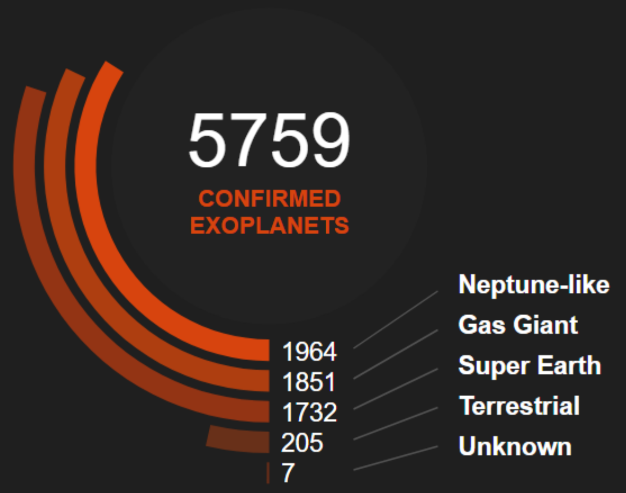
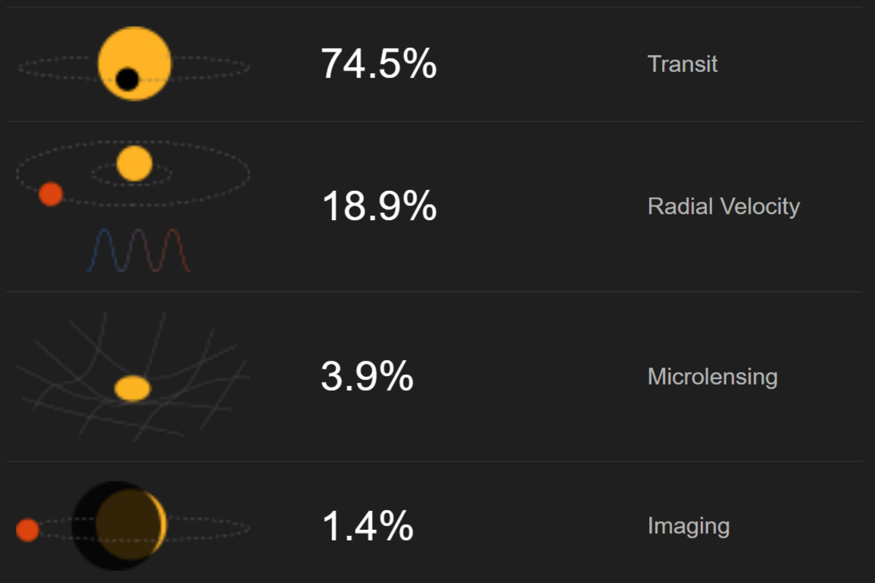
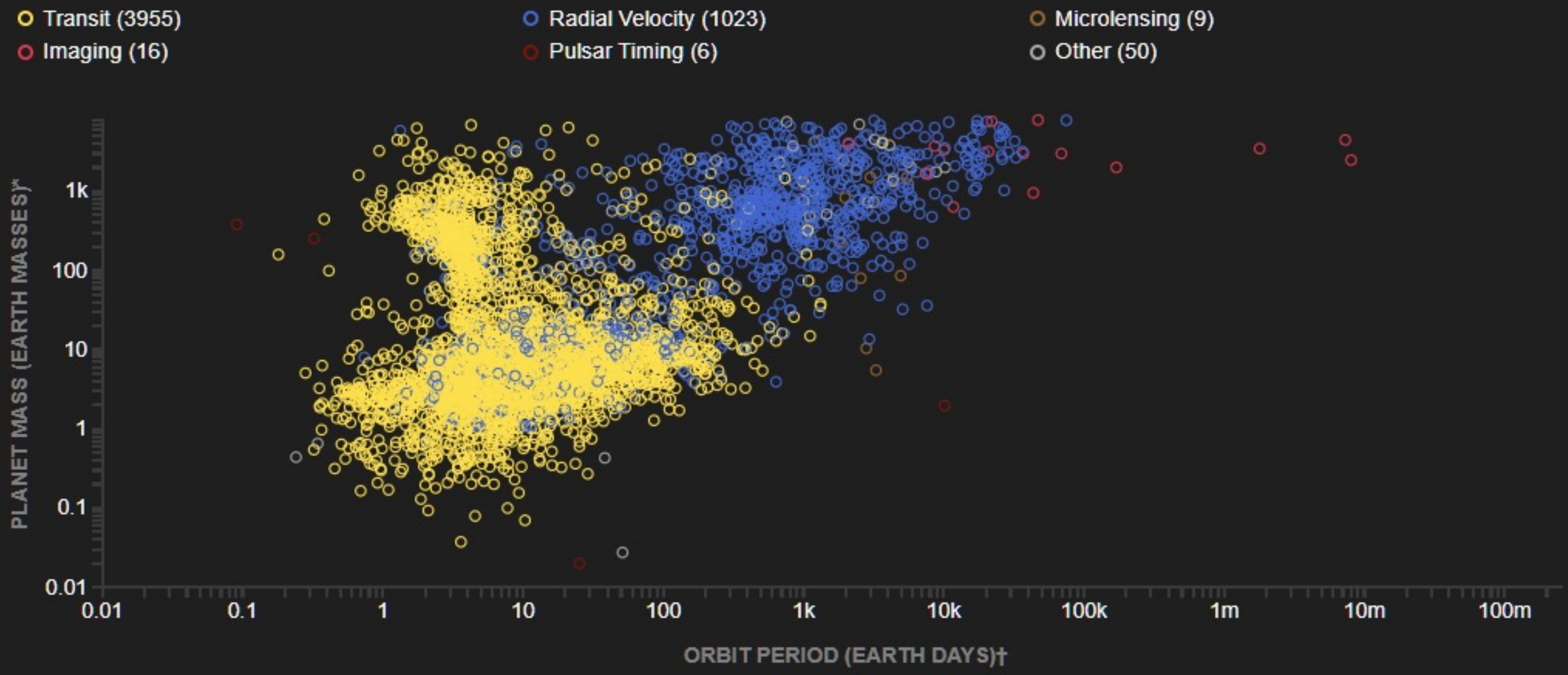
High Contrast Imaging of Exoplanets

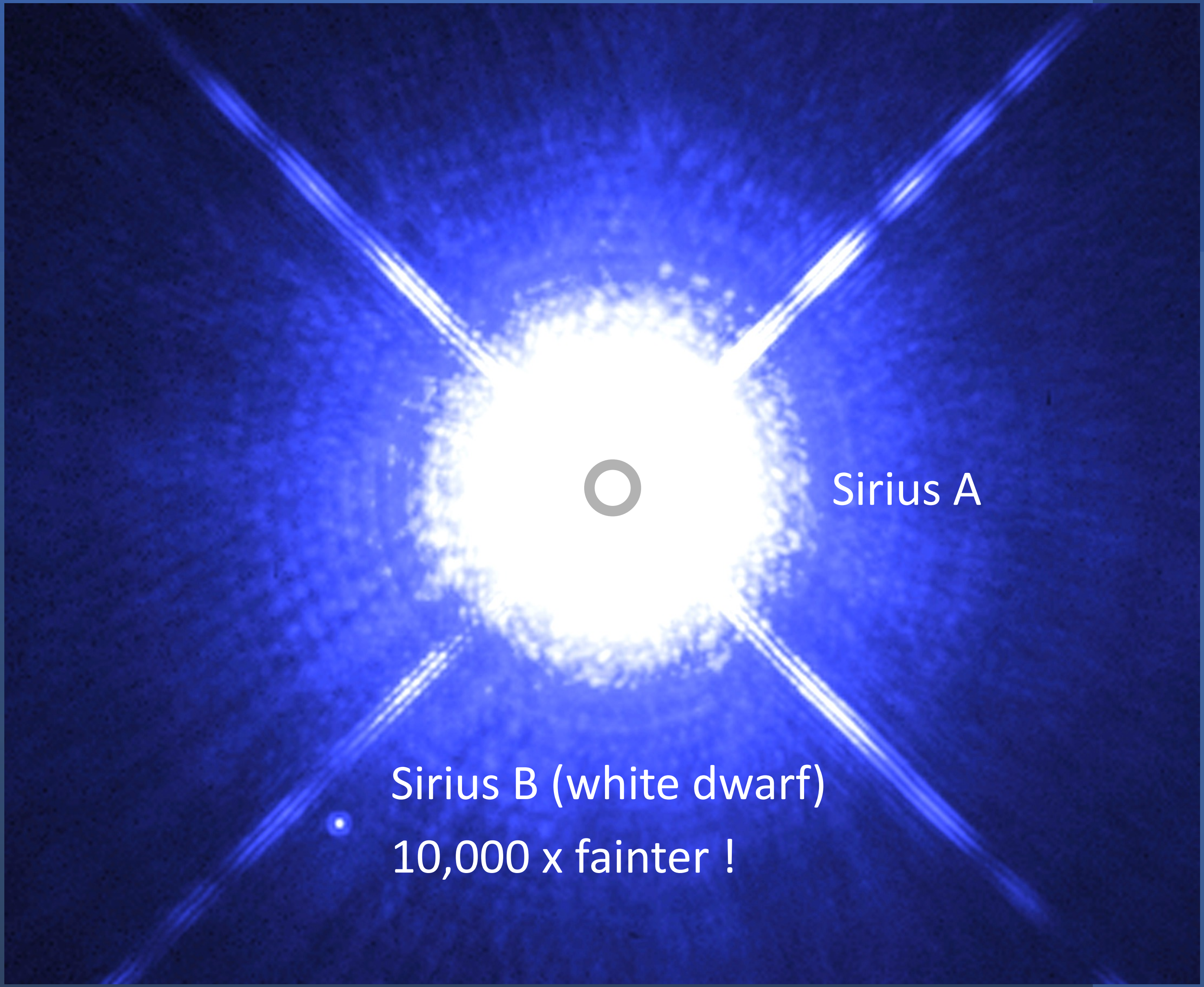
KISS short course

Dimitri Mawet
David Morrisroe Professor of Astronomy, Caltech
Senior Research Scientist, JPL


5759
CONFIRMED EXOPLANETS
1964
1851
1732
205
7
Neptune-like
Gas Giant
Super Earth
Terrestrial
Unknown


74.5%
Transit
18.9%
Radial Velocity
3.9%
Microlensing
1.4%
Imaging


Transit (3955)
Radial Velocity (1023)
Microlensing (9)
Imaging (16)
Pulsar Timing (6)
Other (50)
PLANET MASS (EARTH MASSES)*
1k
100
10
1
0.1
0.01
0.01
0.1
1
10
100
1k
10k
100k
1m
10m
100m
ORBIT PERIOD (EARTH DAYS)†


Sirius A
Sirius B (white dwarf)
10,000 x fainter !

$$L_{firefly} = \frac{A(\lambda)}{4}\left(\frac{R_p}{a}\right)^2 L_{\odot}\phi + \kappa(\lambda)B(\lambda, T_p)4\pi R_p^2$$

Navigator Program Public Engagement Team, NASA

Navigator Program Public Engagement Team, NASA

Extreme flux ratio relative to the star

10^{-4} for self-luminous gas giants

10^{-8} for temperate Earth-size planets orbiting late-type stars

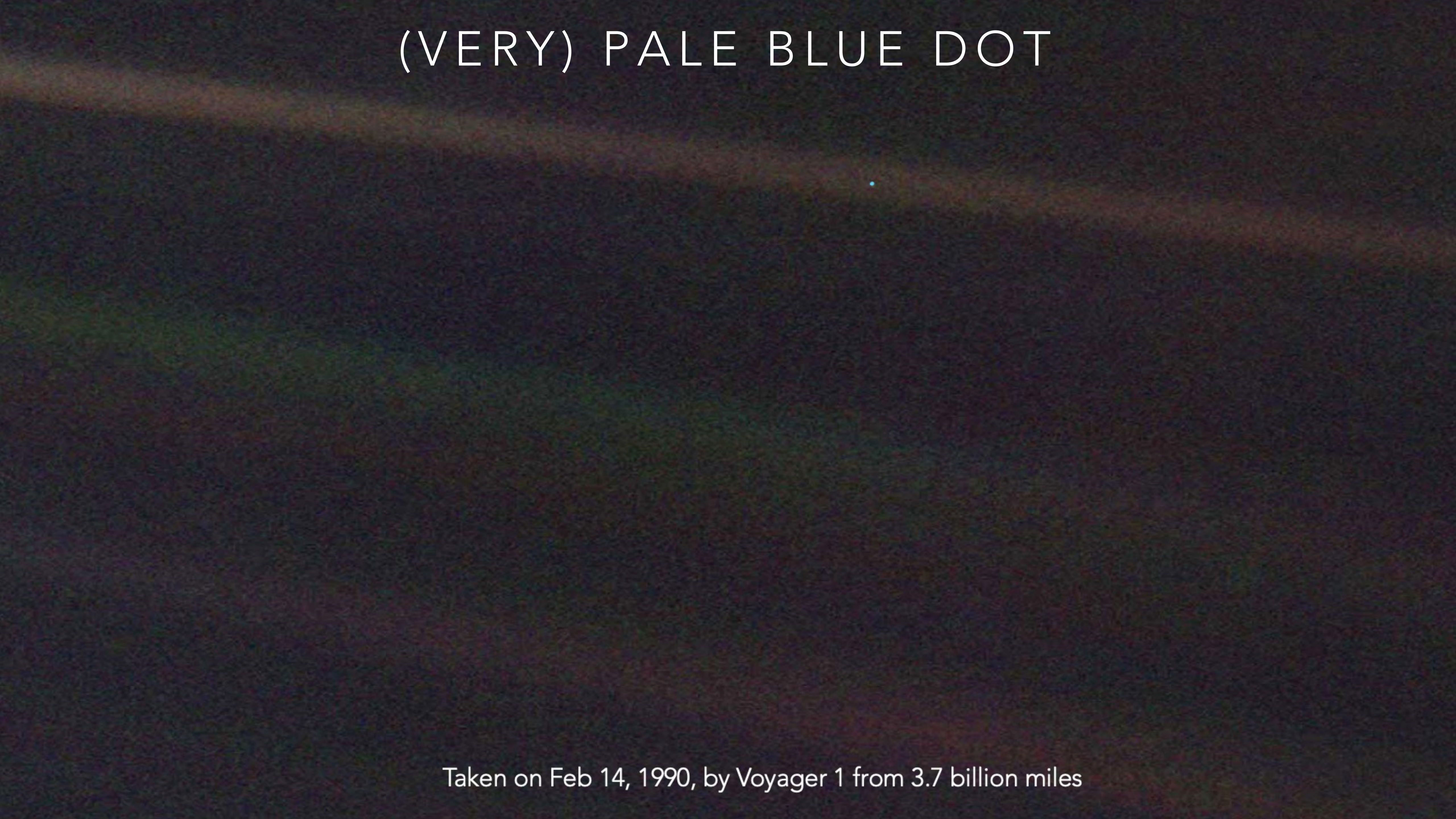
10^{-10} for temperate Earth-size planets orbiting Sun-like stars

Tiny angular separation

0".1 (1 AU at 10pc)

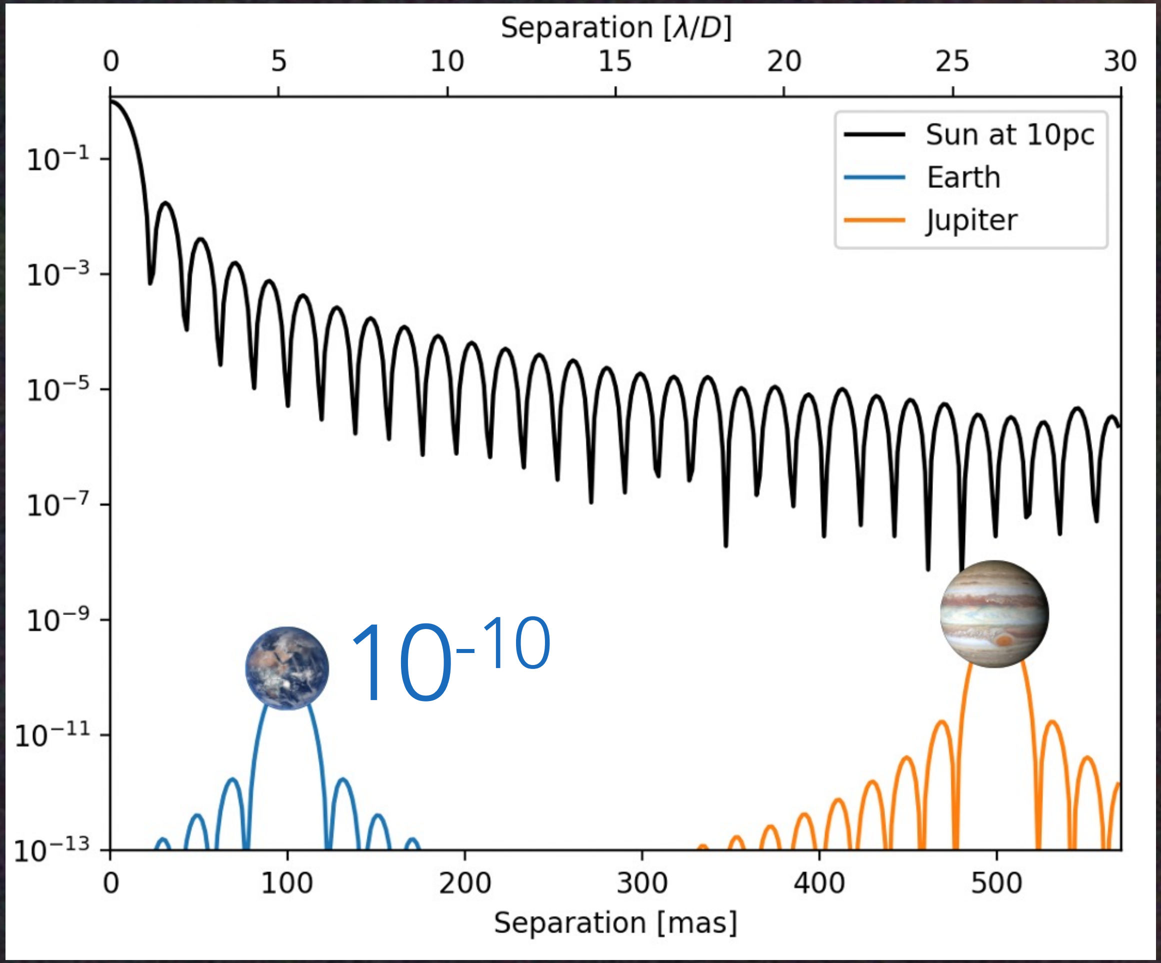
Navigator Program Public Engagement Team, NASA

