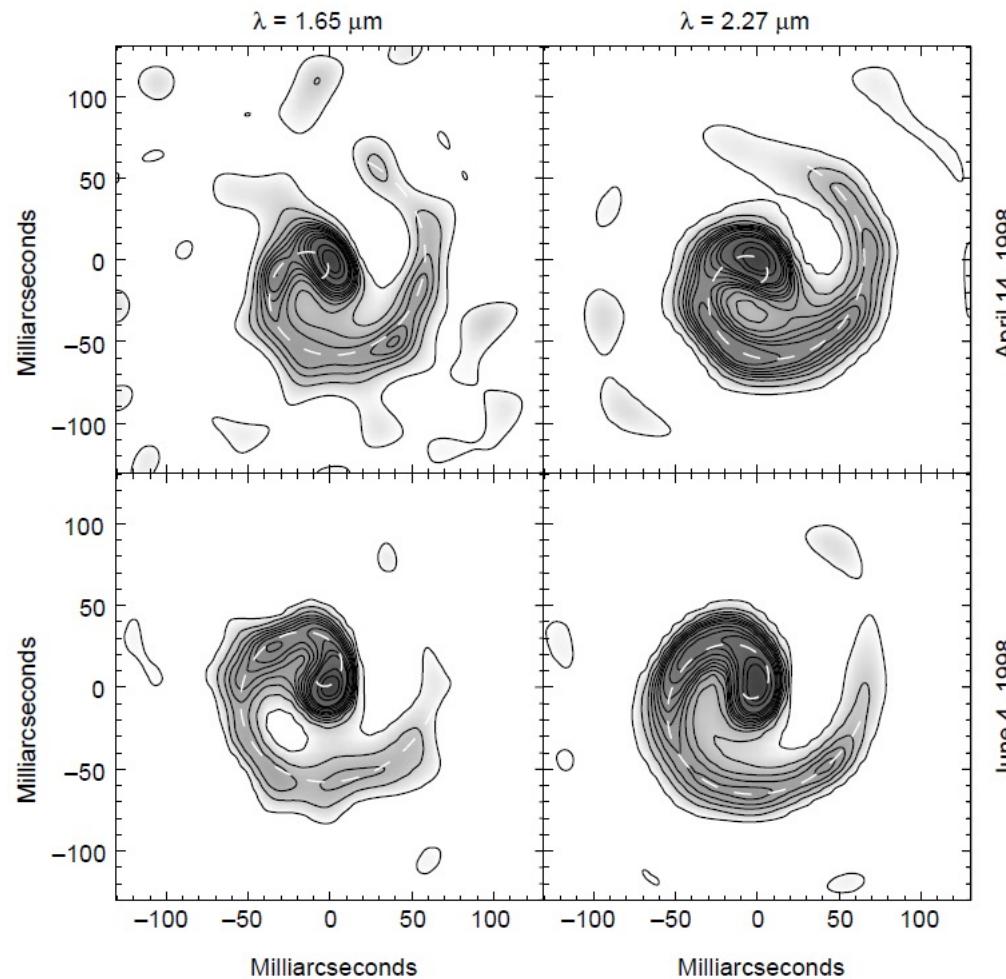
**Each dot in the power spectrum (mod-squared Fourier transform) represents the power at some fringe spatial frequency.**

