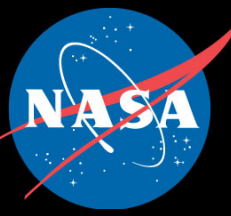
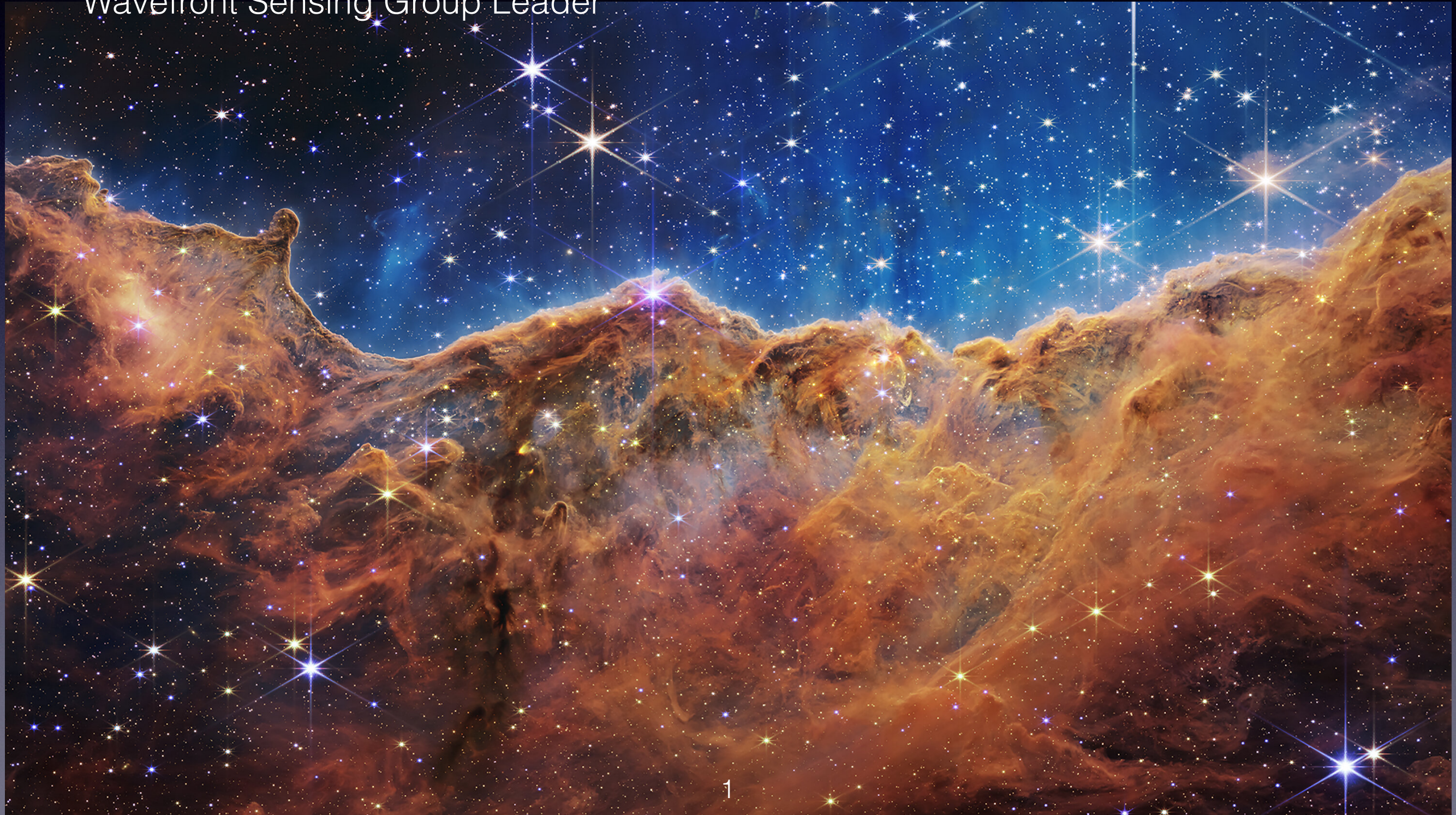


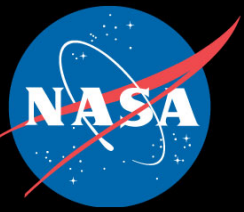
Introduction to Image-Based Wavefront Sensing



Bruce Dean, NASA Goddard Space Flight Center
Wavefront Sensing Group Leader

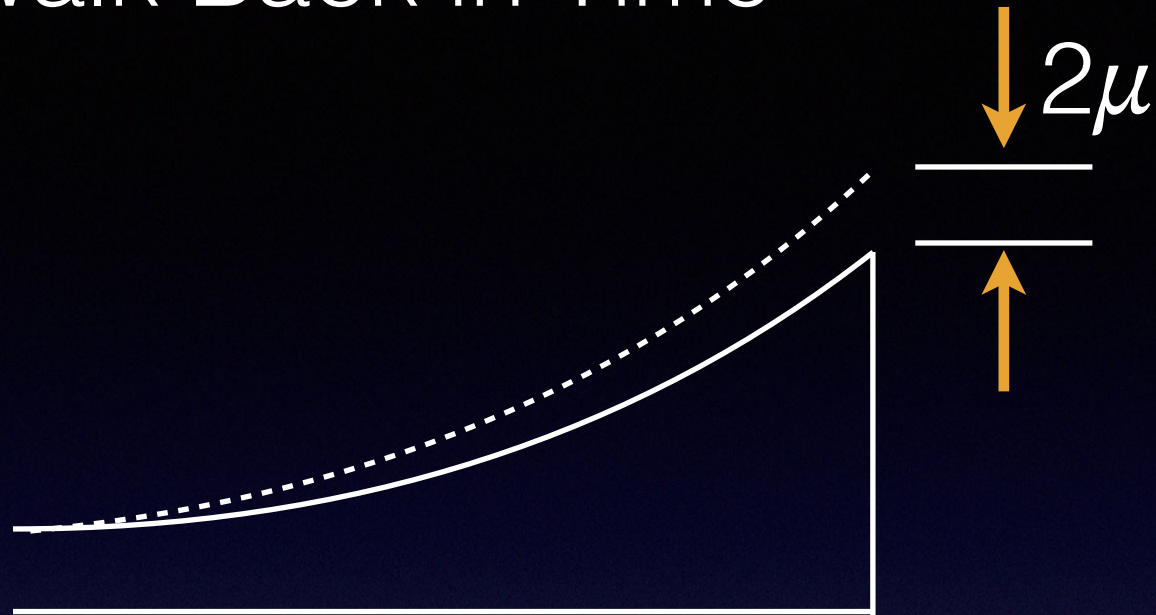


Takeaways



- What is it?
- Motivation
- Engineering, Optical Systems
- Applications

Walk Back in Time



1/35 diameter of a human hair



1990: April May June July August September

↘ 24th Launch

- Sept 1990: a 6-person Board of Inquiry – “Allen Board”
- Laboratory at Hughes Danbury (1980-1982) had been found intact.
- Engineers evacuated the lab and never returned – leaving it in a “fossilized” state. Original coffee cups found.

Hubble Space Telescope Results

1990: April May June July August September

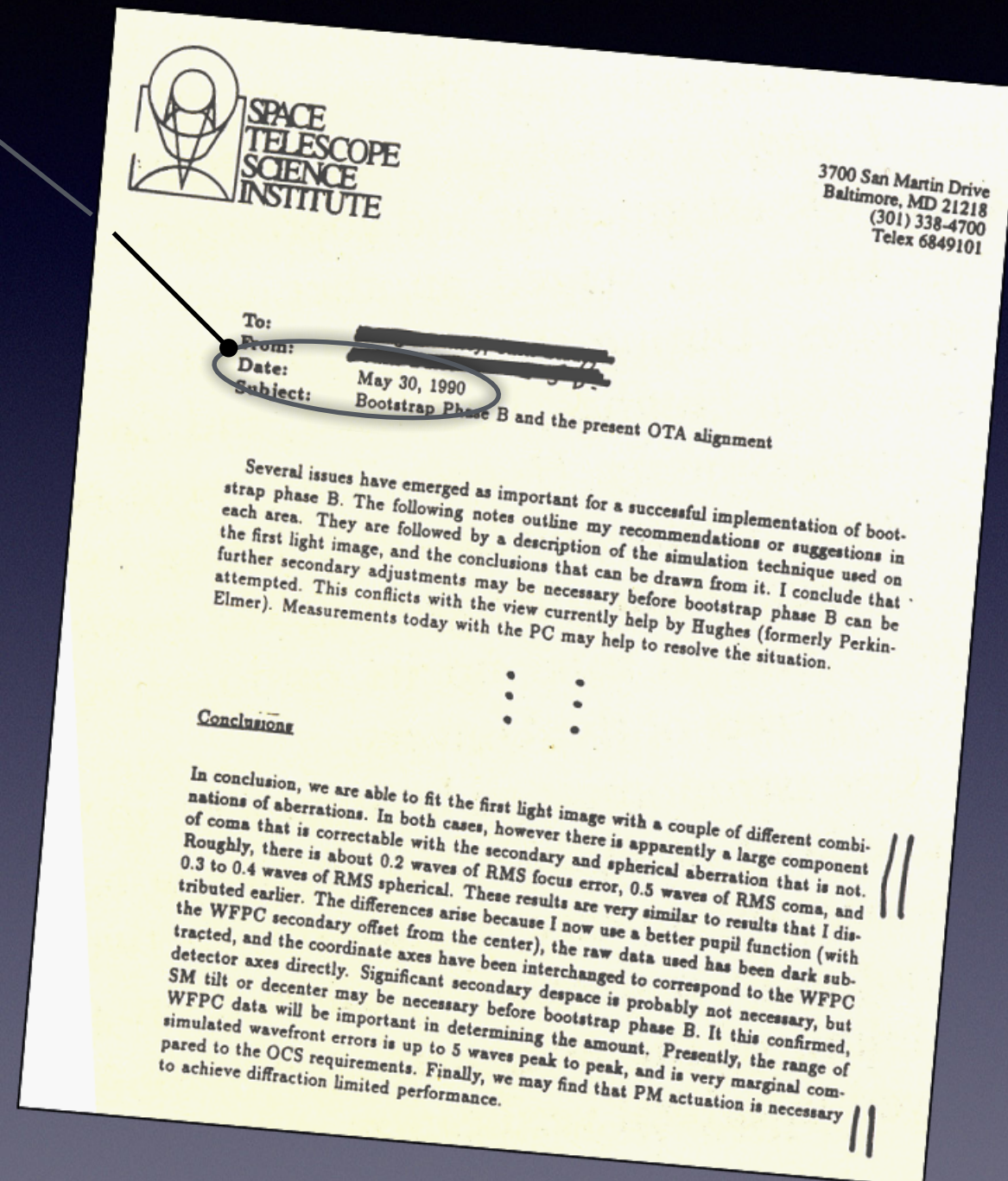
24th Launch

20th First Light

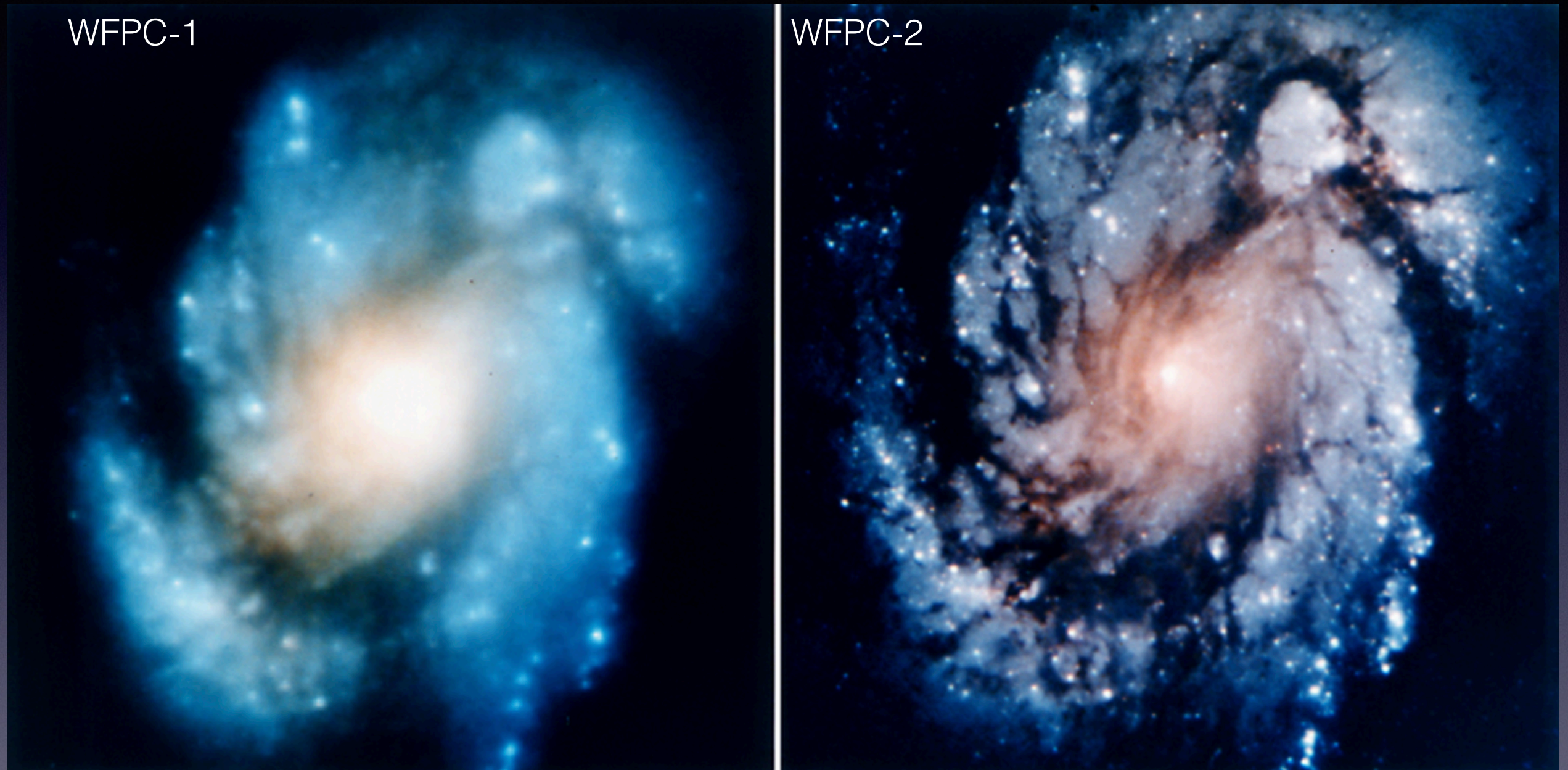
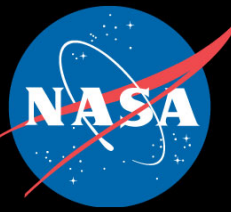
- Note the time period:
about 5 months

Phase Retrieval

- 10 days - Chris Burrows at the STScI: characterize Z11
- Follow on work confirmed the results (used to build COSTAR)



Hubble Space Telescope: before and after



Galaxy M100: dramatic improvement in Hubble Space Telescope's view

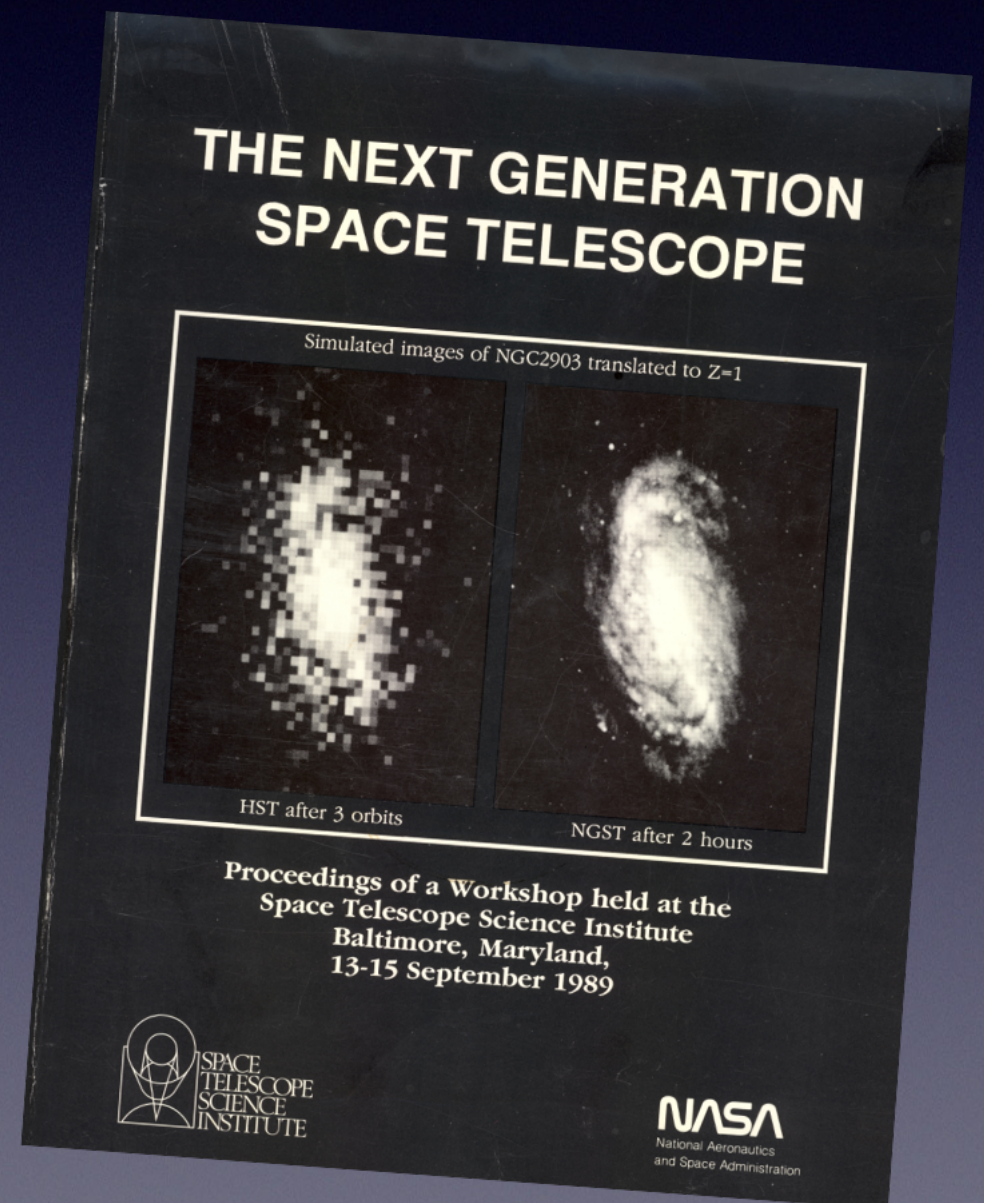
Phase Retrieval already under consideration for JWST