(VERY) PALE BLUE DOT



Taken on Feb 14, 1990, by Voyager 1 from 3.7 billion miles

(VERY) PALE BLUE DOT

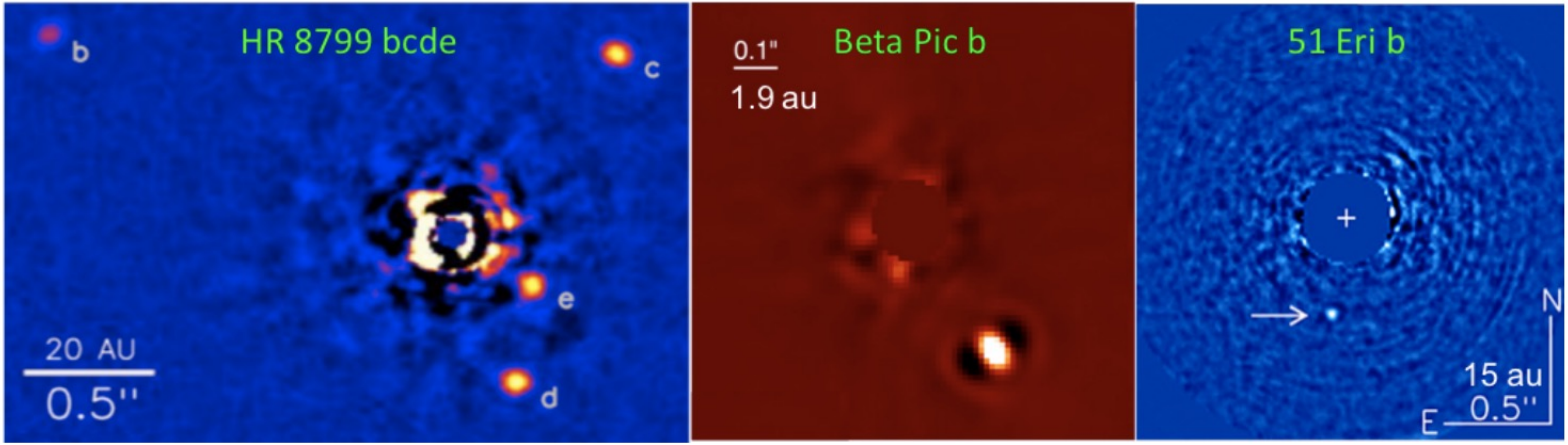


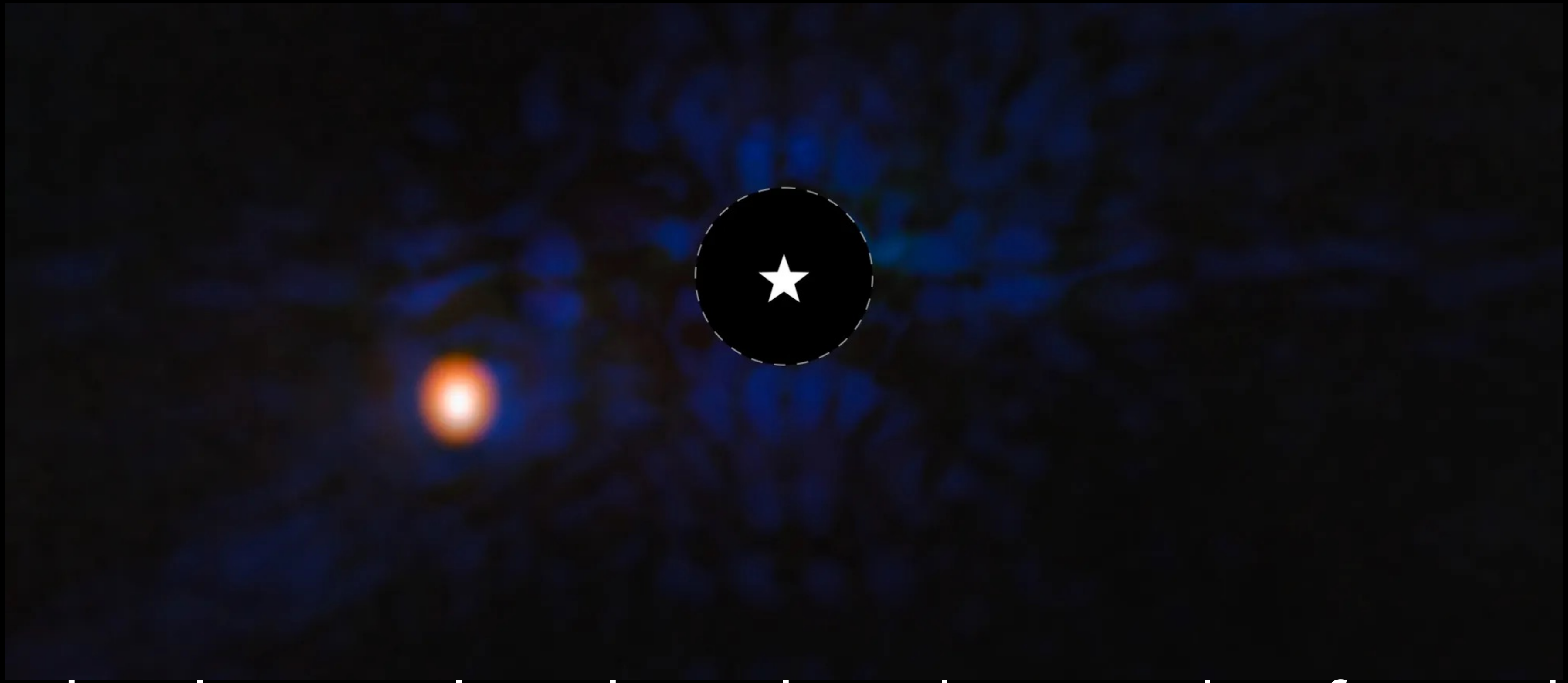
Taken on Feb 14, 1990, by Voyager 1 from 3.7 billion miles

Why direct imaging?

- Direct imaging: taking actual pictures of exoplanets (unresolved=point sources)
- Direct detection enables detailed characterization:
  - Astrometry -> orbits
  - Photometry -> bulk parameters (T, M, R, A)
  - Spectroscopy -> composition

Taking ugly but real pictures, none of these fake artistic renditions

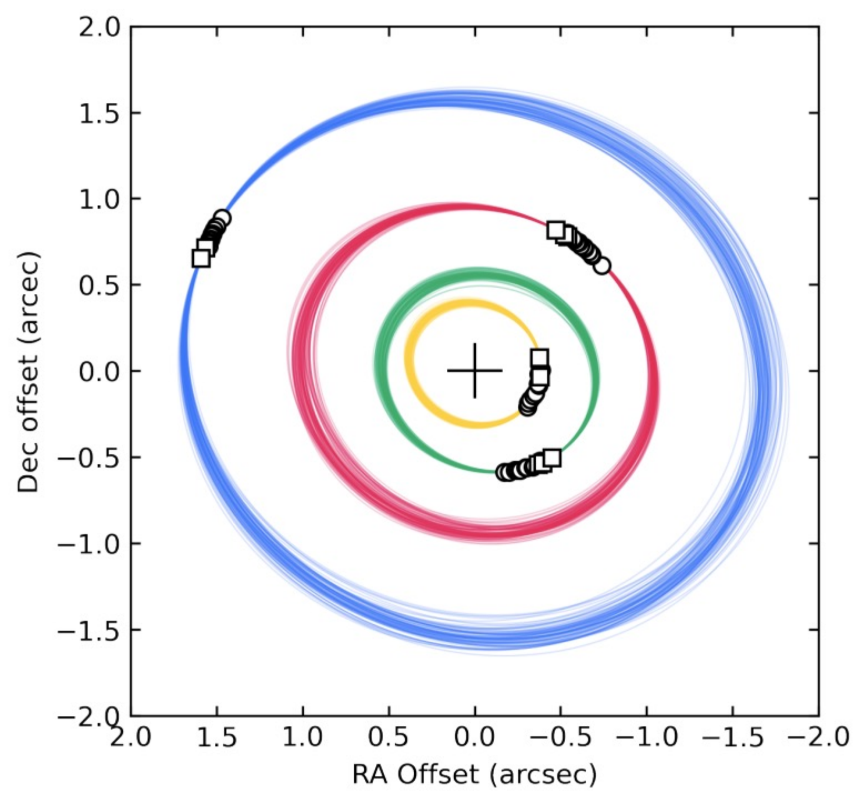


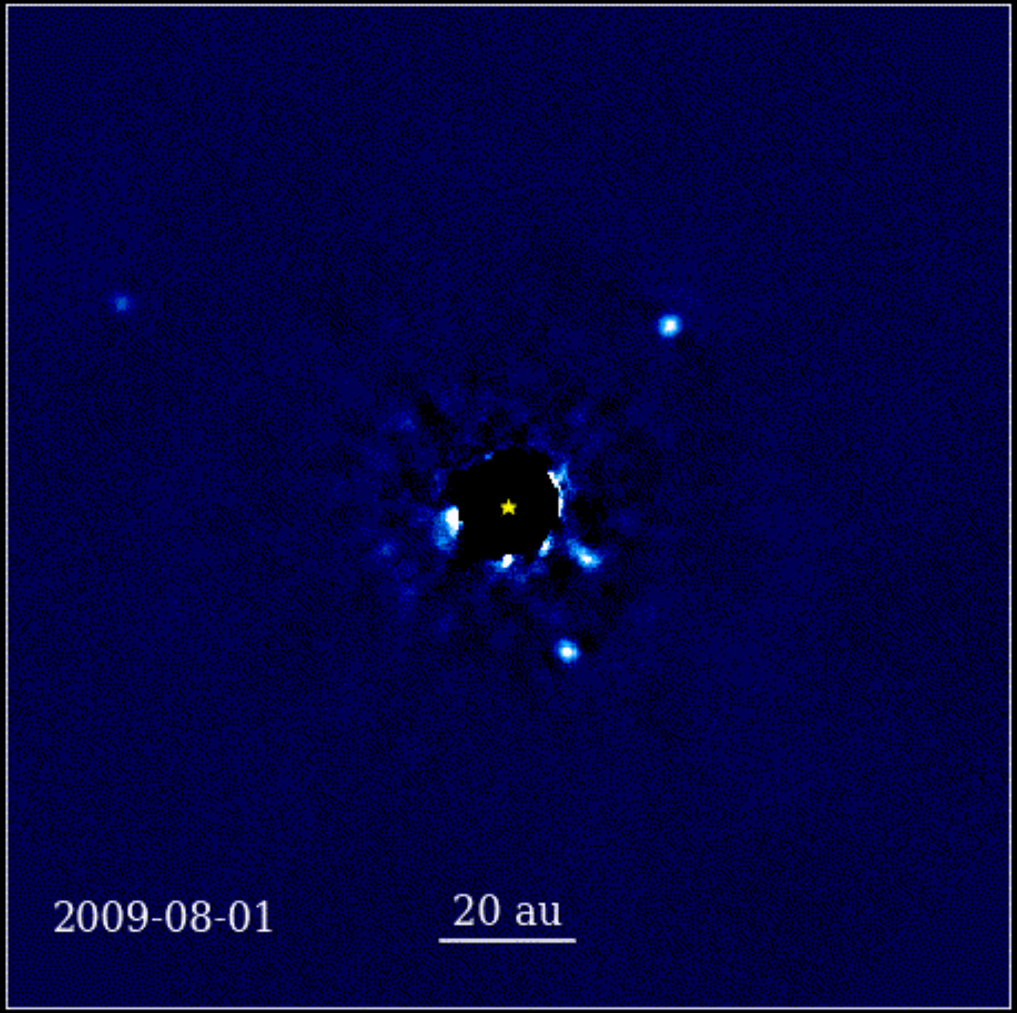


Epsilon Indi Ab resolved in the thermal infrared by JWST

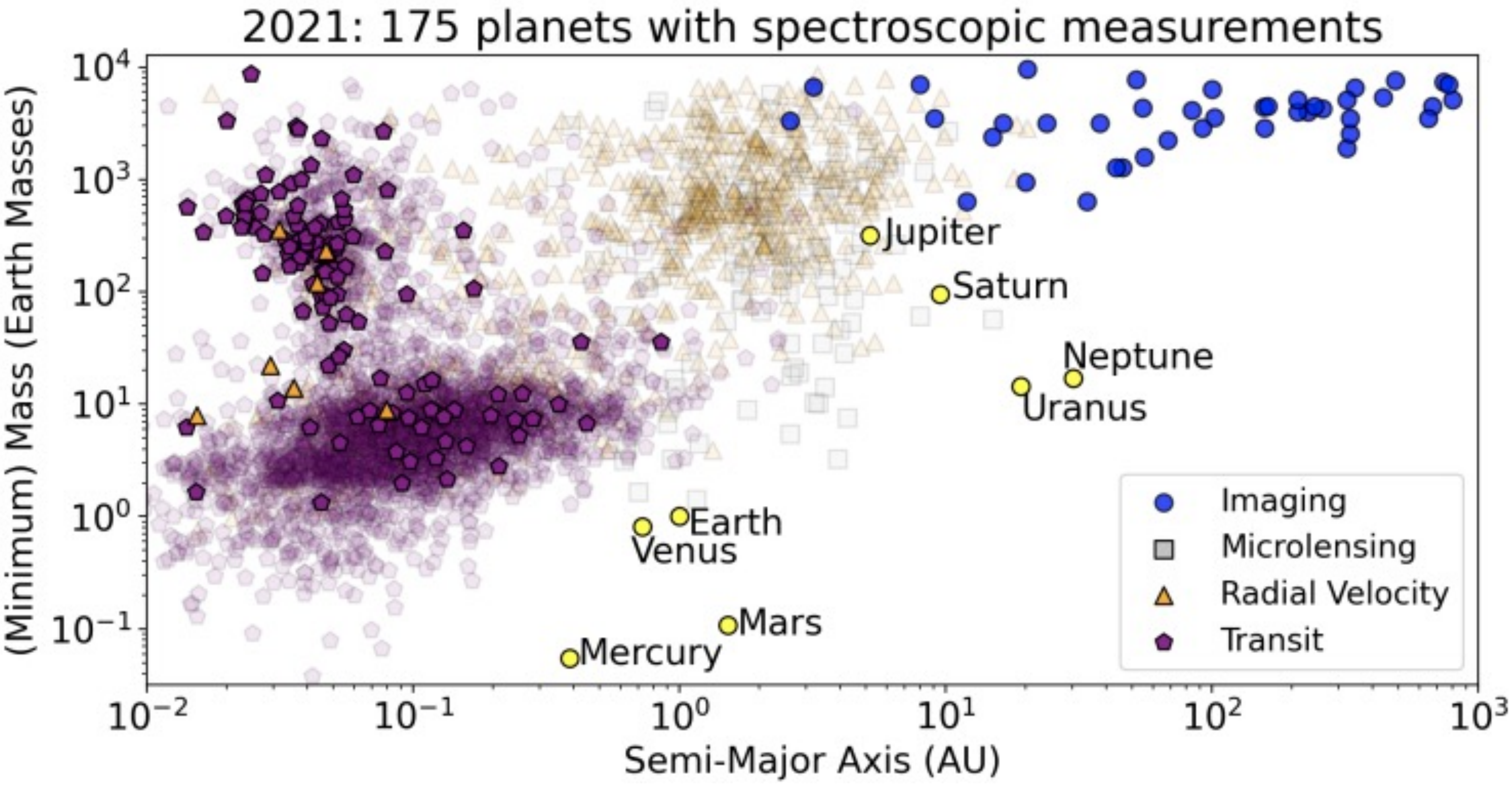
Matthews+2024

Direct imaging enables orbit measurements





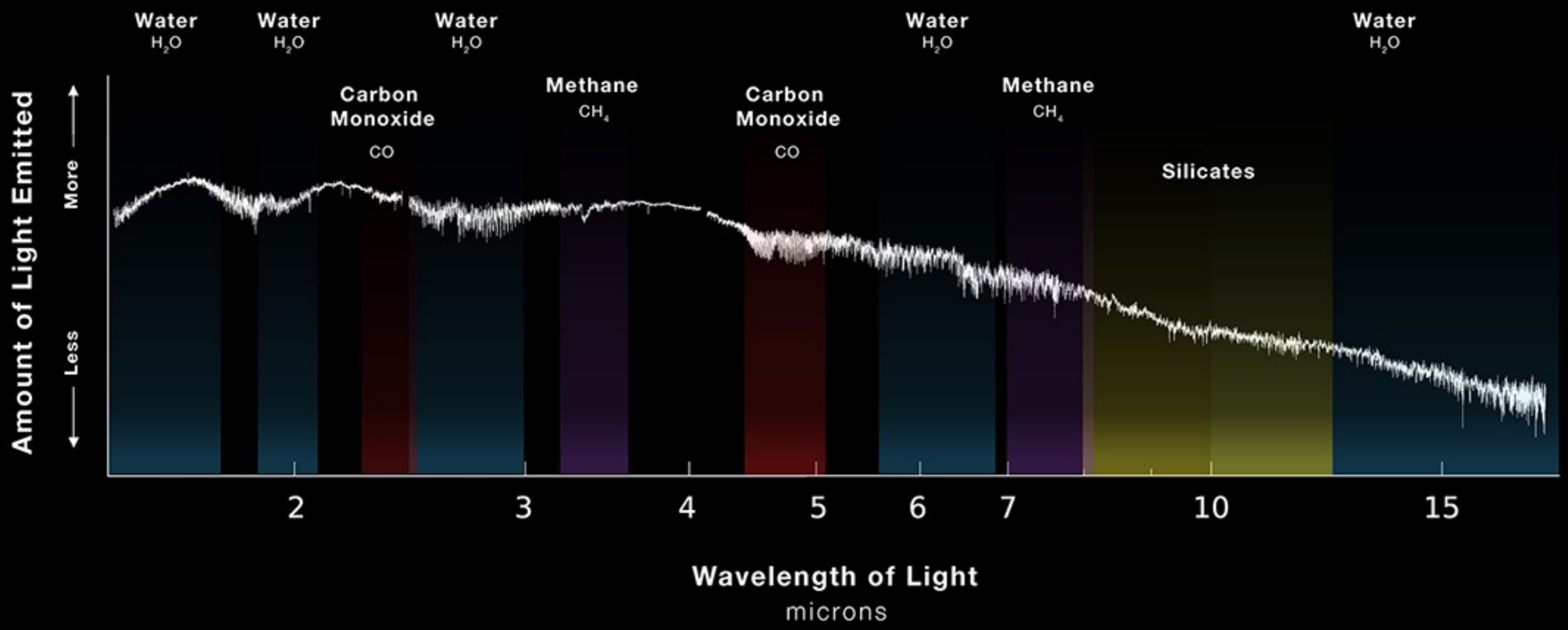
Direct imaging enables direct characterization of atmospheres



