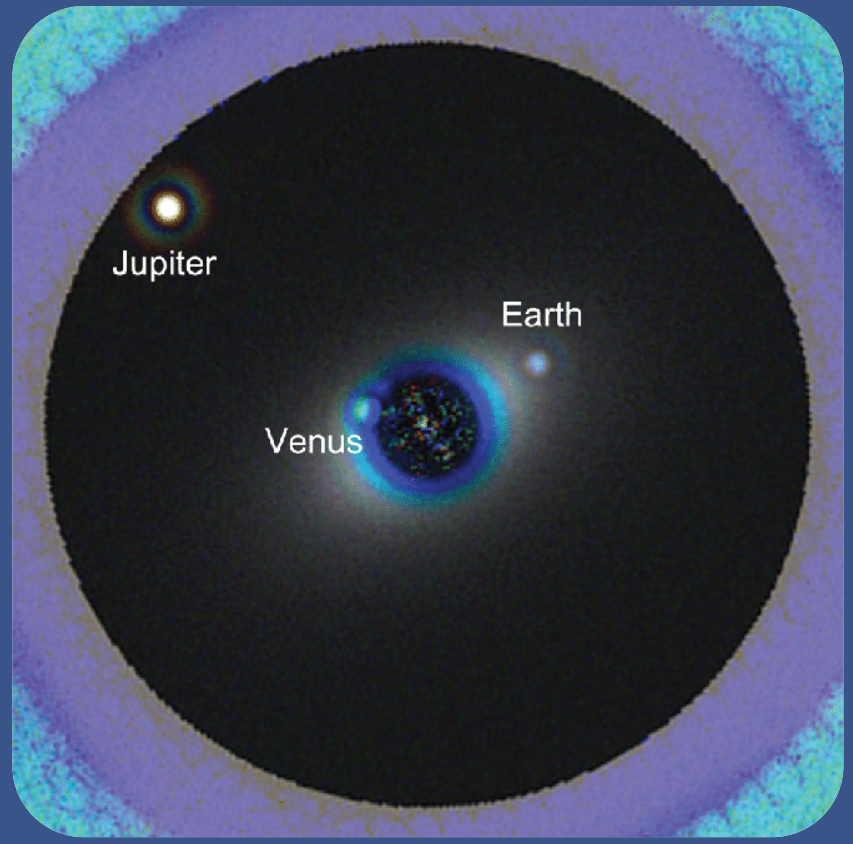
# High-contrast imaging of exoplanets with future large ground- and space-based telescopes : current limitations and perspectives.

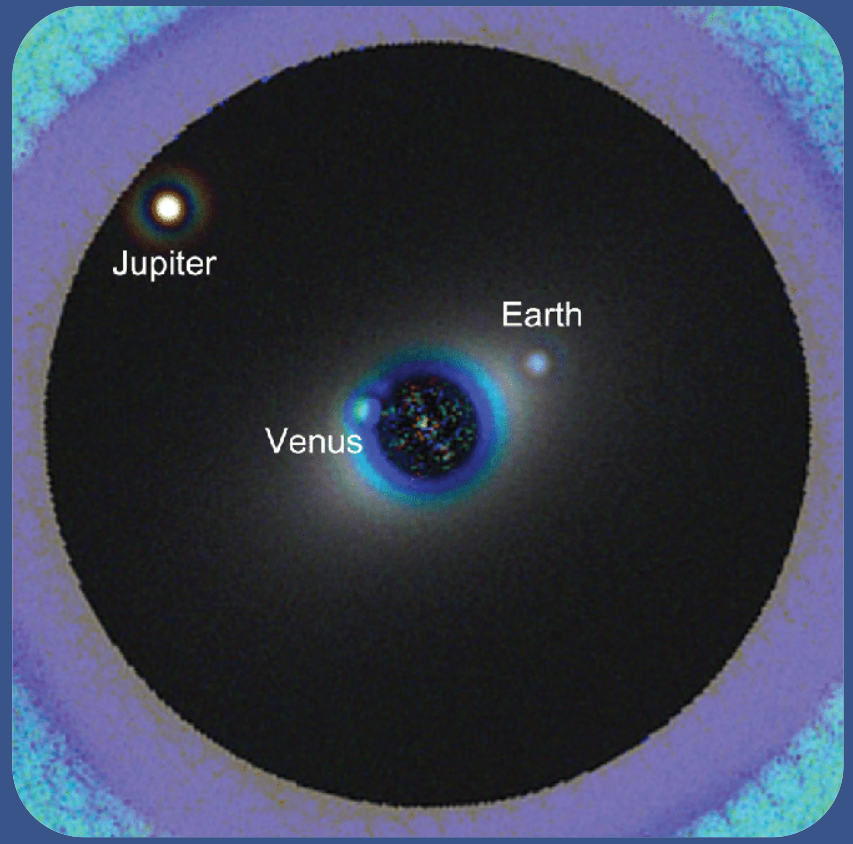
**Johan Mazoyer**

Jet Propulsion Laboratory
California Institute of Technology

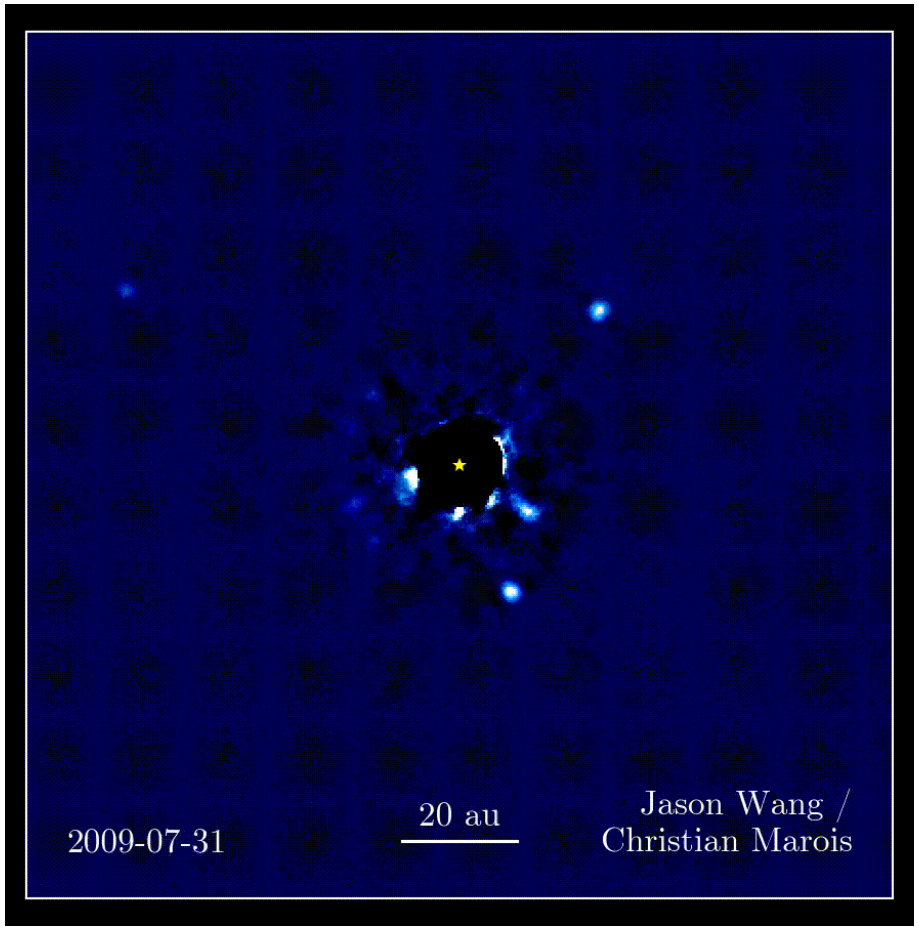


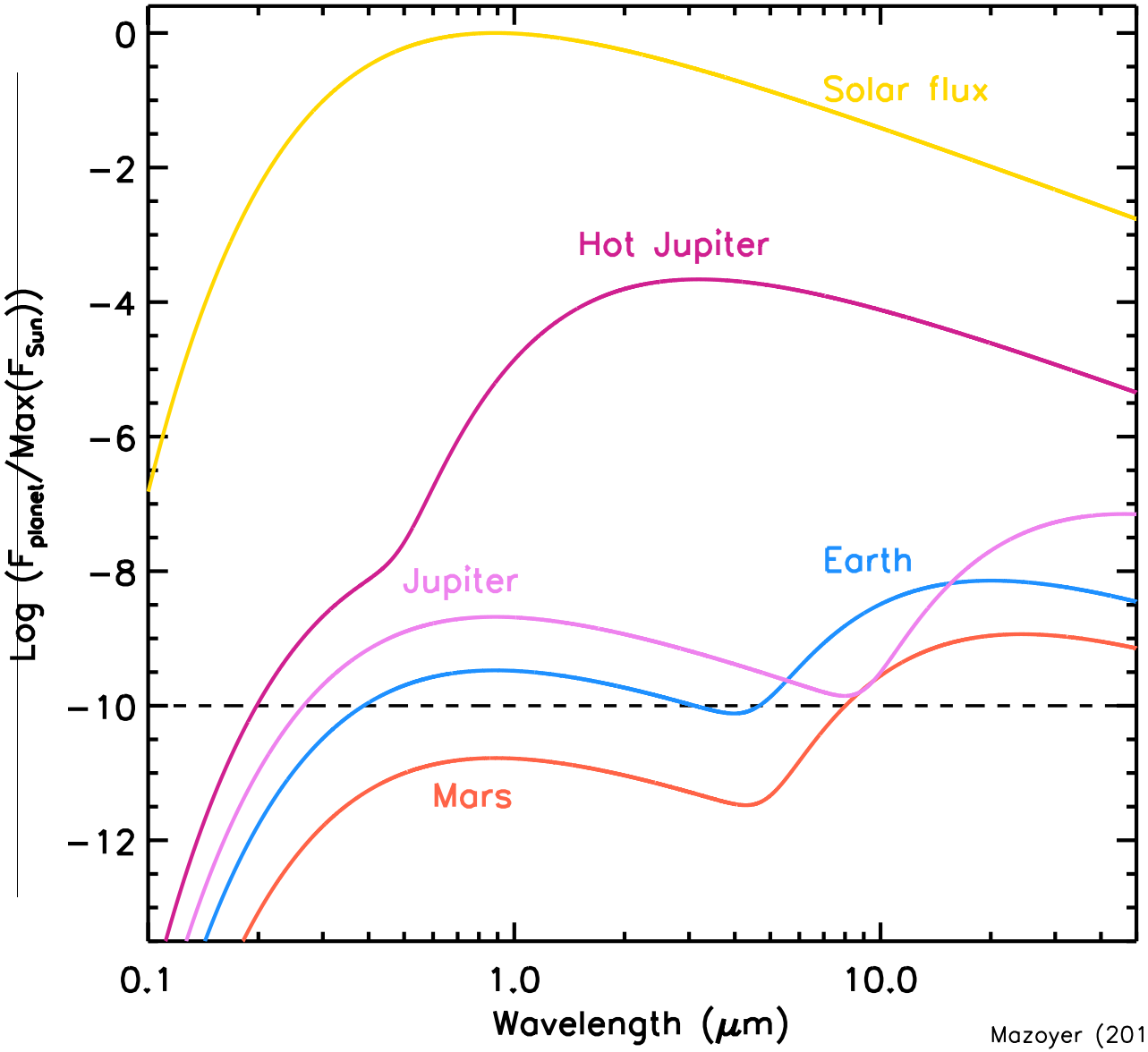
# How to image this ?

(for only 10 times the cost of TESS)



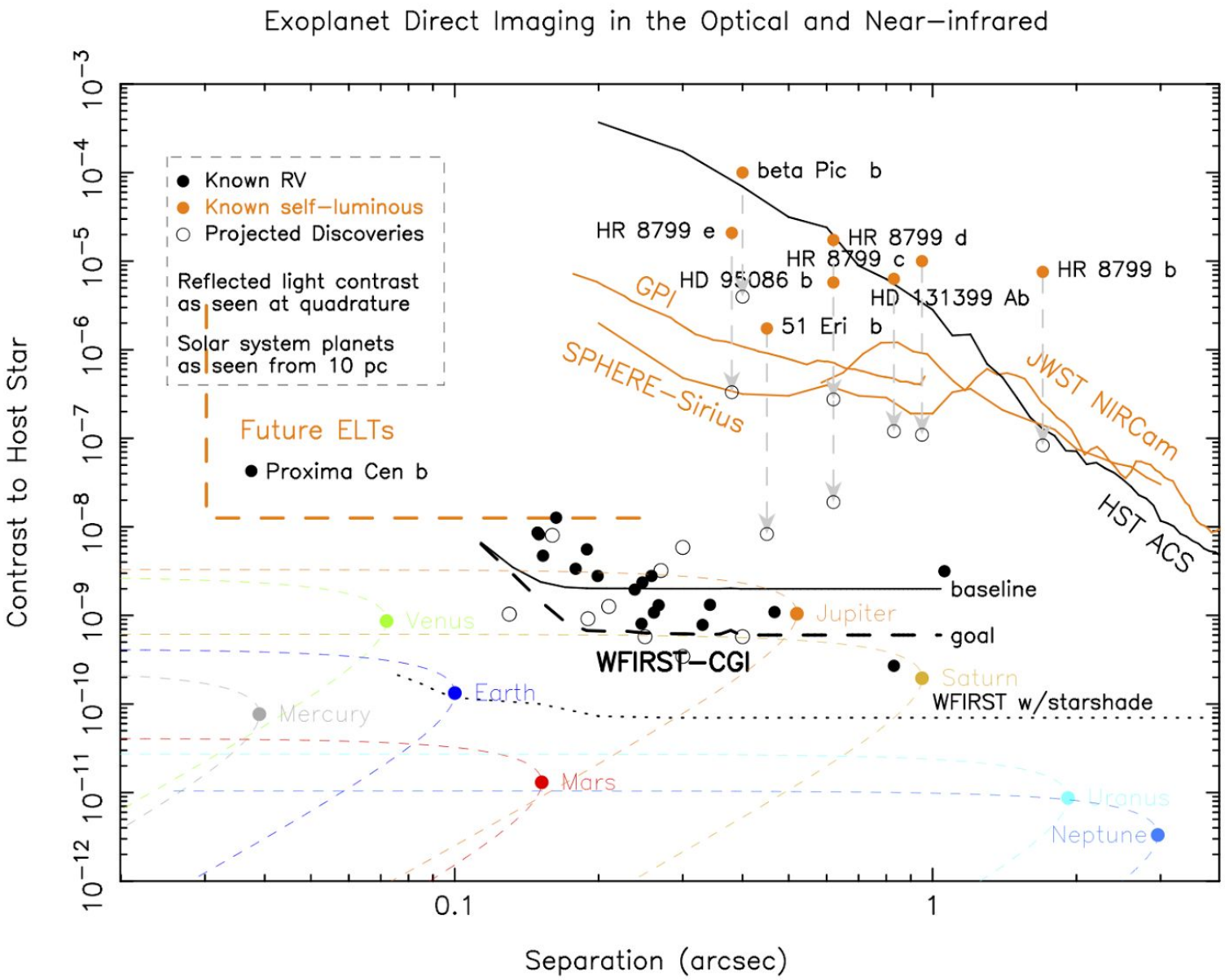
# High contrast imaging




Mazoyer (2014)

# High contrast imaging: Toward $10^{-10}$



# High contrast imaging: Toward $10^{-10}$

**Space-based**
LUVOIR, Habex

**Space-based**
WFIRST/CGI

**Ground-based**
ELTs instruments
Theoretical limit from ground (Guyon 2005)

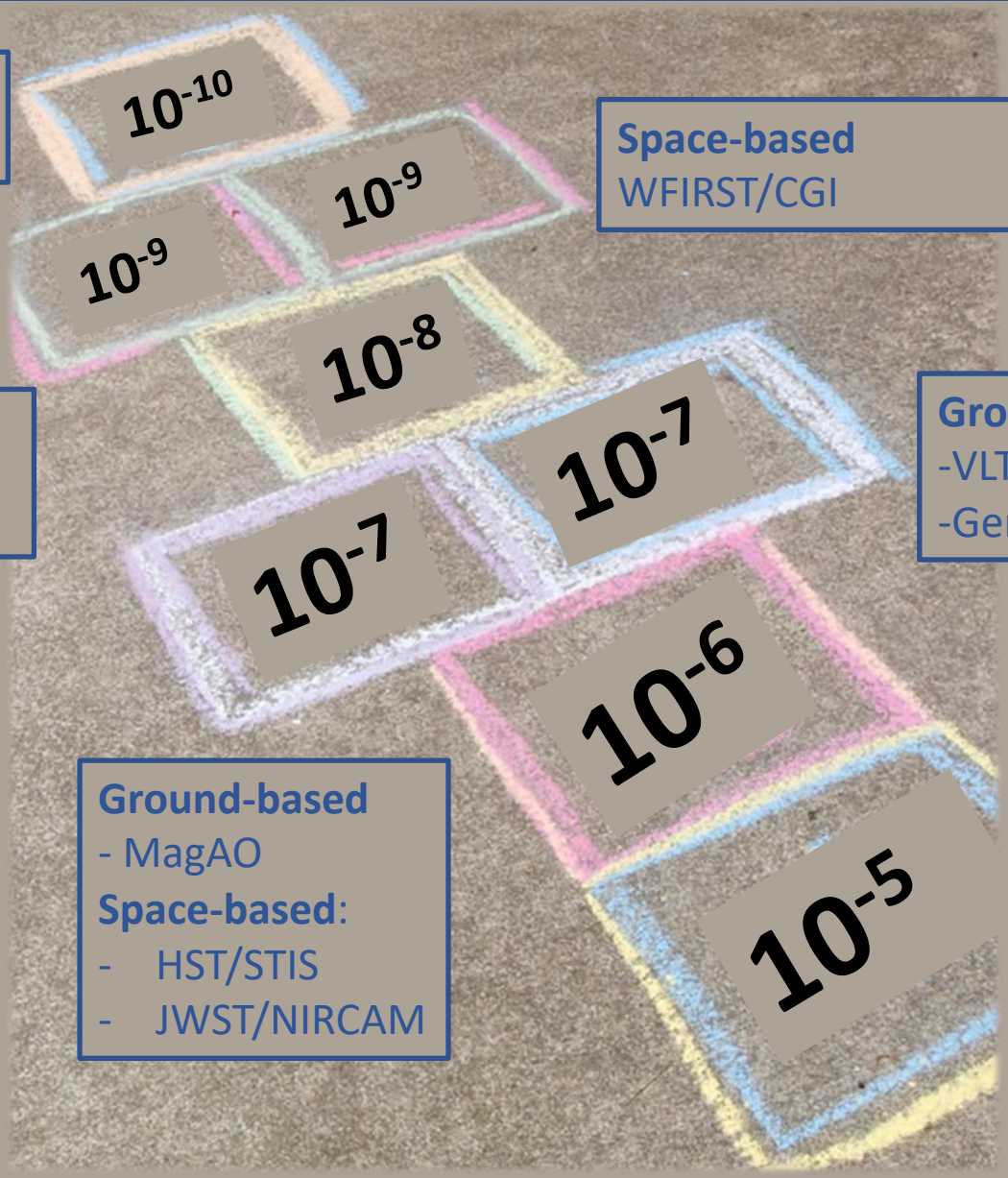
**Ground-based**
-VLT / SPHERE
-Gemini / GPI