**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



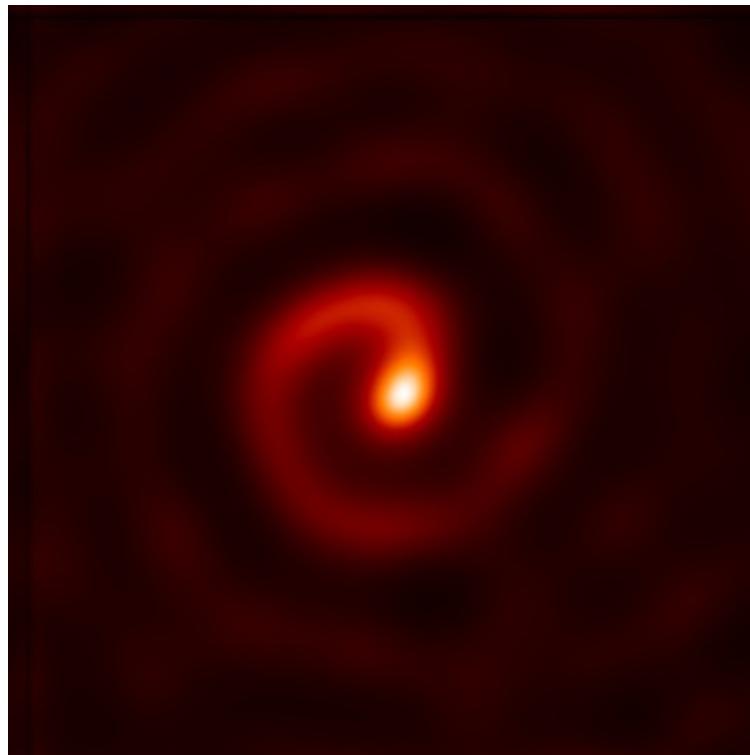
**Wolf-Rayet stars are the last stage of the evolution of the most massive stars ( $M > 20M_{\text{Sun}}$  !)**

**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!

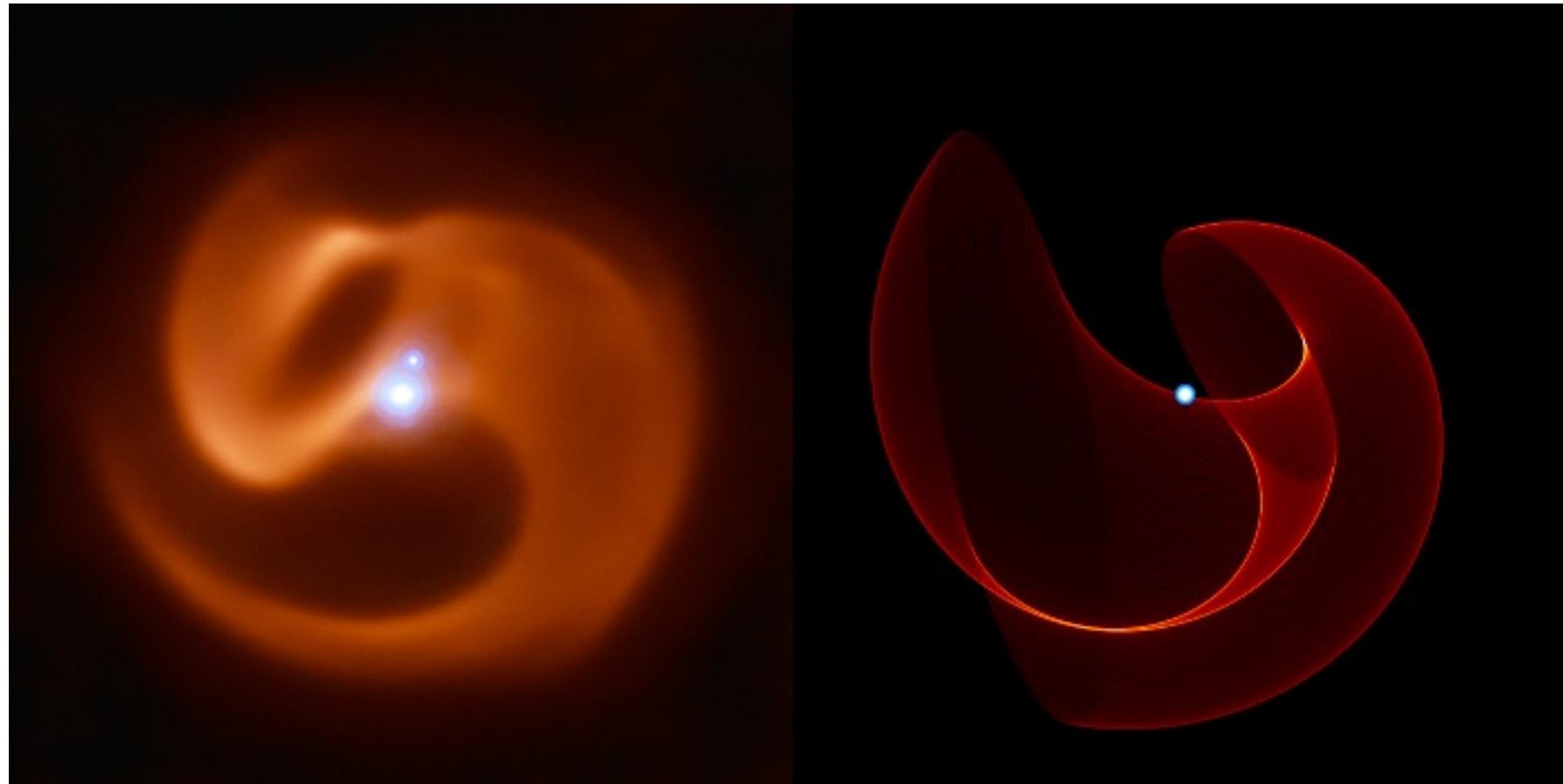
WR stars are believed to be the progenitors of some supernovae and gamma ray bursts