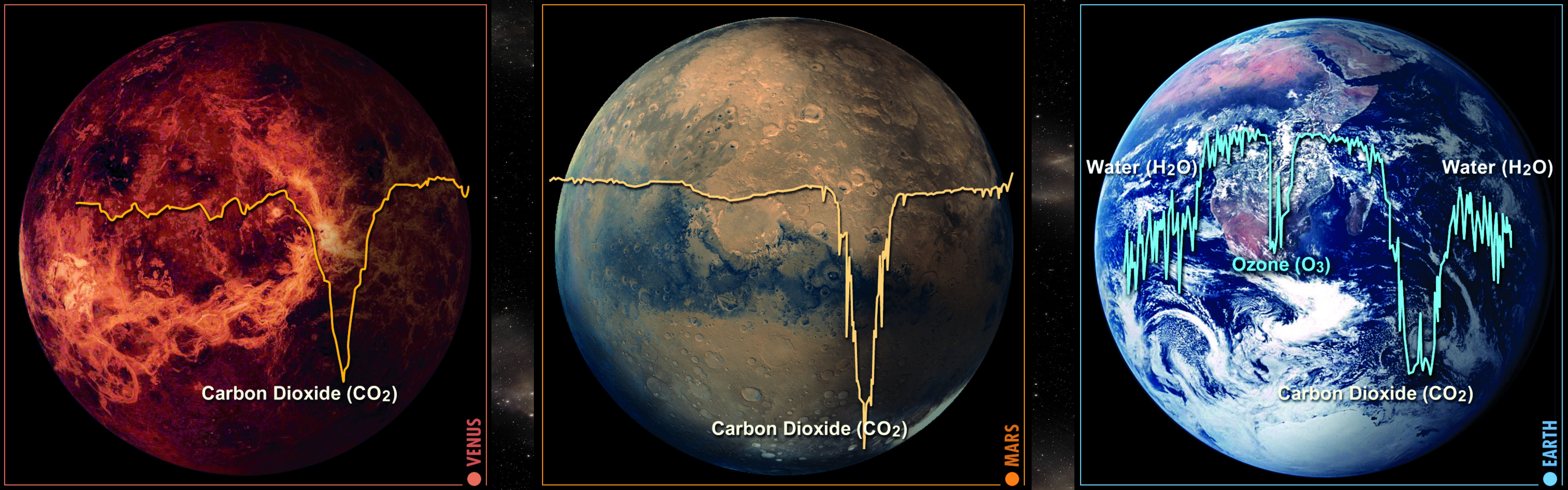
EXOPLANET VHS 1256 b

EMISSION SPECTRUM

NIRSpec and MIRI | IFU Medium-Resolution Spectroscopy

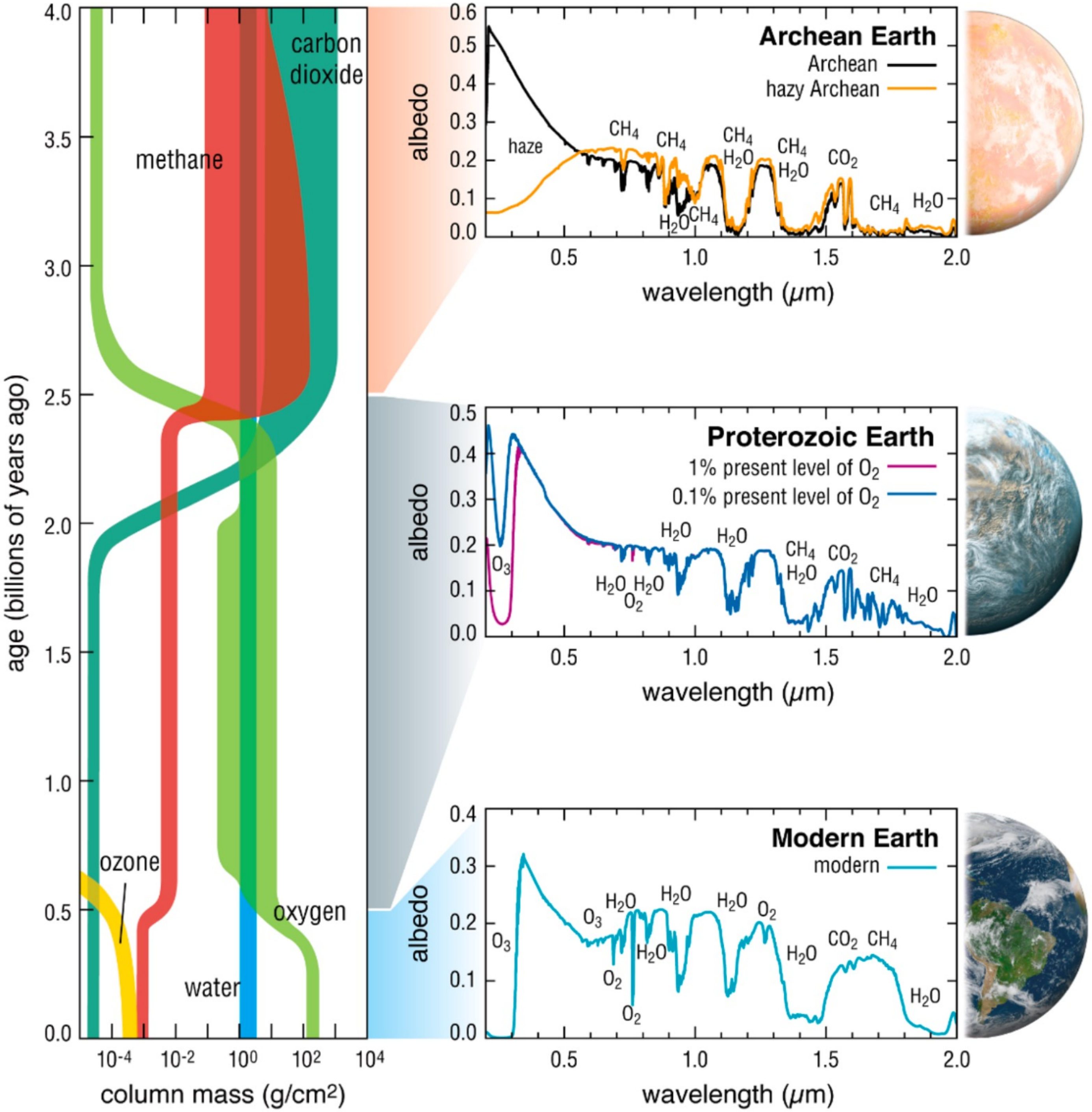


WEBB
SPACE TELESCOPE

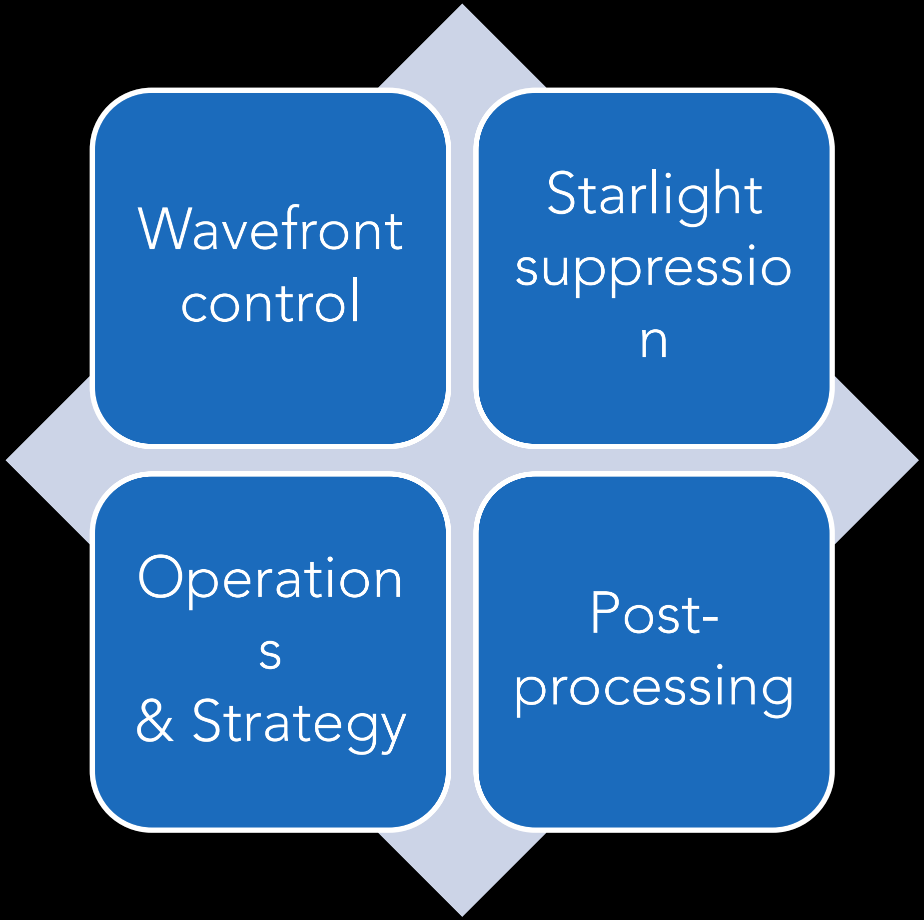

Carbon Dioxide (CO2)
VENUS
Carbon Dioxide (CO2)
MARS
Water (H2O)
Water (H2O)
Ozone (O3)
Carbon Dioxide (CO2)
EARTH

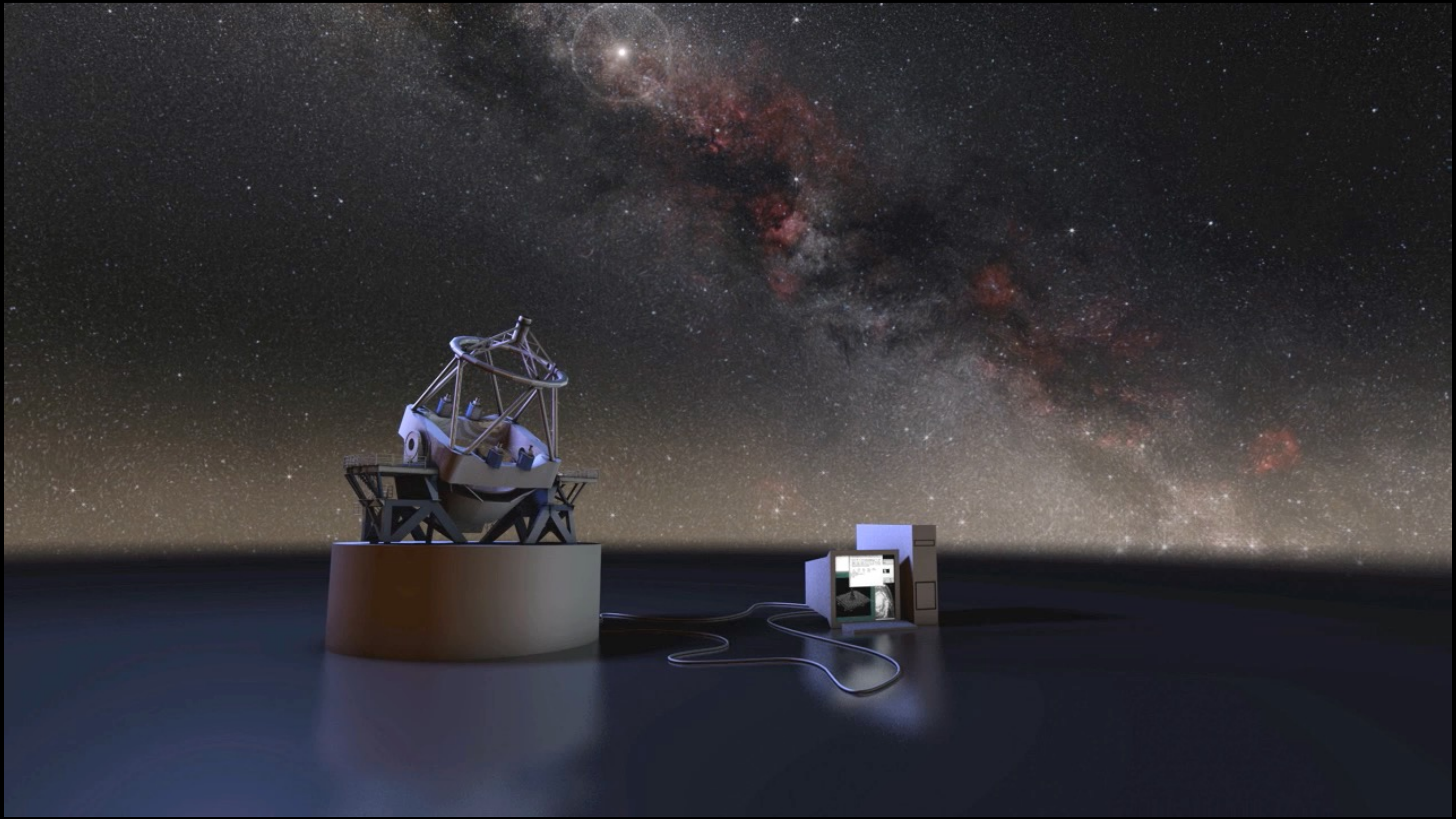
Concentrations of biosignature gases over Earth's history, during Archean, Proterozoic, and modern Earth eras. HWO is required to be able to detect the gaseous byproducts from oxygen-producing synthesizers or methane- producing synthesizers, if present at concentration levels similar to Earth over the last 3.5 Gy of its history.

Credit: Britt Griswold, Giada Arney, and Shawn Domagal-Goldman.