**Ground-based**
- MagAO

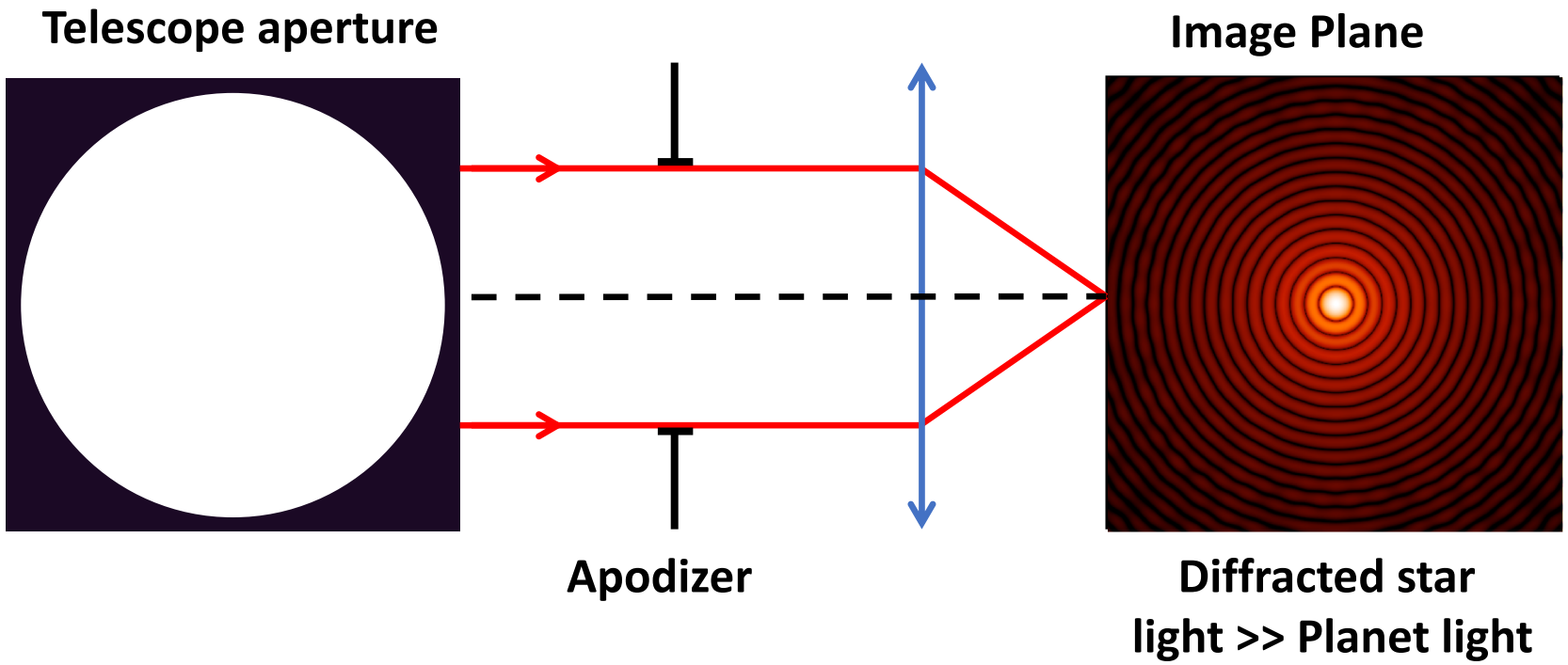
**Space-based**:
- HST/STIS
- JWST/NIRCAM

**Ground-based**
-VLT / NACO
-Gemini / NICI

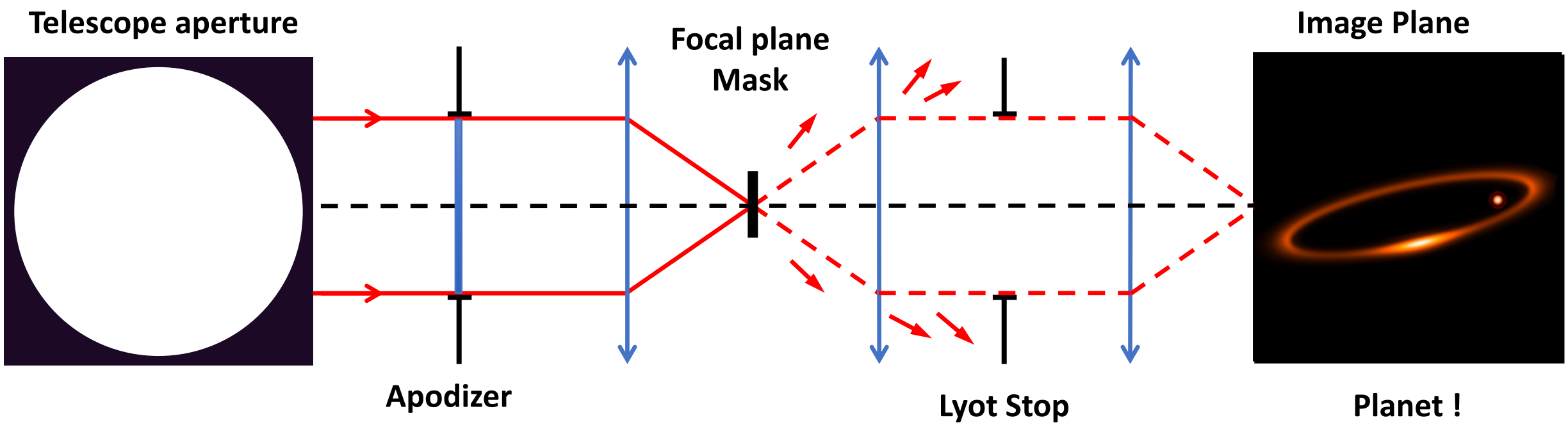
**Space-based**:
- HST / NICMOS
- HST / ACS



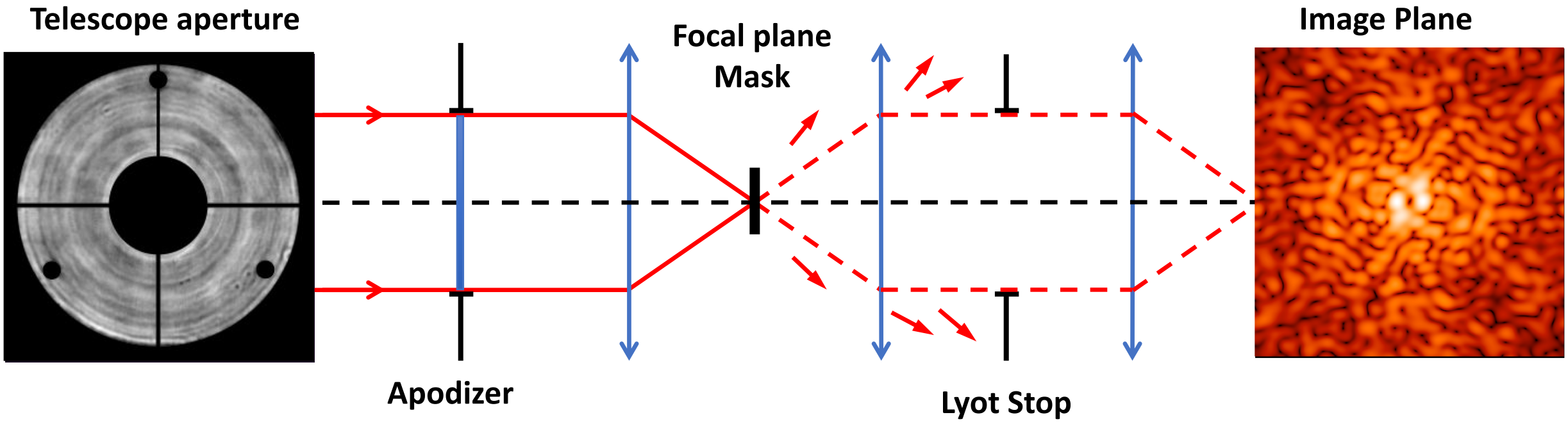
# Coronagraphy



# Coronagraphy

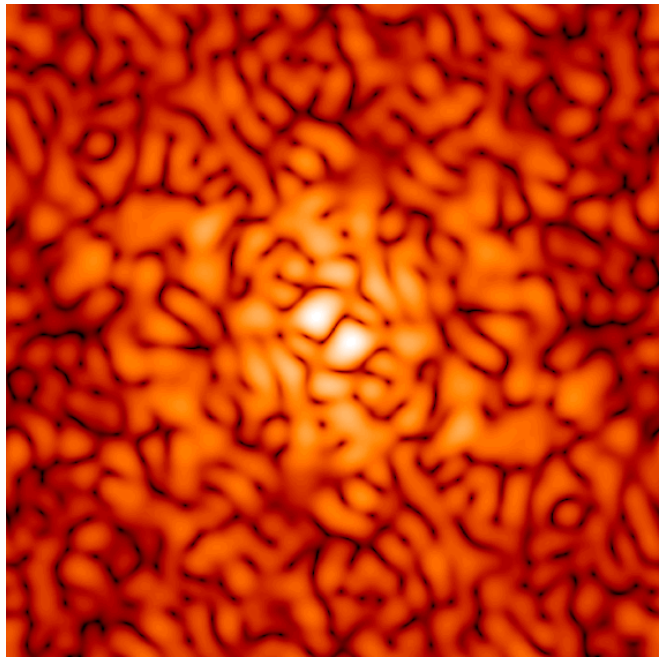


# Coronagraphy: limitations

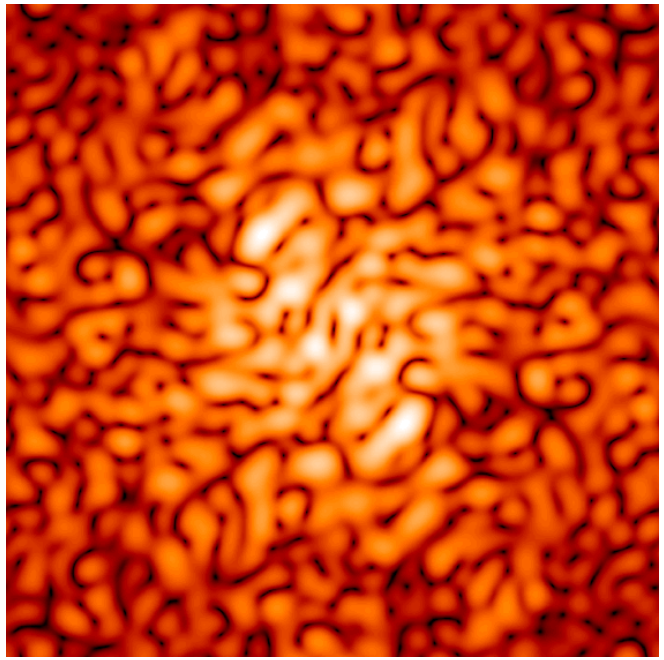



- **Origin of the speckles**
  - **Classical AO residues** (ground-based telescope)
  - **Defects** of the optics (space and ground based)
  - **Complex apertures**