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

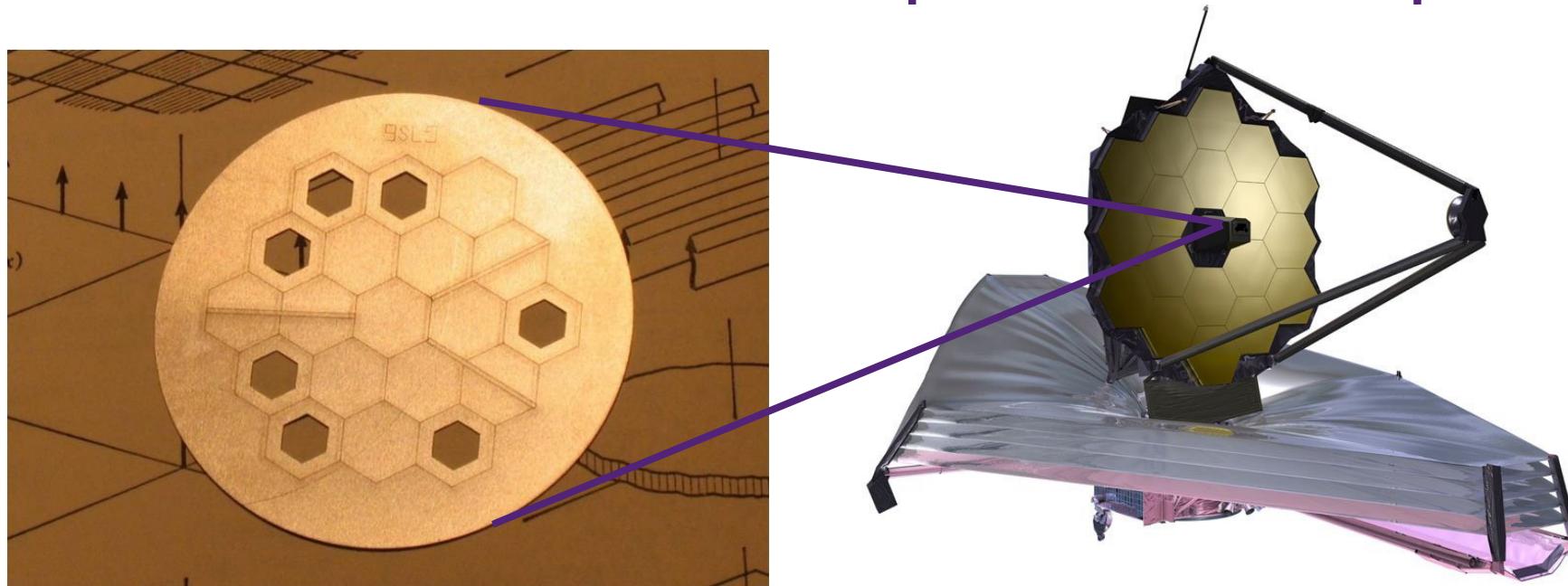
# Wolf-Rayet 140 with JWST



# Apep: Dance of Dragons