NGST: Next Generation Space Telescope

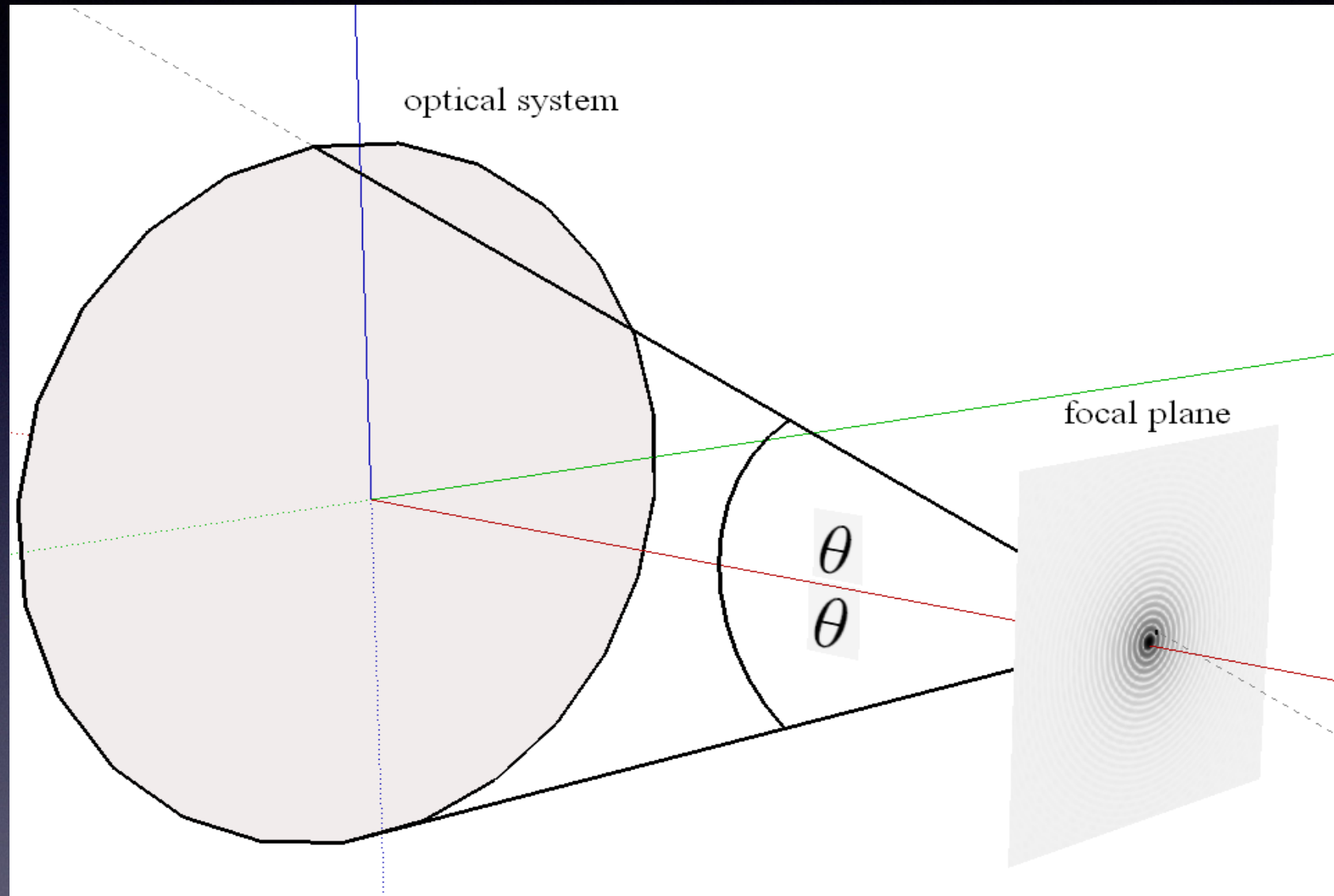
- Alan Wissinger (Perkin Elmer) "Sensing and Control for Large Optical Systems," p. 232
- Refers to phase-retrieval technique under development by Ed Siebert.



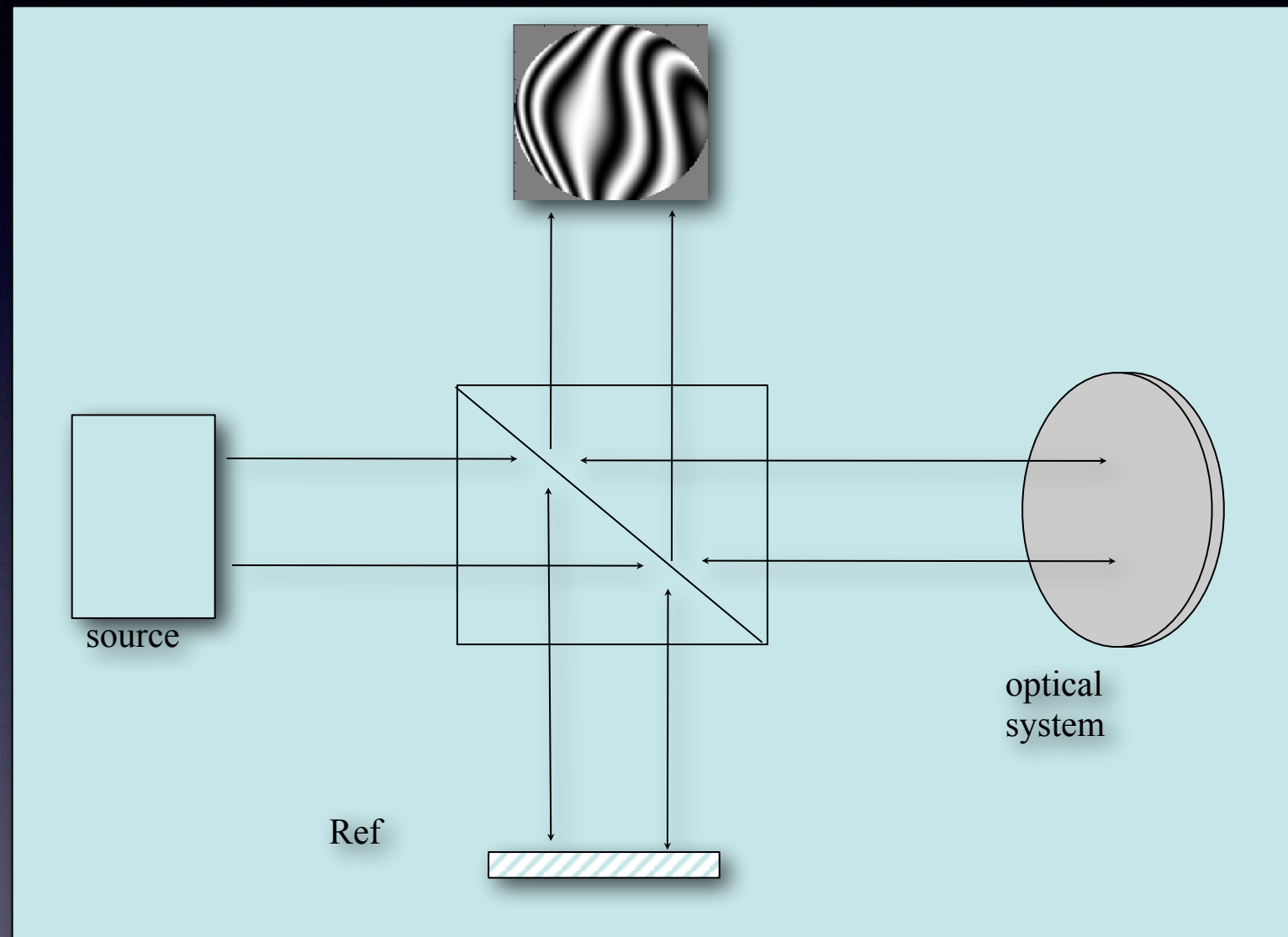
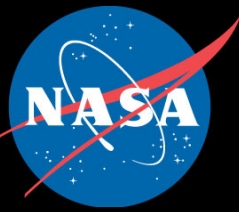
Aug 4th 2002



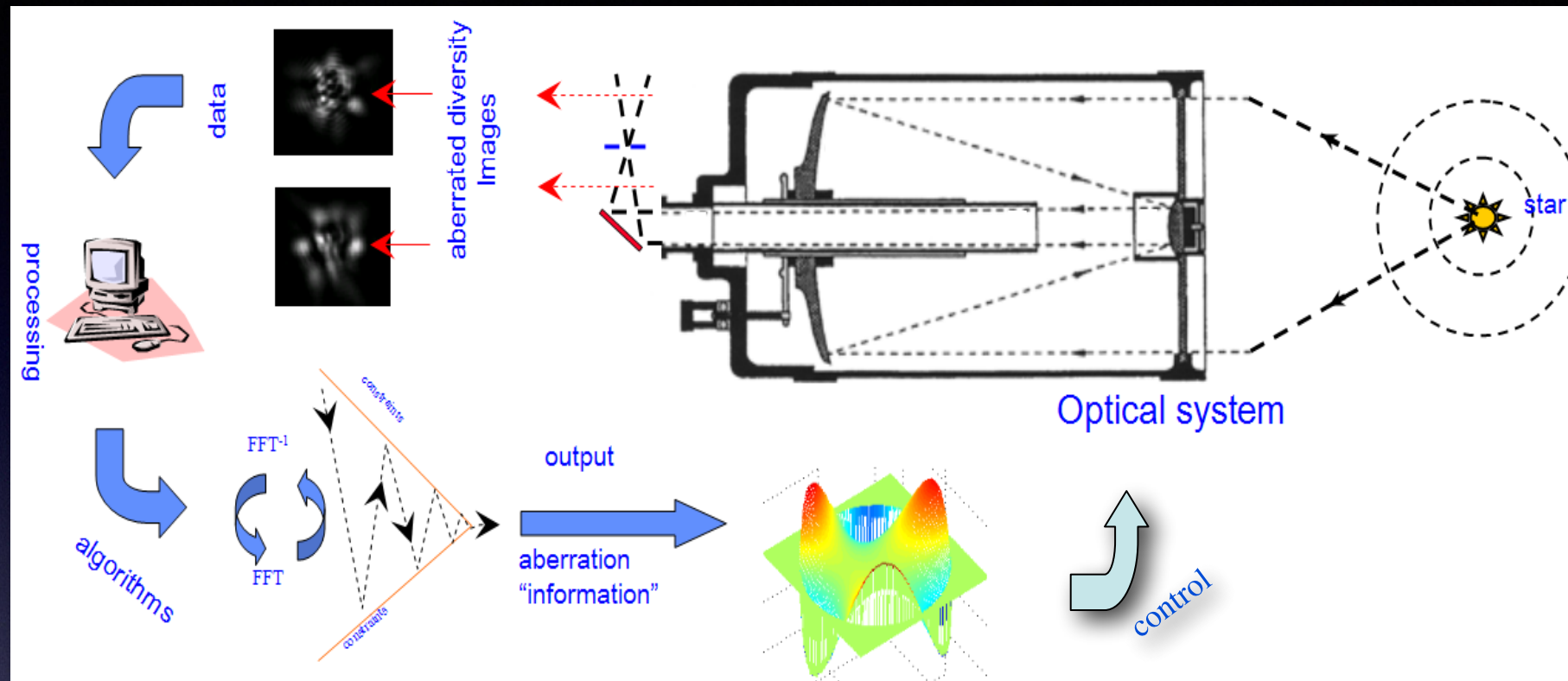
Phase Retrieval: Image Based Optical Sensing



Compared to Interferometer



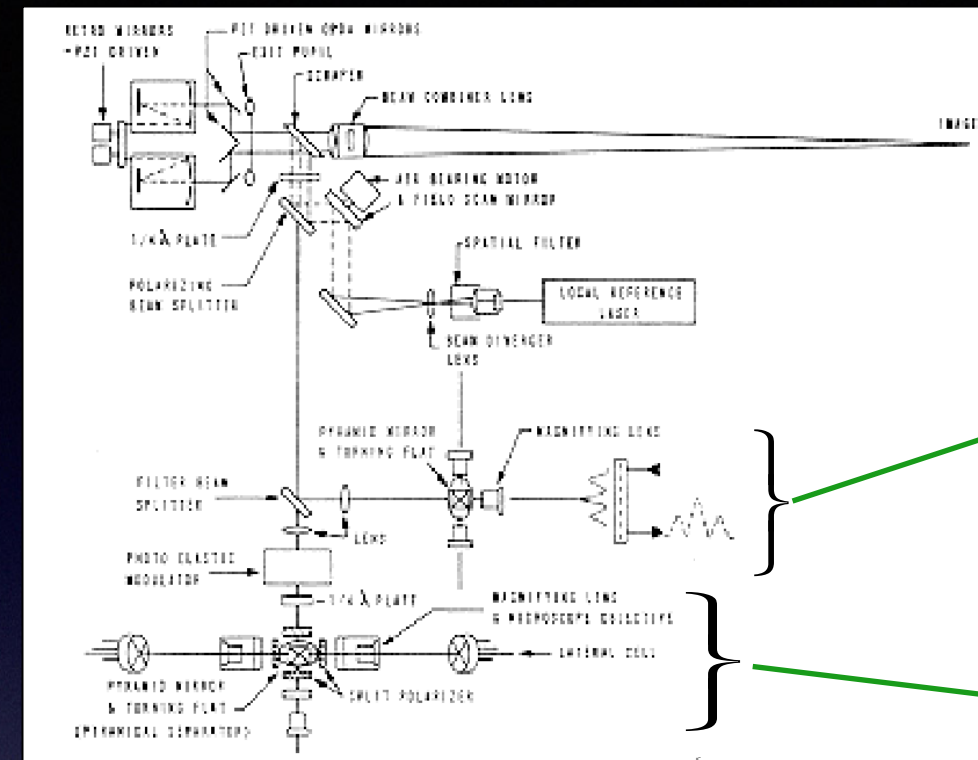
Closed Loop Phase-Retrieval System



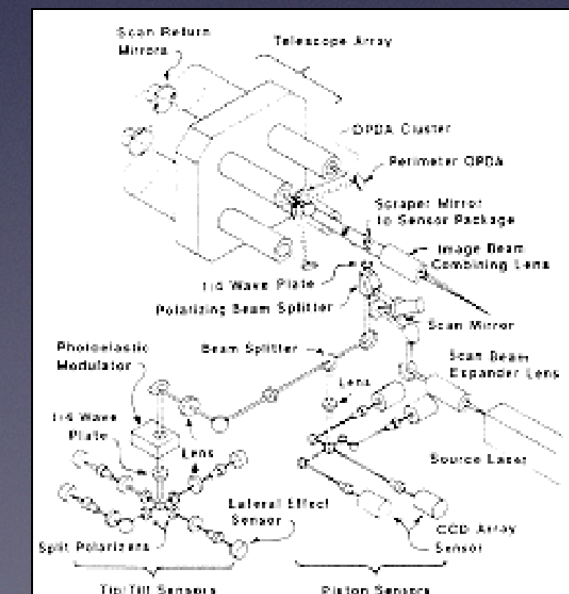
- Science camera collects data
- Basic Trade: hardware (conventional) / computational solution
- Delay - when the images are captured / wavefront is returned (latency).

Conventional Approach

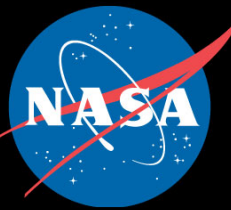
- System complexity - increased cost and potential system failures,
- Optically Complicated - Every degree of freedom needs a sensor!
- Hardware intensive and complicated.



Only 3-degrees of freedom detected:



Concept



- Phase from intensity data?
- Complex numbers:
- Phase part is decoupled from intensity

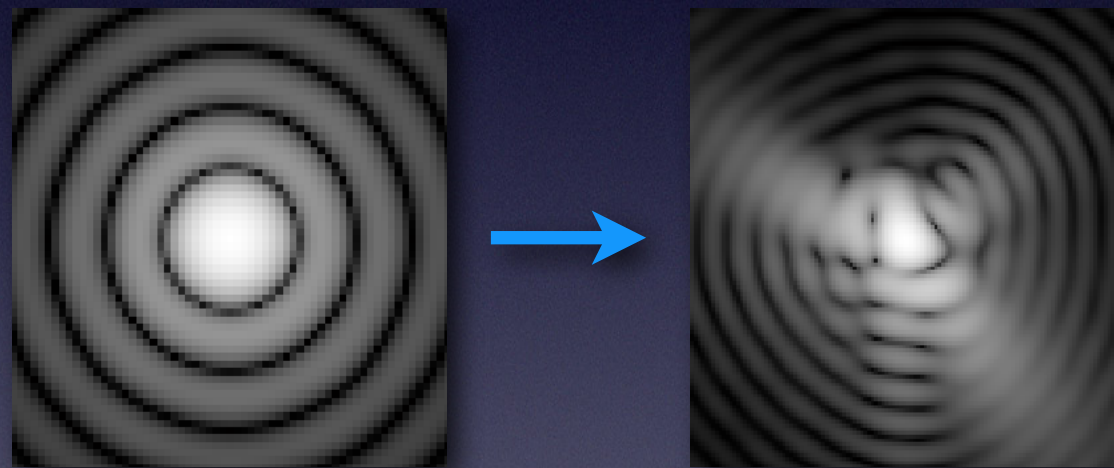
intensity phase

$$z = x + i y = r e^{i\theta}$$

$$\Rightarrow |z|^2 = r^2 e^{i\theta} e^{-i\theta} = r^2 \neq r^2(\theta)$$

Phase Recovery Fact

- Phase-recovery fact: optical aperture “scatters” phase information into the intensity data
- Star image –normally an airy disk for a circular aperture:

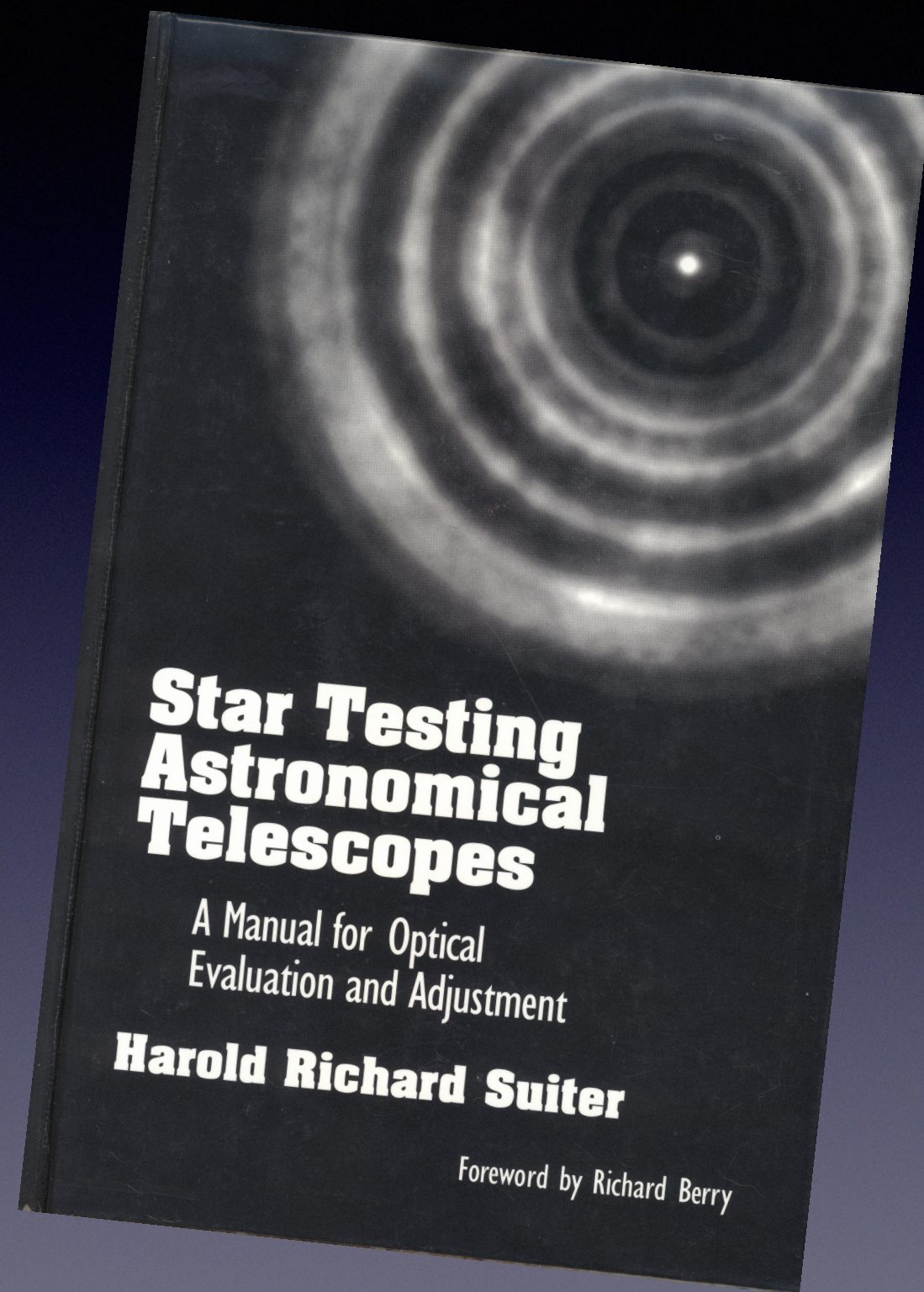


- Intensity is now a function of the phase:

$$r^2 = r^2(\theta)$$

- Algorithm: indirectly recover phase from intensity.