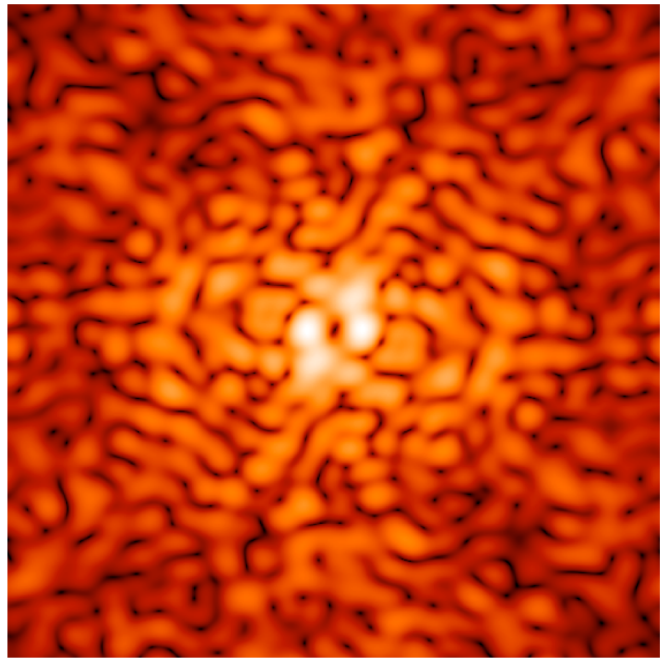
# Speckles



**Dynamic speckles**
$\tau \ll$ exposure time
**=> Averaged on one frame**

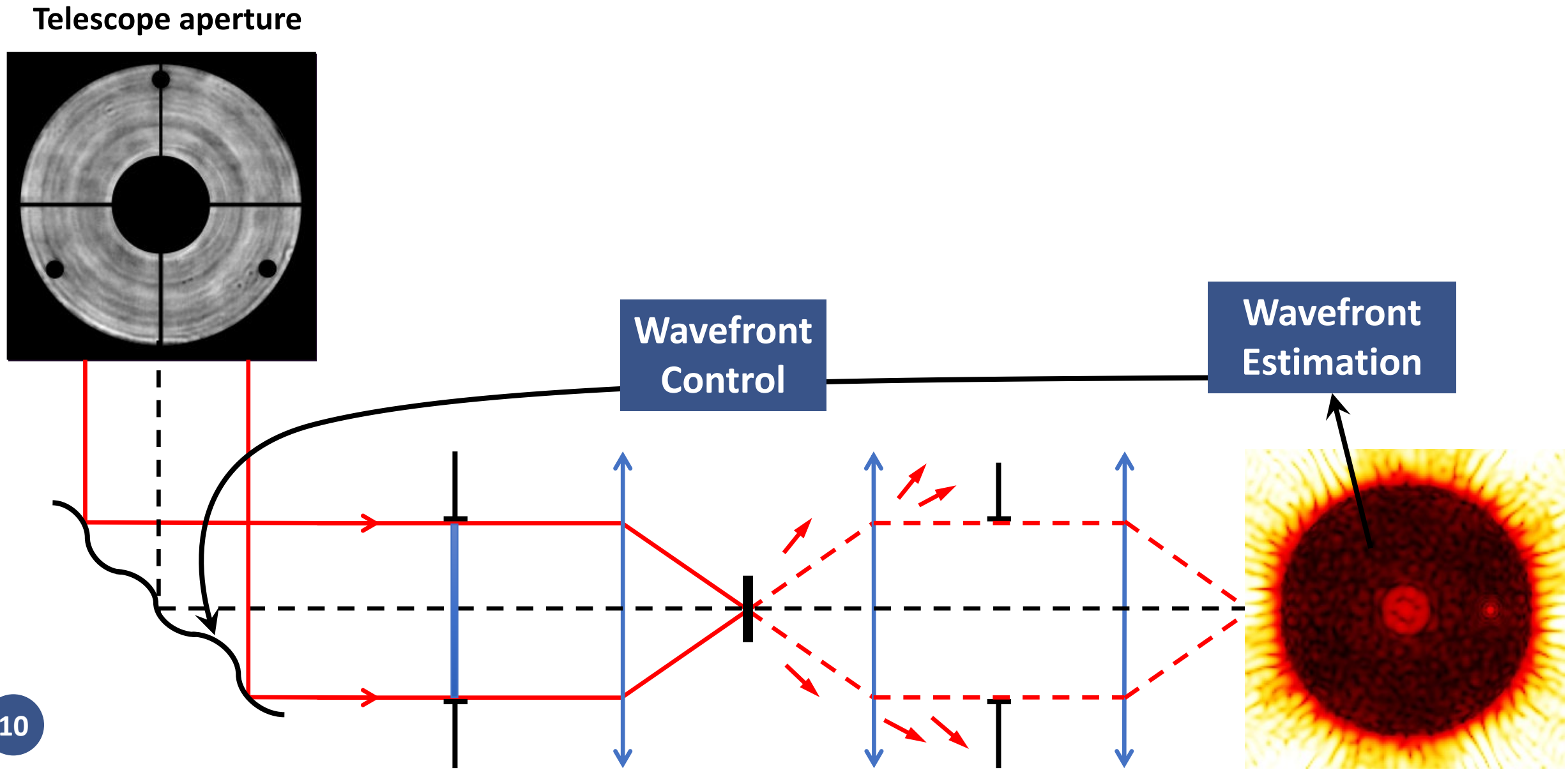


**Quasi-static speckles**
$\tau \approx$ exposure time
**=> Active correction in closed loop**

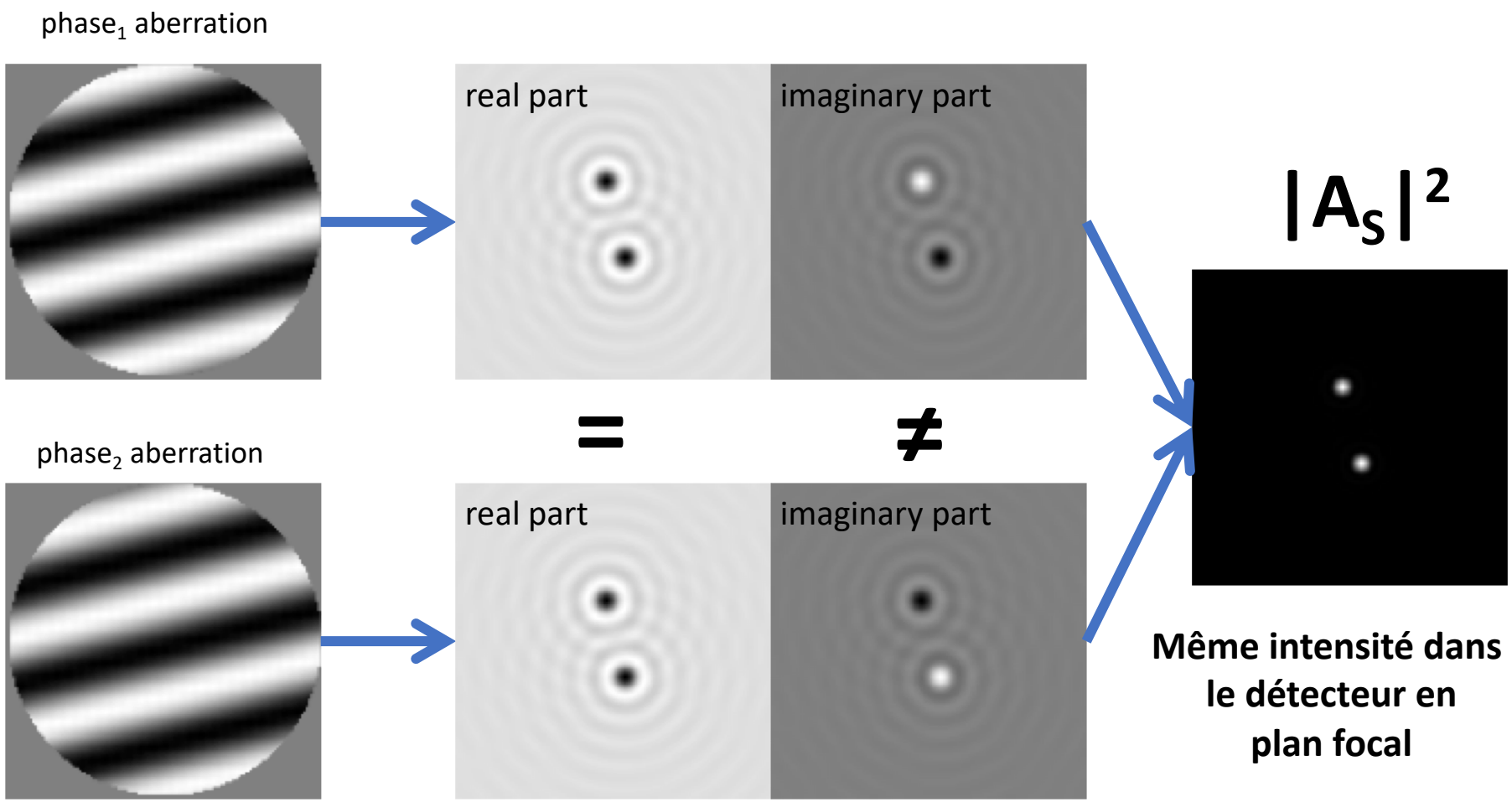


**Static speckles**
$\tau \gg$ exposure time
**=> Active correction in open loop (calibration)**
**=> Post treatment technique (e.g. roll subtraction )**
**Have to be corrected if very high !**

# Coronagraphy



# Measure field in focal plane



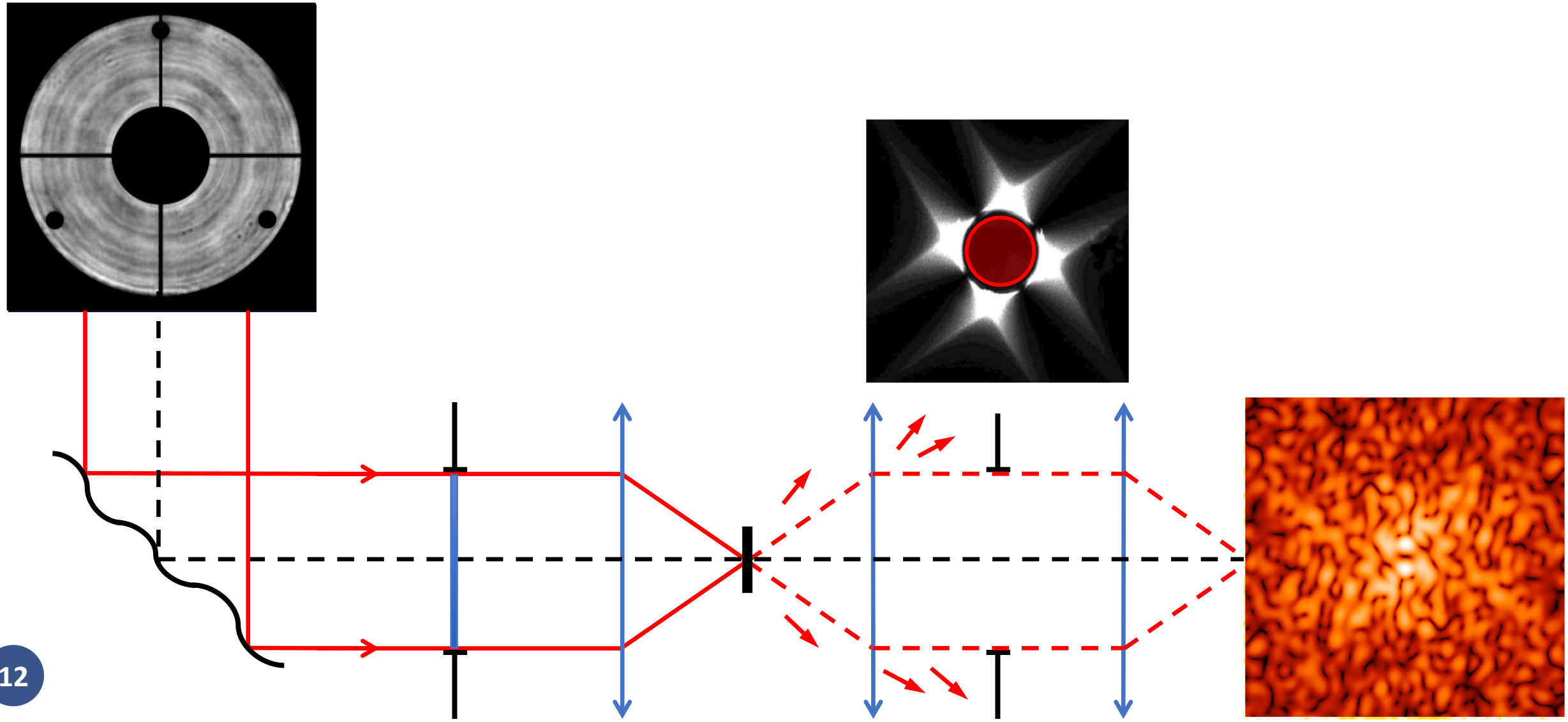

**Même intensité dans le détecteur en plan focal**

2 distinct wavefront before the coronagraph

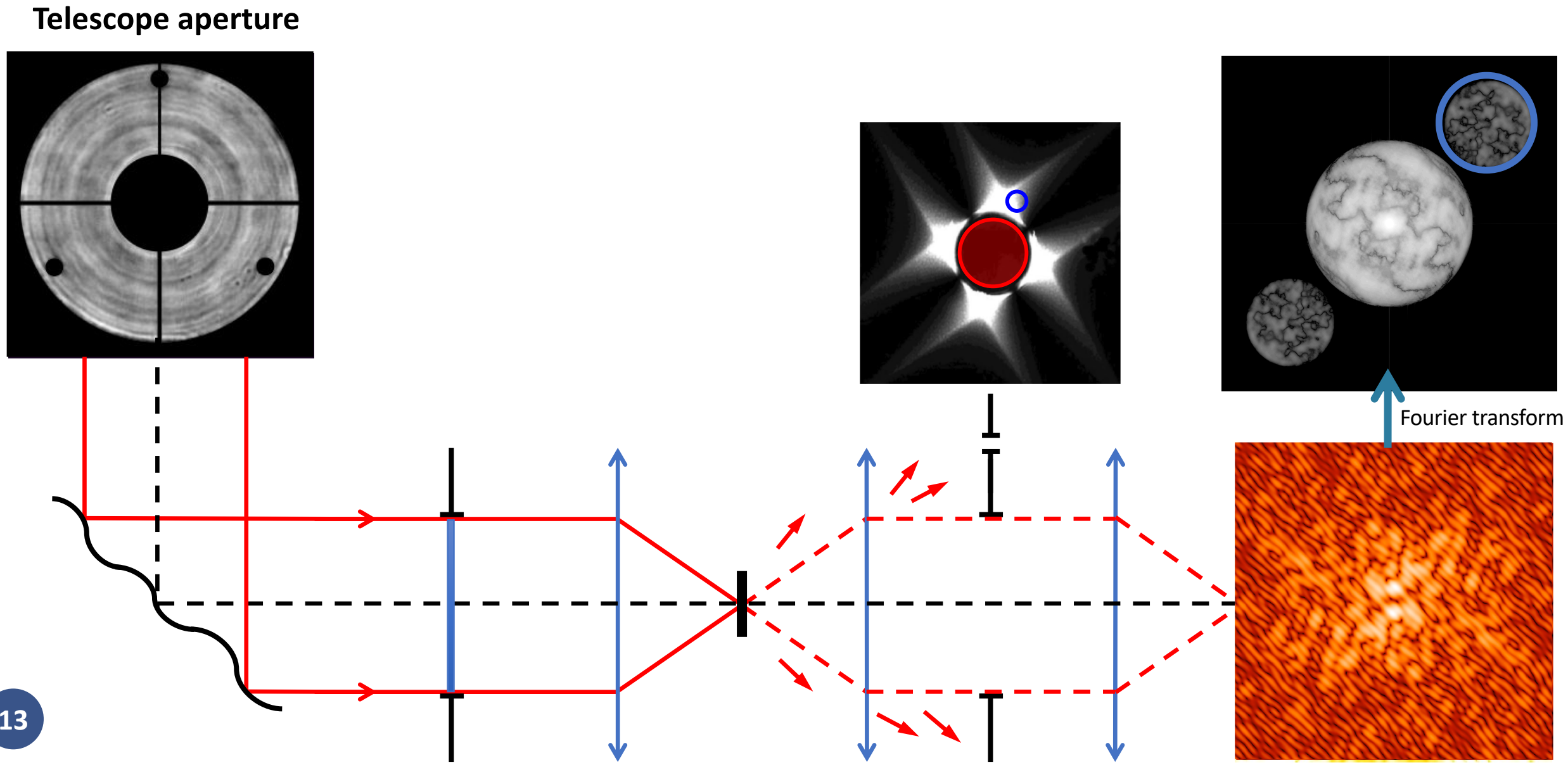
Complex EM field in the focal plane

# Self-coherent camera (SCC)

**Telescope aperture**



# Self-coherent camera (SCC)



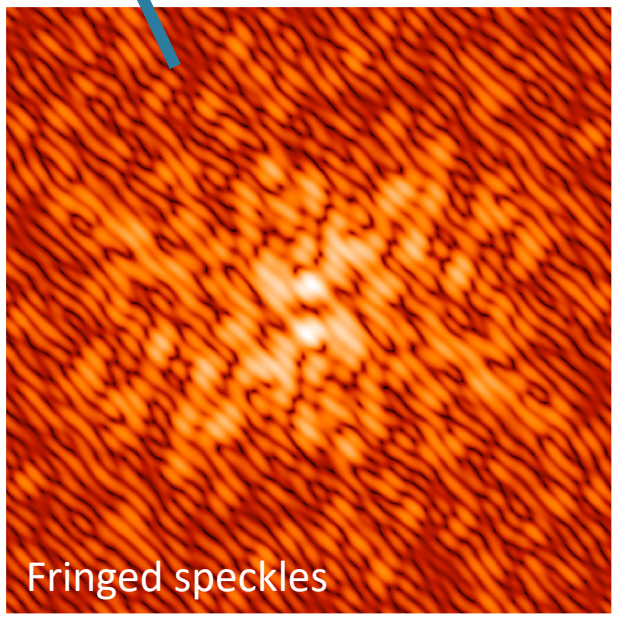
# Self-coherent camera (SCC)

Intensity through the 2 pupils

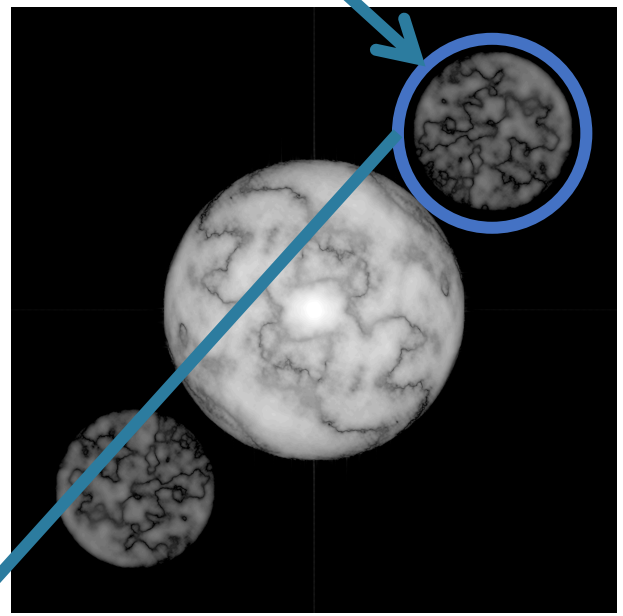
Conjugate interference terms

$$I(\vec{x},\lambda) = |A_S|^2 + |A_R|^2 + A_S^* A_R \exp\left(-\frac{2i\pi\vec{x}.\vec{\xi}_0}{\lambda}\right) + A_S A_R^* \exp\left(\frac{2i\pi\vec{x}.\vec{\xi}_0}{\lambda}\right)$$

TF



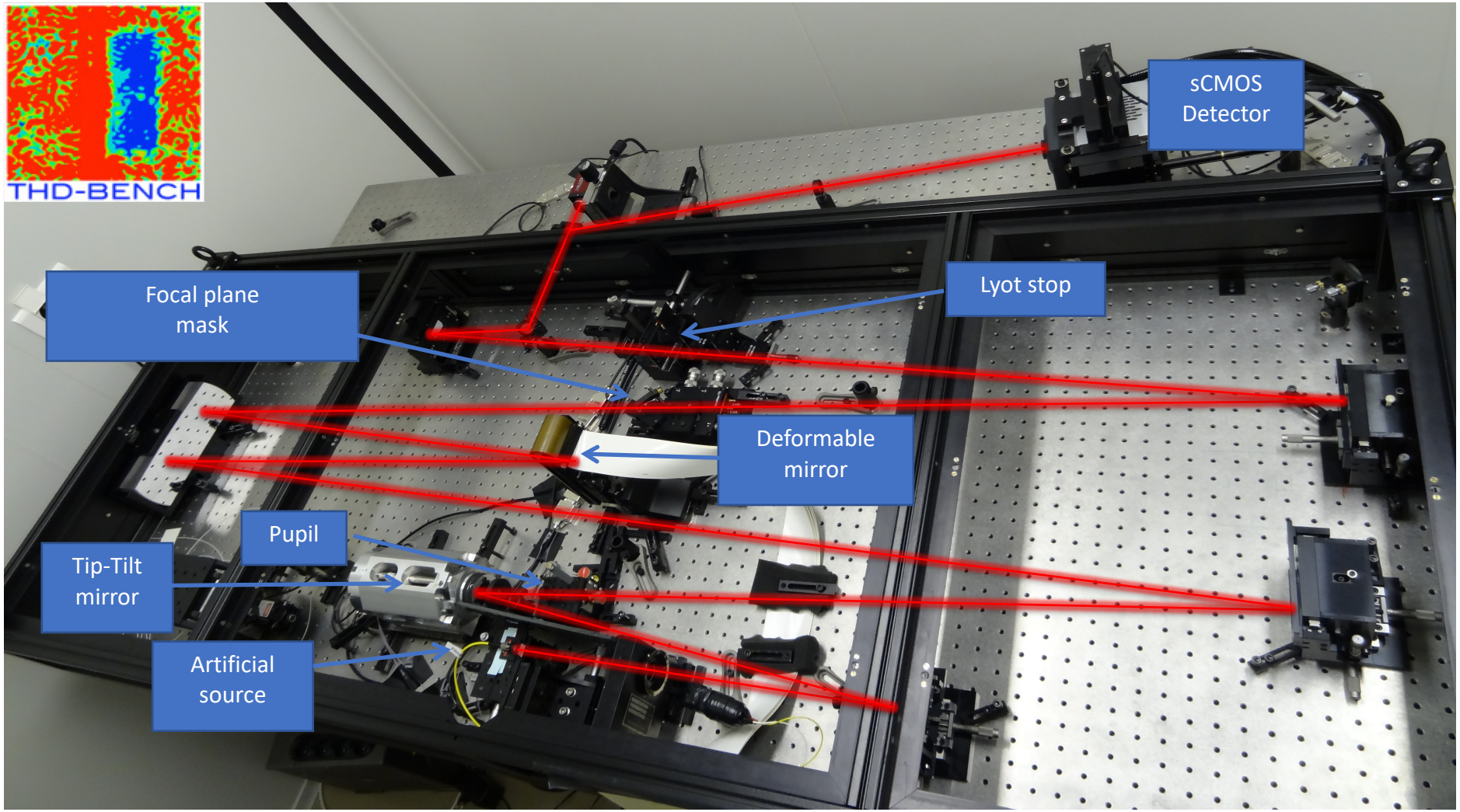

Fourier Transform



$TF^{-1}$

Complex field in focal plane $A_S A_R^*$ ← $FT[A_S A_R^*]$

# Meudon Optical testbed (as in 2015)



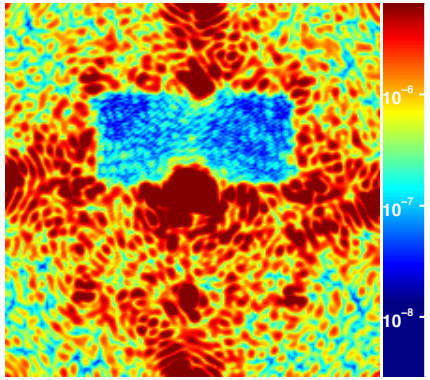
# SCC: Experimental results

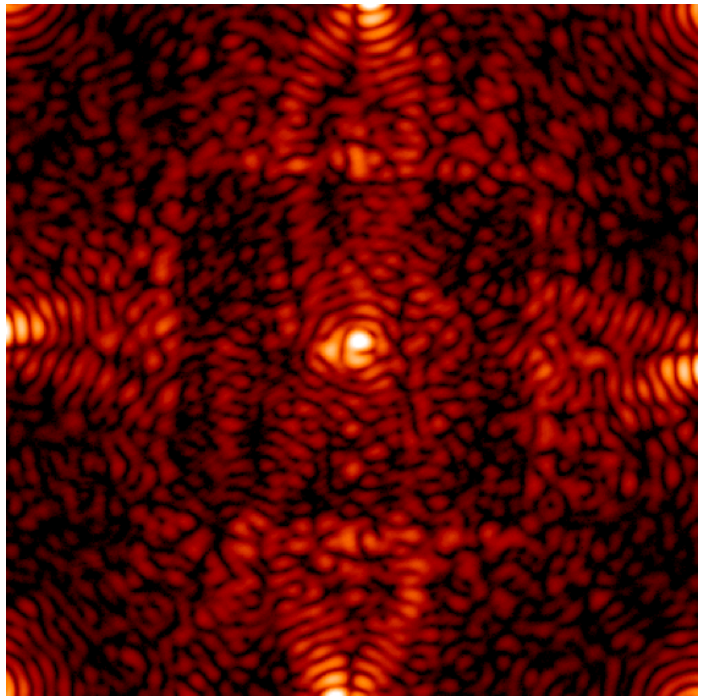
- 2012-2013 : First experimental results of the SCC (Contrast = 3. $10^{-7}$)
  **Mazoyer et al. 2012 (SPIE), Mazoyer et al. 2013a (A&A)**