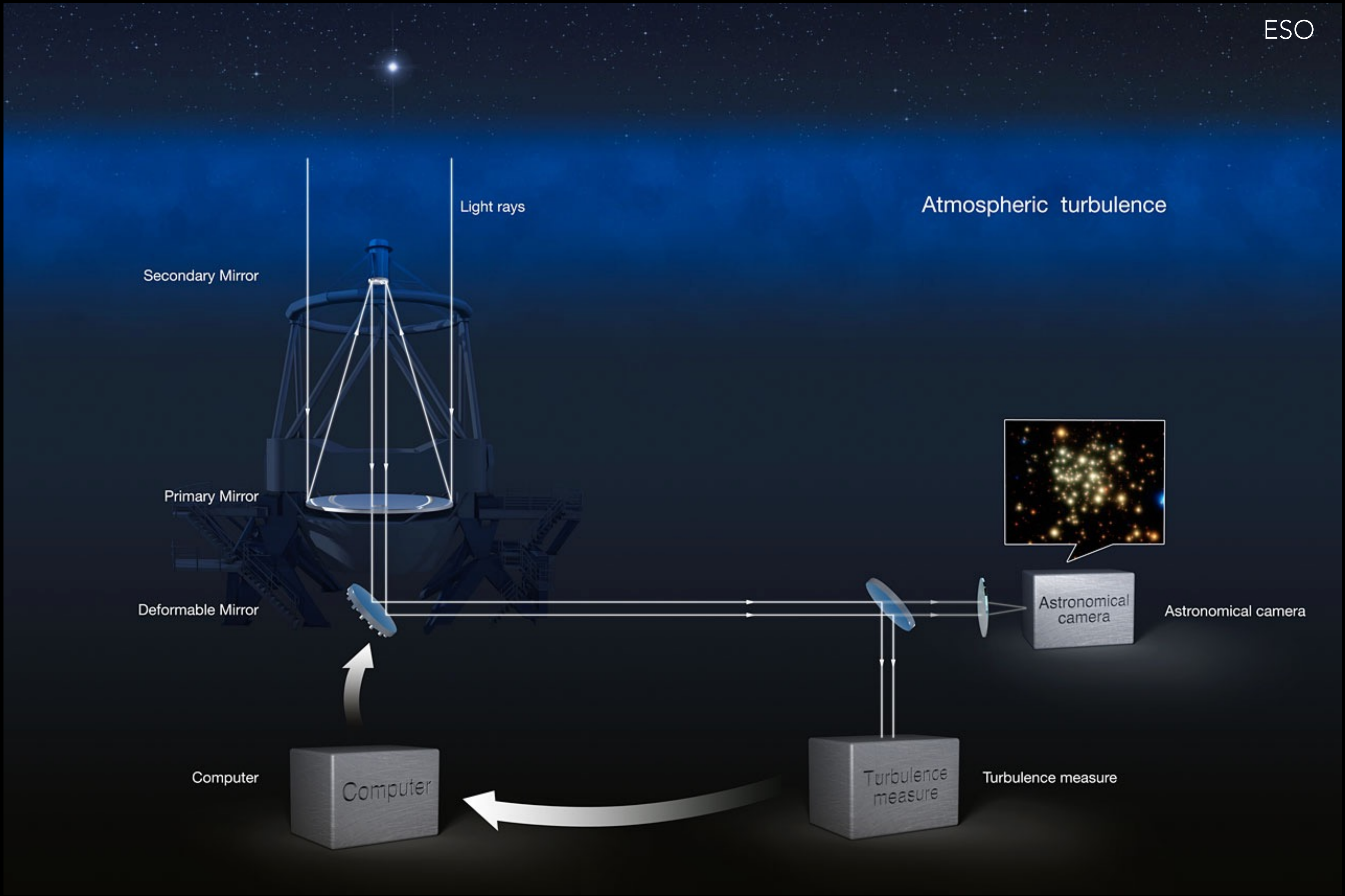
THE 4 PILLARS OF HIGH CONTRAST IMAGING





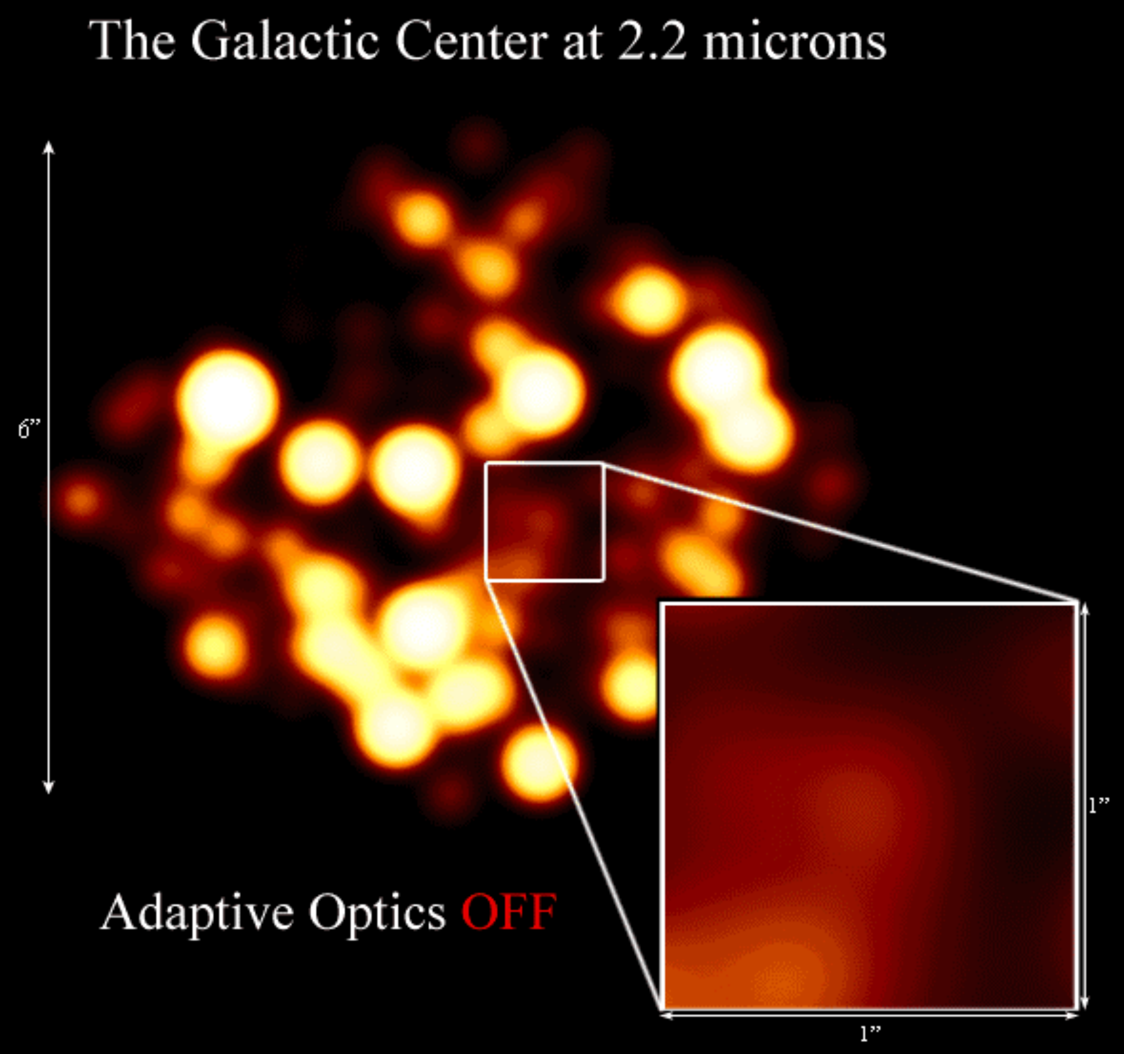
"If we had the means of continually measuring the deviation of rays [...] so as to correct [...] the aberration pattern, we could expect to compensate [...] for any inherent imperfection of the optical figure."

- HORACE W. BABCOCK, 1953

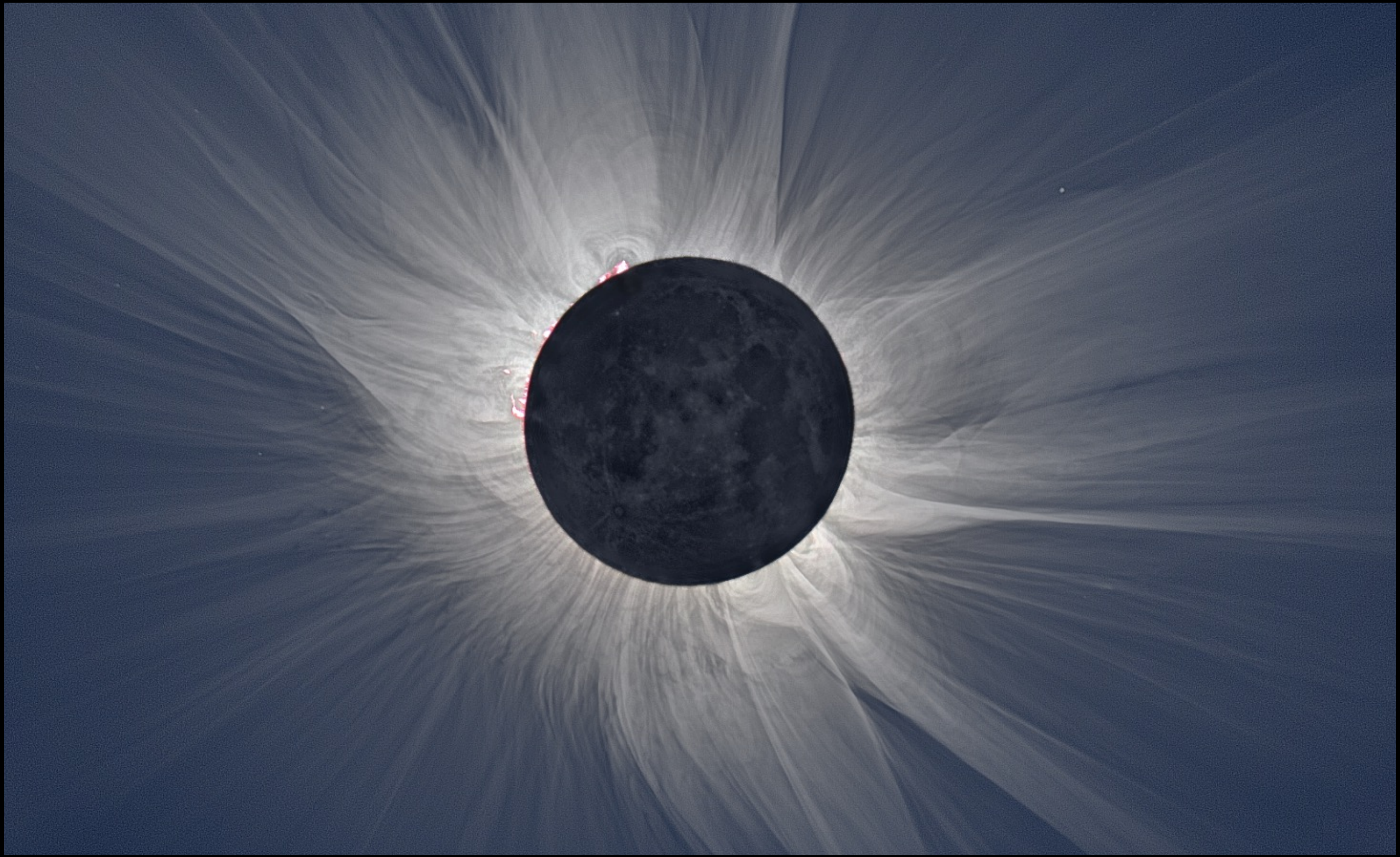


INVENTED BY CALTECH UNDERGRAD, UCB GRAD AND PALOMAR DIRECTOR HORACE BABCOCK IN 1953

ADAPTIVE OPTICS IN ACTION



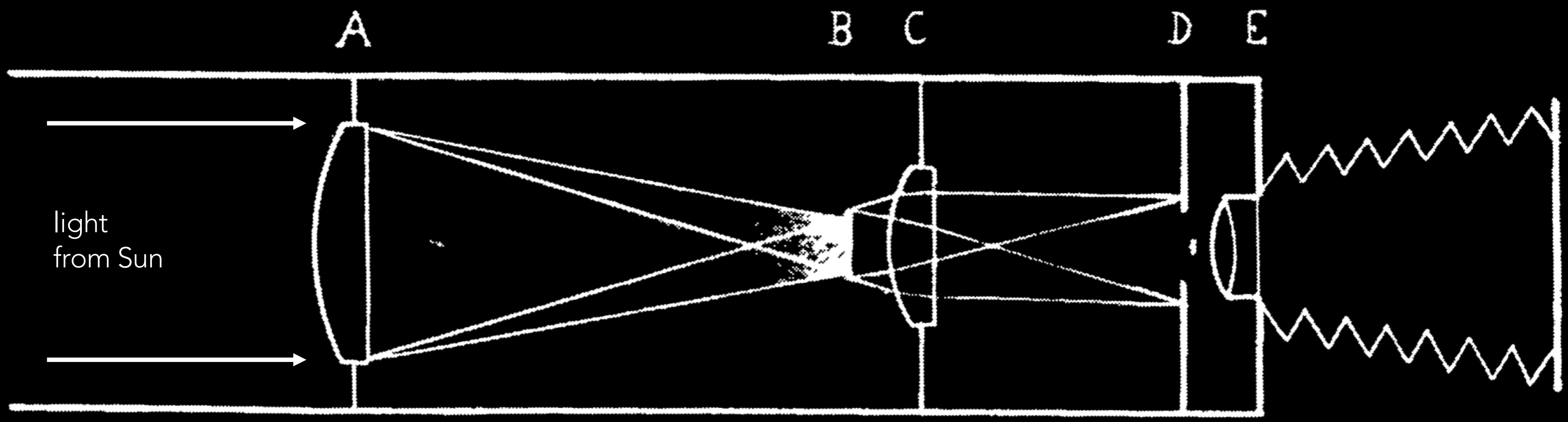
CREATING ARTIFICIAL ECLIPSES



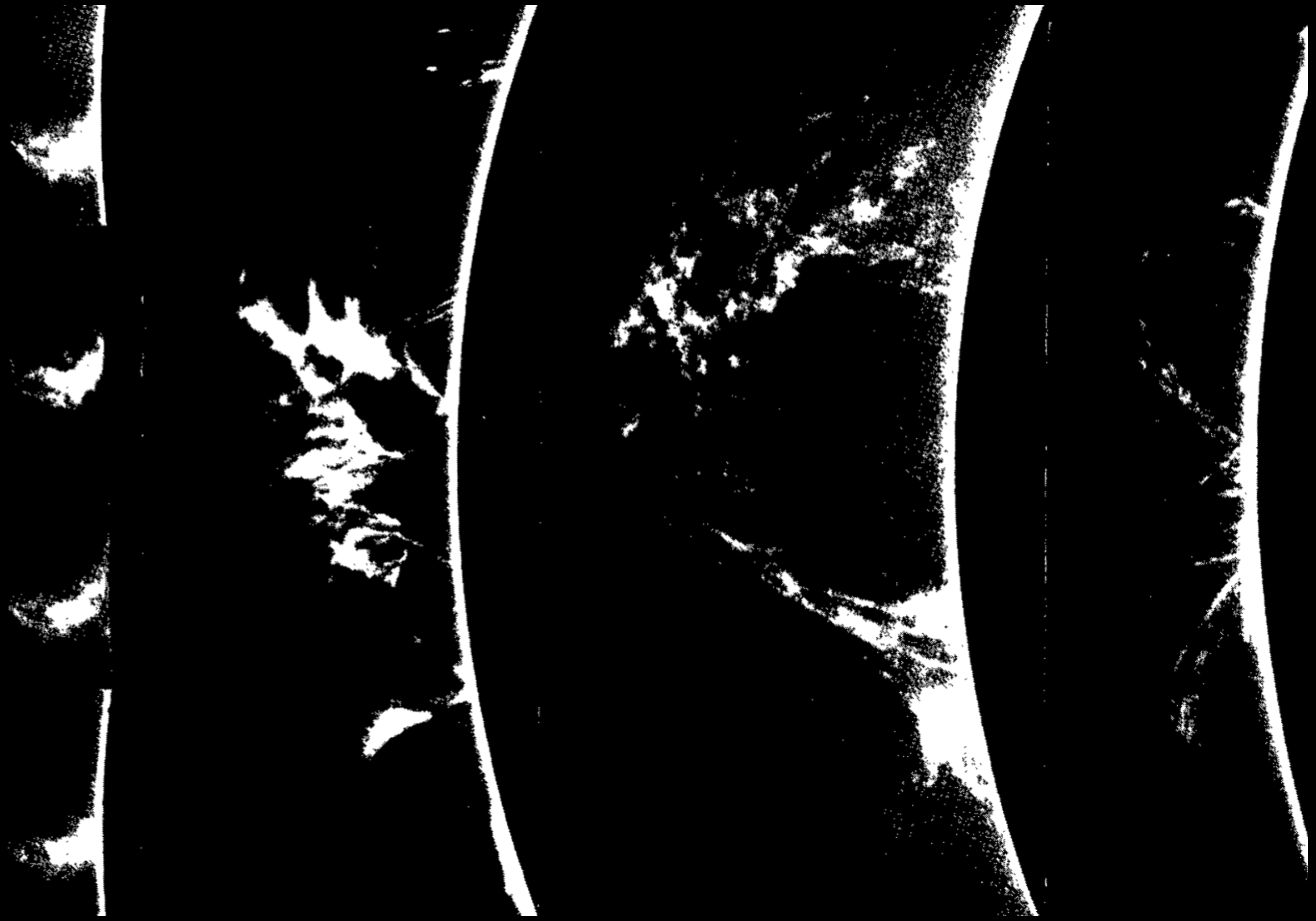
CORONAGRAPHY, BERNARD LYOT 1930

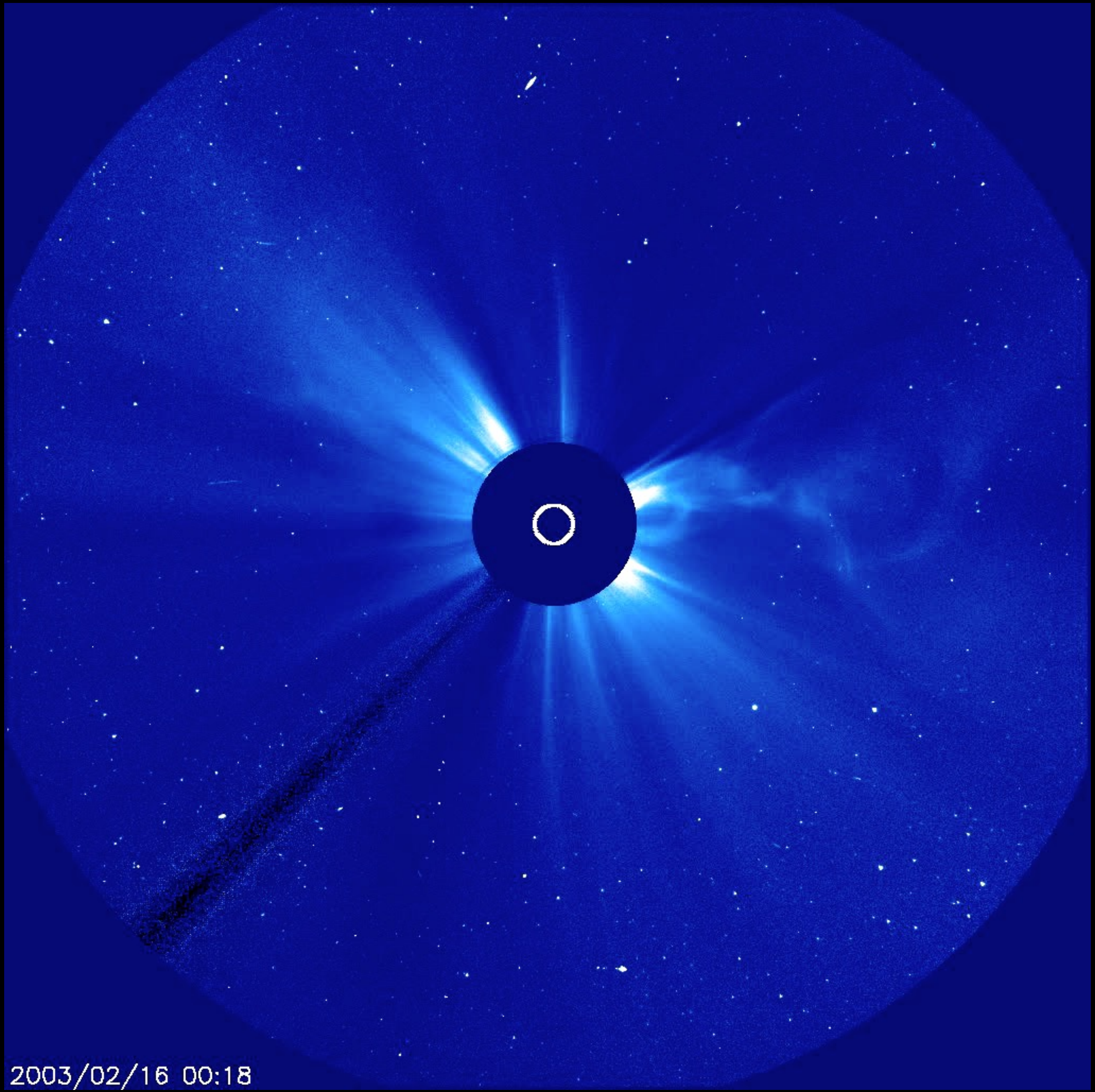
“The rareness of total eclipses of the Sun, their short duration and the distances one has to travel to observe them have, for more than half a century, led astronomers and physicists to seek for a method which enables them to study the corona at any time.”

LYOT'S CORONAGRAPH



SOLAR CORONA IN 1930S WITH LYOT'S CORONAGRAPH!