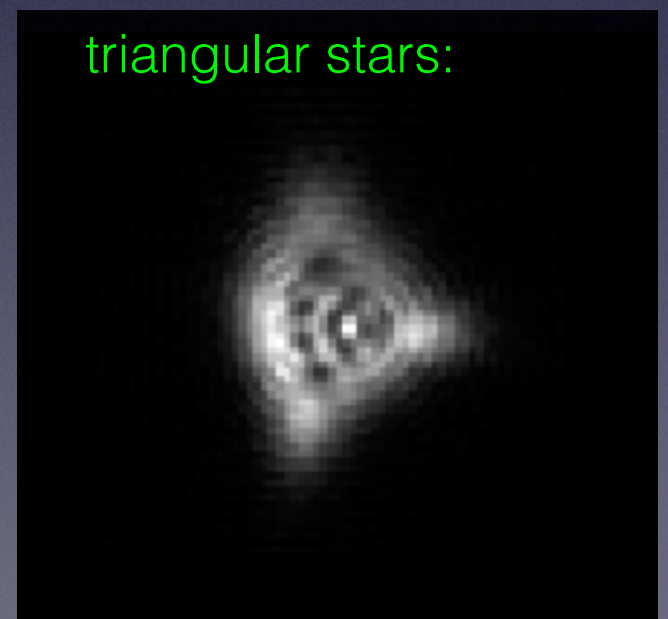
Star Test!



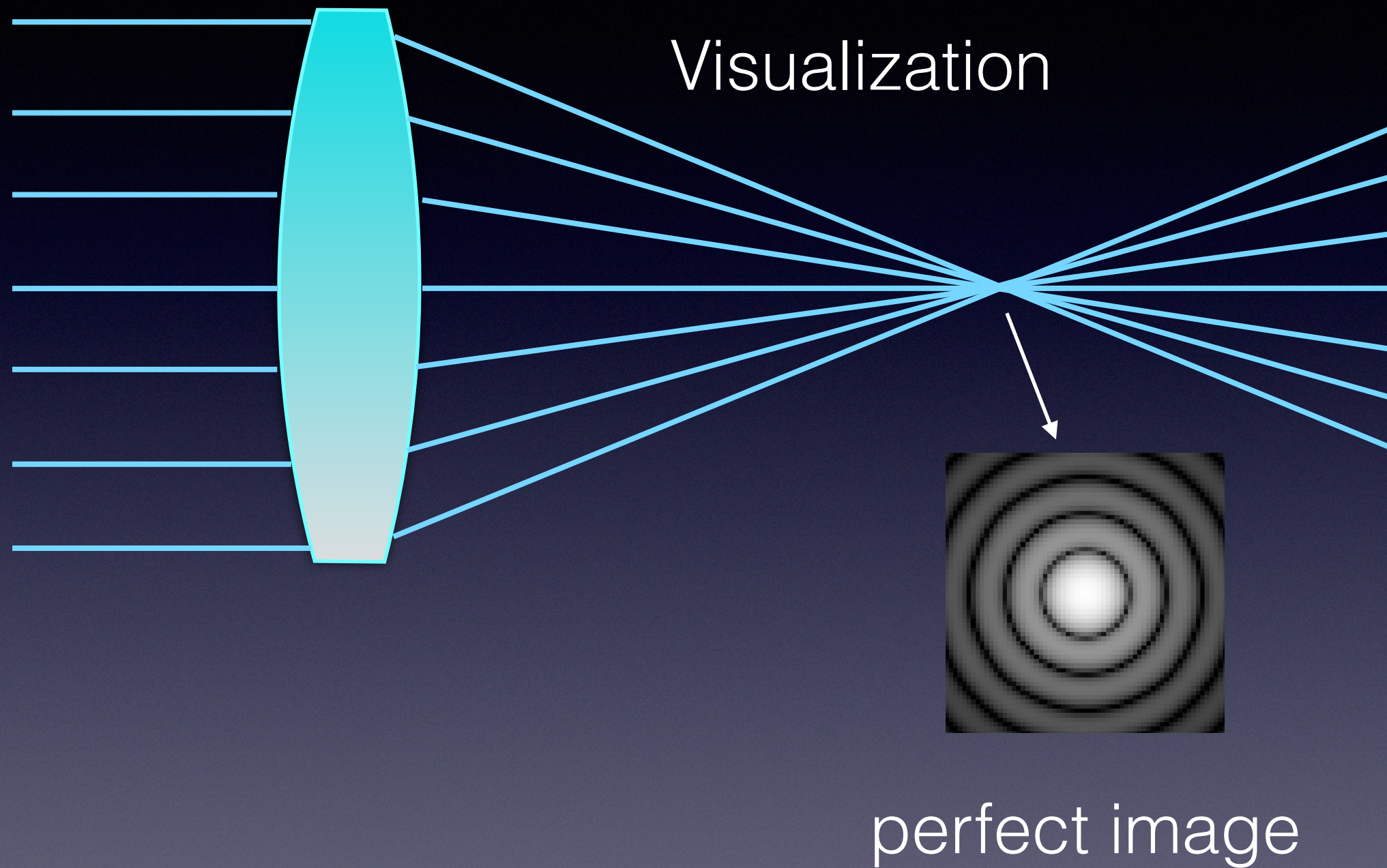
*based on
pattern
recognition*

Pinched Optics
(stress in mount)

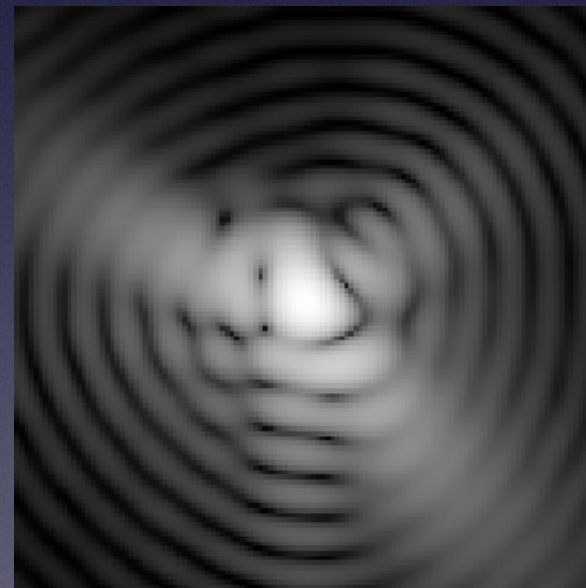
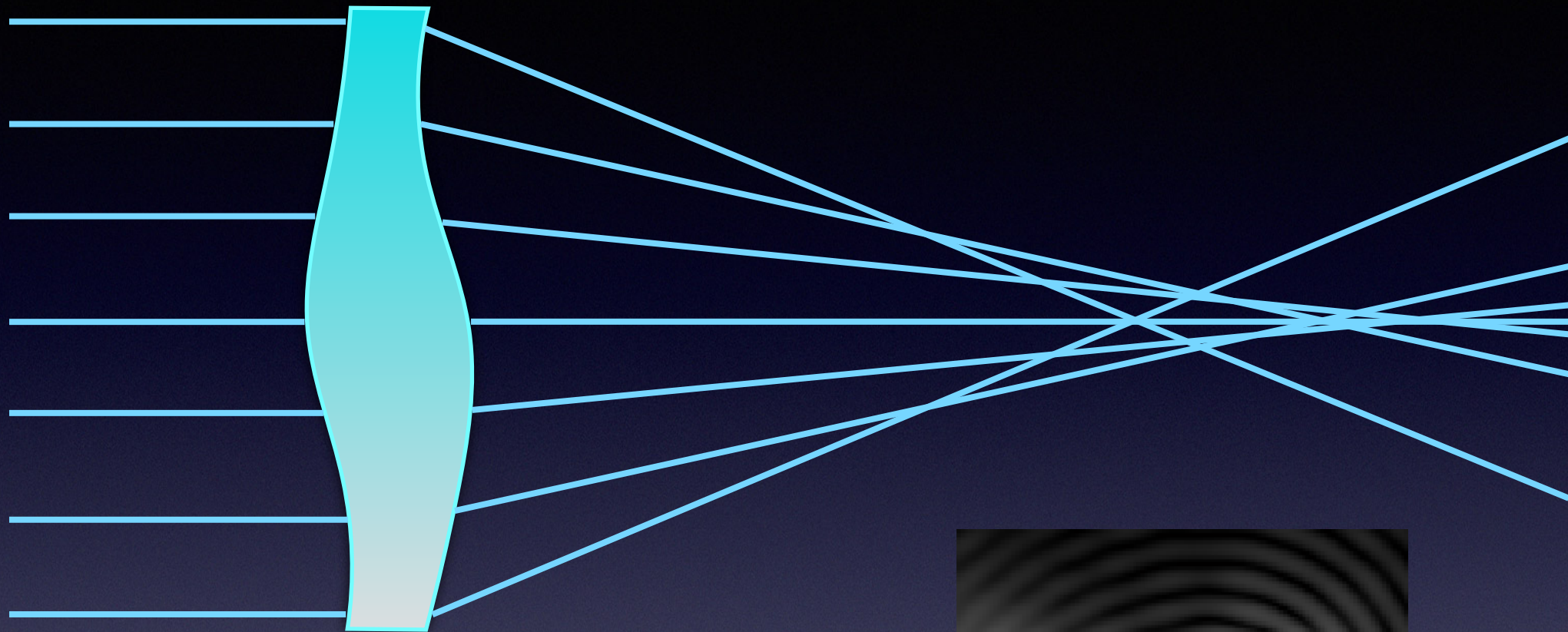
triangular stars:



Optical Imaging

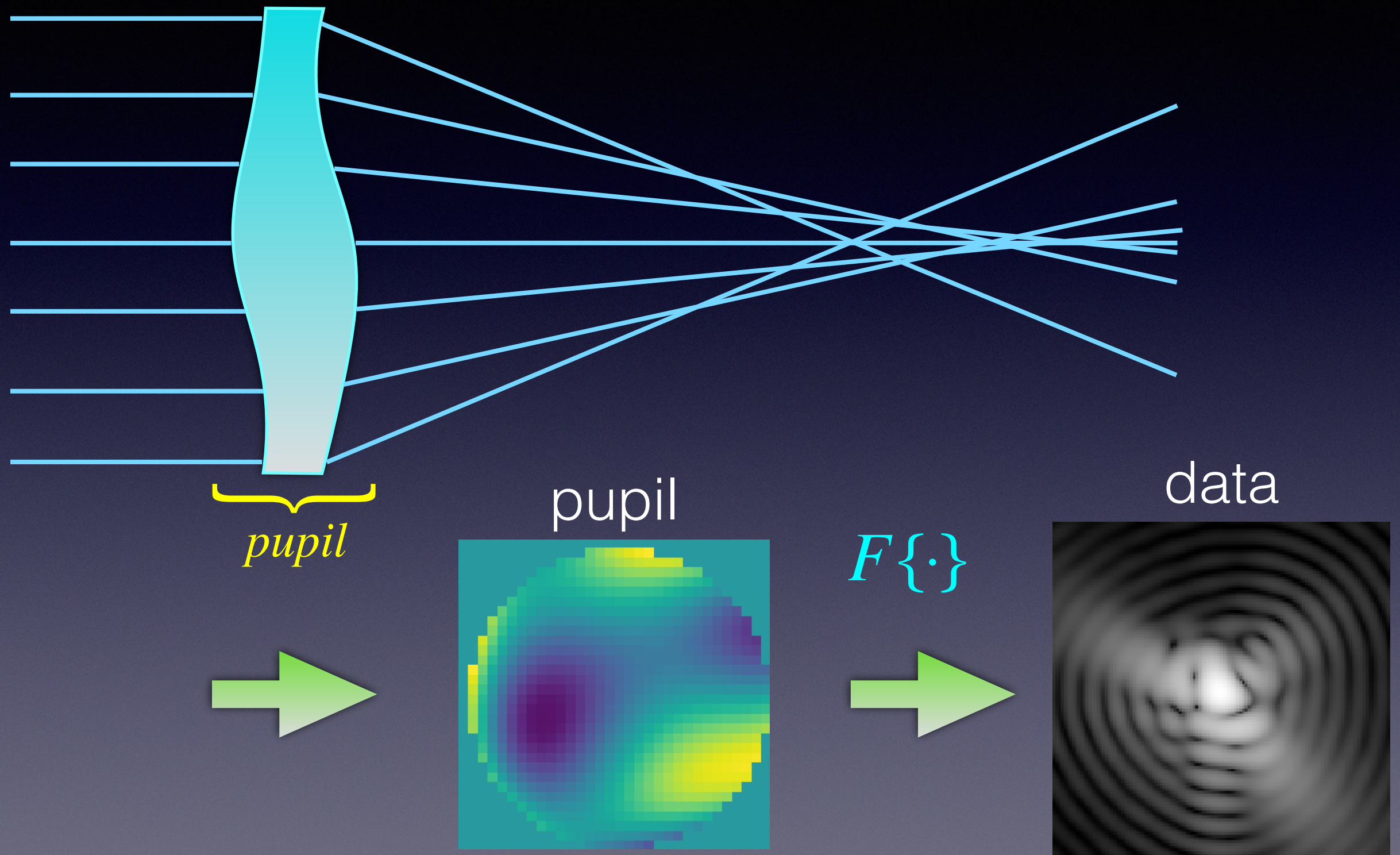


Optical Phase Errors, Imperfections

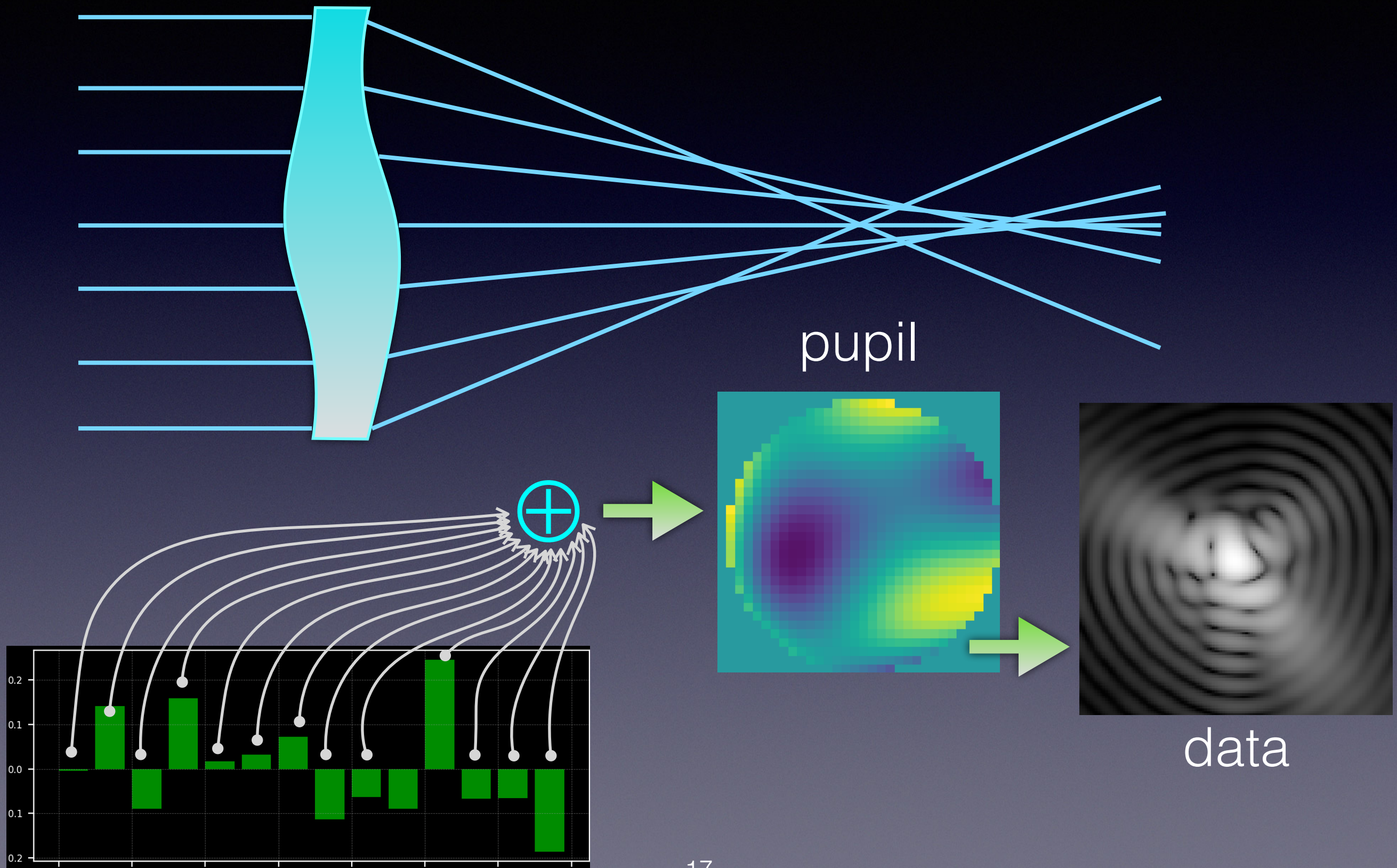


aberrated image

How to Quantify?