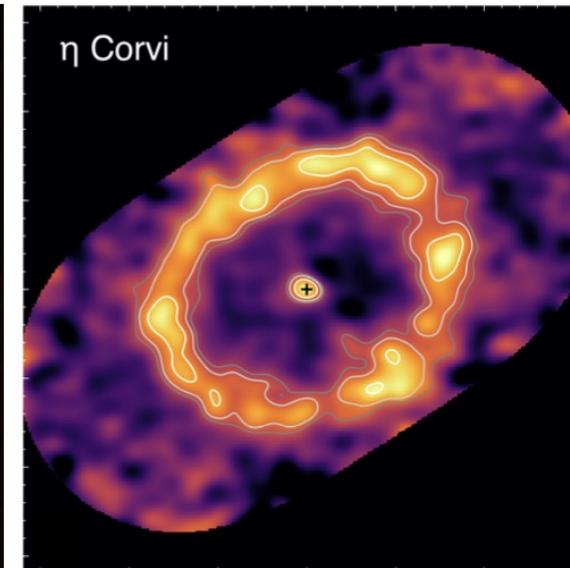
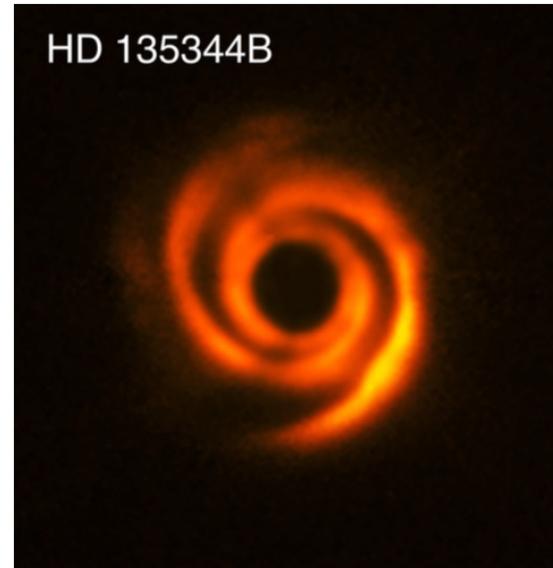
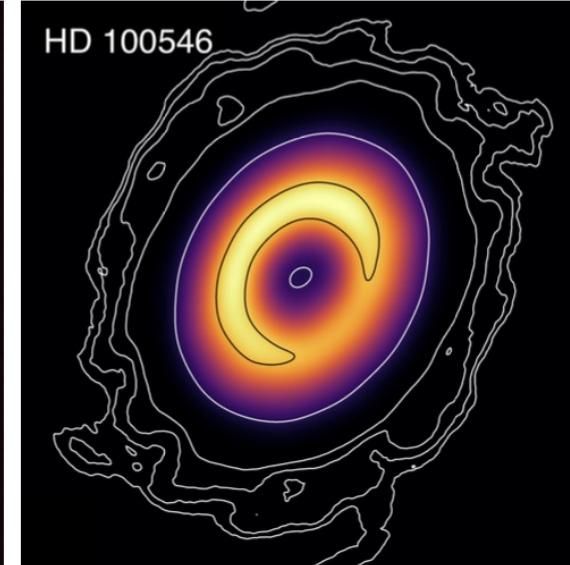
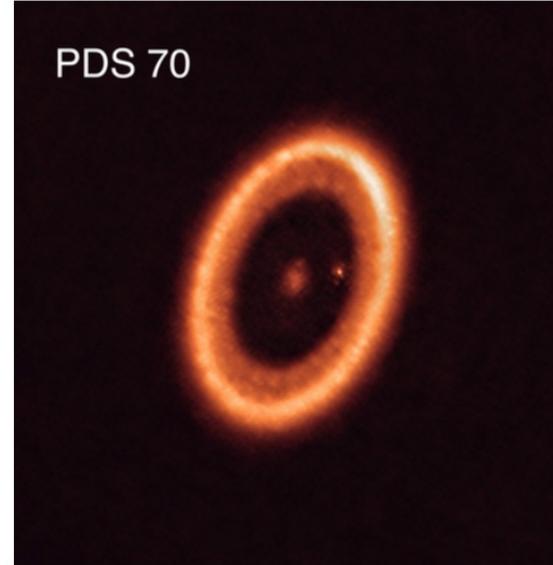