- 2014 : Improvement of the experimental results by a factor 12. First results in larger spectral band (bw = 3%, Contrast = 2. $10^{-8}$)
  **Mazoyer et al. 2014a (A&A)**

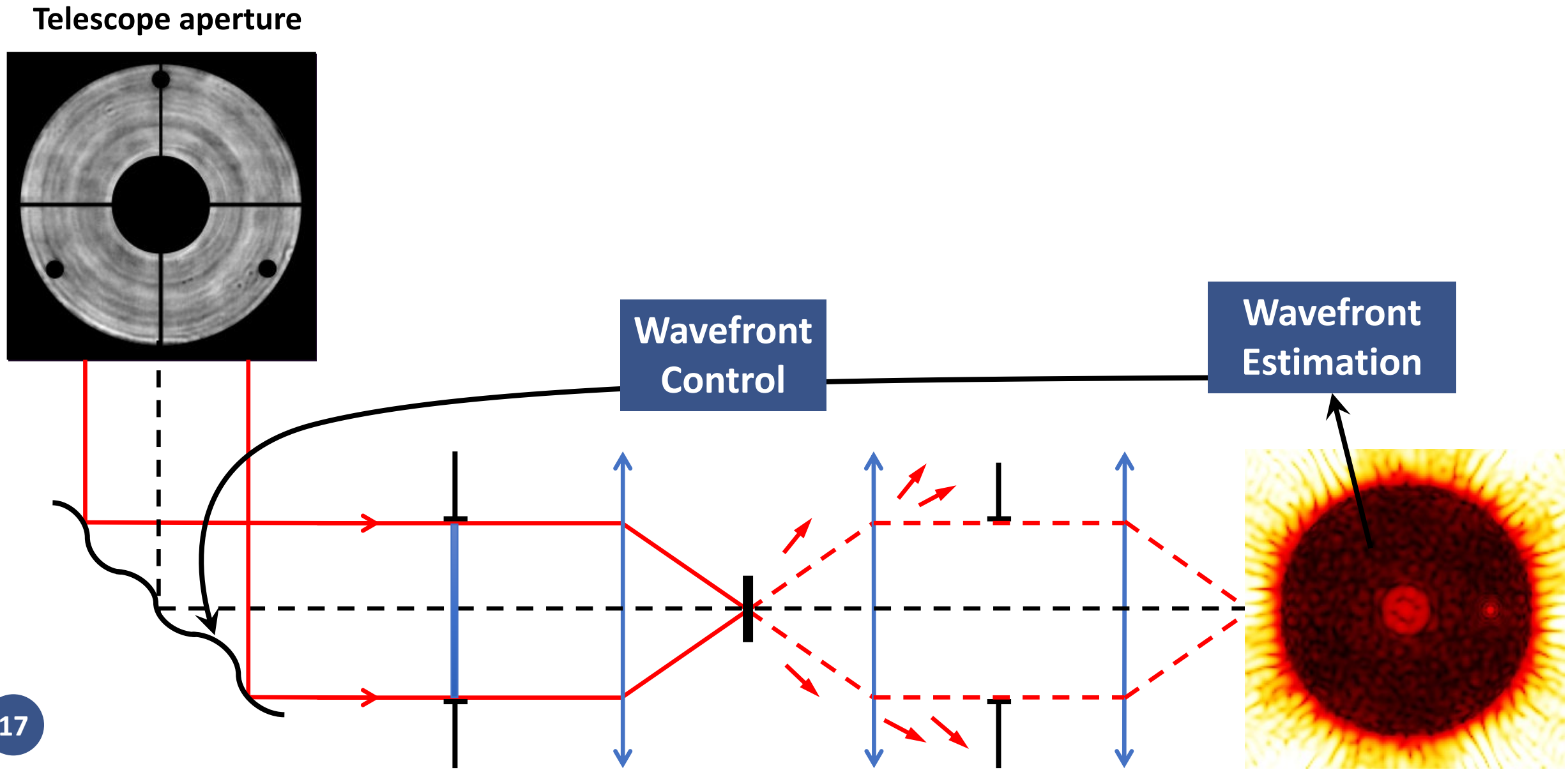
- 2016 : Results and correction in large spectral band (up to 30%)
  **Delorme et al. 2016**

- 2015-2018 : Palomar. First on sky validation on the 100 inch telescope.
  **Galicher et al in prep.**

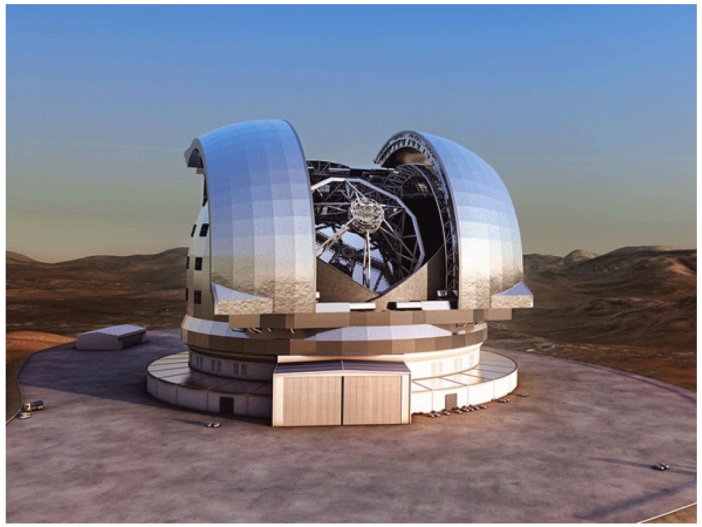


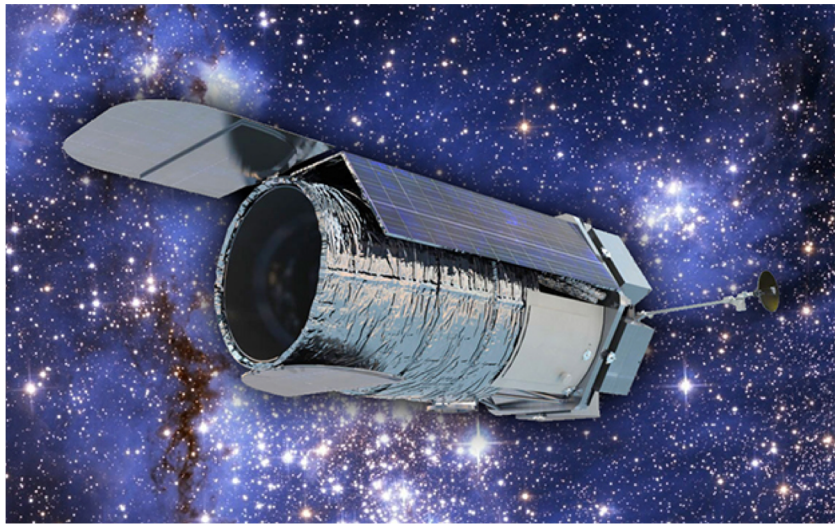
# Coronagraphy



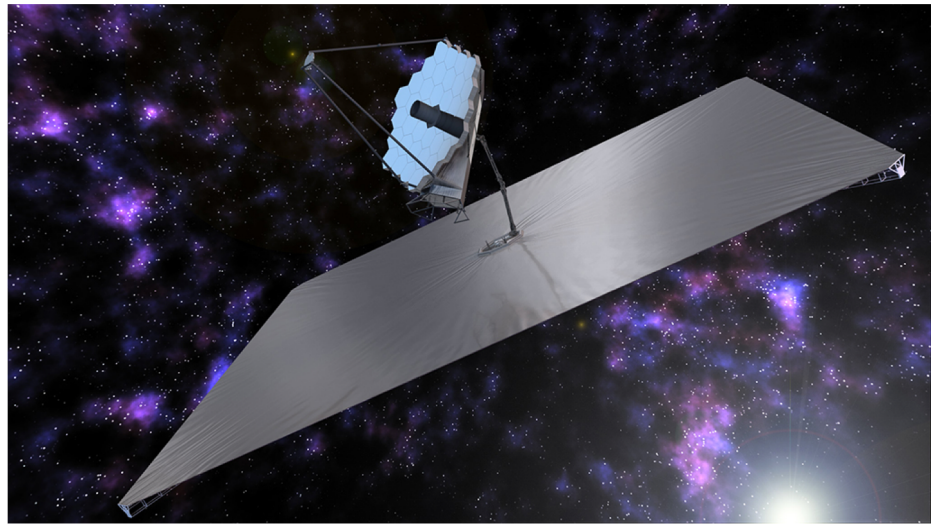
# Aperture discontinuity



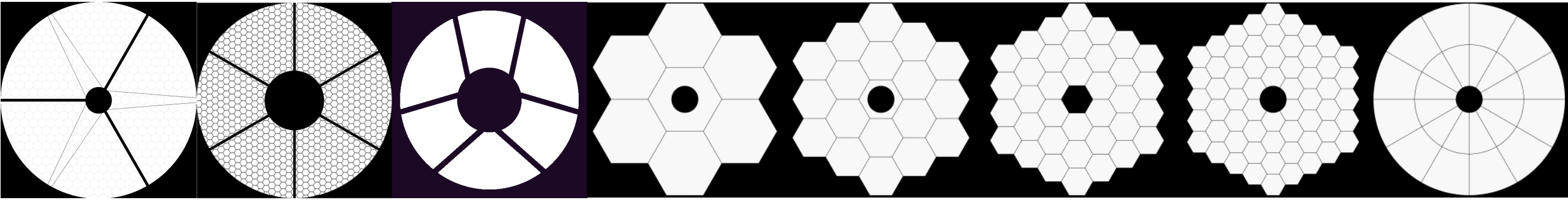
ELTs (< 10 years)



WFIRST (< 10 years)



LUVOIR ( ~ 20 years)



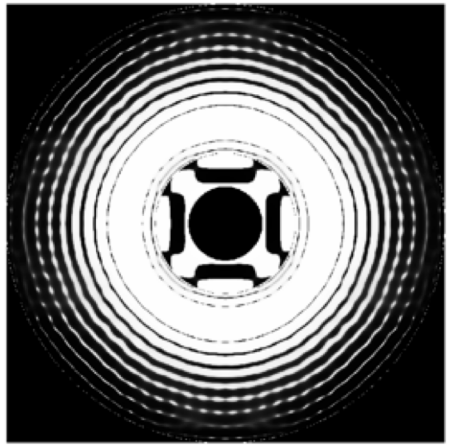
TMT E-ELT WFIRST

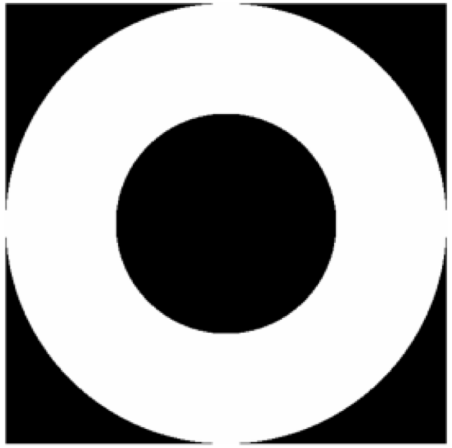
Apertures for Segmented Coronagraph Design and Analysis (SCDA) program (JPL)

# Another important metric: throughput

- **2 types of throughput :**
  - **Number of incoming planetary photons that actually reach the final focal plane (Transmission)**

Apodization

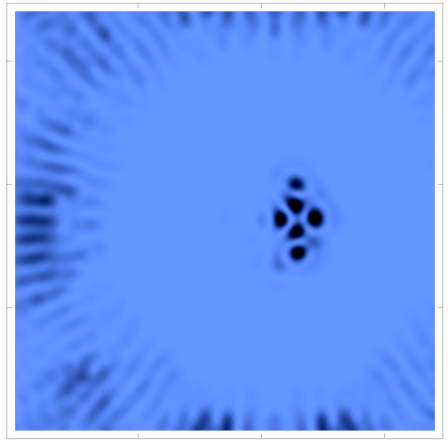




Lyot stop

  - **Deformation of the off-axis PSF (Airy throughput):**

Expected center of the PSF

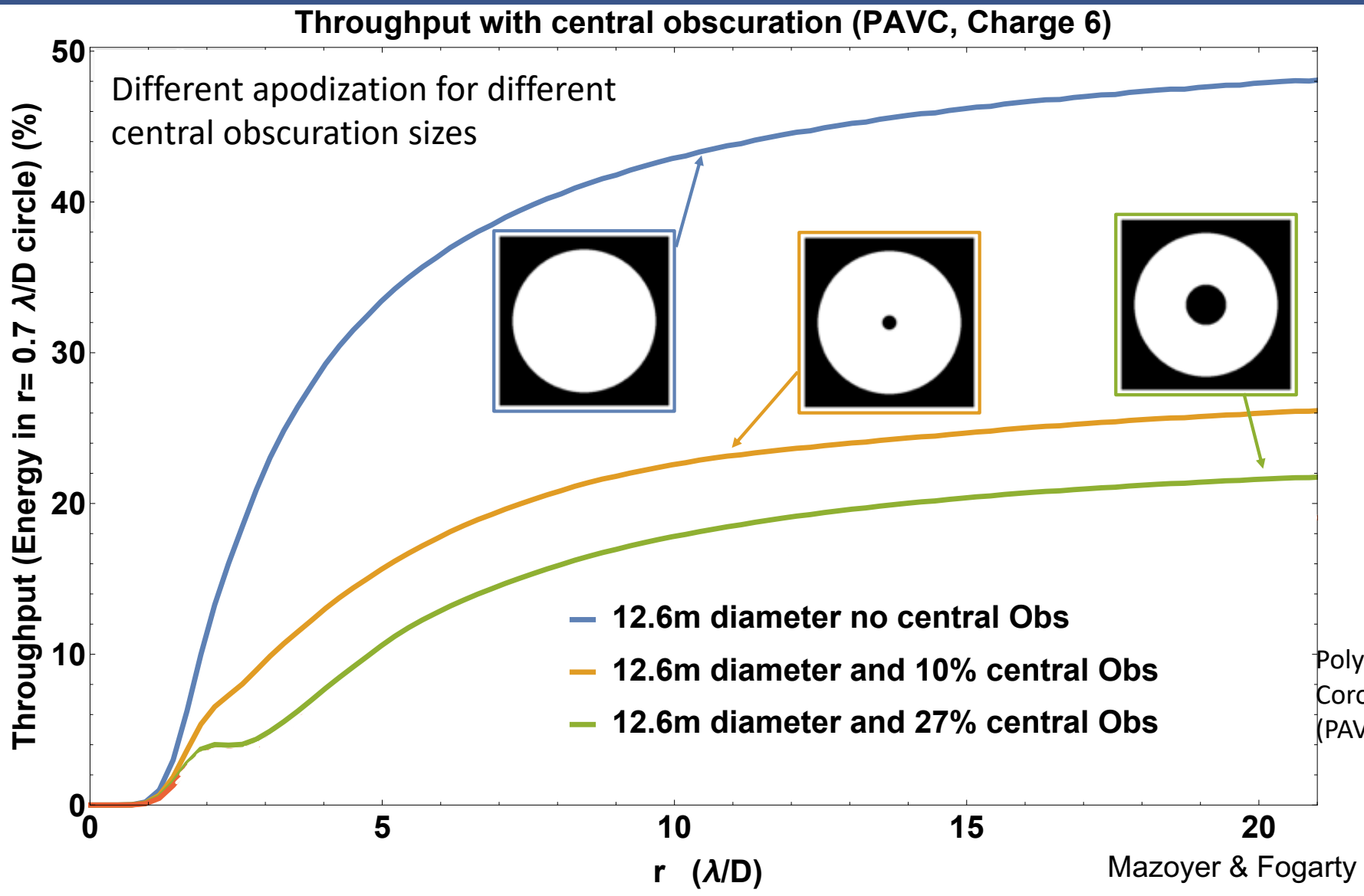


3 λ/D off-axis PSF

**Reflective methods:**

- Low impact on transmission
- High strokes on the mirrors => high impact on Airy throughput