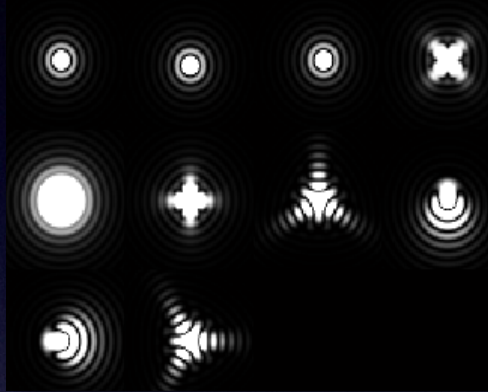


How to Quantify?

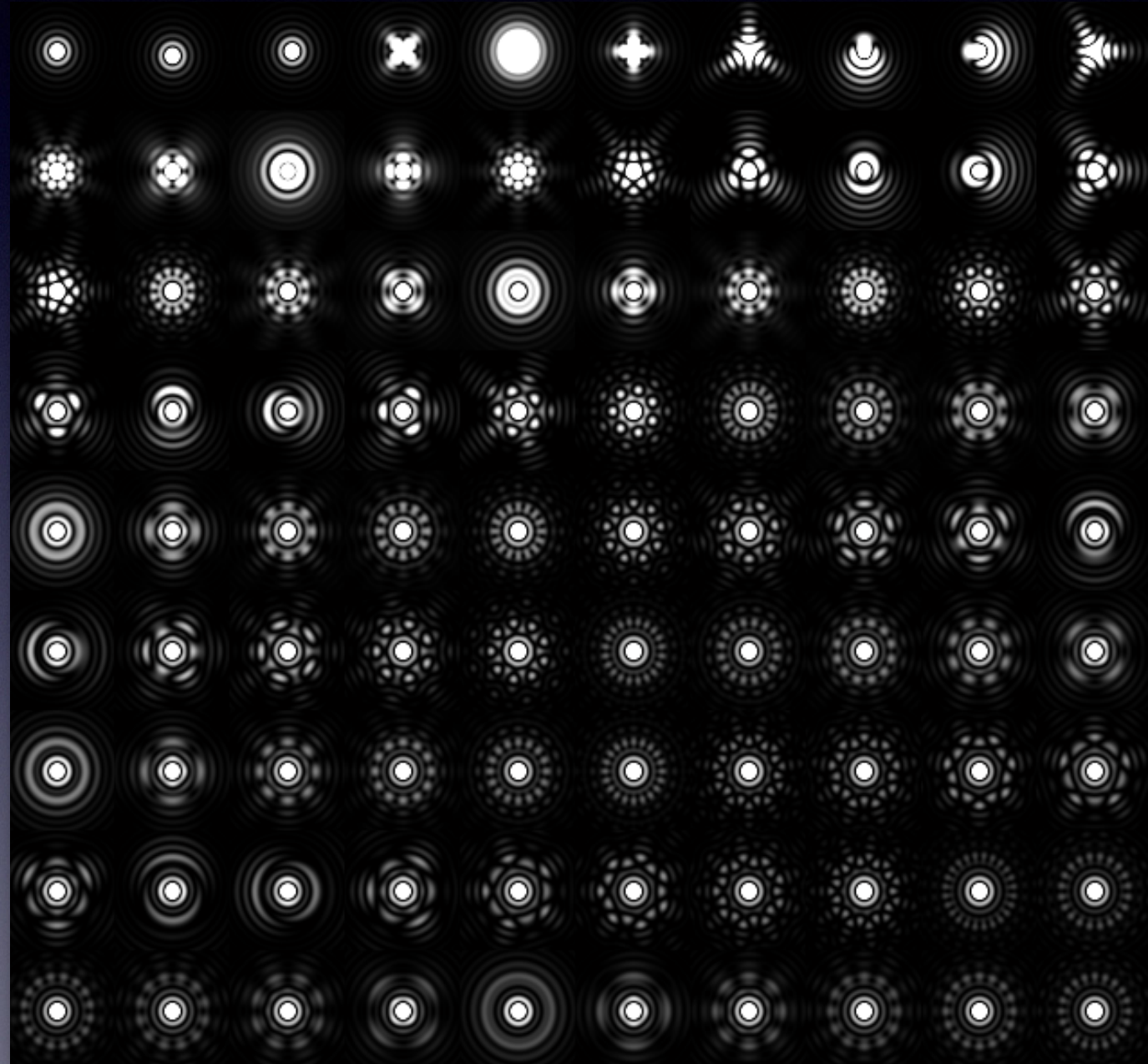


Intensity Taxonomy (“basis” functions of star-test):

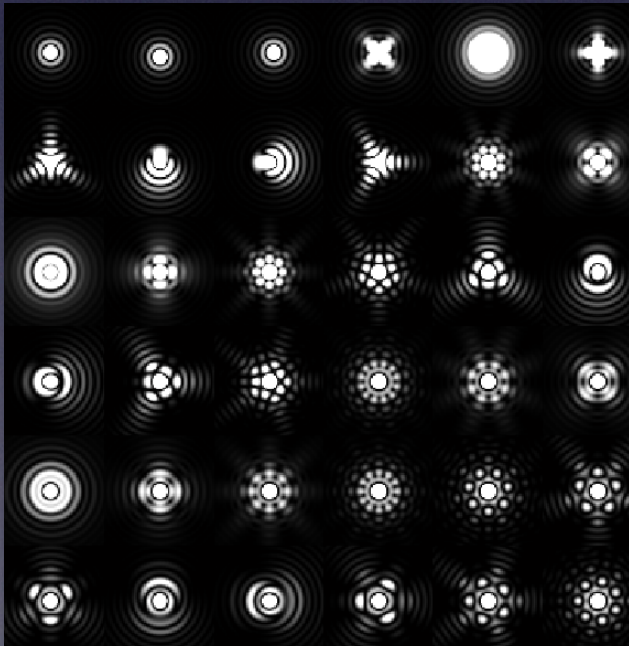
Order 3



Order 12



Order 7

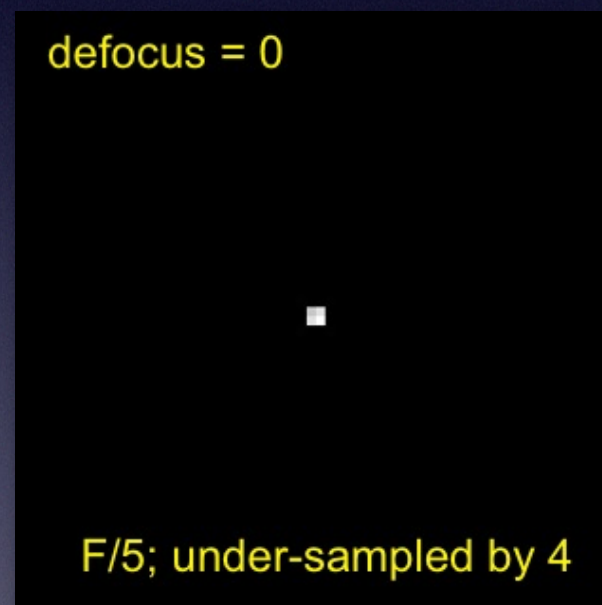


Implementation

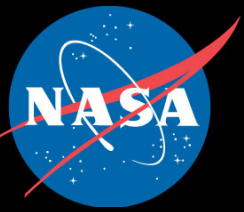
- Star-test does not work well for a focused star image - unless the star is over-sampled,

```
psfsize = 128; % number of pixels in focal plane = psfsize X psfsize
lambda = 0.6328e-6; % HeNe wavelength; units are meters
f_num = 5; % Optical System F/#
pixel_size = 6e-6; % assume 6 micron pixel size in focal plane
```

- Example:



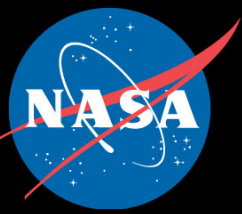
- To solve this problem:
- Enhance the visibility of the aberration “signal” of the star-test: defocus the image - i.e., a diversity function



Engineering with Diversity Functions

- **Good candidates:** parameters that produce “strong” effects in the data,
- **Engineering** a good diversity function: identifying functions that are simple to implement without degrading SNR.

Typically: Defocus



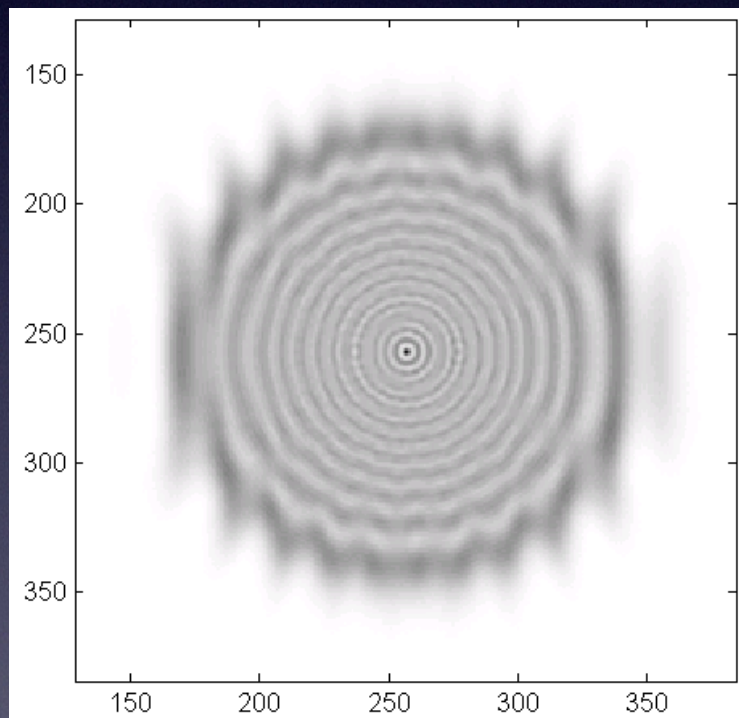
How Much Defocus?

- There is an “optimal” amount
- Use estimation theory
- **Cramer-Rao Bound:** a lower bound on the error bars associated with estimation from noisy data
- In this framework: the “signals” are the aberrations
- Want to vary the defocus to provide the maximum contrast in the signal

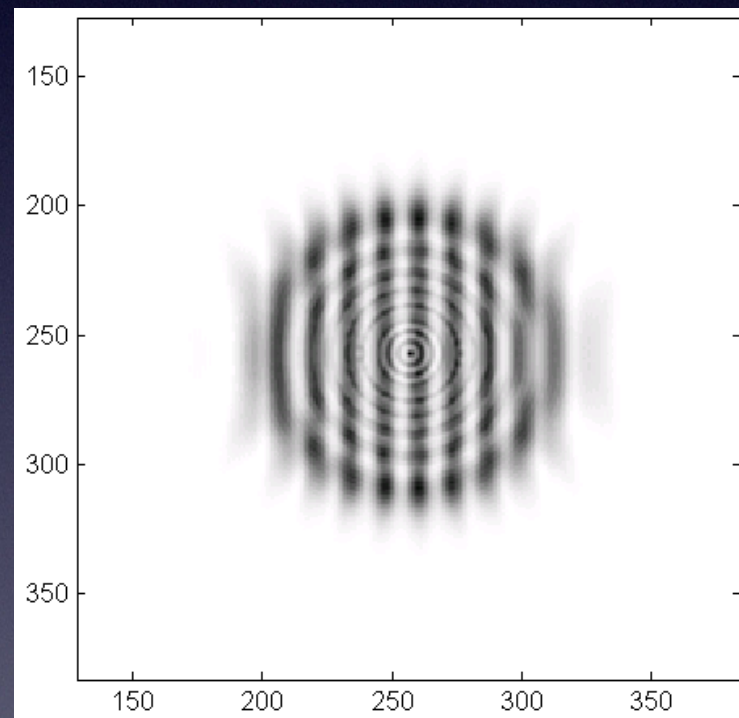
Example

Sinusoidal phase signal: certain defocus values can enhance signal contrast ...

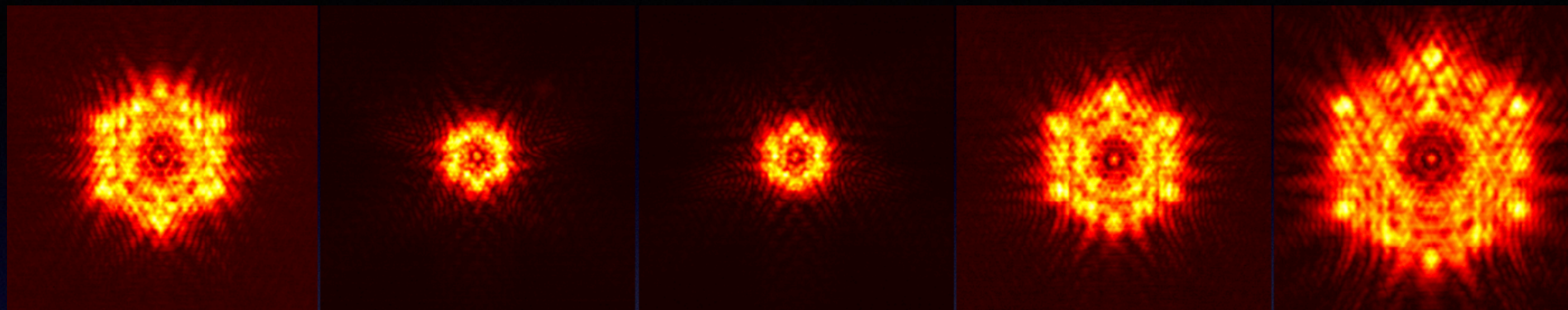
poor contrast



good contrast



JWST Diversity Values



-8λ

-4λ

$+4\lambda$

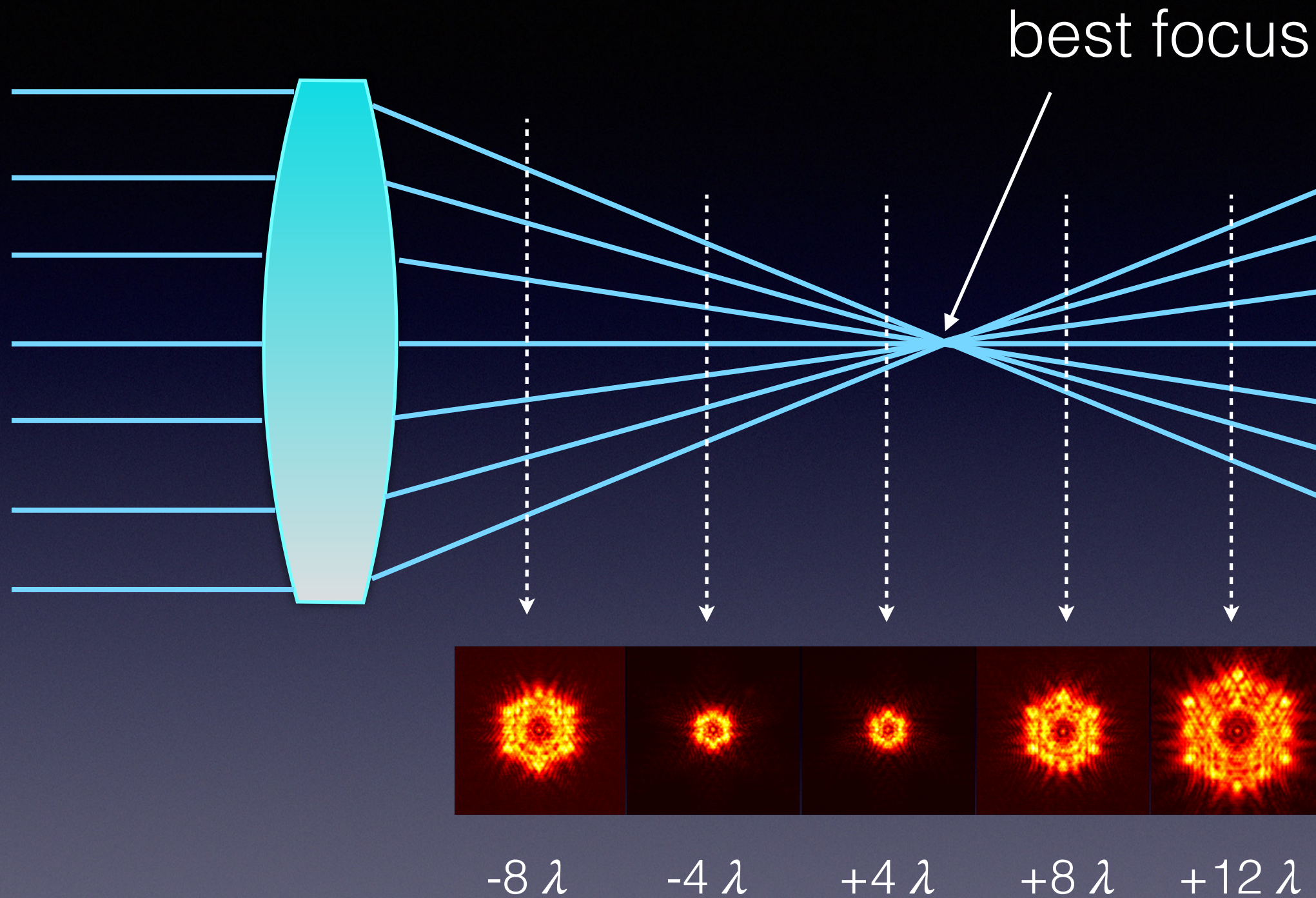
$+8\lambda$

$+12\lambda$

- Calculated* based on dominant spatial frequencies
- Values were built into hardware
- Implemented using the so-called “weak lenses”

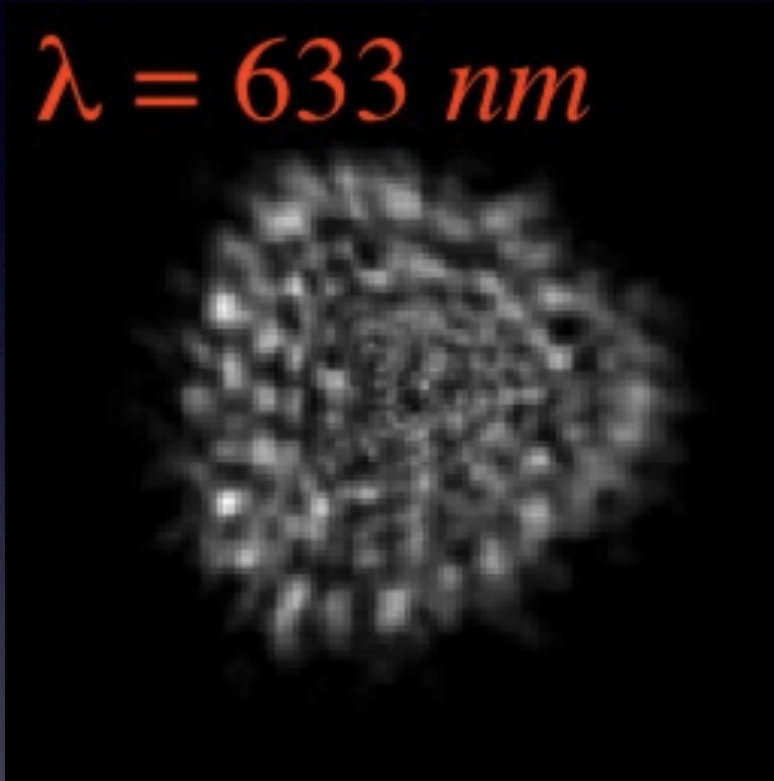
* B. Dean, C. Bowers, “Diversity Selection for Phase-Diverse-Phase-Retrieval,” JOSA, 20(8), 2003, pp. 1490-1504