# Aberrations on James Webb Space Telescope



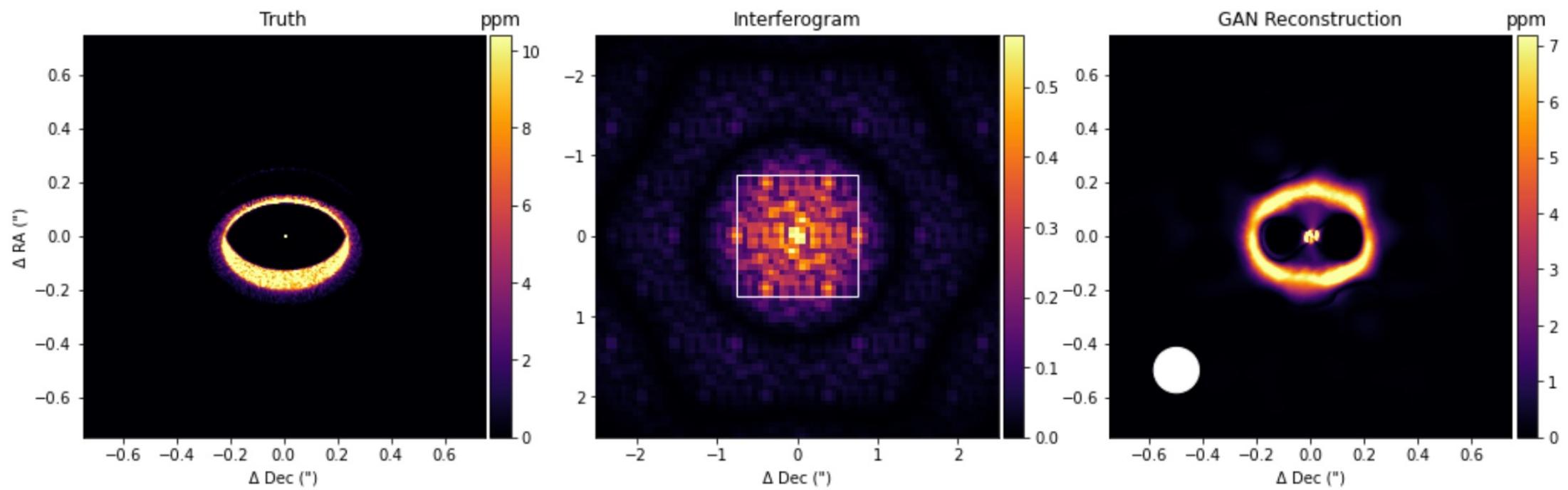
You can use a mask in reverse – to work out what the phase errors are, given an image

# Our Observations



THE UNIVERSITY  
OF QUEENSLAND  
AUSTRALIA

# Using Machine Learning to Enhance AMI



# Questions!

CRICOS 00025B