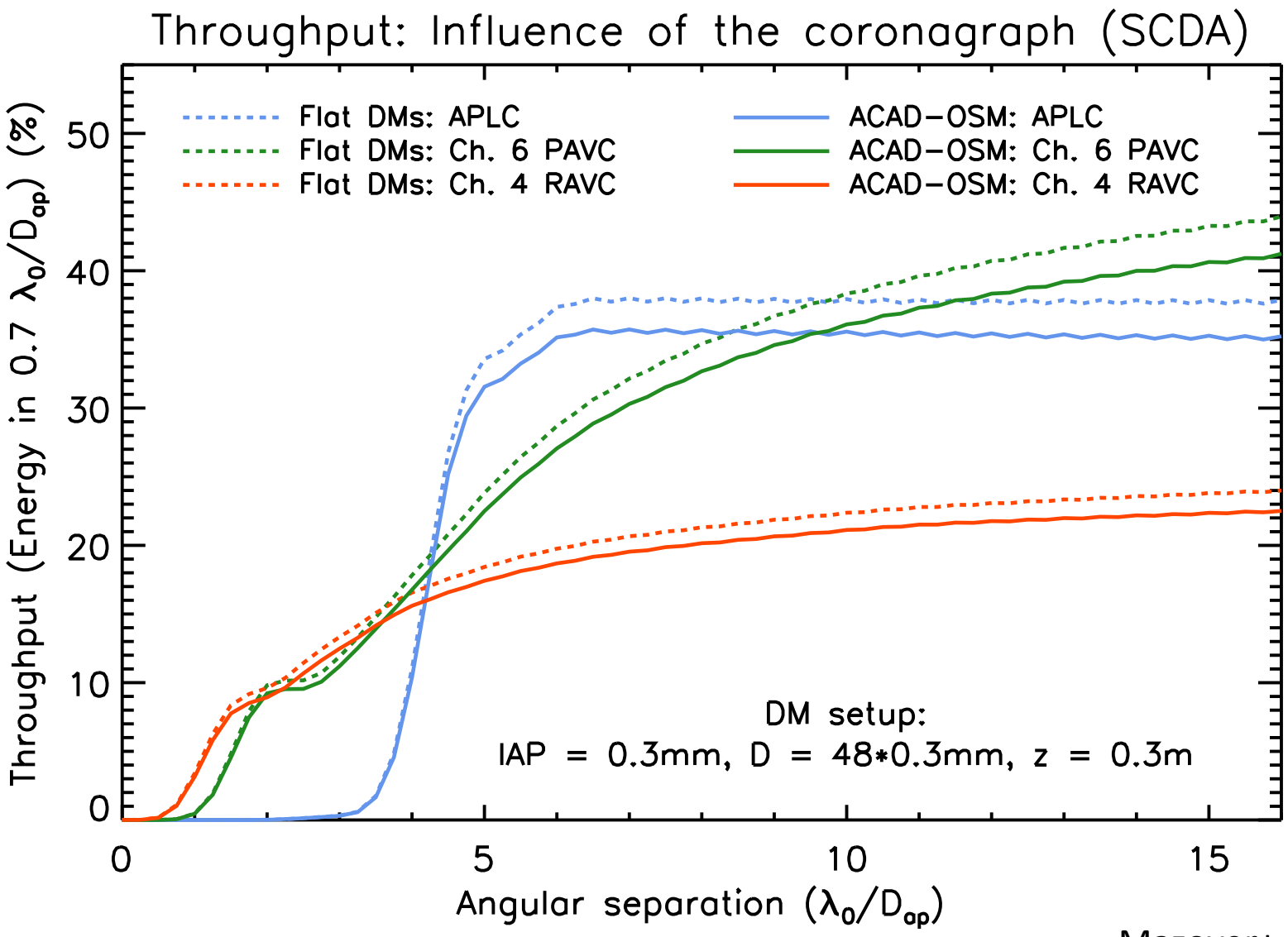
# The impact of central obstruction




Polynomial Apodizers Vortex Coronagraphs
(PAVC, Fogarty+ 2017)