Diversity Defocus Visualization

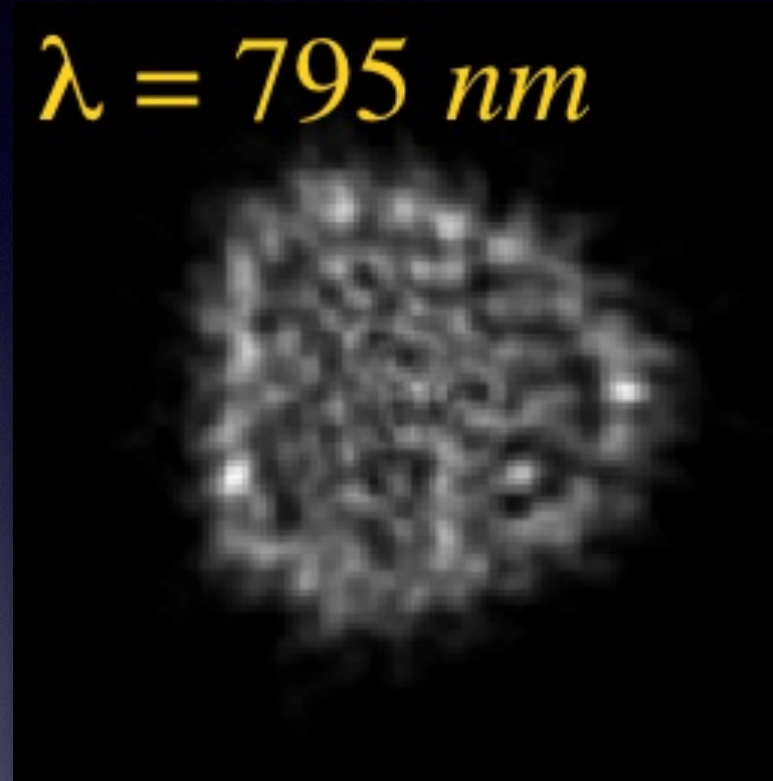


Wavelength (not a good diversity function):

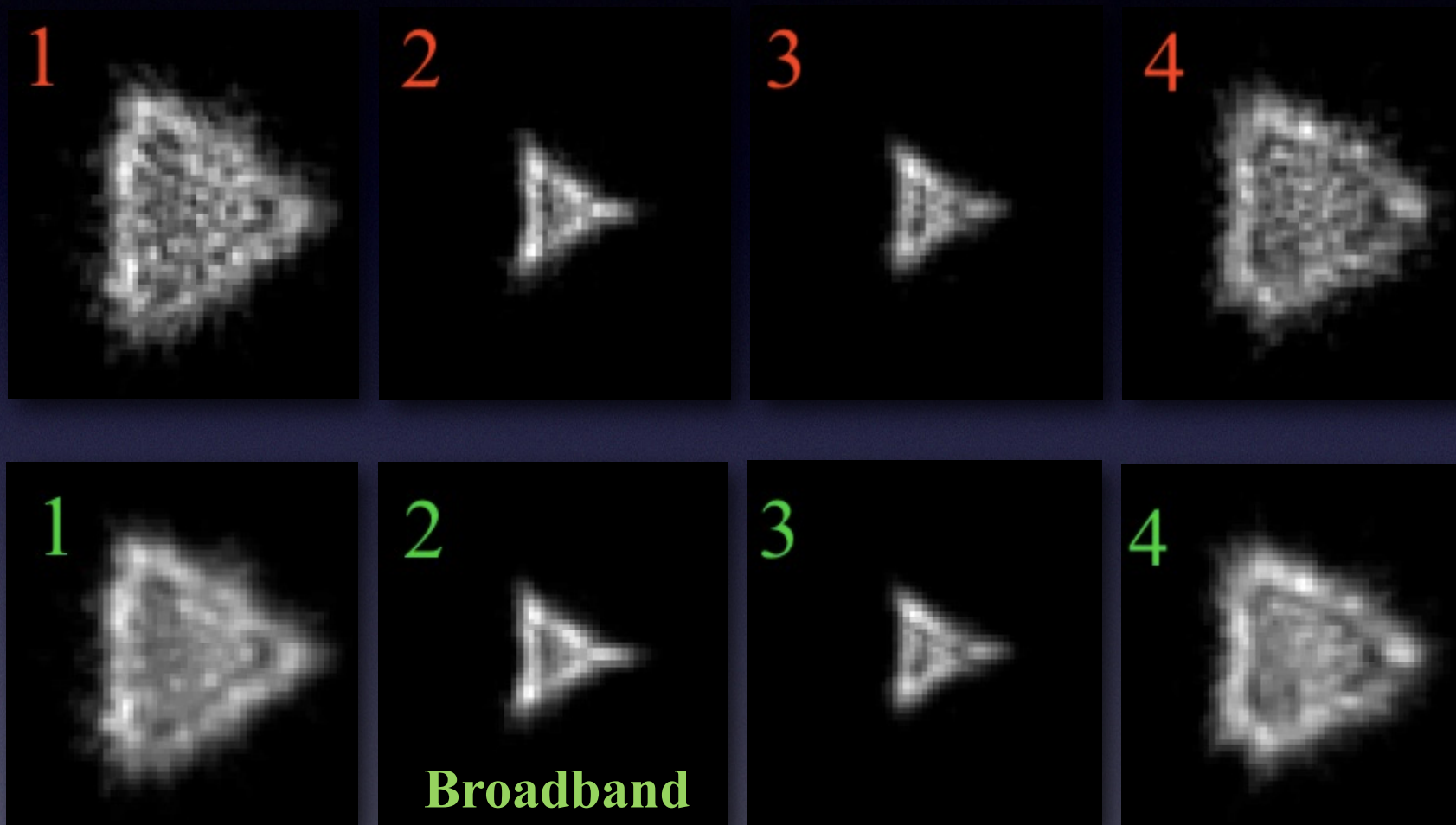
$\lambda = 633 \text{ nm}$



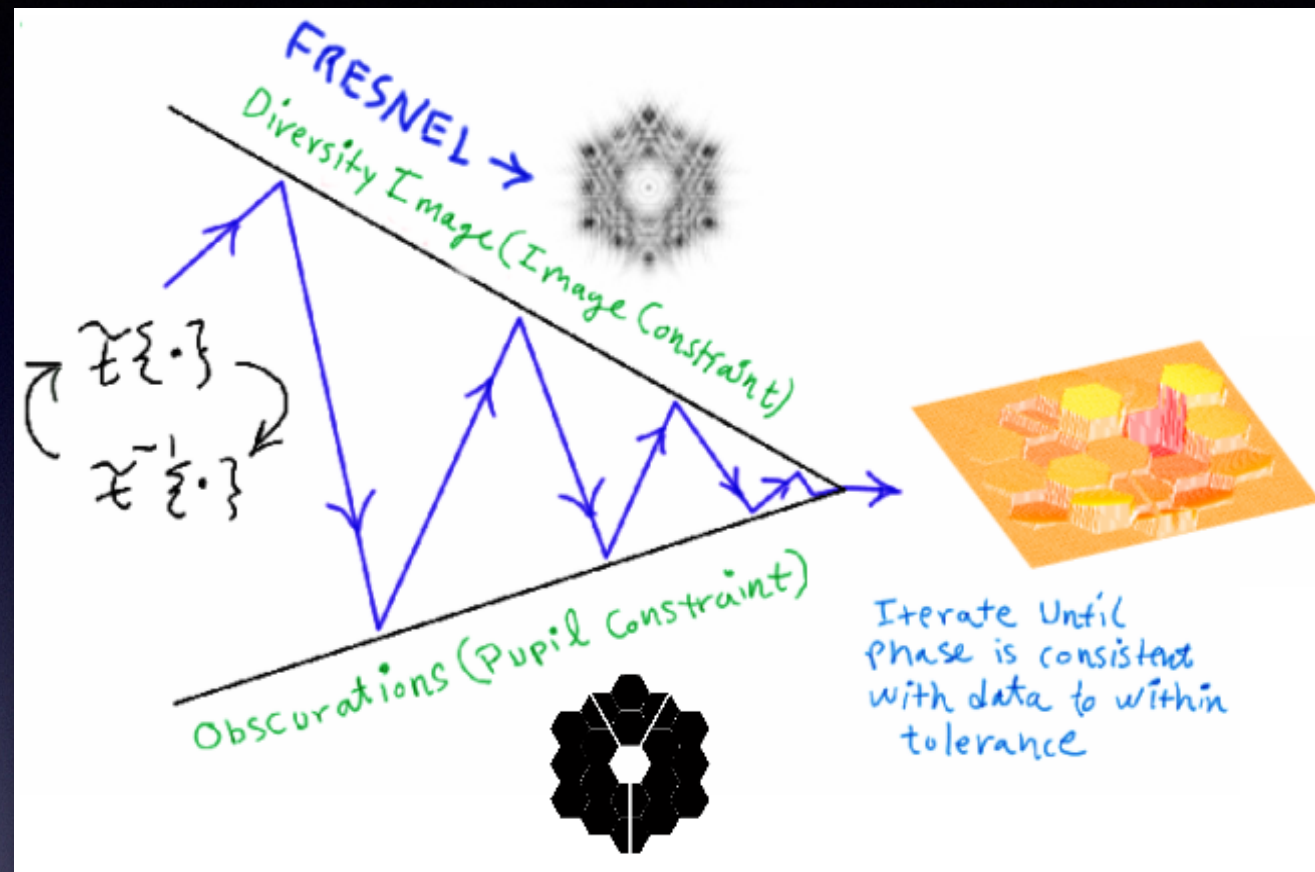
$\lambda = 795 \text{ nm}$



Trefoil in Red Light



Algorithms: Iterative Transform

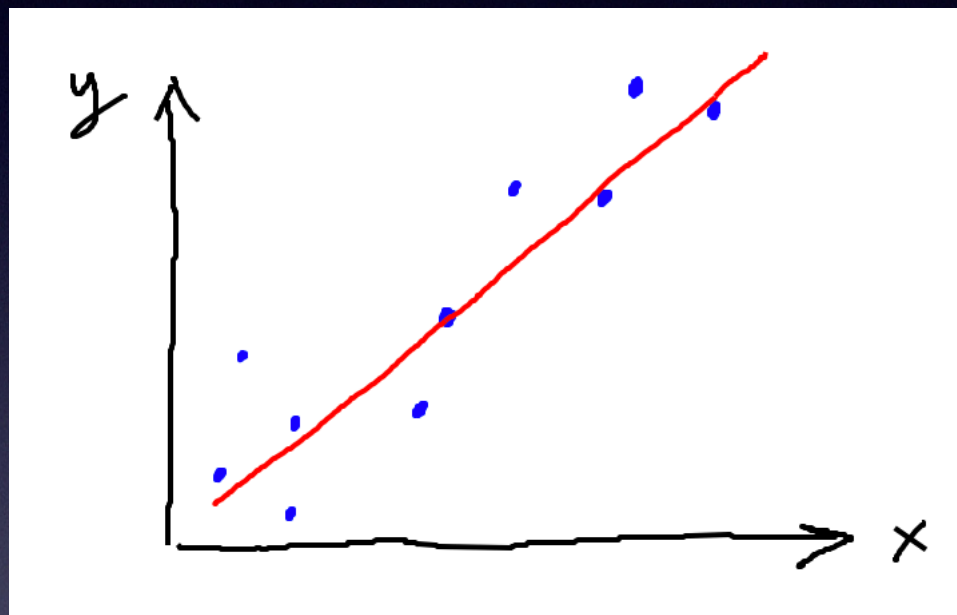


- R. W. Gerchberg and W. O. Saxton, "A practical algorithm for the determination of phase from image and diffraction plane pictures," *Optik (Stuttgart)* **35**, 237–246 (1972).
- D. L. Misell, "A method for the solution of the phase problem in electron microscopy," *J. Phys. D* **6**, L6–L9 (1973).

Algorithms: Parameter Based Phase-Retrieval

min [Objective Function]:

$$\frac{\partial}{\partial a_m} \sum_{j=1:N} \left\| \text{PSF}_{\text{data},j} - \text{PSF}_{\text{model},j}(\lambda, f_{\#}, \text{Pixel}, \Phi_{\text{DIV}}, \vec{a}) \right\|^2 = 0$$



$$e^2 = \sum_l |y_{\text{data},l} - y_{\text{model},l}|^2$$

$$y_{\text{model},l} = ax_l + b$$

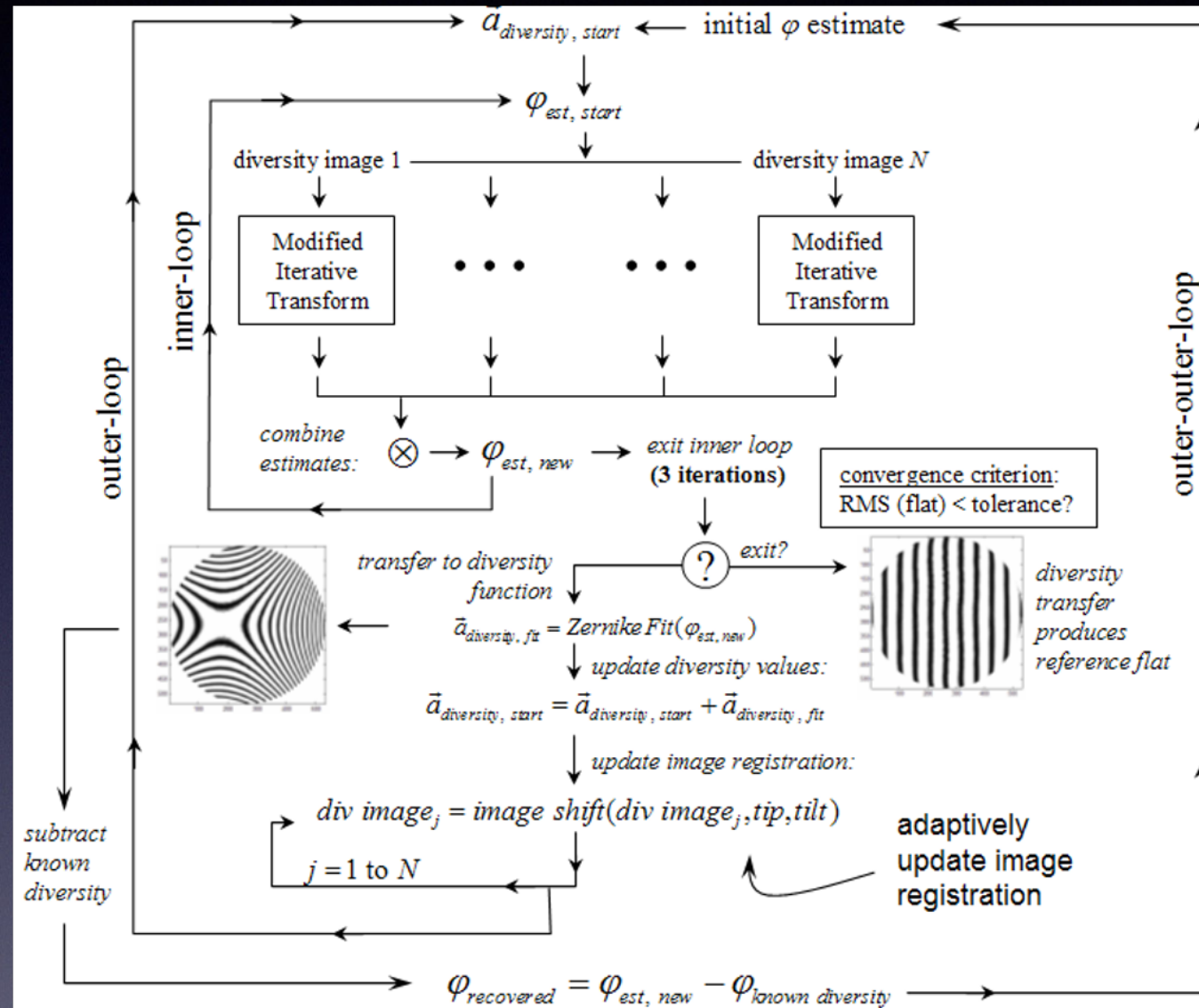
$$de^2 = 0 \Rightarrow \text{normal equations}$$

Numerical Methods:

Newton, Quasi-Newton, Steepest Decent, Simplex, Levenburg-Marquardt, Simulated Annealing, ...