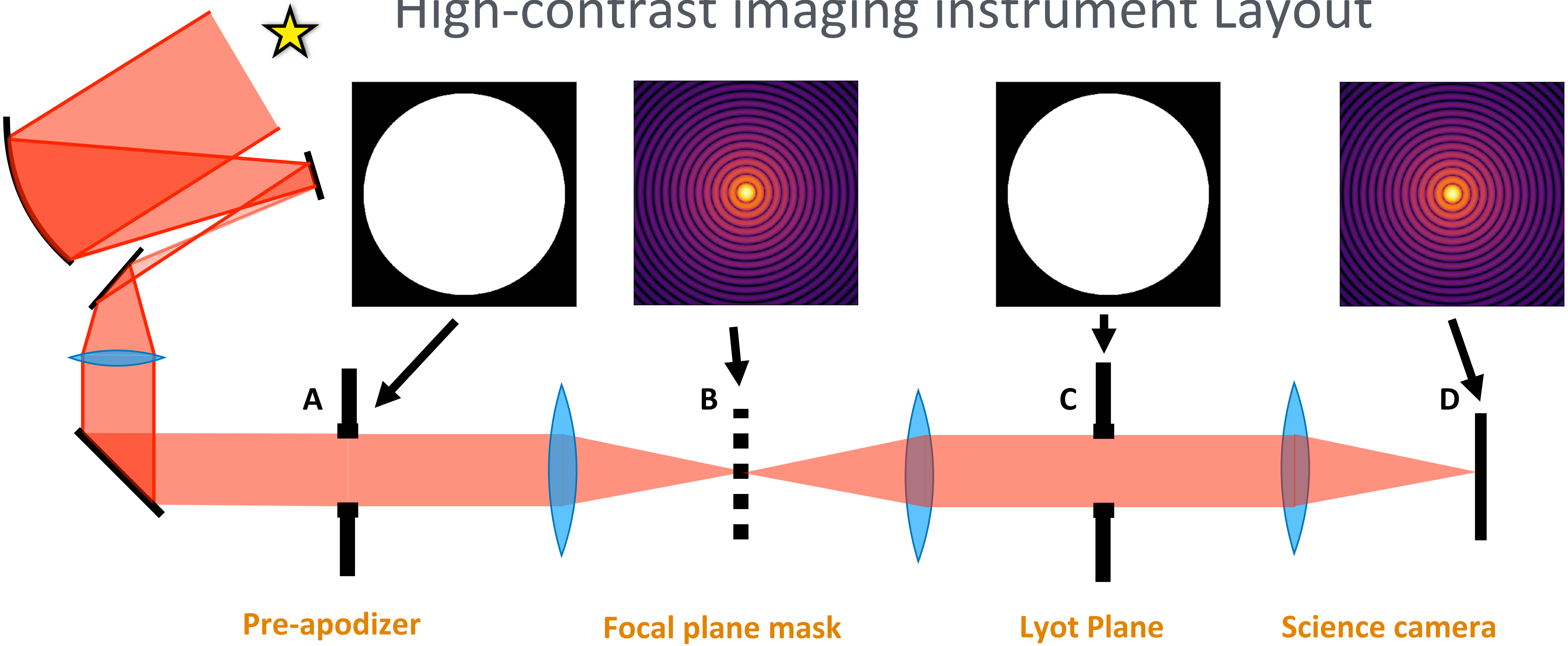

2003/02/16 00:18

WAVEFRONT CONTROL & CORONAGRAPH IN ACTION

Definitions and nomenclature for modern coronagraphs

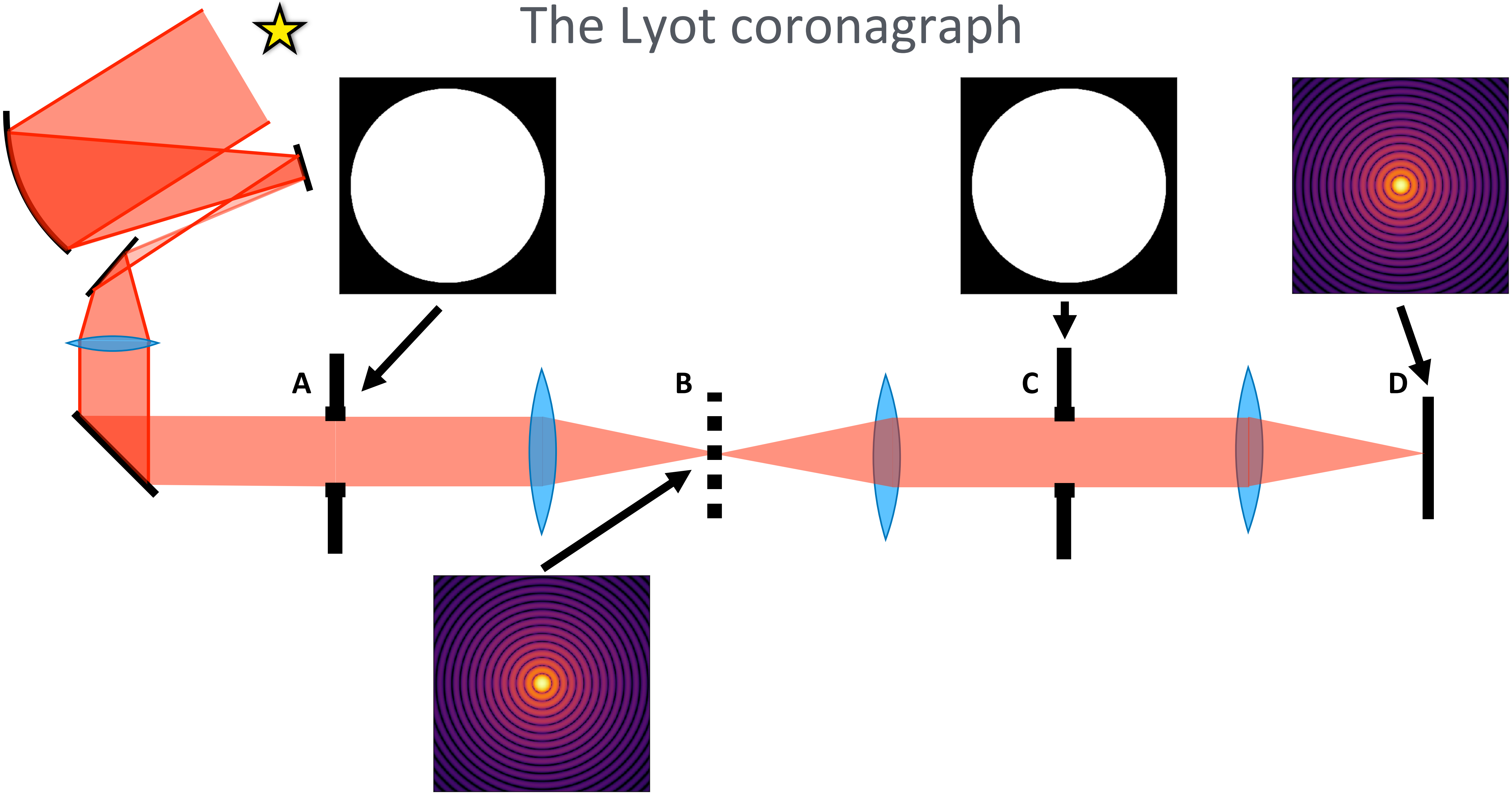
- **Flux ratio**: ratio of intensities between unattenuated starlight and planet light.
- **Raw contrast**: how much did you suppress your starlight?
- **Planet throughput**: how much planet light comes through?
- **Inner working angle (IWA)**: how close can you find planets to a star? Typically defined as 50% off-axis transmission point.
- **Outer working angle (OWA)**: how far can you find planets from a star? Typically maxed out at the wavefront control system outer control radius (N/2, where N is the number of control elements over the diameter).
- **Dark hole**: high contrast region in the final image, typically extending from the IWA to the OWA.
- **Bandwidth**: optical bandwidth of broadband filter used for imaging, typically 10% or 20%.
- **Robustness**: how robust is the coronagraph to aberrations (e.g. pointing, focus) or stellar diameter.

High-contrast imaging instrument Layout



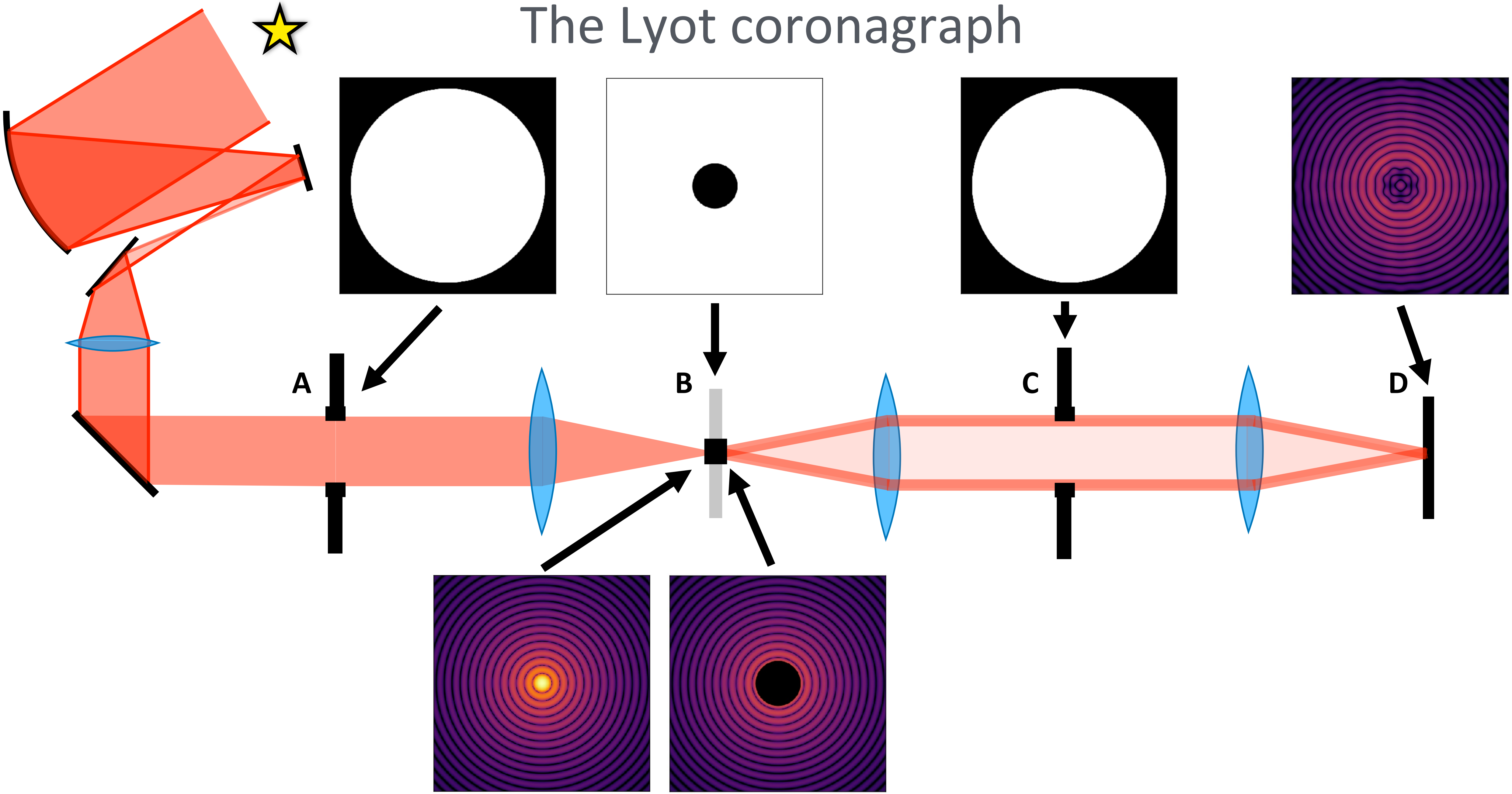
Apodization: purposely changing the input intensity profile of an optical system