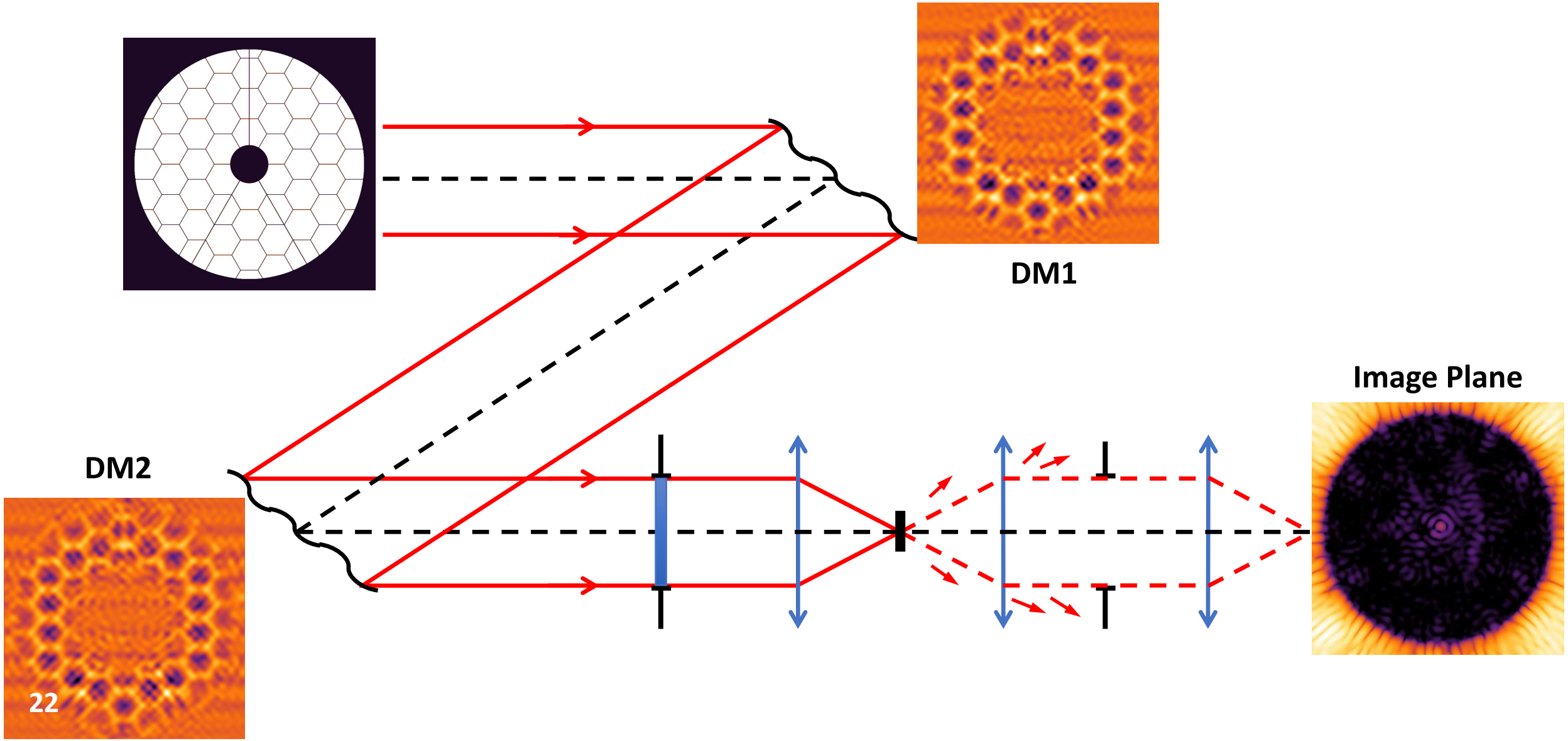
Mazoyer & Fogarty

# Different coronagraphs designs

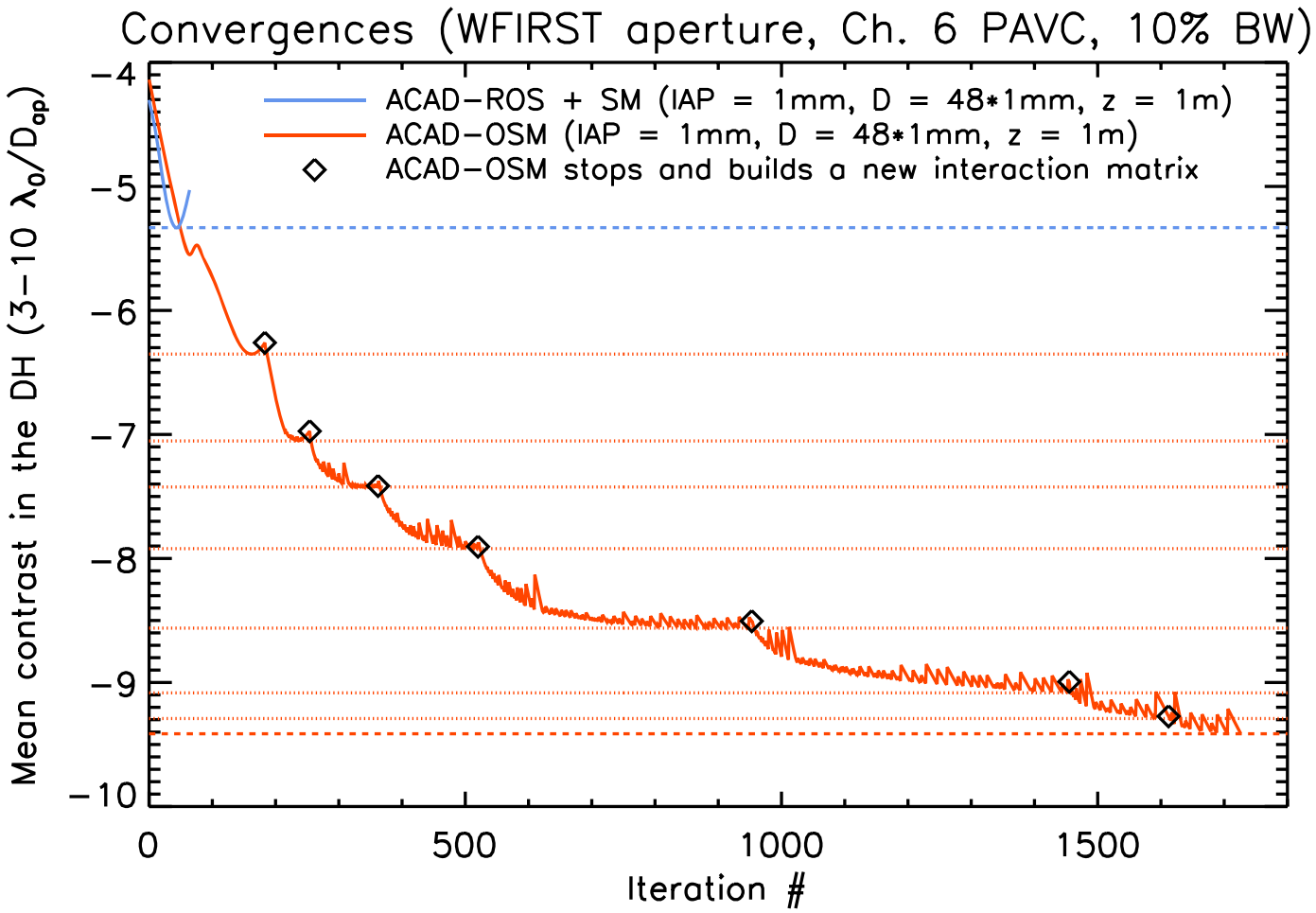


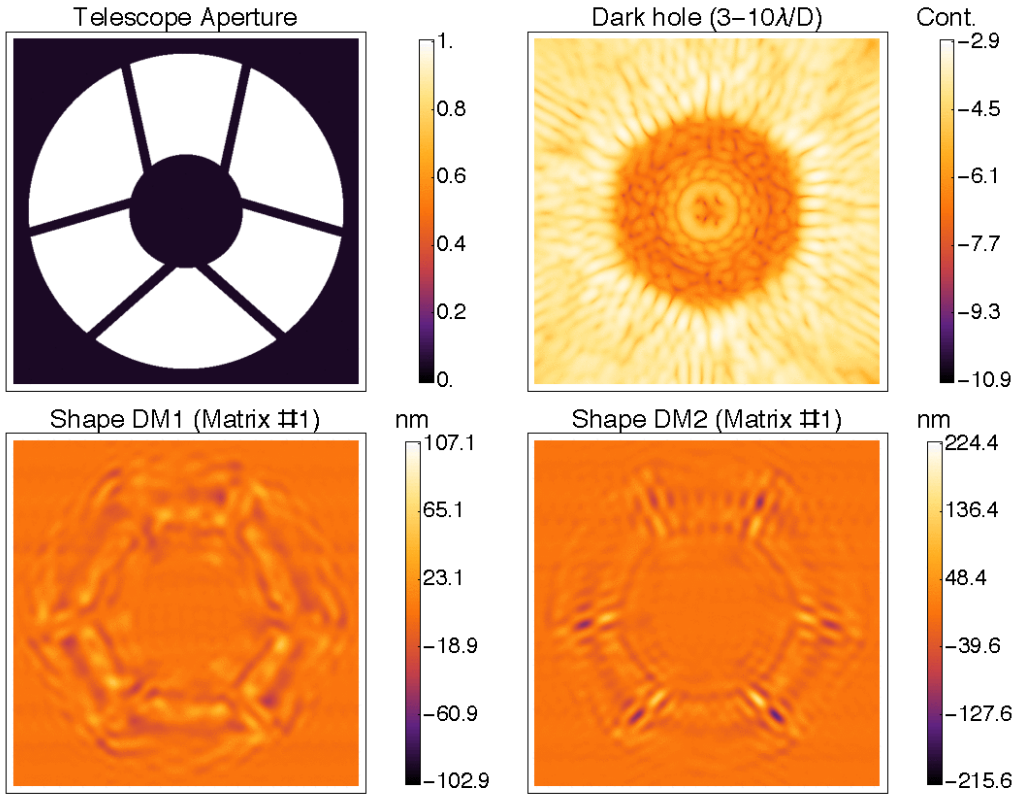

Mazoyer+ 2018

# Active Correction of Aperture Discontinuities



# Active Correction of Aperture Discontinuities - optimized stroke-minimization

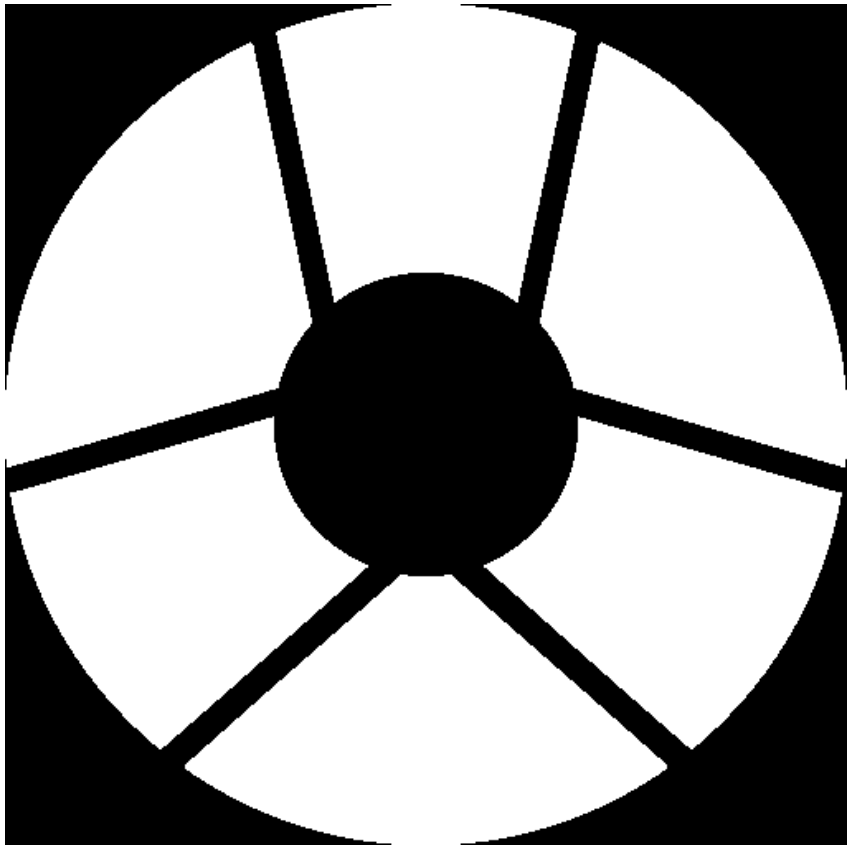


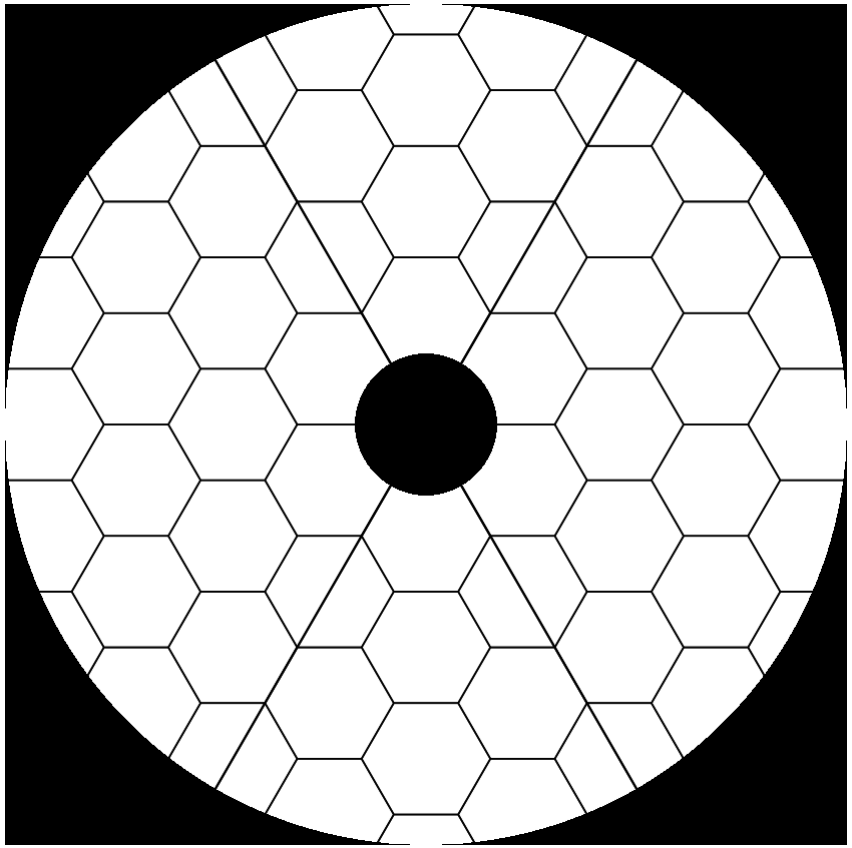

Mazoyer+ 2018

# What is the hardest ?

WFIRST pupil

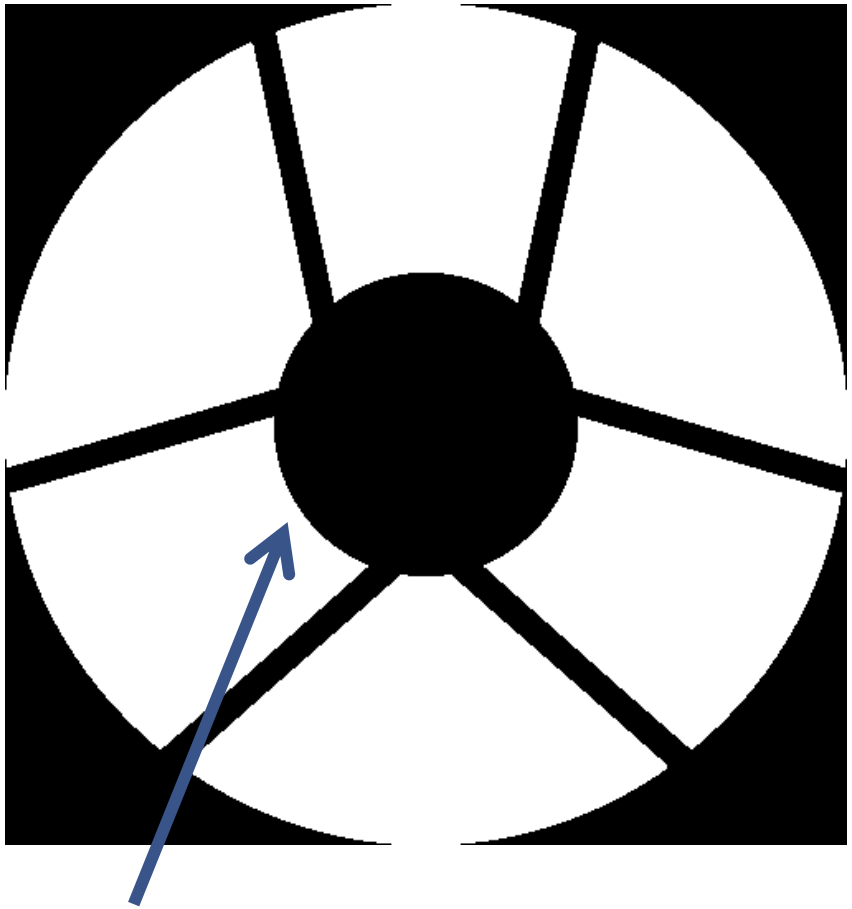


LUVOIR like Pupil



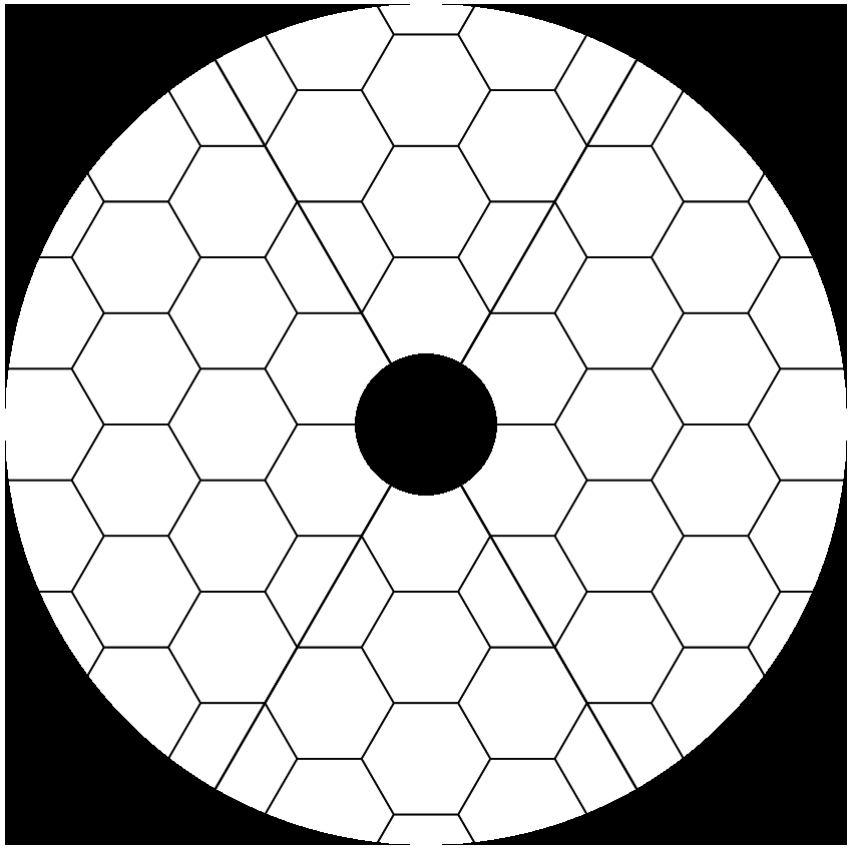
# What is the hardest ?

WFIRST pupil



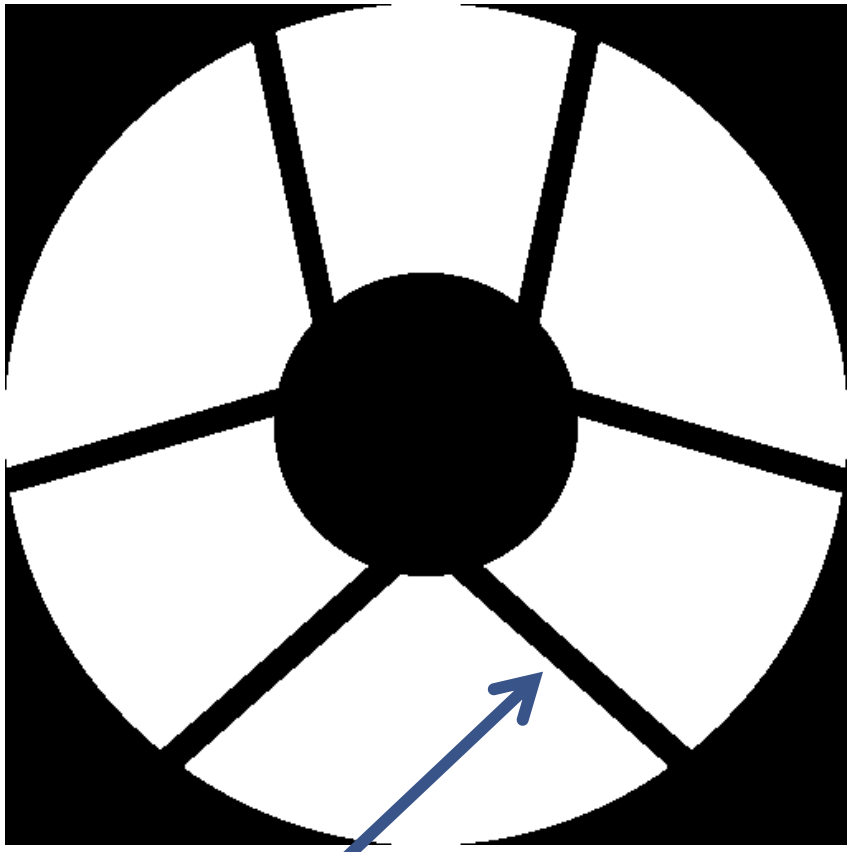
Huge central obstruction => strong impact on throughput

LUVOIR like Pupil

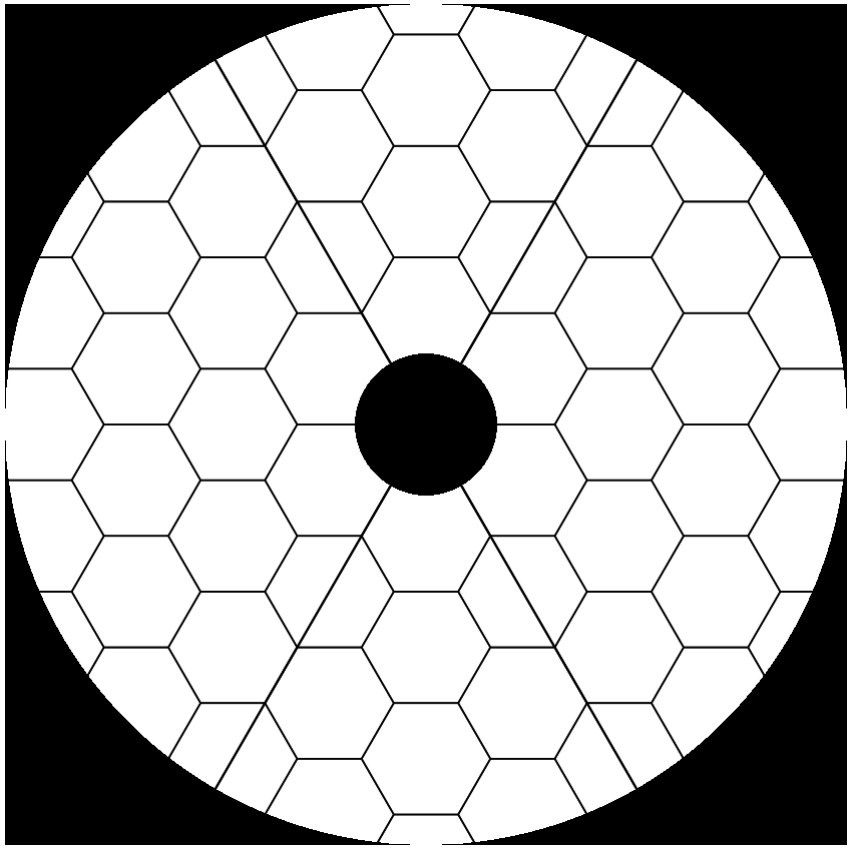


# What is the hardest ?

WFIRST pupil



LUVOIR like Pupil

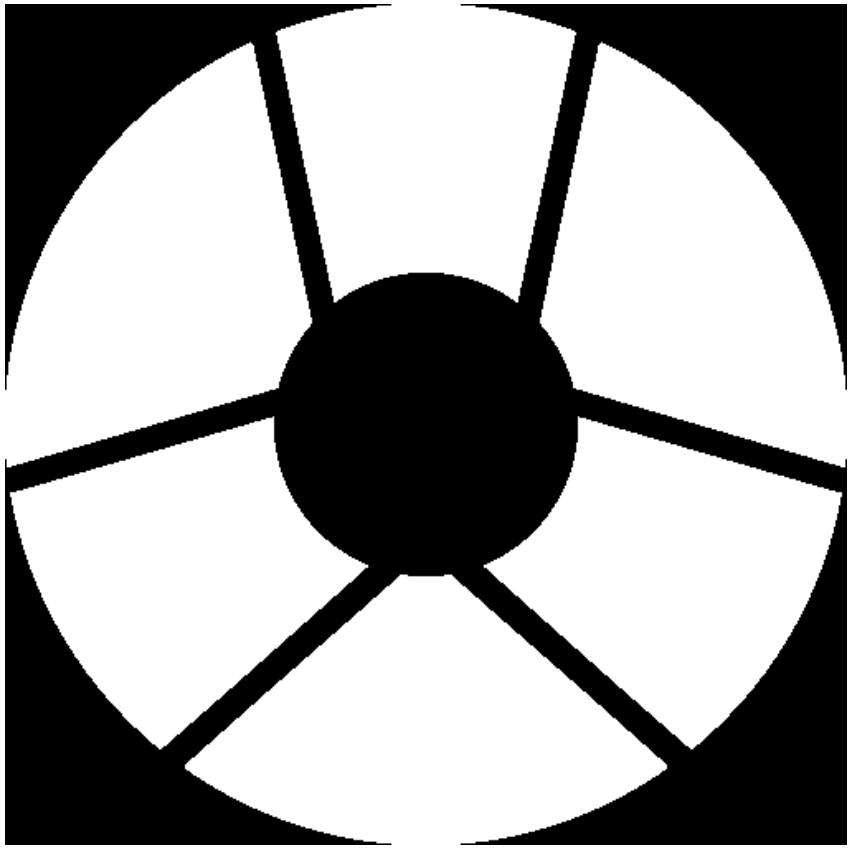


**Thick spiders:**

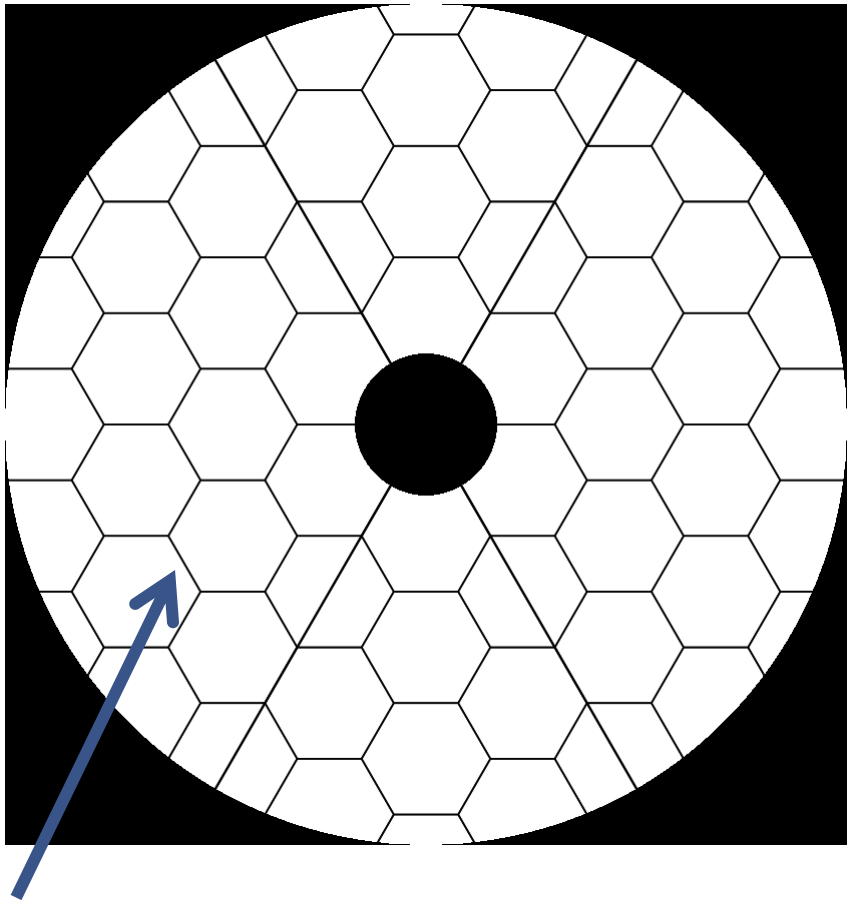
- limit the contrast achieved by active methods
- create high strokes => distort off-axis PSF => strong impact on the Airy throughput