JWST Flight Implementation

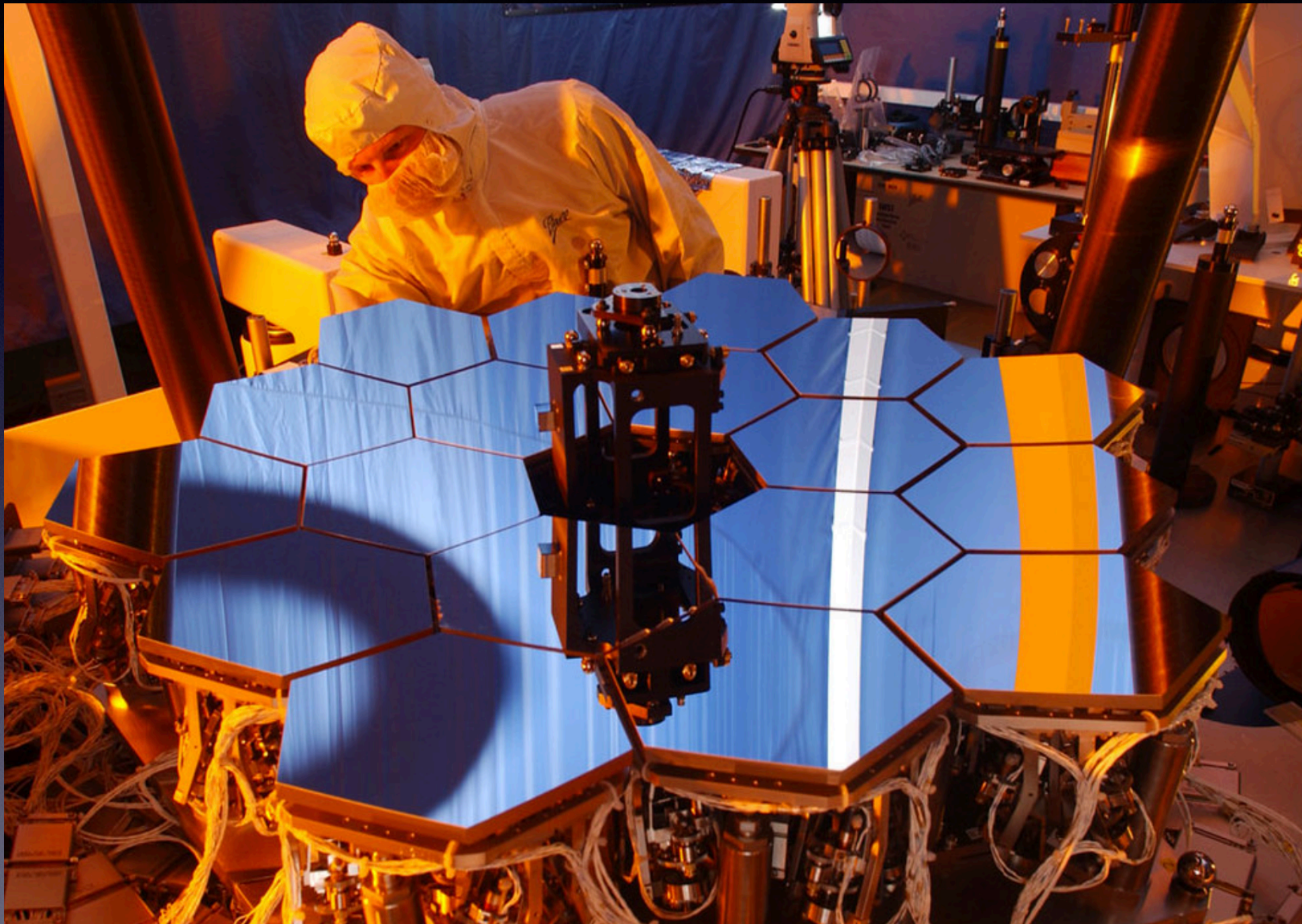
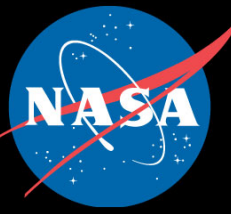
Hybrid* method, incorporates advantages from each approach:



Solved the phase-wrapping problem that plagued earlier implementations

* B. H. Dean, D. L. Aronstein, J. S. Smith, R. Shiri, and D. S. Acton, "Phase retrieval algorithm for JWST flight and testbed telescope," Proc. SPIE 6265, 626511 (2006)