The Lyot coronagraph

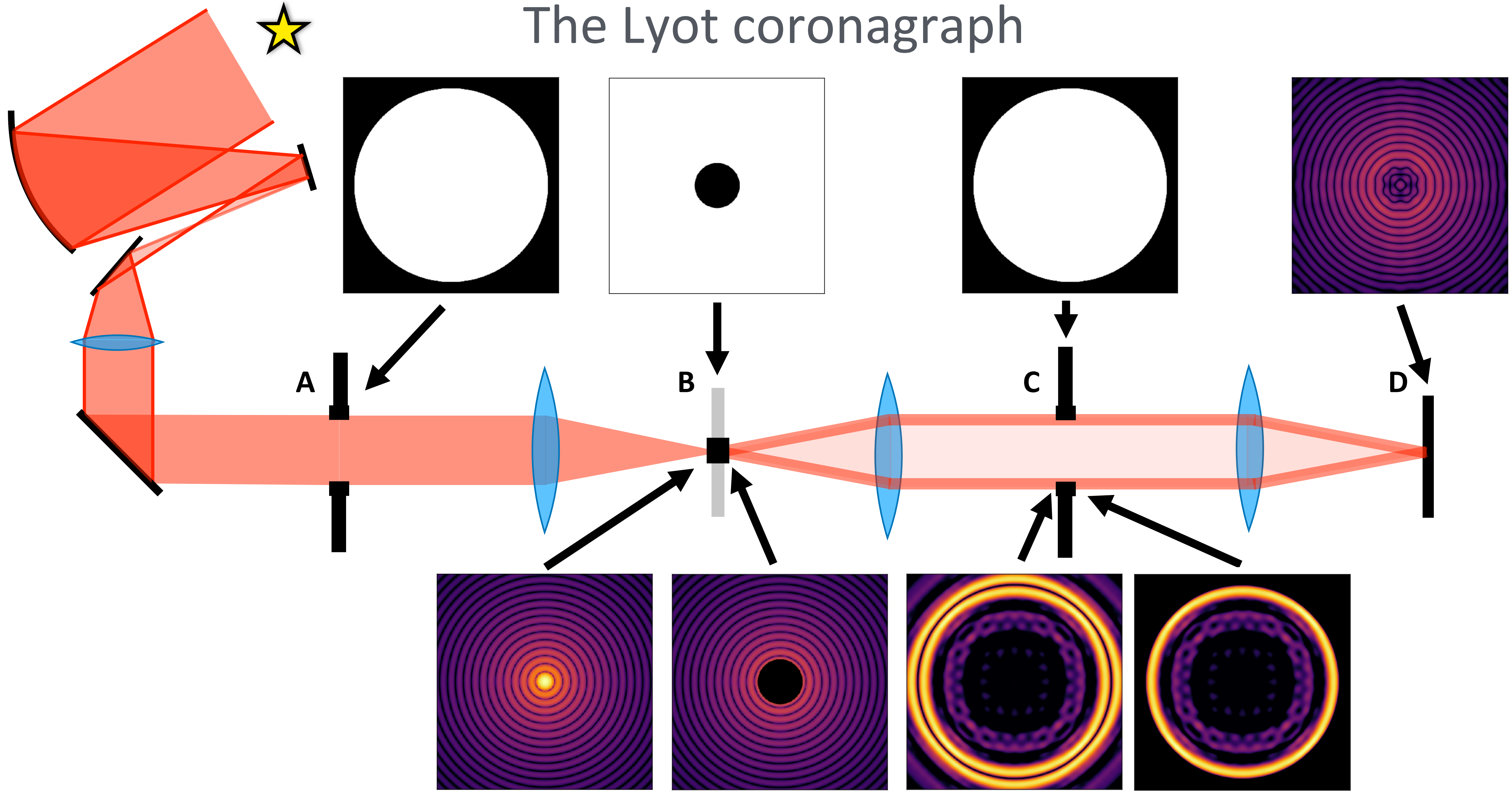


David Doelman

The Lyot coronagraph

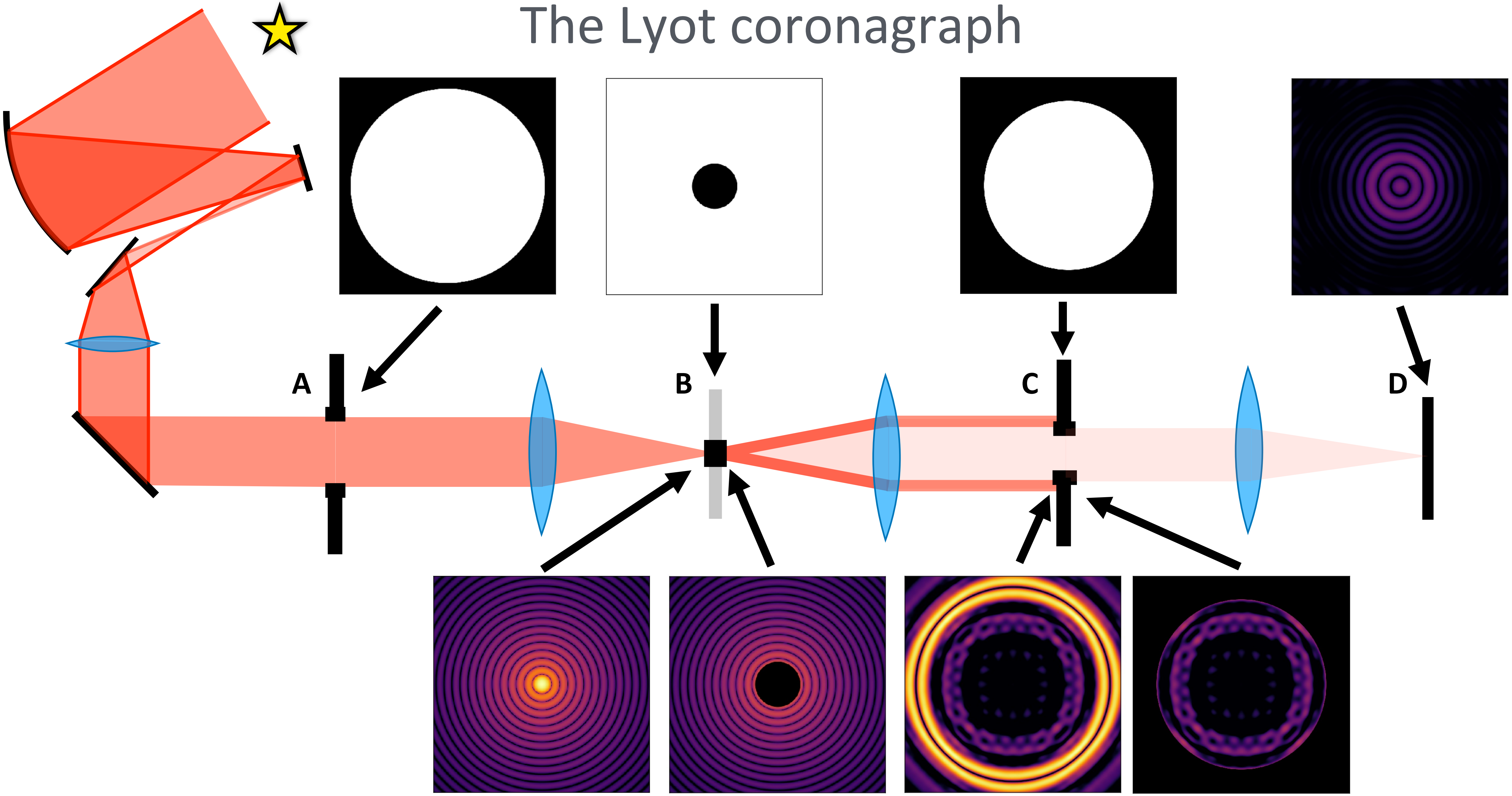


The Lyot coronagraph



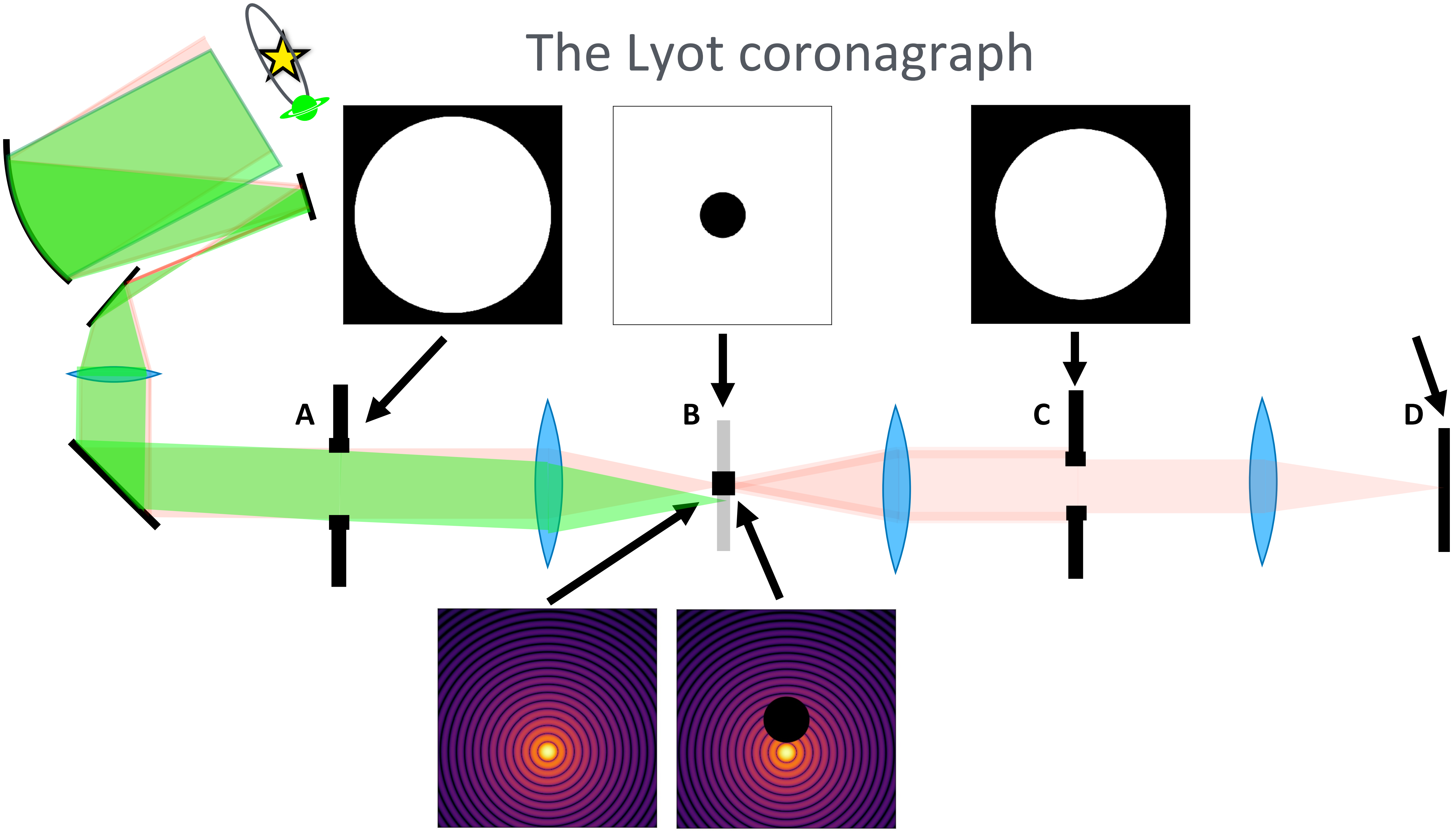
David Doelman

The Lyot coronagraph



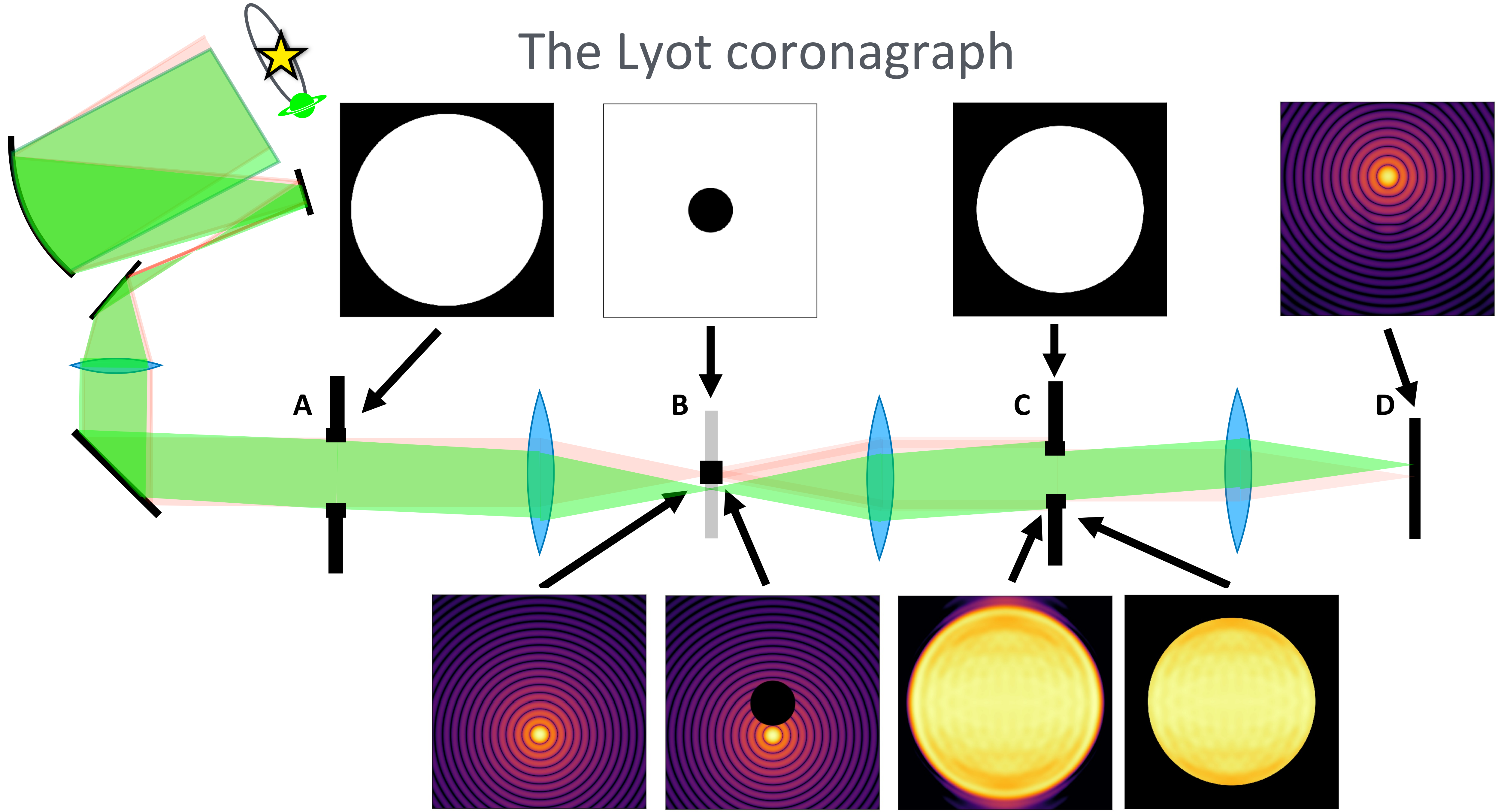
David Doelman

The Lyot coronagraph



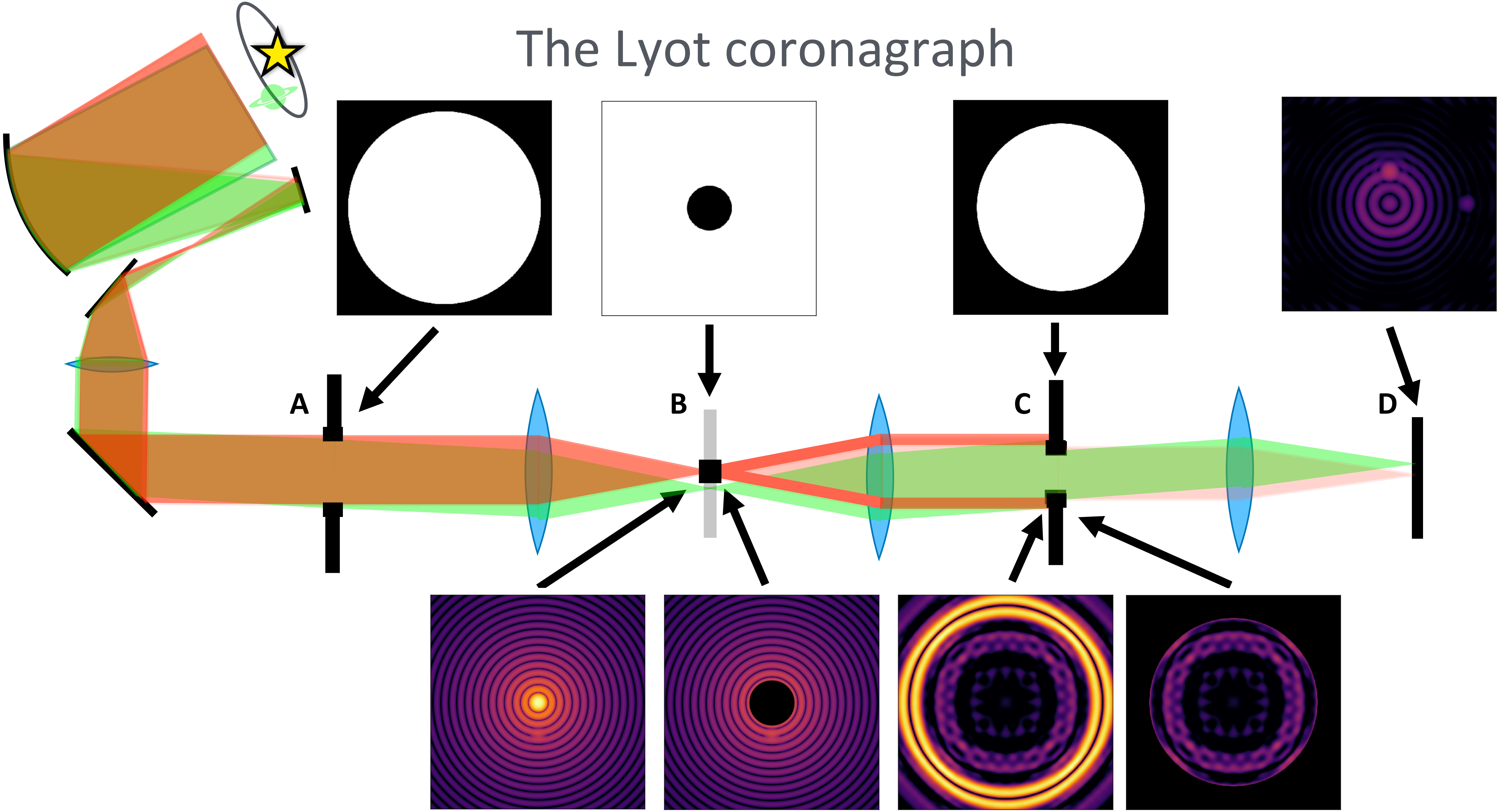
David Doelman

The Lyot coronagraph

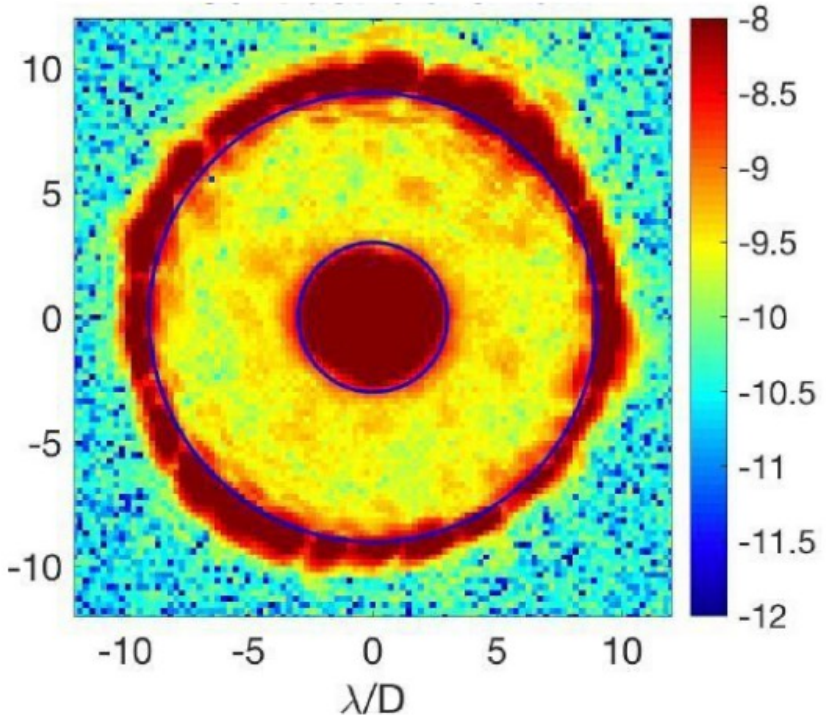


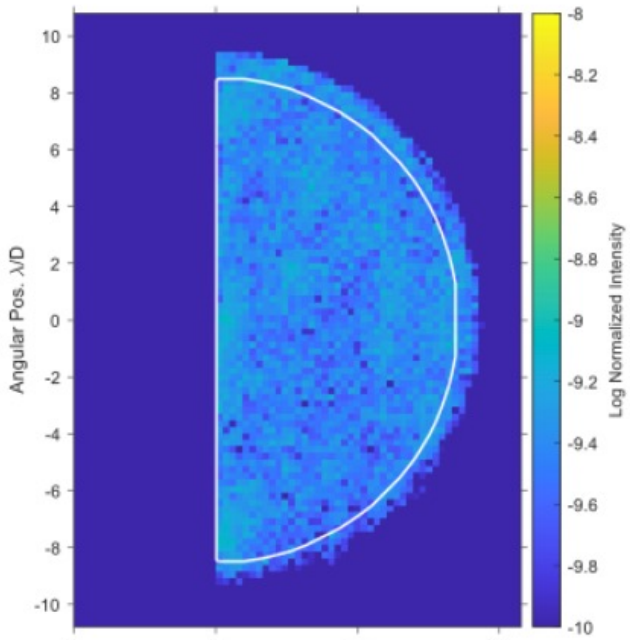
David Doelman

The Lyot coronagraph



The Classical Lyot Coronagraph holds the deeper contrast ever recorded in the lab