# What is the hardest ?

WFIRST pupil



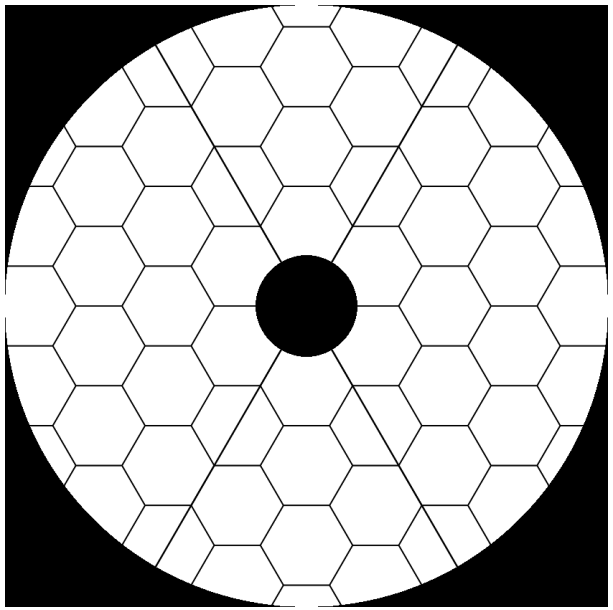
LUVOIR like Pupil

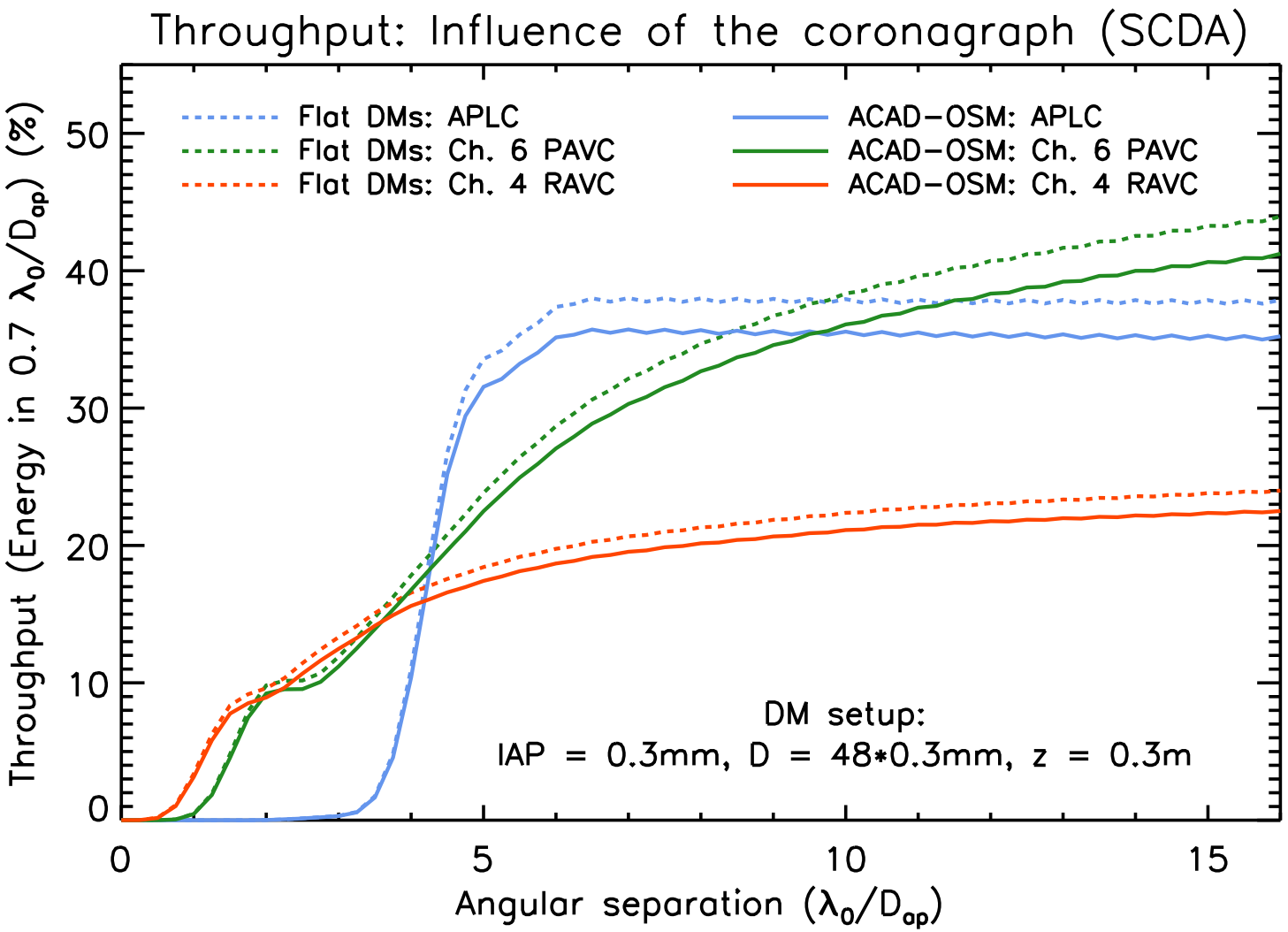


**Segmentation**:

- Not very different from spiders, and usually a lot finer

# Different coronagraphs designs

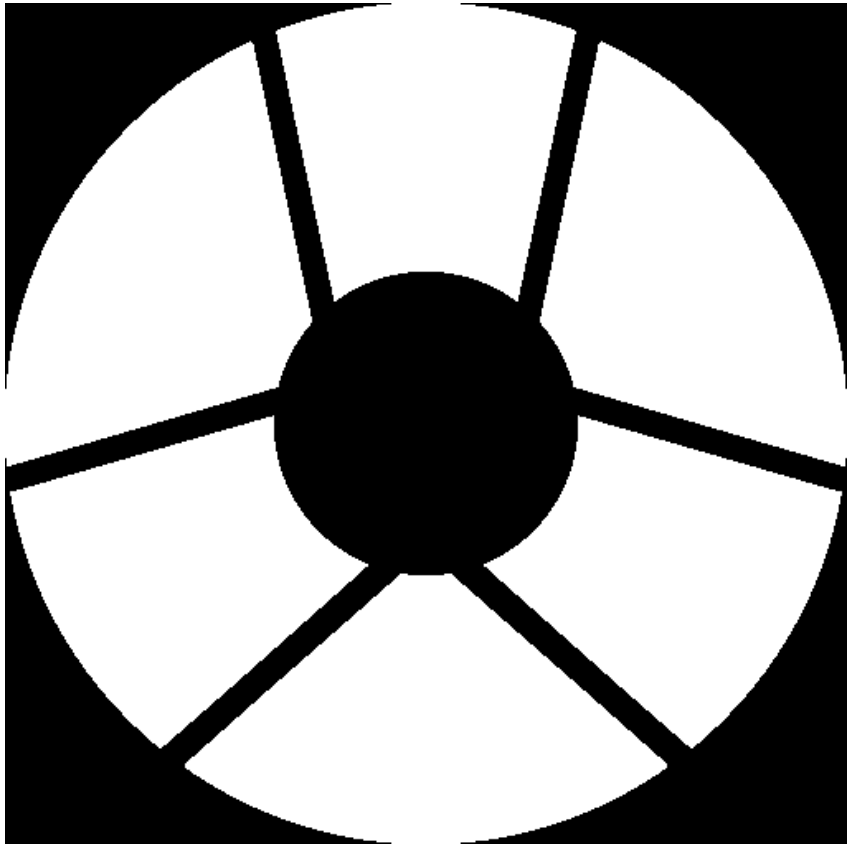





Mazoyer+ 2018

# A more difficult aperture

WFIRST pupil



# Parametric space

- **WFIRST aperture 10 % bandwidth around 550 nm**
- **Fixed number of actuators. Size of the pupil driven by the size of the inter-actuator distance**

| Inter-DM dist. (Z) / DM Size (D) | 0.3 m | 0.3 m | 1.0 m | 1.5 m |
|---|---|---|---|---|
| 0.1 mm x 48 act. | RAVC4 / SAVC6 /APLC | RAVC4 / SAVC6 /APLC | RAVC4 / SAVC6 /APLC | RAVC4 / SAVC6 /APLC |
| 0.3 mm x 48 act. | RAVC4 / SAVC6 /APLC | RAVC4 / SAVC6 /APLC | RAVC4 / SAVC6 /APLC | RAVC4 / SAVC6 /APLC |
| 0.7 mm x 48 act. | RAVC4 / SAVC6 /APLC | RAVC4 / SAVC6 /APLC | RAVC4 / SAVC6 /APLC | RAVC4 / SAVC6 /APLC |
| 1.0 mm x 48 act. | RAVC4 / SAVC6 /APLC | RAVC4 / SAVC6 /APLC | RAVC4 / SAVC6 /APLC | RAVC4 / SAVC6 /APLC |

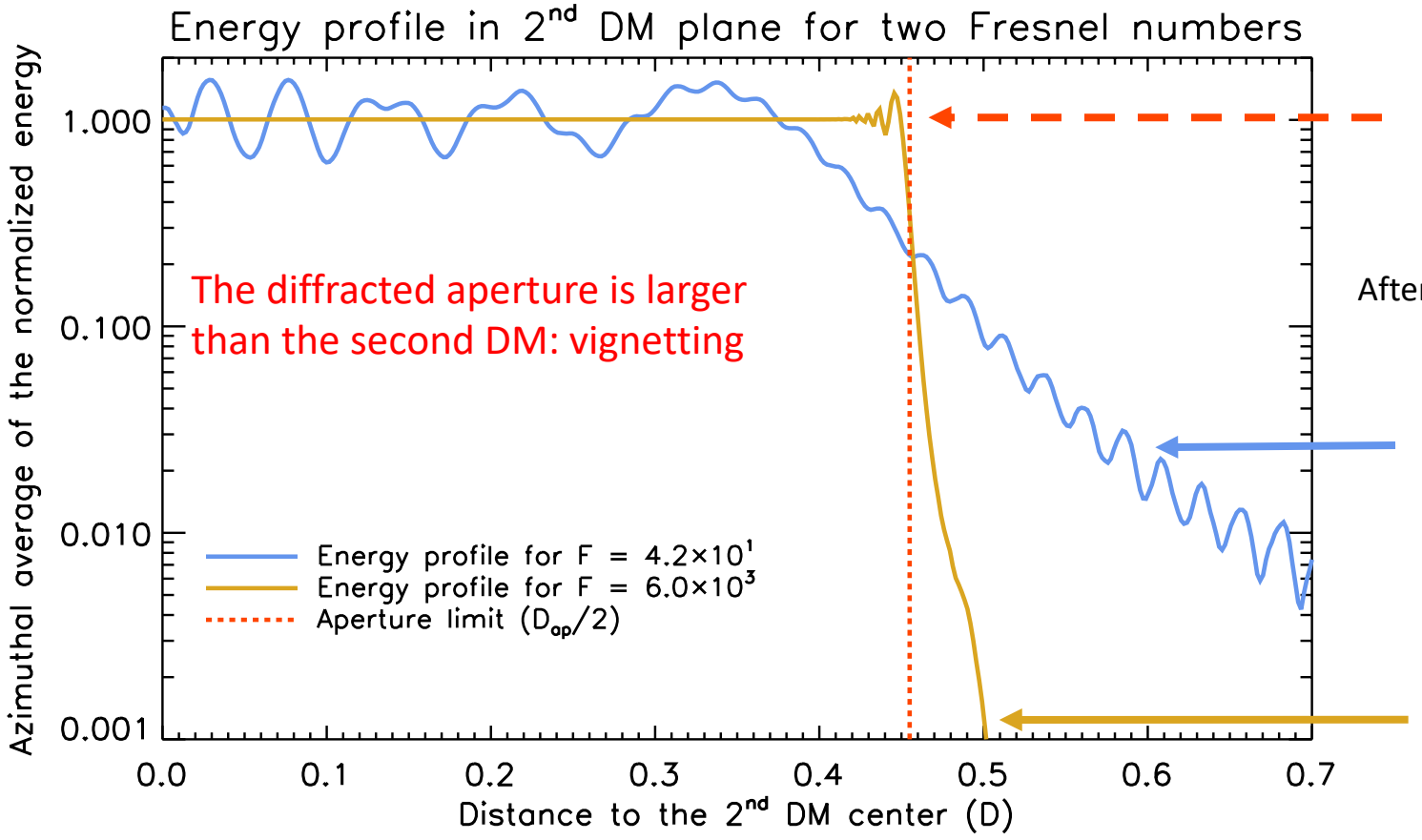
Boston Micromachines DMs (e.g. Gemini/GPI) → 0.3 mm x 48 act.

Xinetics DMs (e.g. WFIRST) → 1.0 mm x 48 act.

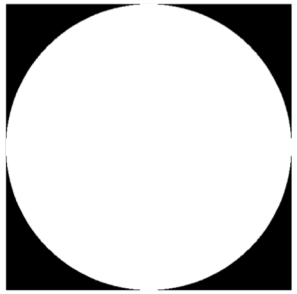
WFIRST mission set-up → 1.0 m / RAVC4 / SAVC6 /APLC

# Impact of the DM setup

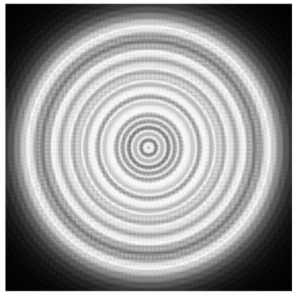
- **Two competing effects**
  - **Vignetting of the beam by the second DM:**

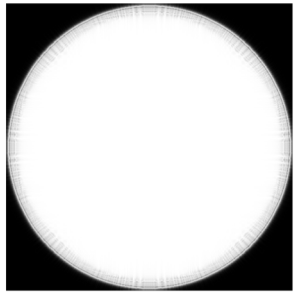



Initial aperture (1st DM)



After propagation (2nd DM)





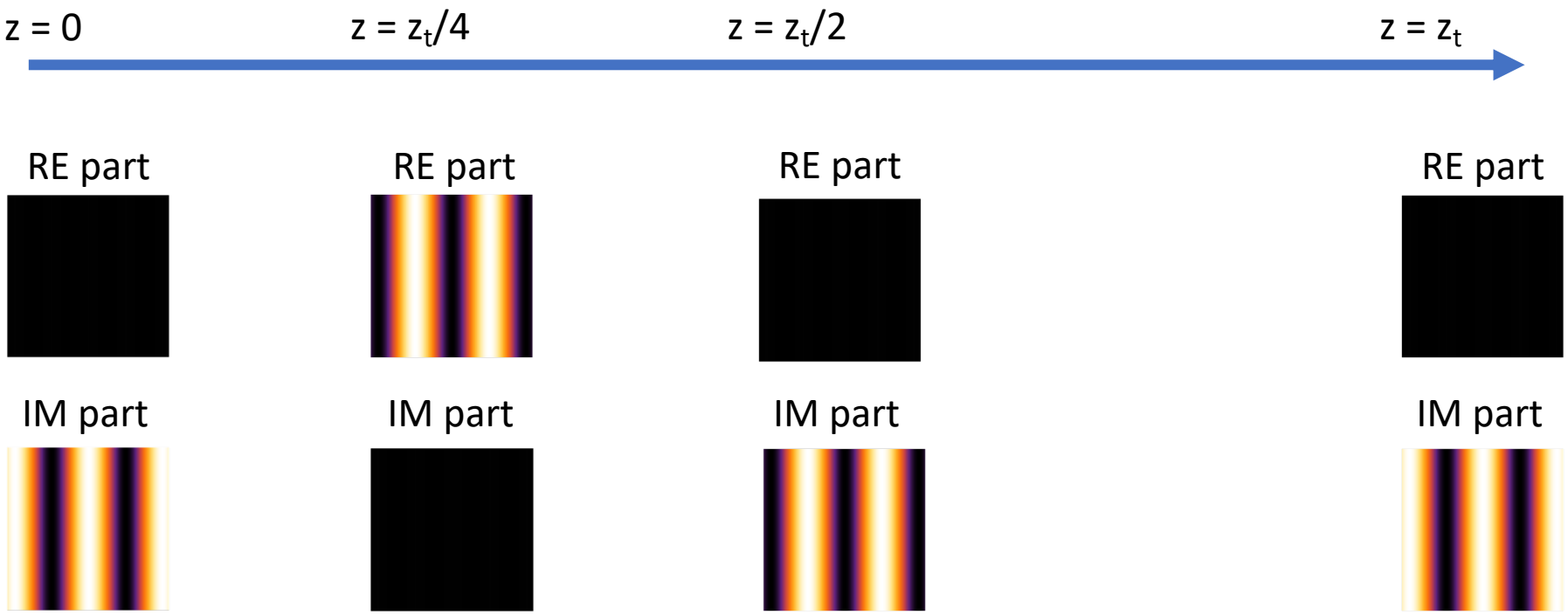
Favor large Fresnel numbers

# Impact of the DM setup

- **Two competing effects**
  - **Vignetting of the beam by the second DM:**
    - **Favor large Fresnel Number**
  - **Talbot effect:**
    - **Favor small Fresnel Number**