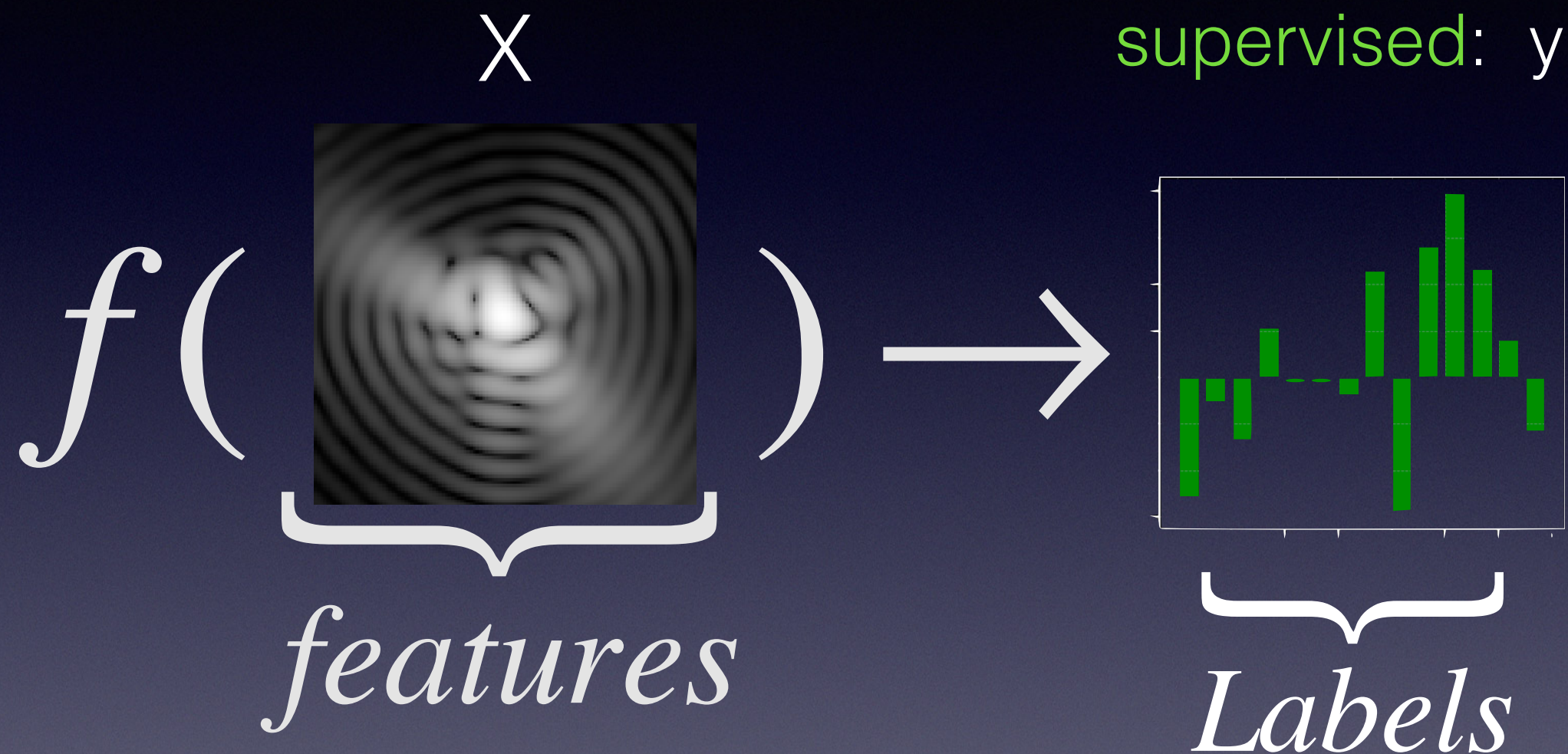
JWST TRL-6 Testbed

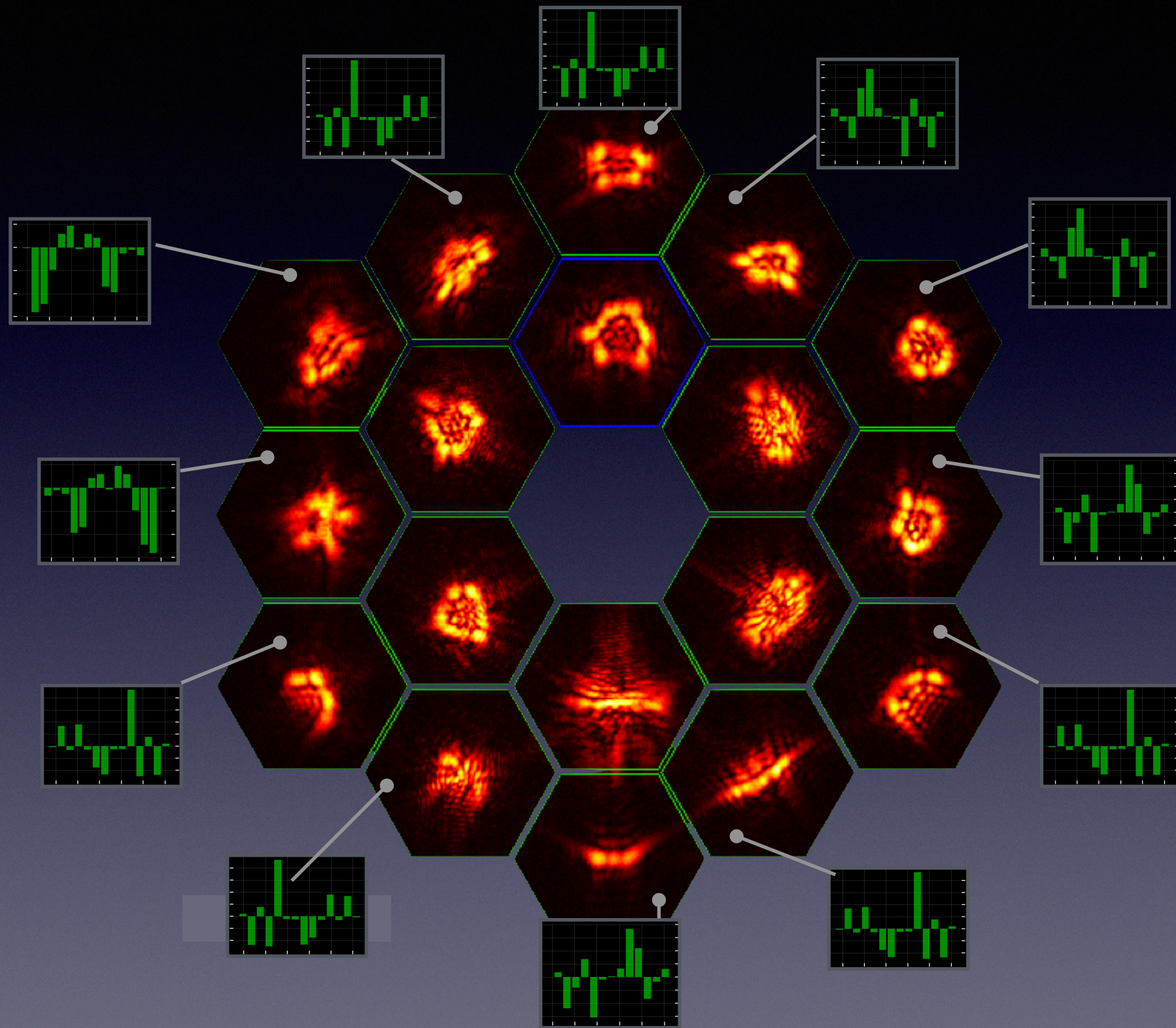


Other Methods: Pattern Recognition

$$\underbrace{y}_{\text{labels}} = f(\underbrace{X}_{\text{features}})$$

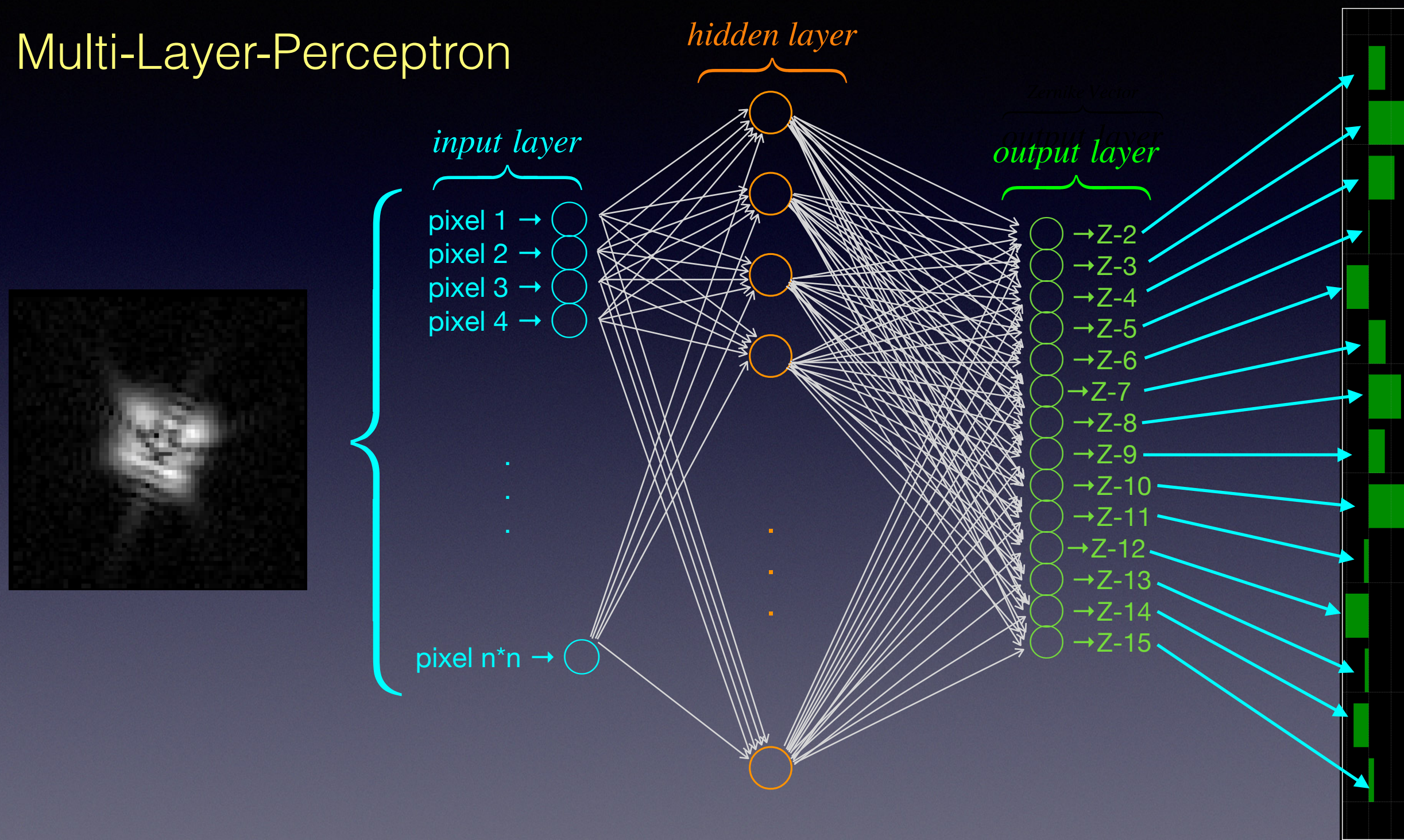
Create Mapping



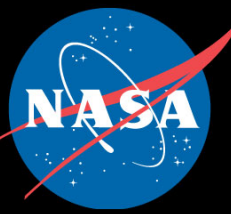


“Naive” Architecture

Multi-Layer-Perceptron

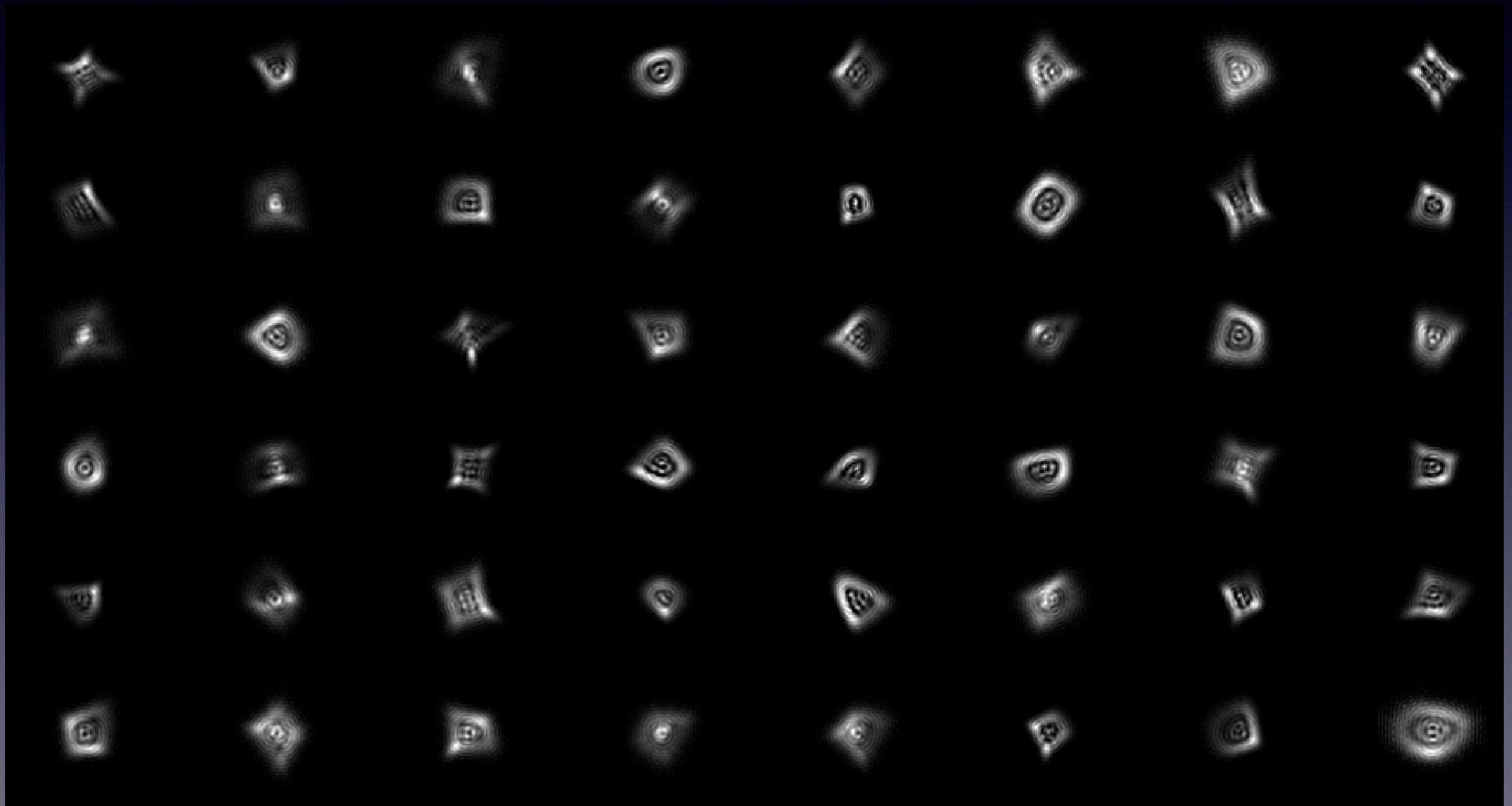


Performance

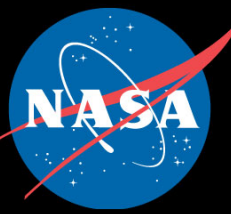


Pattern Recognition

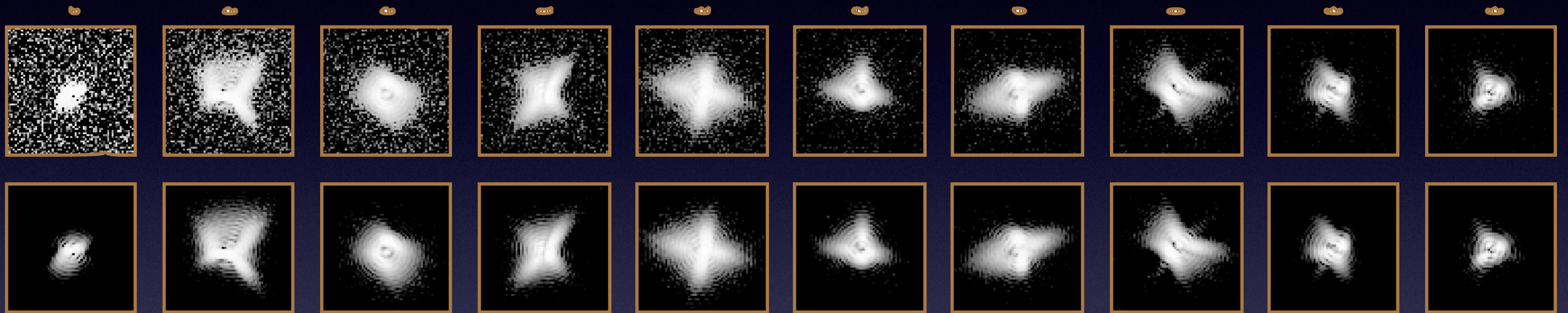
ability to generalize



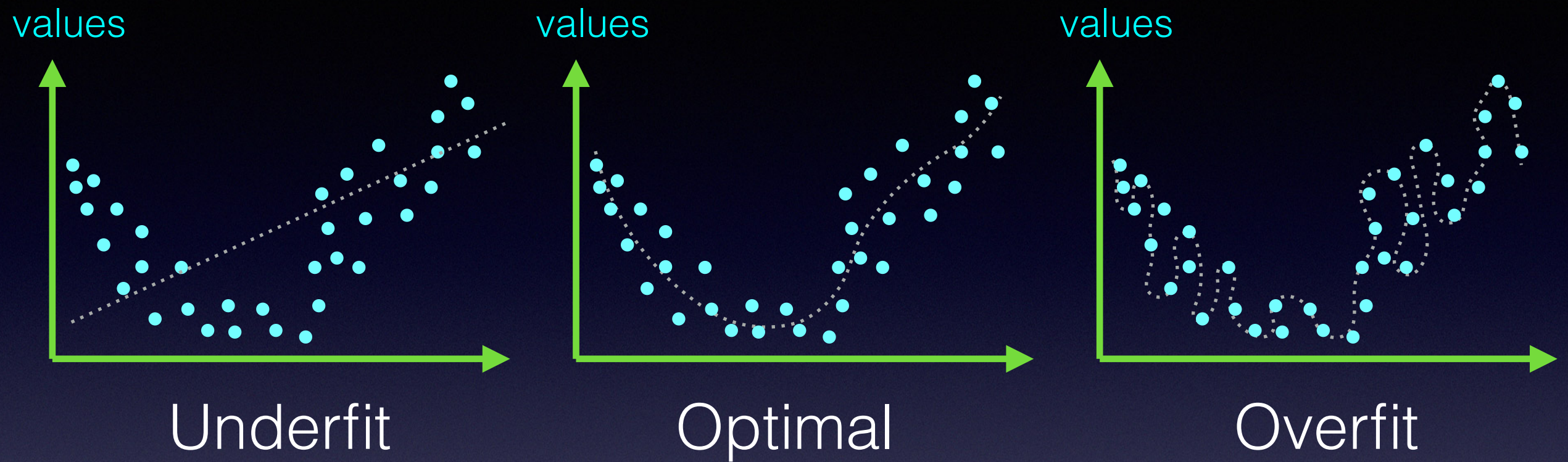
Generalization



Signal-Noise-Ratio $\longrightarrow$



Performance



Performance



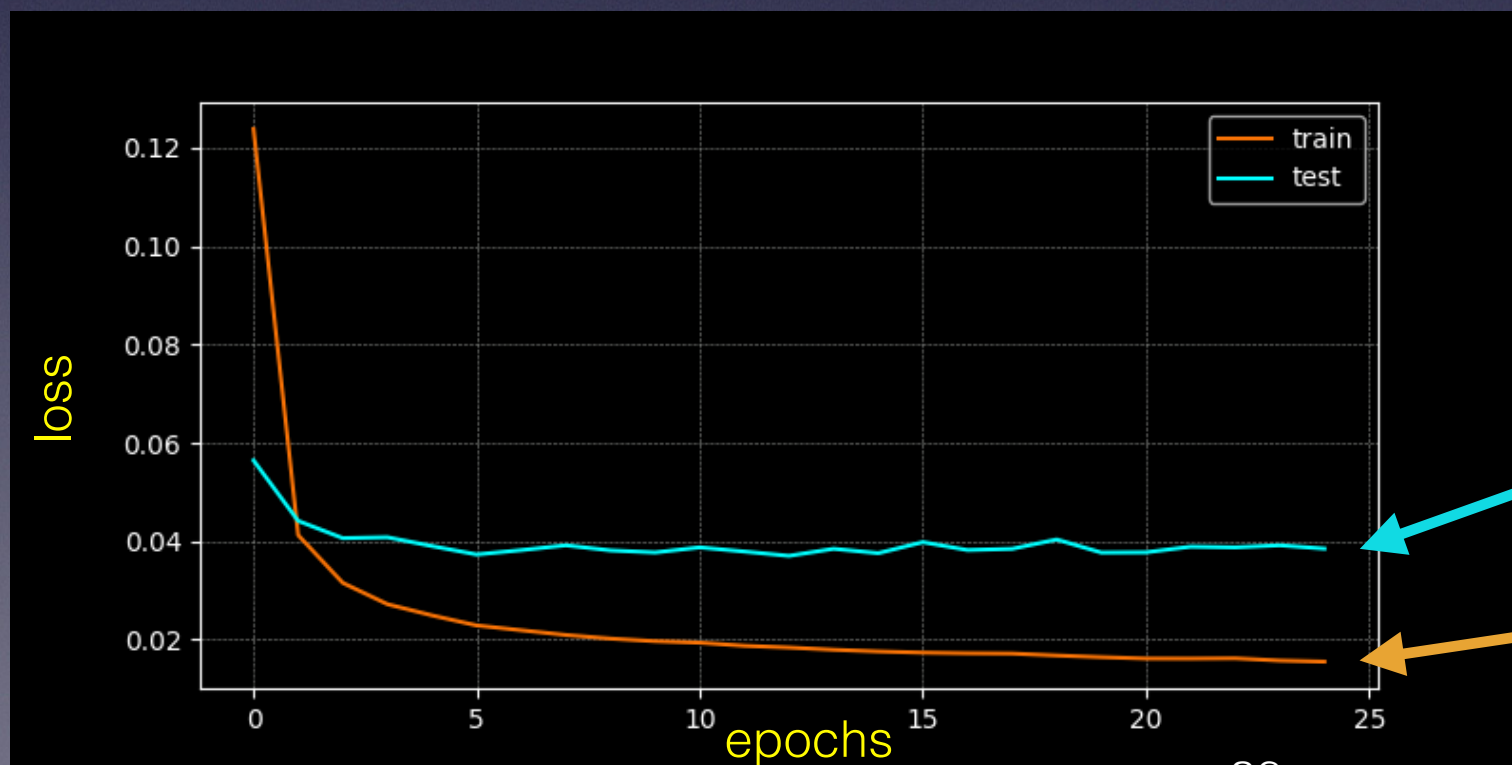
Underfit



Optimal



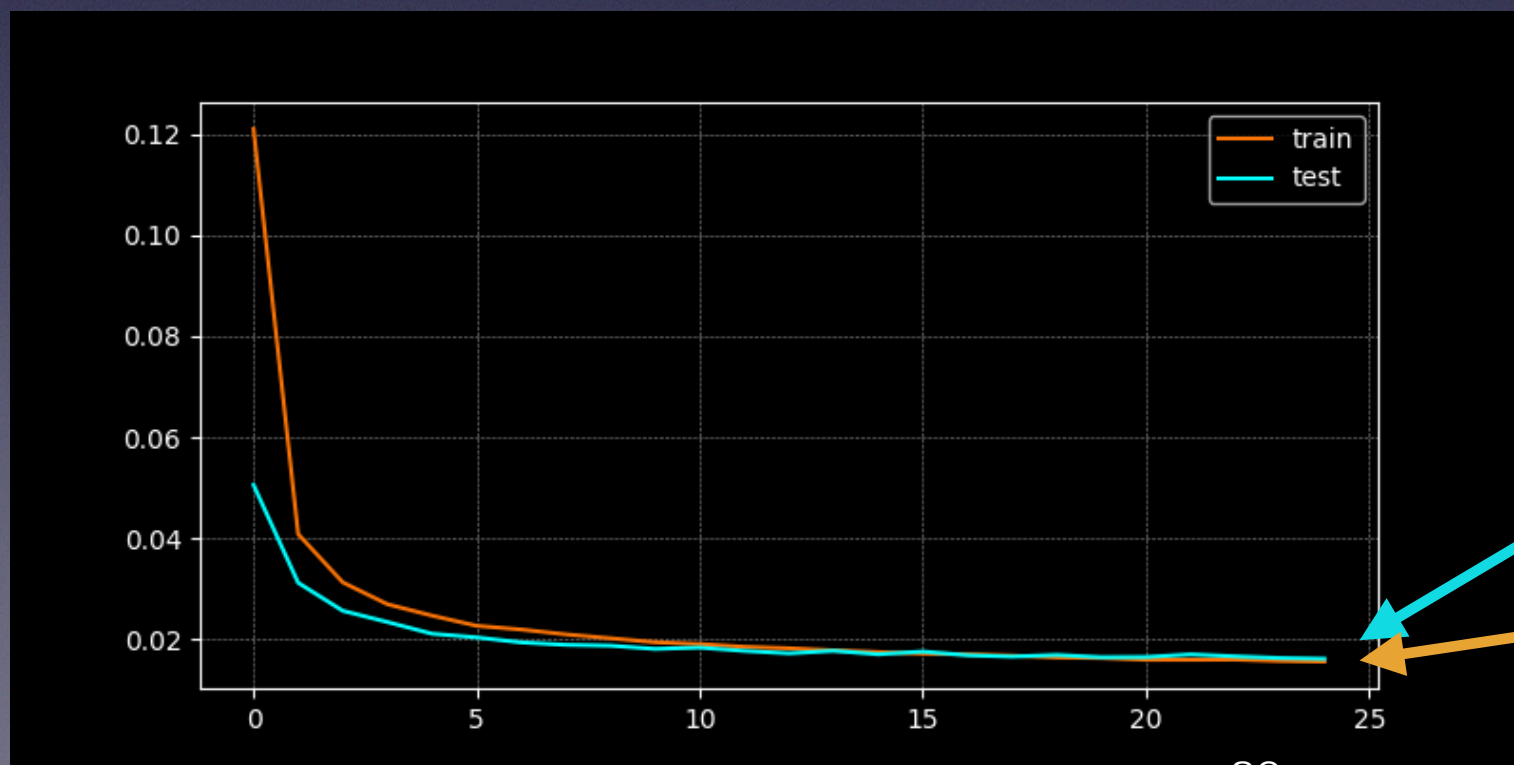
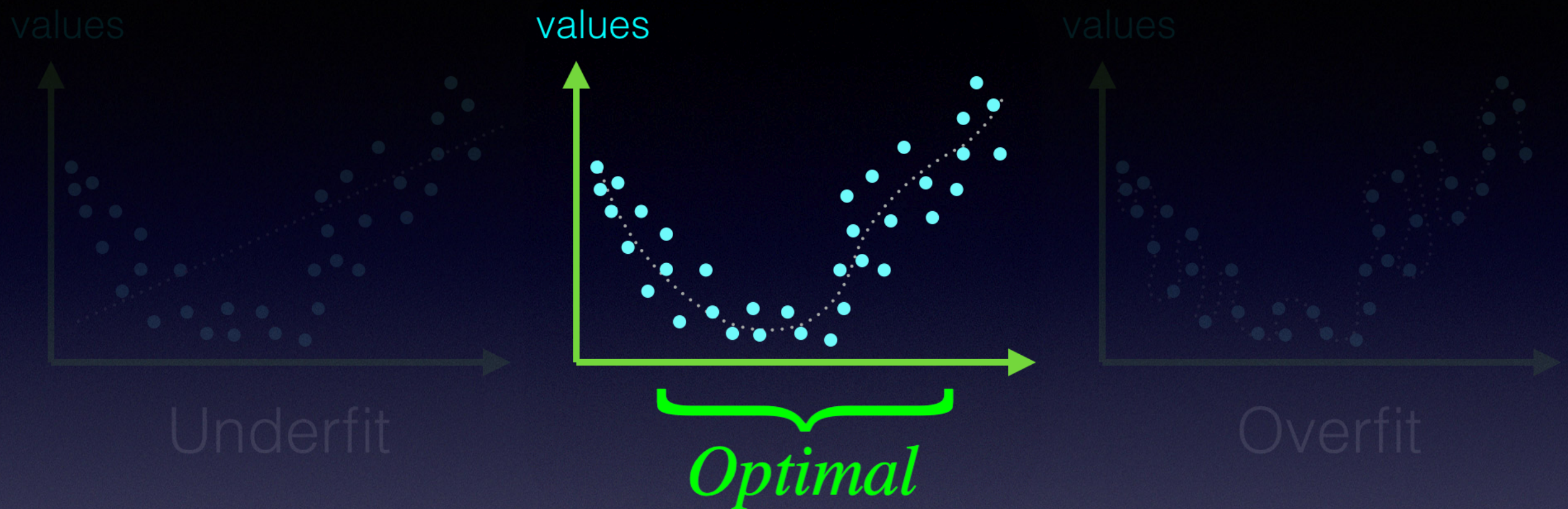
Overfit