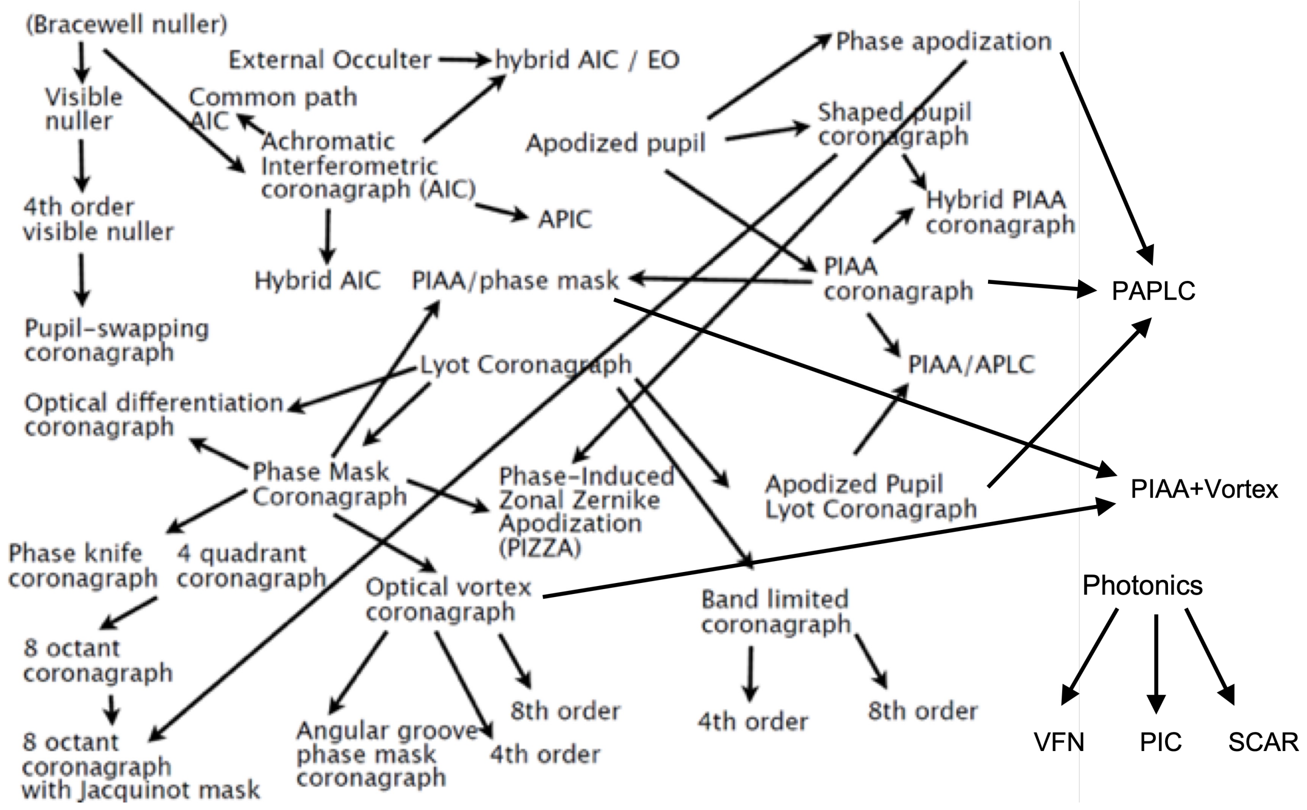


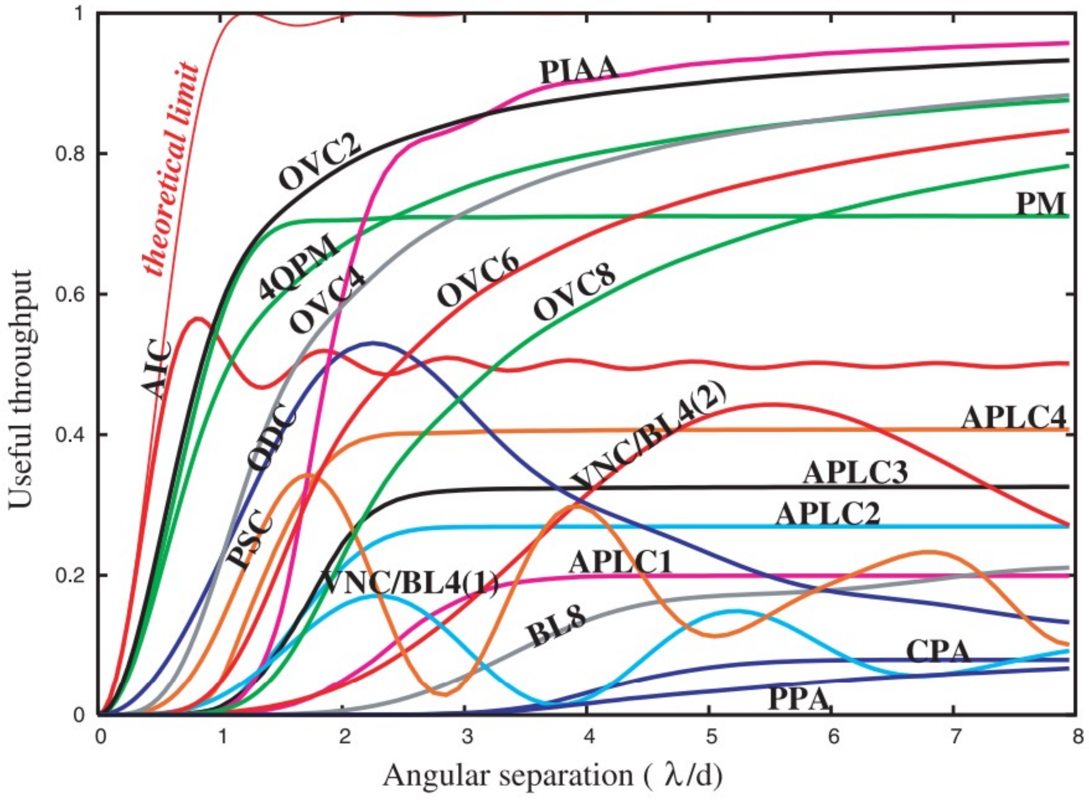
360 dark hole, 10% bandwidth, 3 to 8 λ/D: 3.82×10^{-10}

180 dark hole, 20% bandwidth, 5 to 13.5 λ/D: 3.97×10^{-10}

Caveats: the CLC relies on the deformable mirrors heavily, large IWA, limited robustness

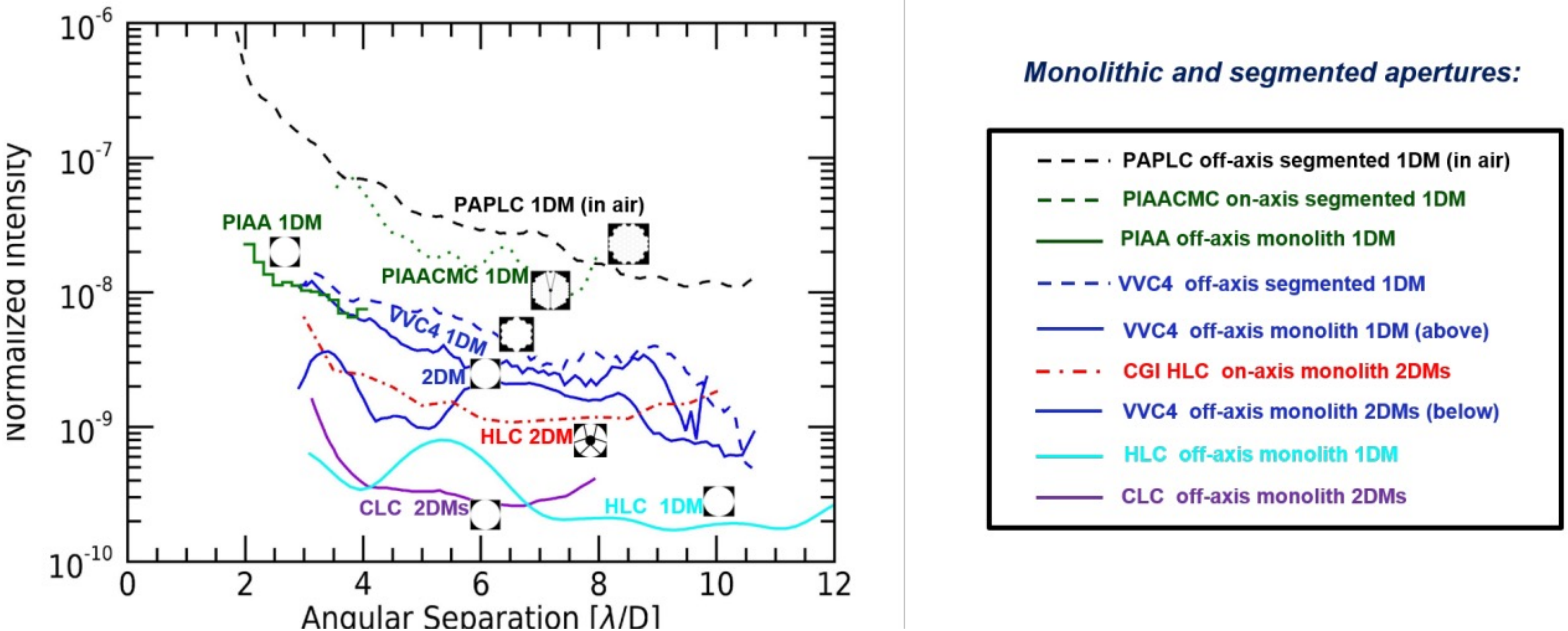
Family tree of coronagraphs: too many concepts





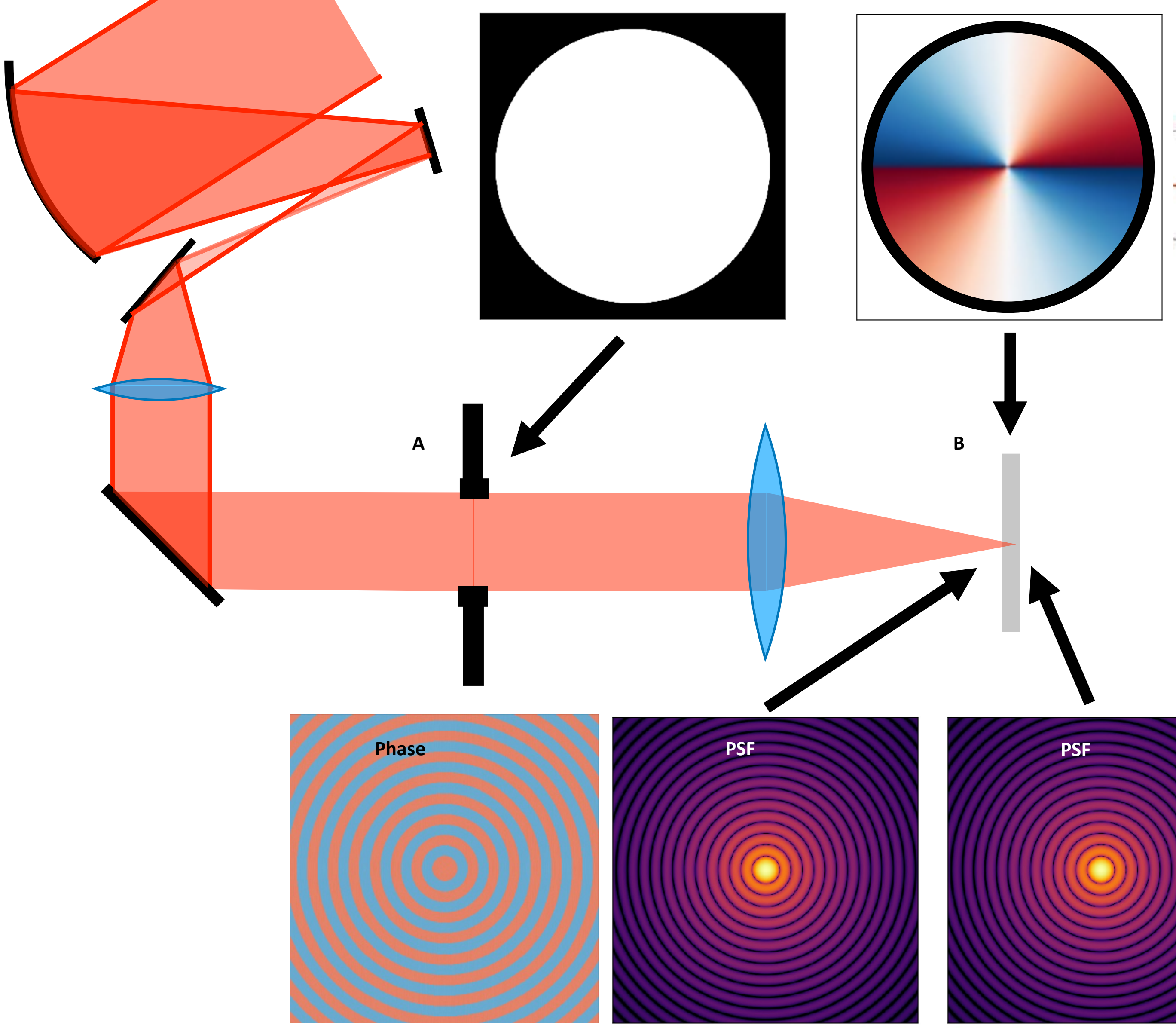
Guyon 2006

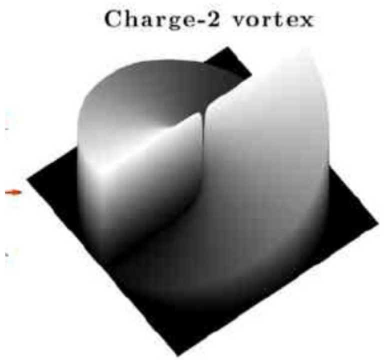
Experimental validation is key



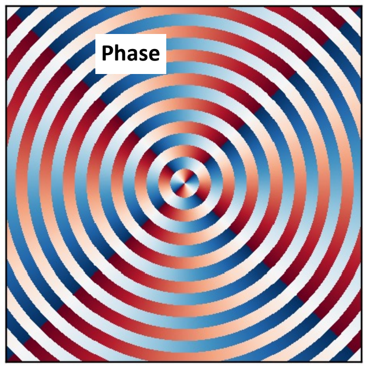
Mennesson et al. 2024

Vortex coronagraph



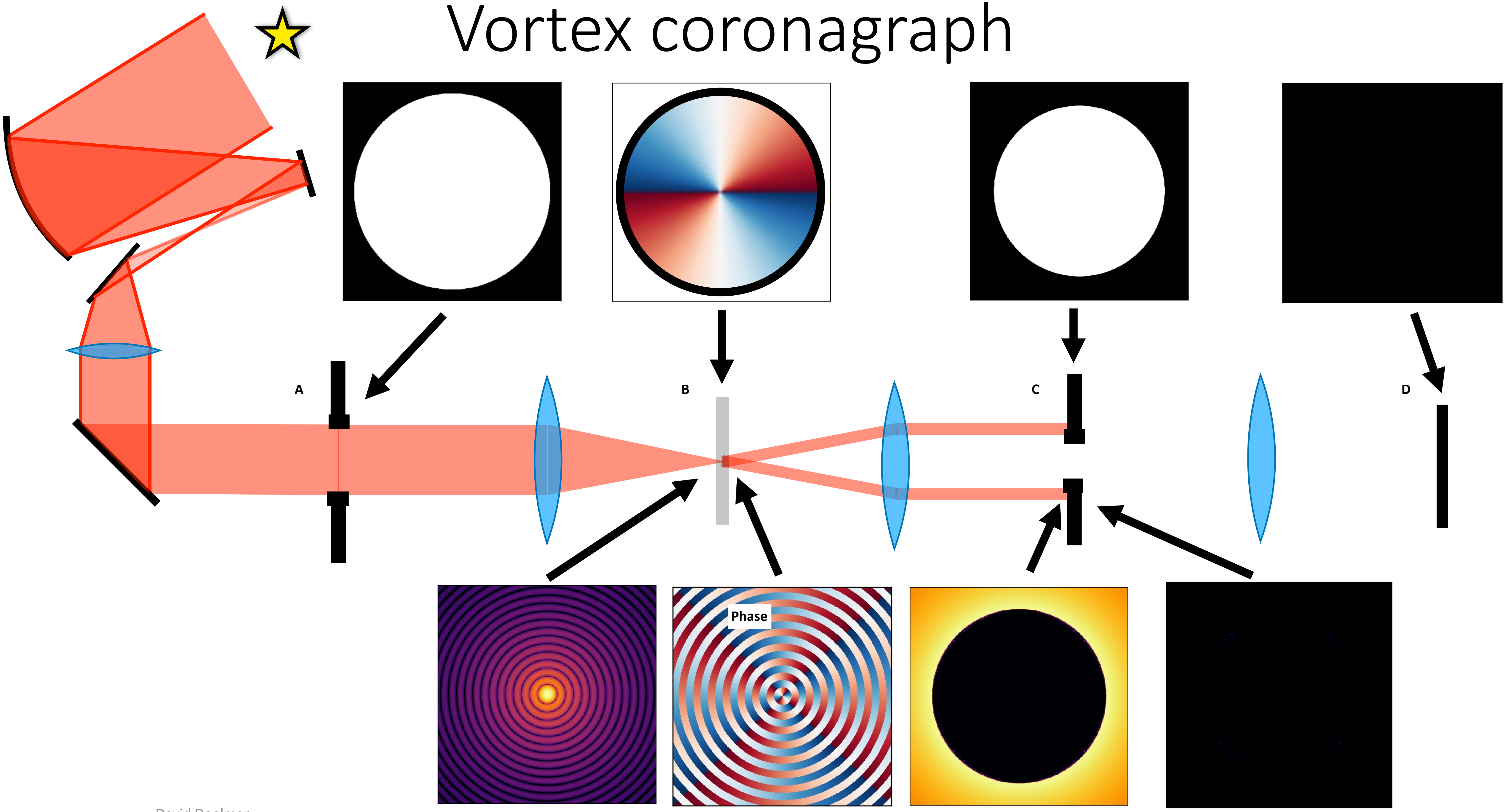


Delacroix et al. 2014



- **Azimuthal phase pattern**
- **Charge is the amount the phase goes through 0**
- **Even charges deliver optimal performance for clear apertures**
  - Perfect rejection proof: see Mawet et al. 2005, Appendix C