error for test set larger

error for train set smaller

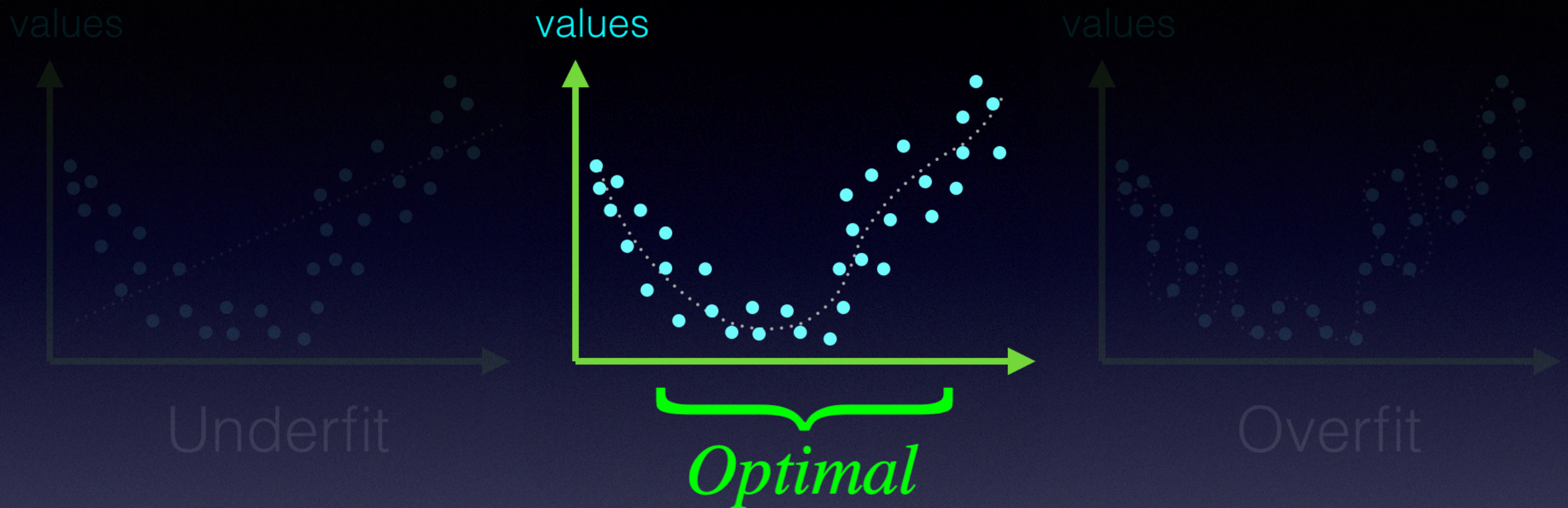
Performance



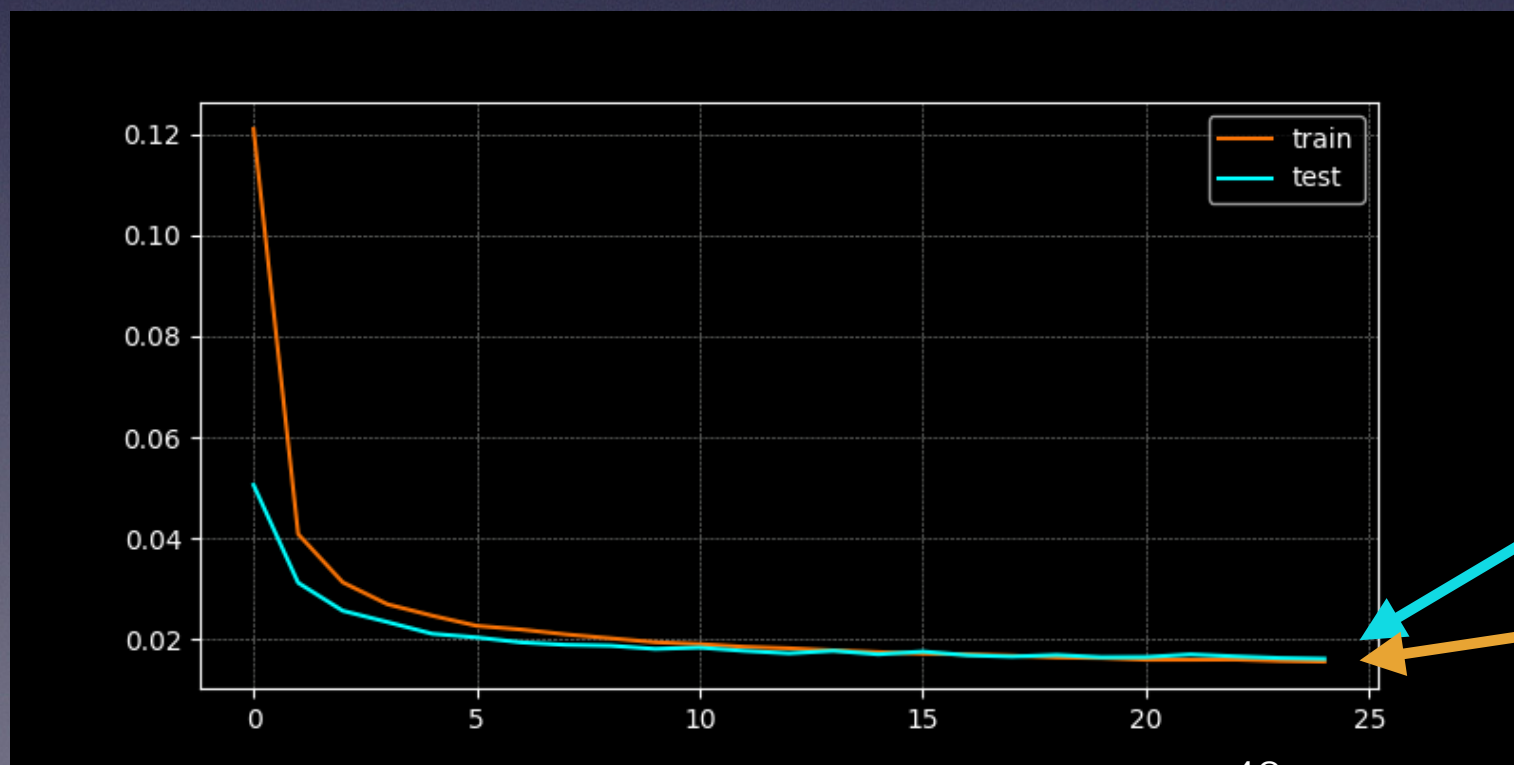
error for test set

error for train set

Performance



Best for
Generalization



error for test set

error for train set

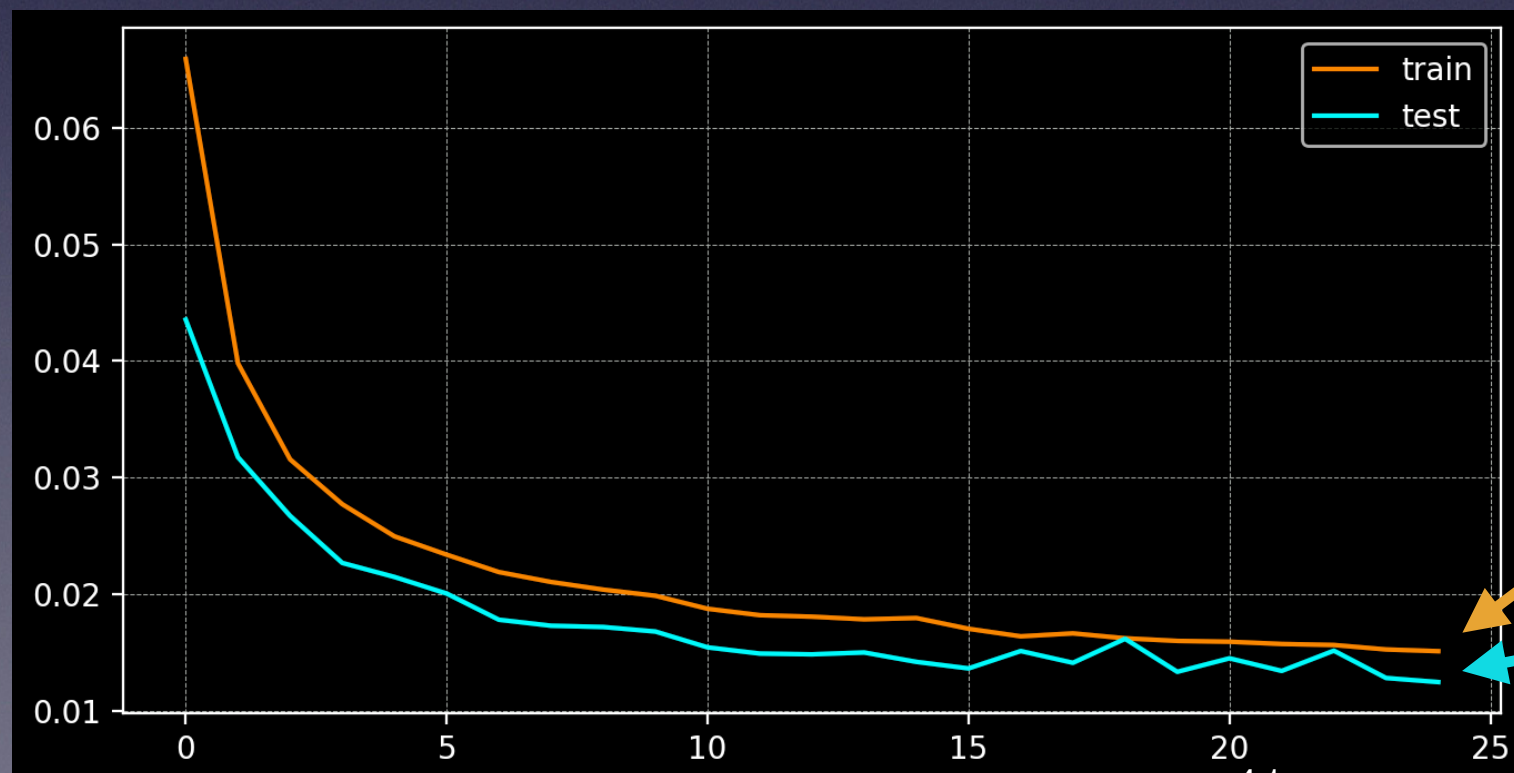
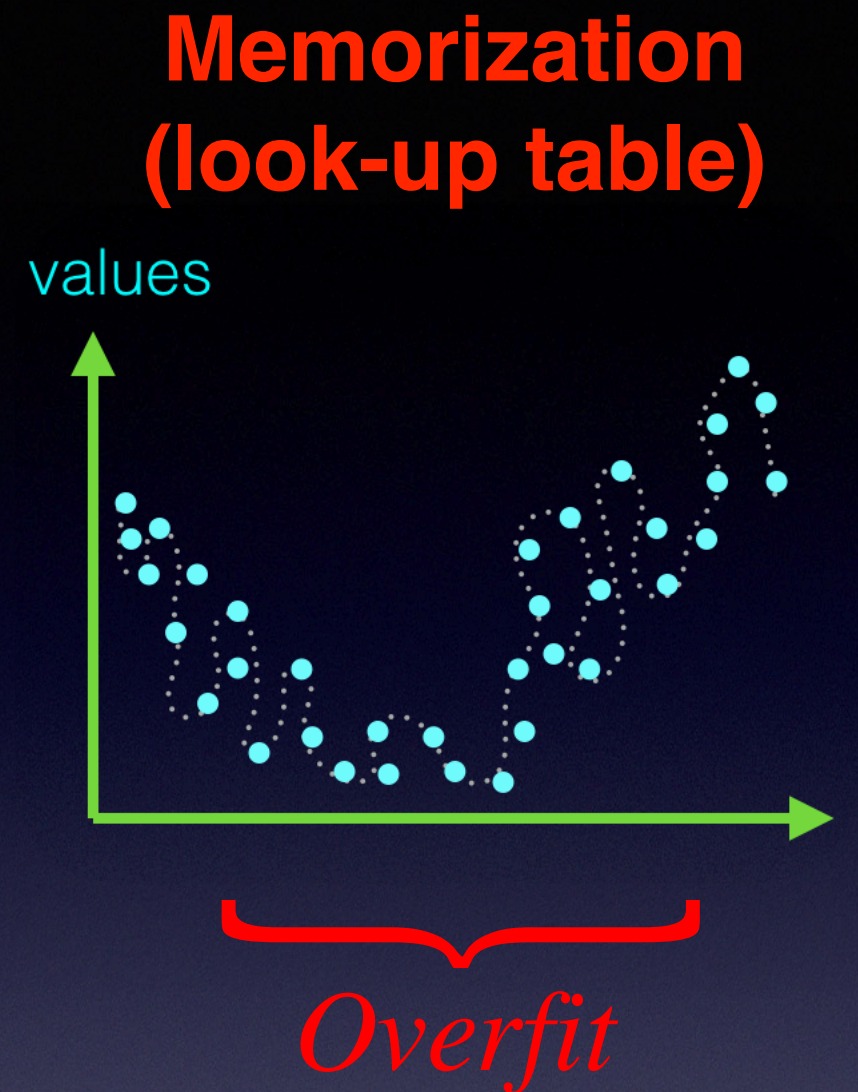
Performance



Underfit



Optimal



error for train set

error for test set

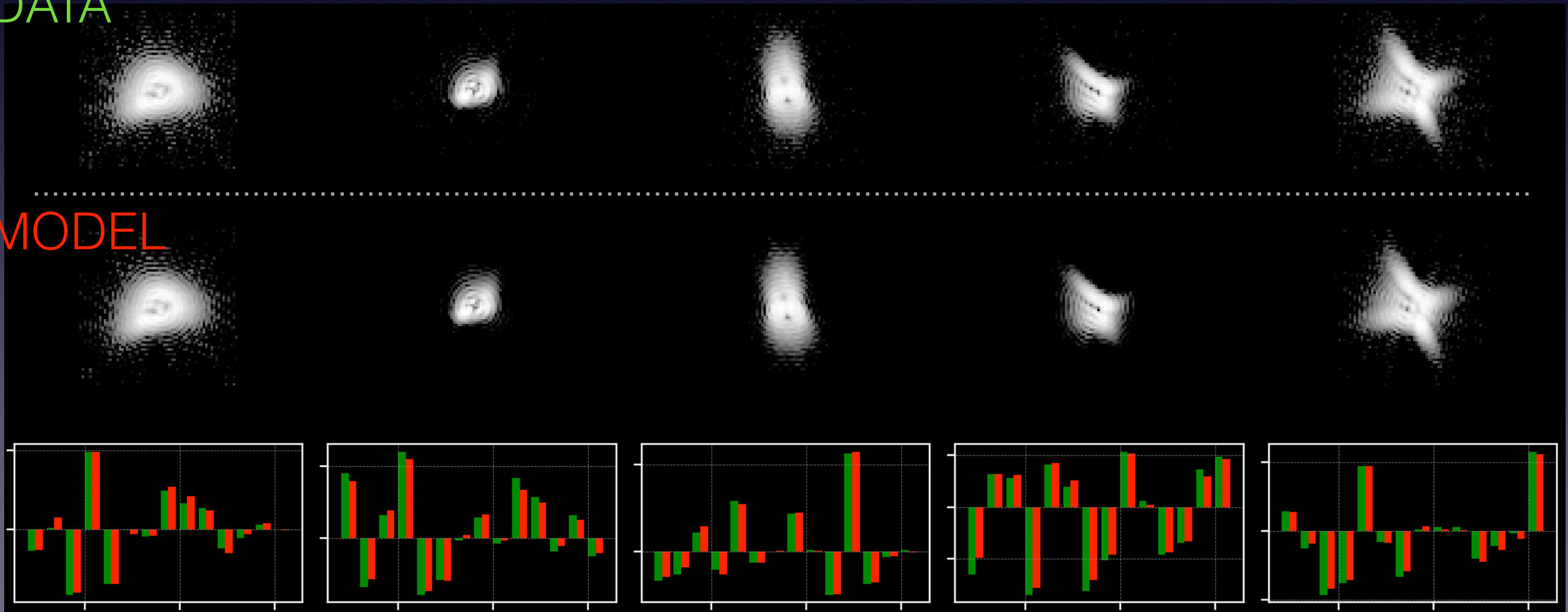
Results

Convolutional Neural Net:

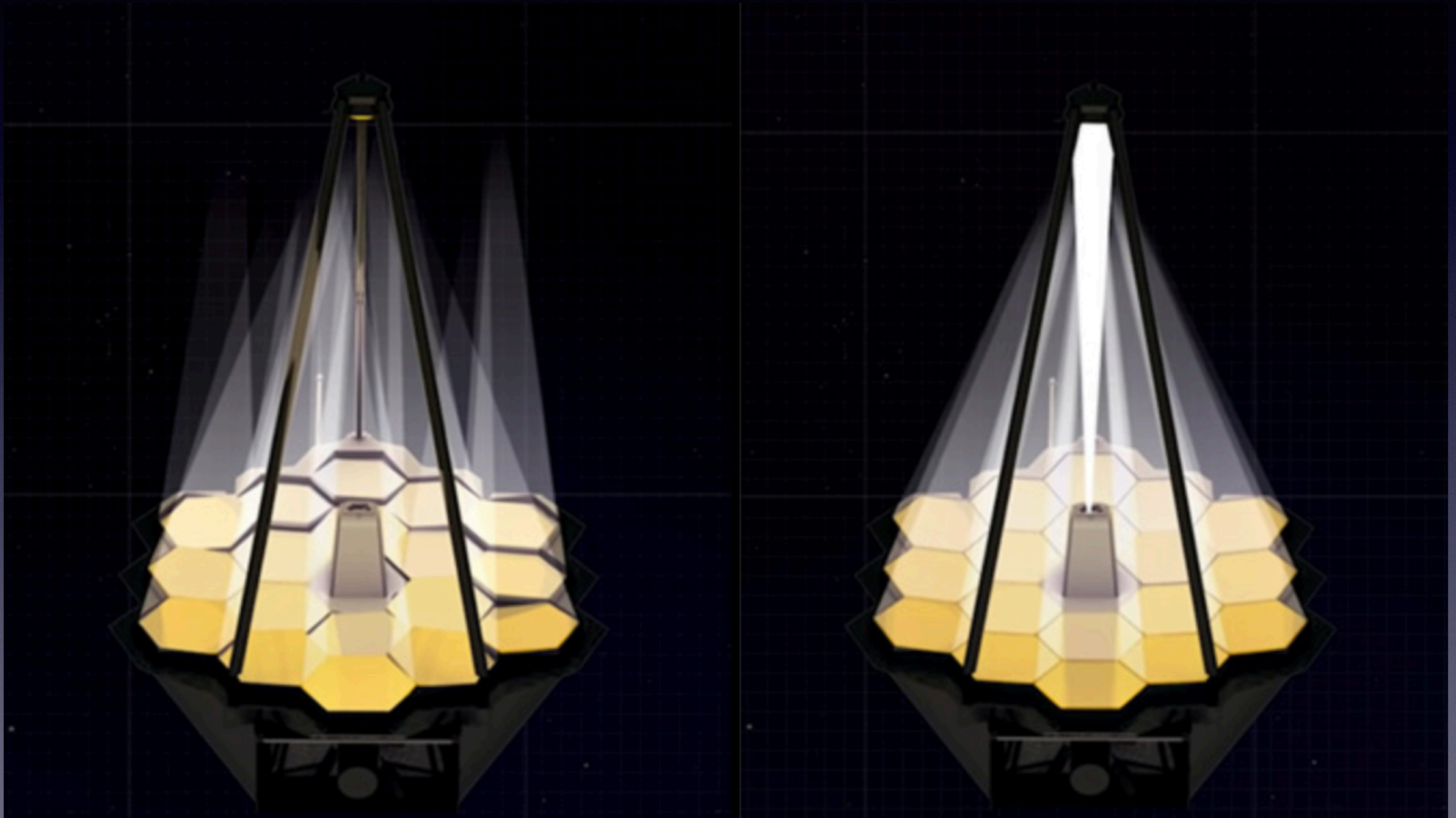
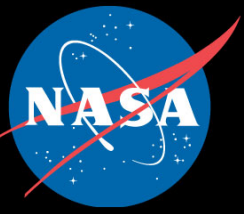
Mean RMS Error:
 $\lambda/64 = 33 \text{ nm} \pm 16 \text{ nm}$

DATA

MODEL



Application: JWST



Example JWST Phase Retrieval

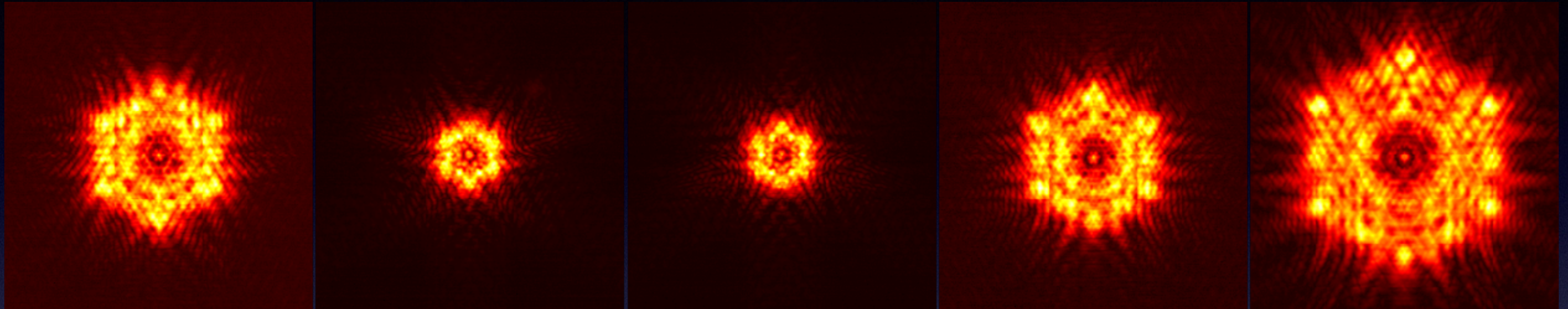
-8λ

-4λ

$+4 \lambda$

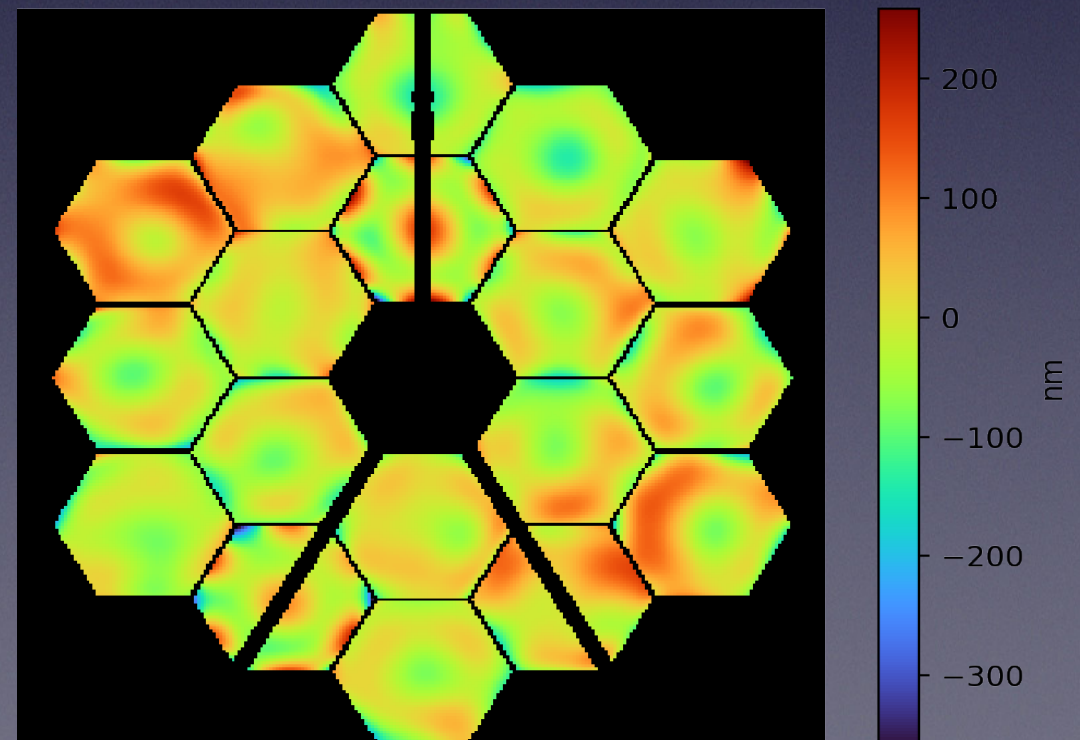
$+8 \lambda$

$+12 \lambda$



T. Zielinski, NASA GSFC

WFE [OTE23 NCA3 F212N]
(RMS:53 nm PV:617 nm)



Summary

- Optical Phase Recovery
- Opens up exciting applications both in space and the laboratory
- Trades hardware for software

Mirrors can be
lightweight

Active control
required

Fab. tolerances
reduced

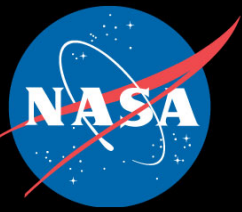
Latency: high-
speed computing

Sensors can be
less intrusive

Utilized for JWST Commissioning

You Can Help!

*National Aeronautics and
Space Administration*



<https://www.nasa.gov/careers/pathways>