Vortex coronagraph



David Doelman

Engineering achromatic vortex masks

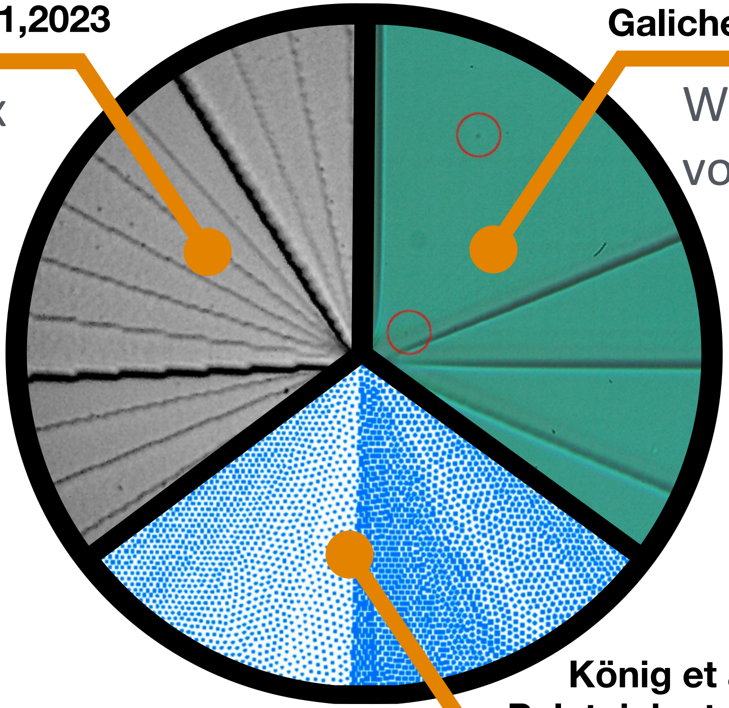
Scalar vortex

Desai et al. 2021,2023

Stepped vortex
+phase dimple

Galicher et al. 2020

Wrapped
vortex



König et al. 2023
Palatnick et al. 2023

Meta-surfaces

Chromatic phase*
No polarization effects

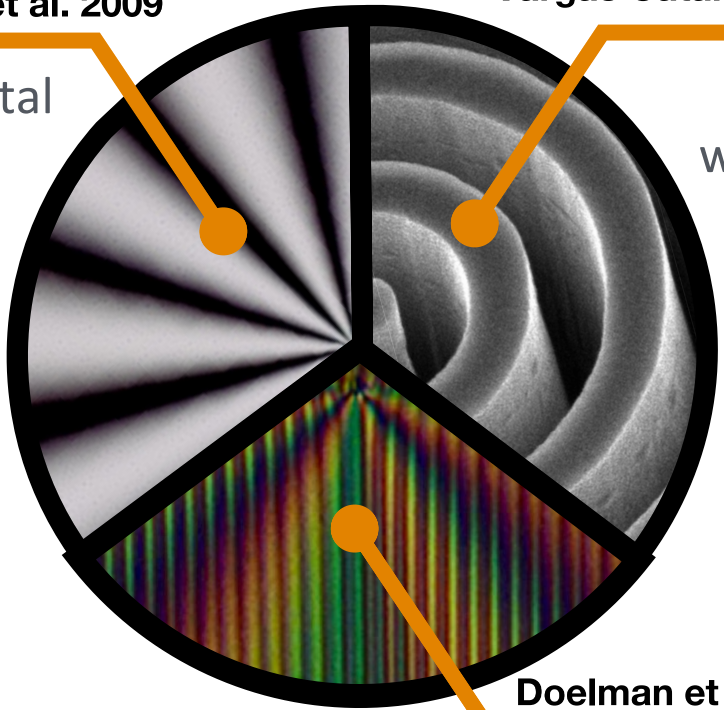
Vector vortex

Mawet et al. 2009

Liquid-crystal
retarder

Vargas Catalan et al. 2018

Sub-
wavelength
gratings

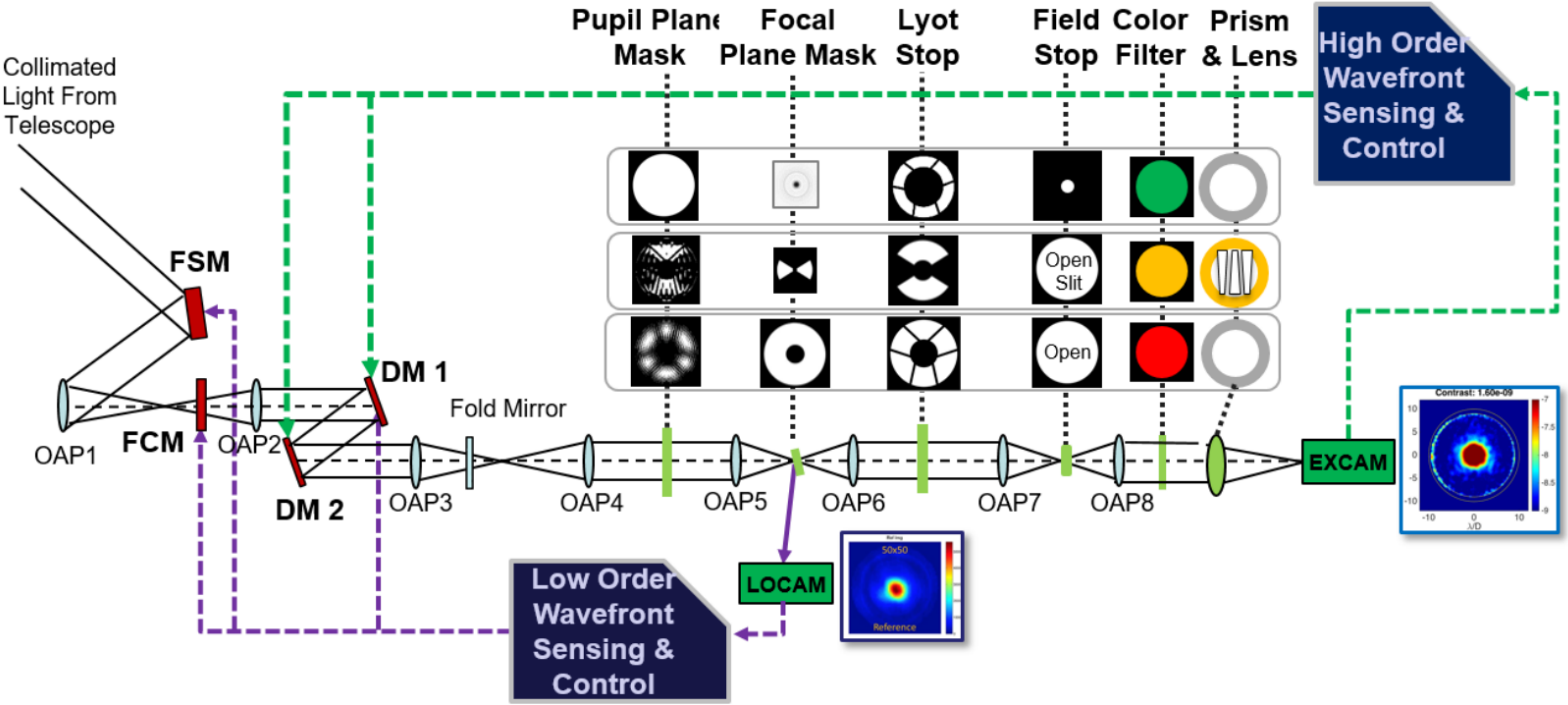


Doelman et al. 2020

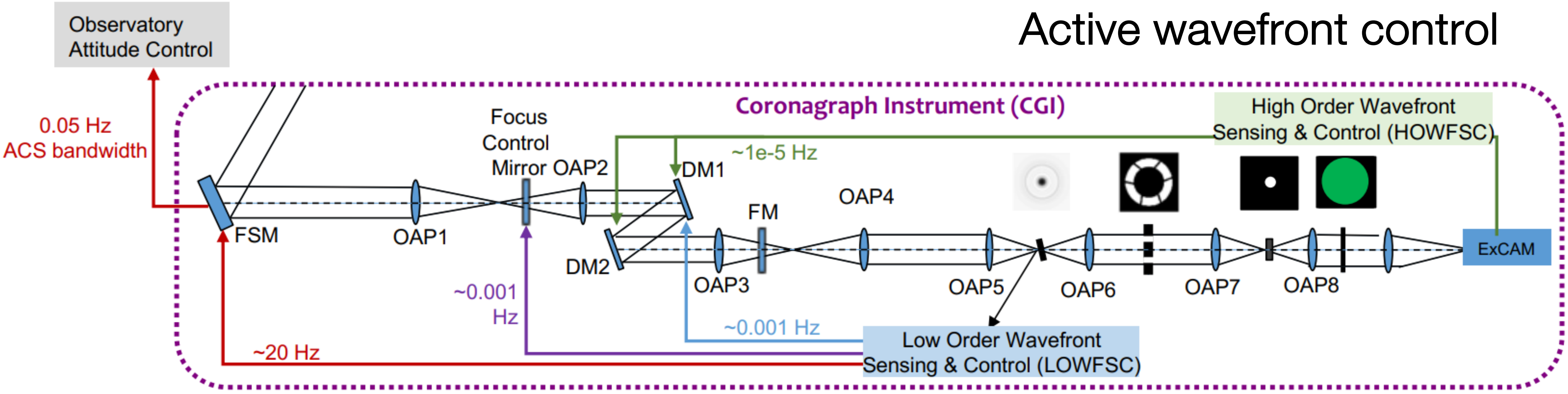
Liquid-crystal vortex grating mask

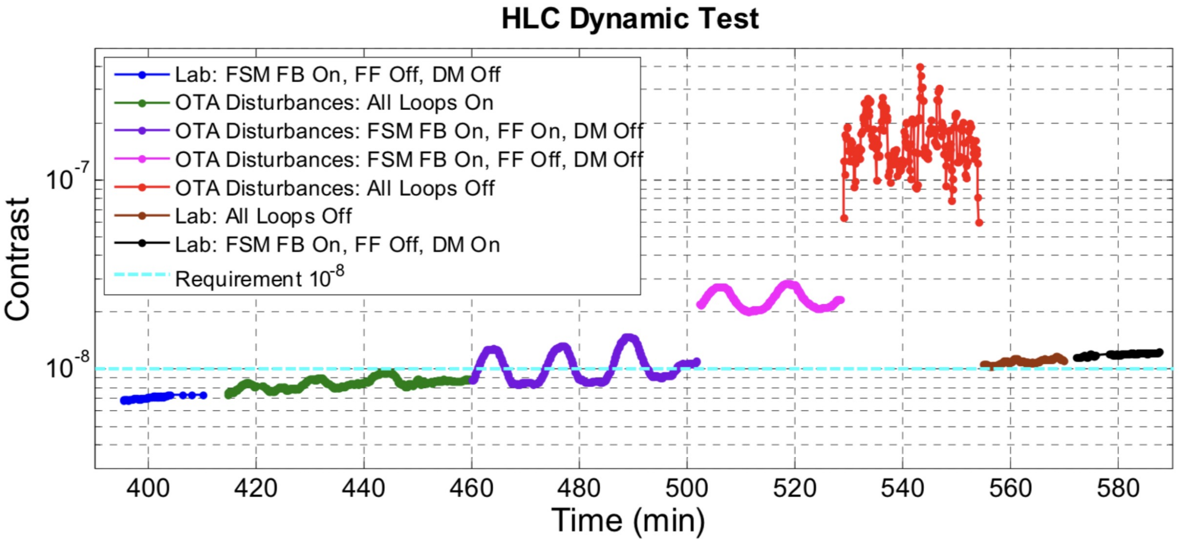
Achromatic phase
Chromatic polarization effects

Typical space-based coronagraph architecture: the Roman Coronagraph

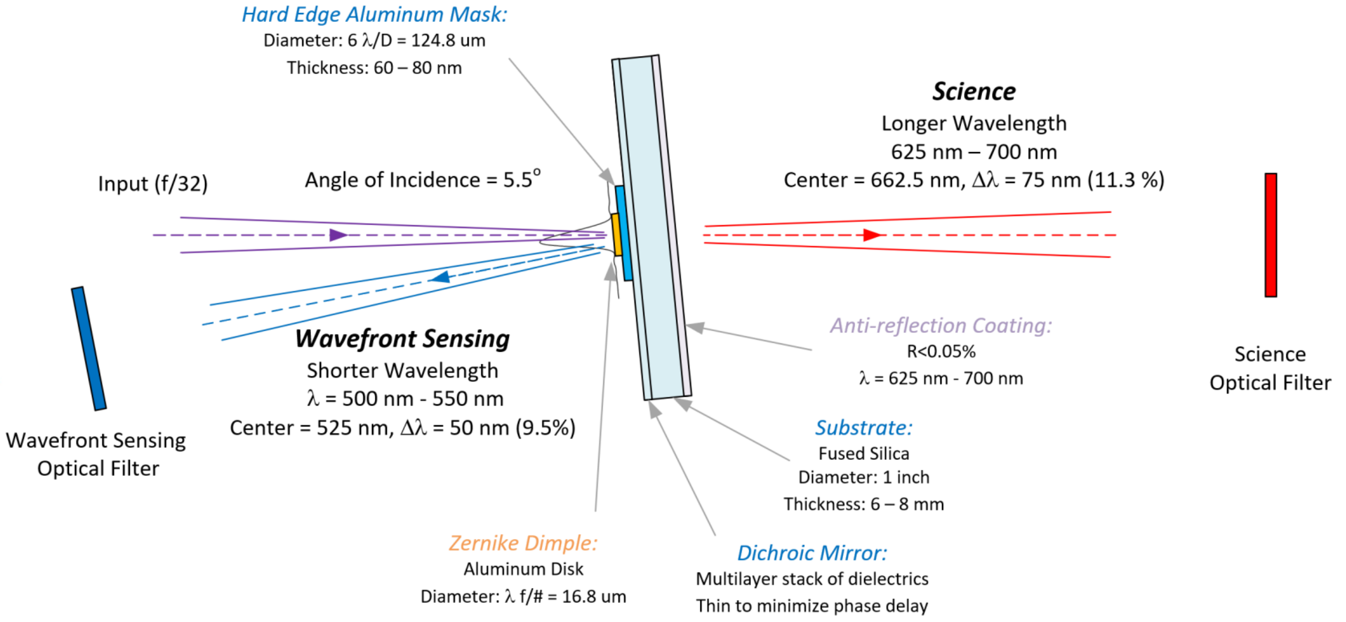


Active wavefront control





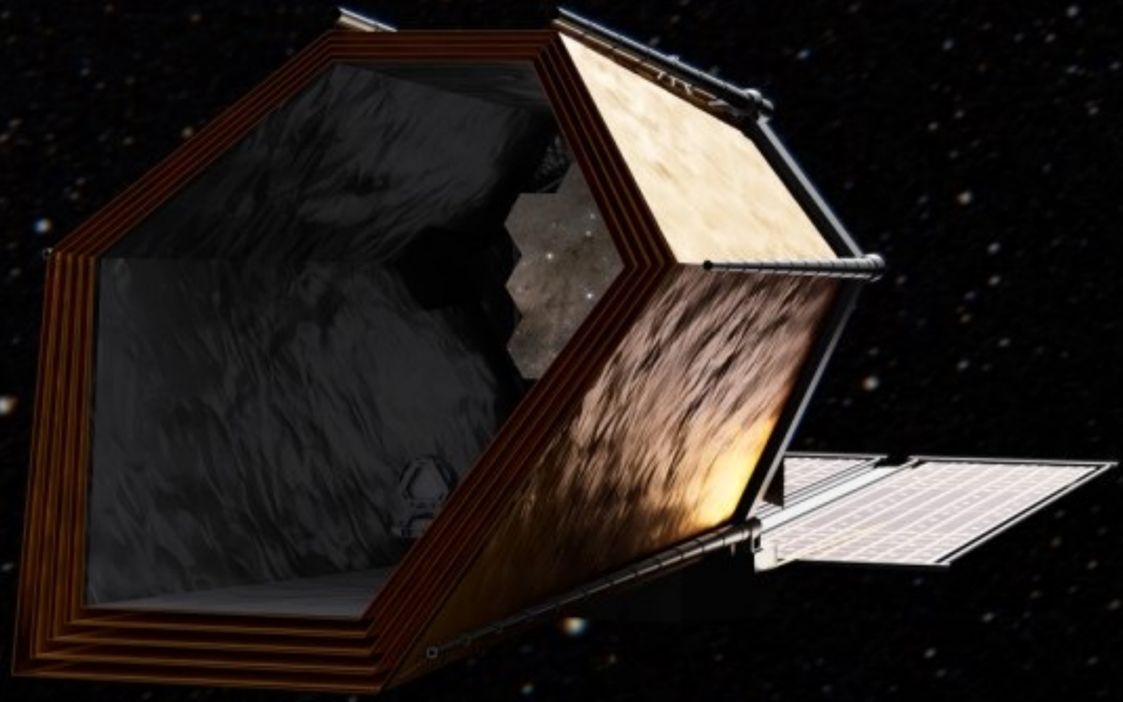
Shi+2018



Wallace+2024

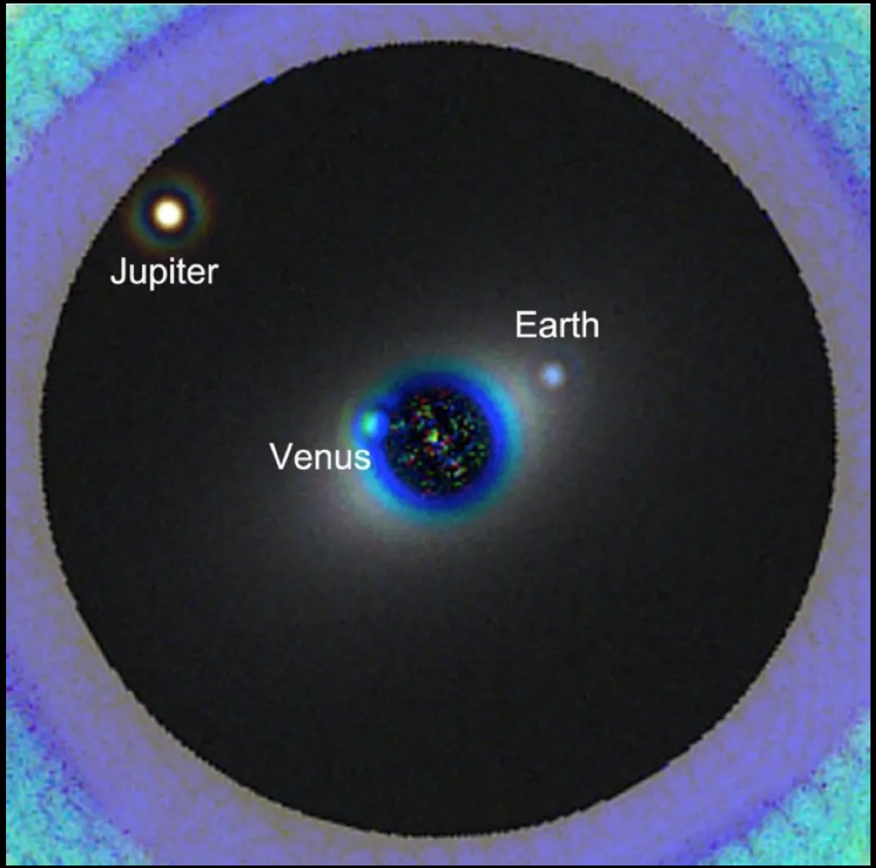
HABITABLE WORLDS OBSERVATORY (HWO)

- NASA's next flagship, recommended by Astro2020
- 6-meter inscribed diameter
- Segmented
- Off-axis (likely)
- 100 nm – 2500 nm
- 3-4 instruments including a coronagraph instrument
- Launch in 2040s



The challenge: imaging Earths with HWO

- 10^{-10} contrast instead of 10^{-8} for Roman
- Residual intensity contrast in the dark hole:
  - $I \propto \varphi^2; \varphi = \frac{2\pi}{\lambda} ne$
  - *$I < 10^{-10}$ in the optical => $ne < 10$ pm*
  - *This requirement is over 20% bandwidth (incl. optical and near-infrared) and over minute to hour to day timescales*



Conclusion: exquisite phase and amplitude control is needed

- Metasurface optics may play a critical role in many areas of future high contrast imaging technologies including but not limited to:
  - Coronagraphic focal plane masks
  - Pupil-plane beam shaping optics and apodizers
  - Wavefront sensing elements as well as their integration into the coronagraph layout
  - Polarization control