Talbot distance

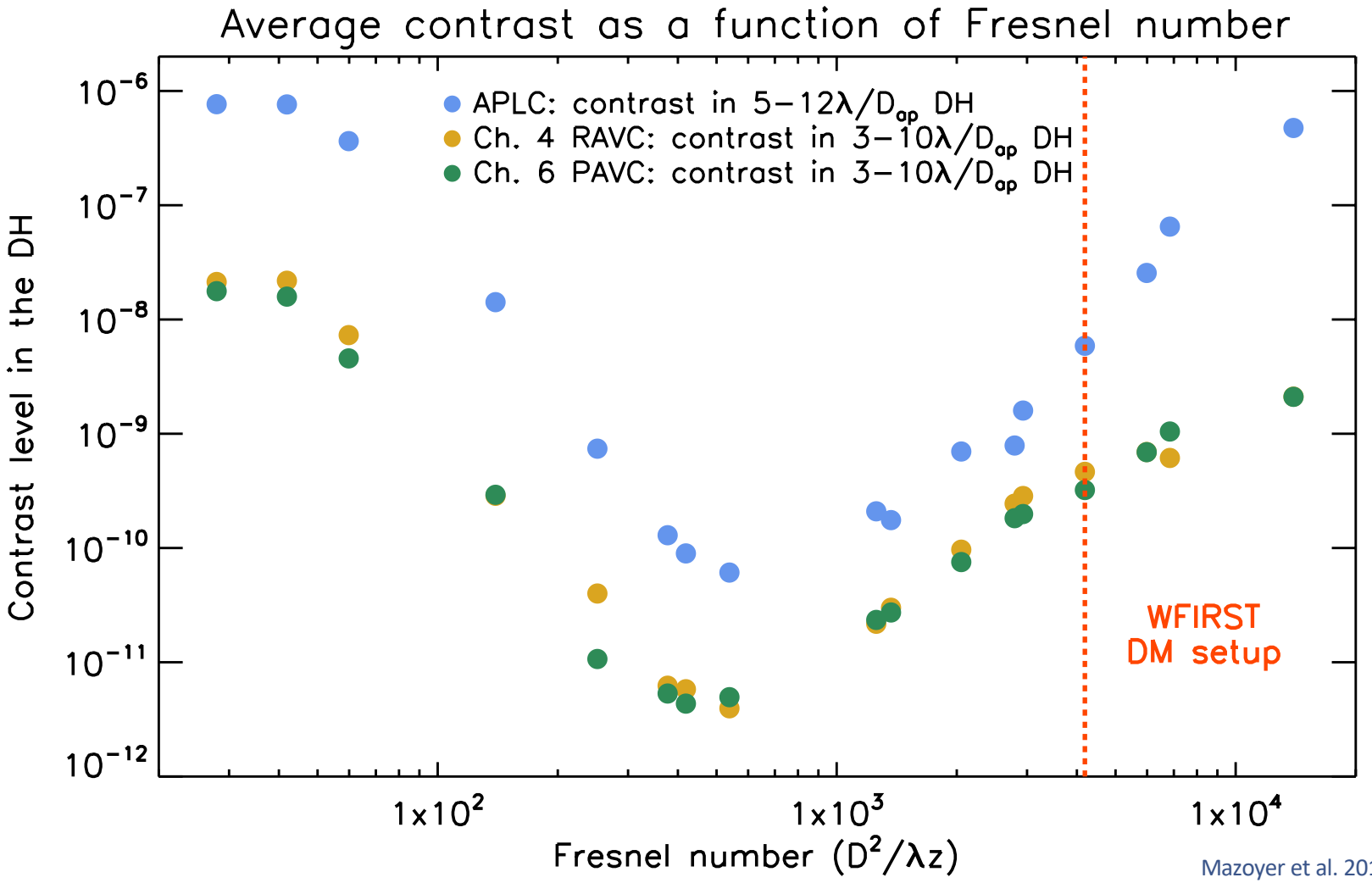
$z_t = 2D^2/(N^2\lambda)$



# Impact of the DM setup

- **The only relevant parameter is the Fresnel number:**

$$F = D^2/\lambda z$$

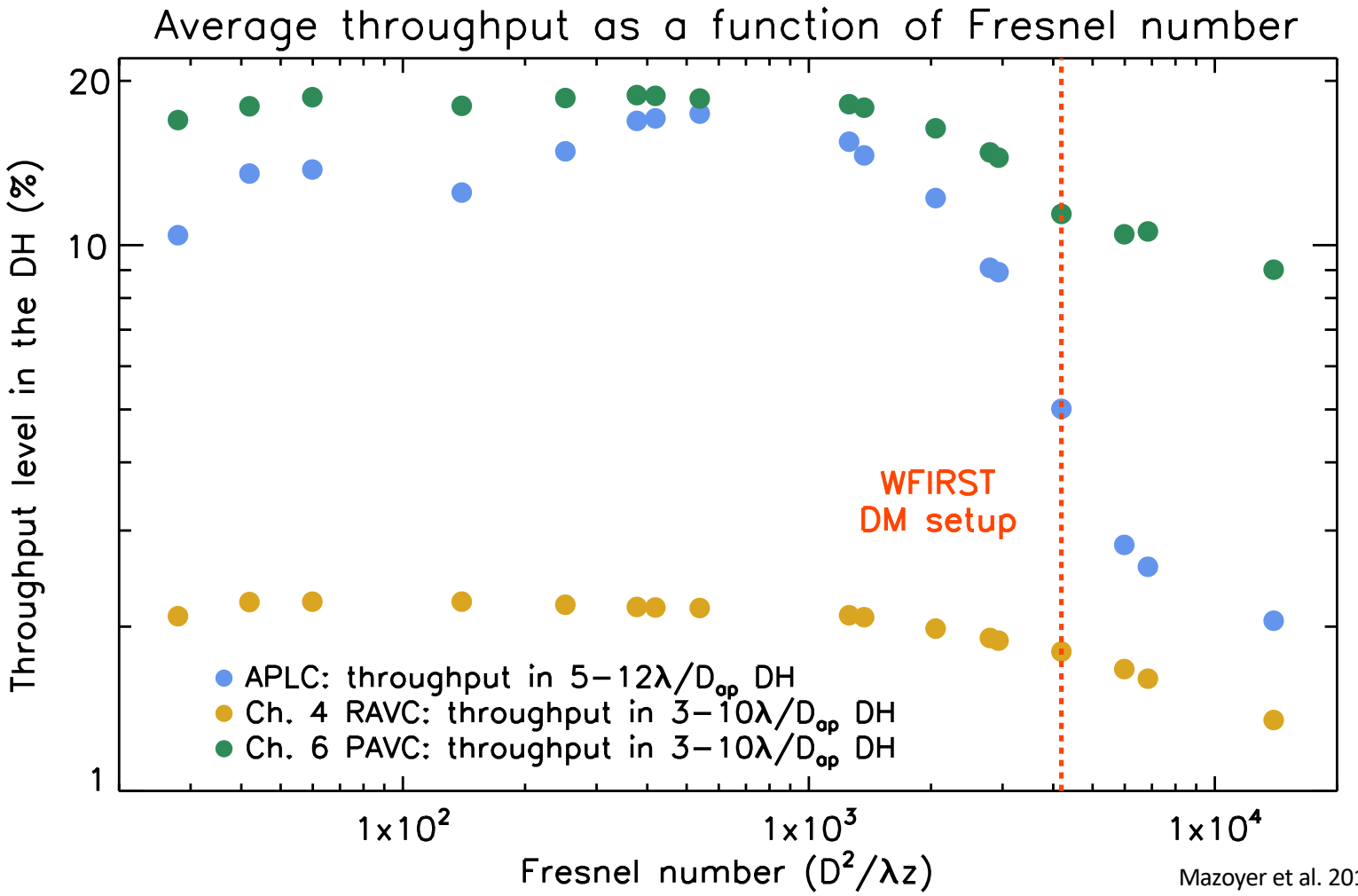



Mazoyer et al. 2018

# Impact of the DM setup

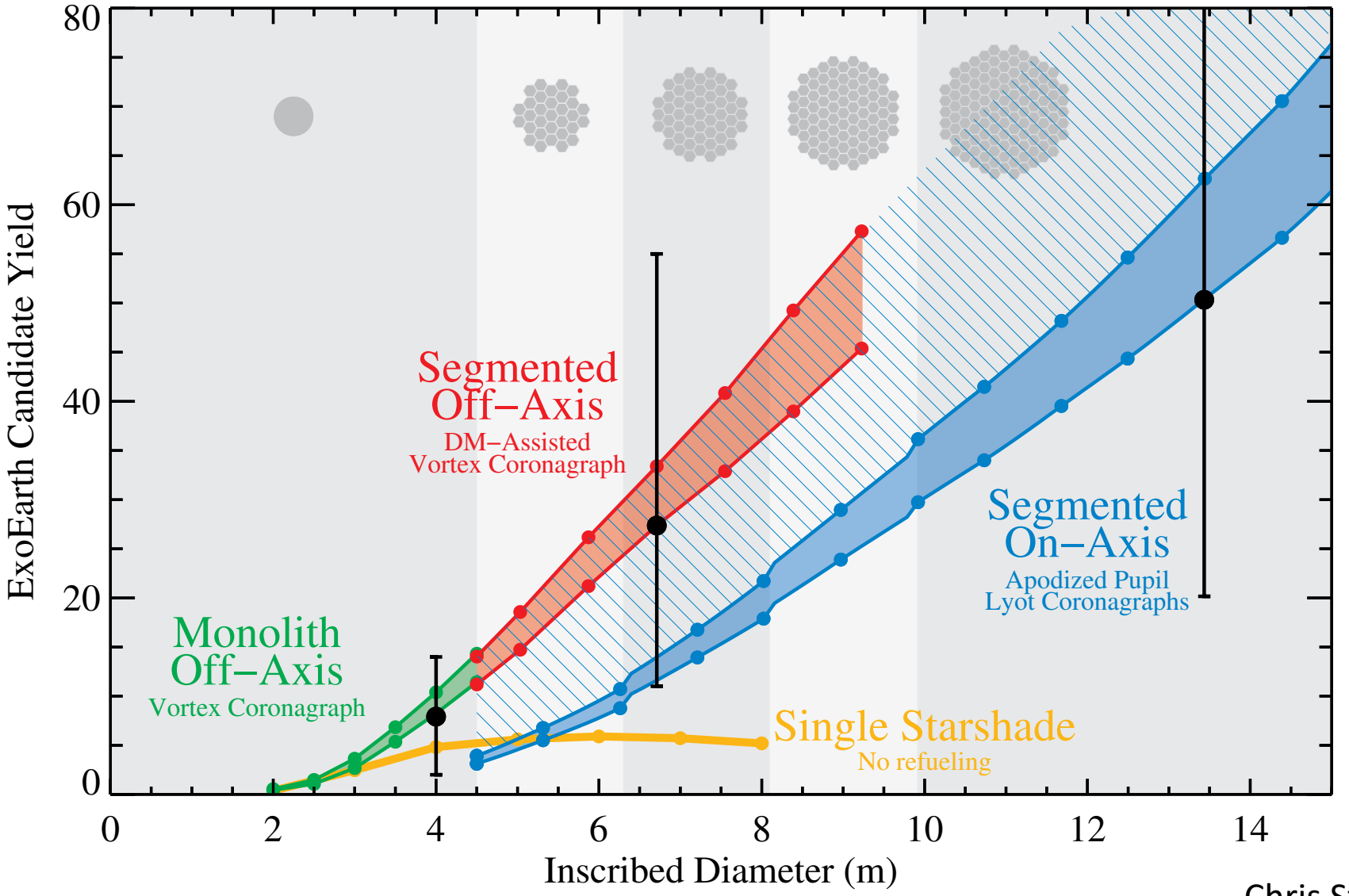
- **The only relevant parameter is the Fresnel number:**

$$F = D^2/\lambda z$$




Mazoyer et al. 2018

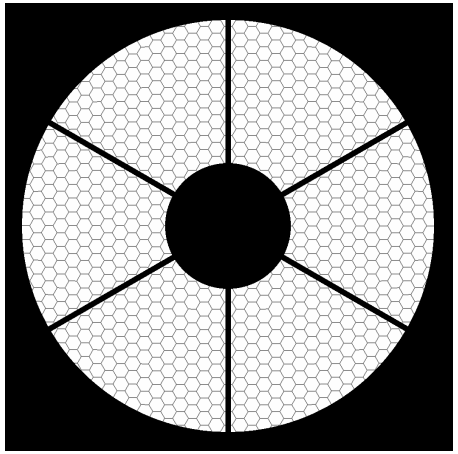
# HabEx or LUVOIR ?

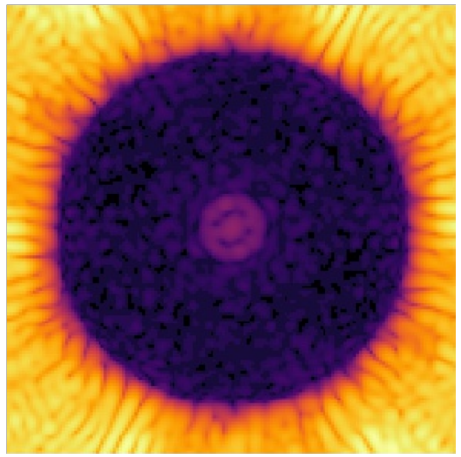



Chris Stark et al. (submitted)

# The need for active control

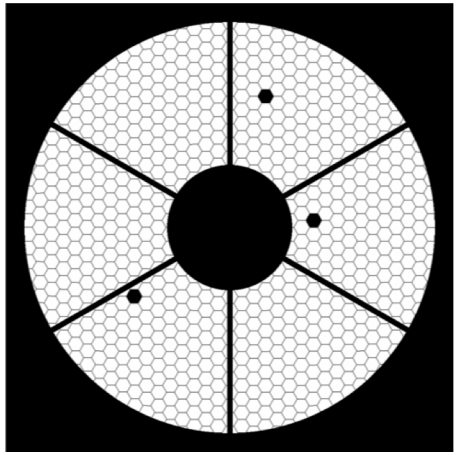
- **Can adapt to change in the pupil during its lifetime**

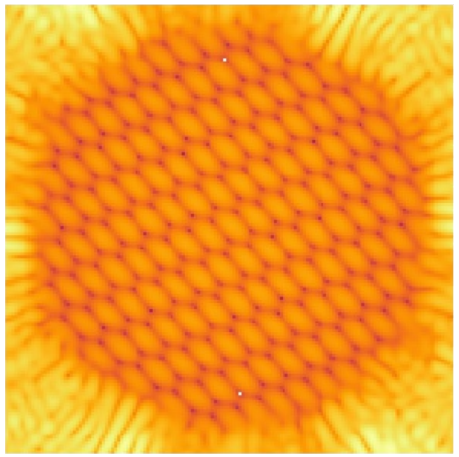




Segment Maintenance

**(daily)**

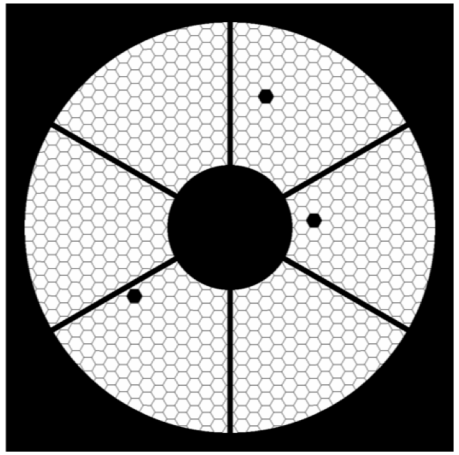


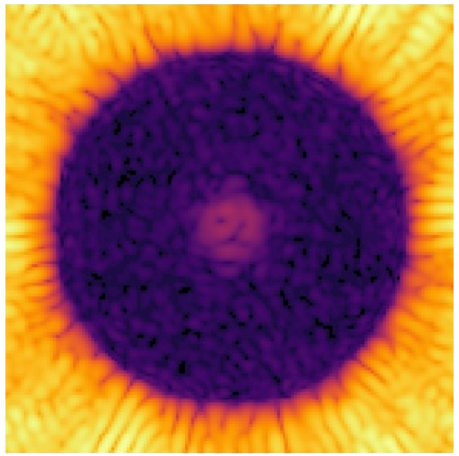


Active Correction

**ACAD-OSM**

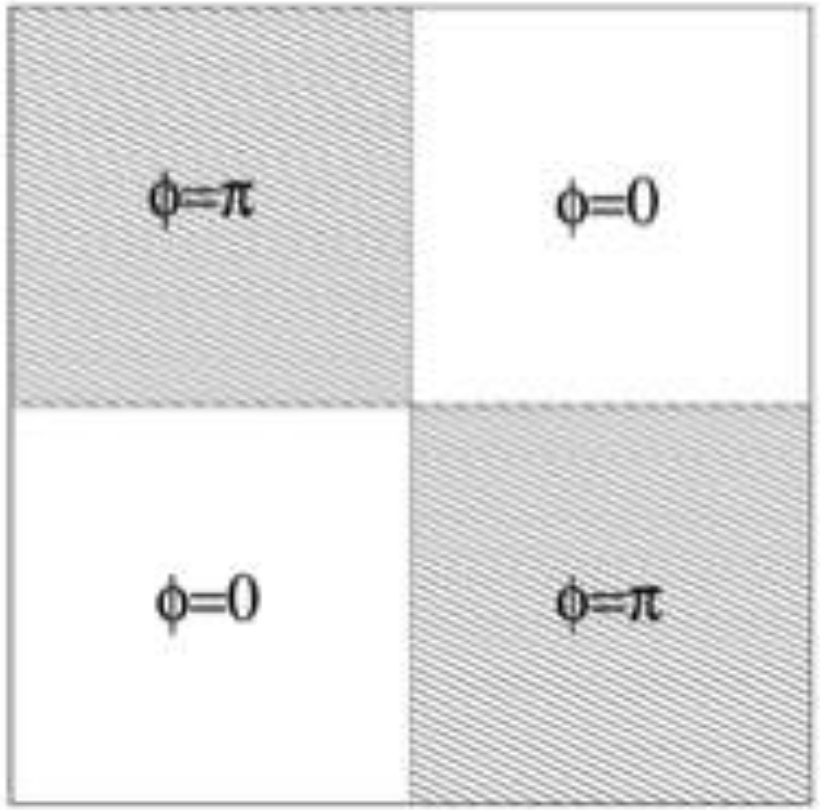
(minutes)





Mazoyer et al. 2018 AJ a and b

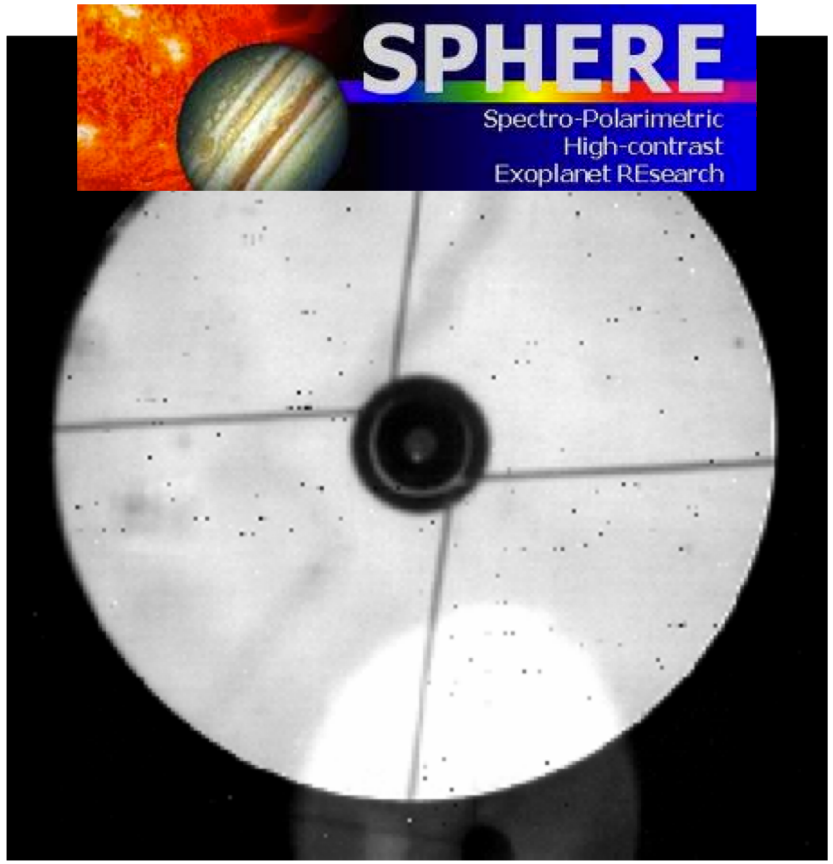
# The need for active control




**4 quadrant phase mask coronagraph (Rouan et al. 2000)**

**State of the art in 2006**

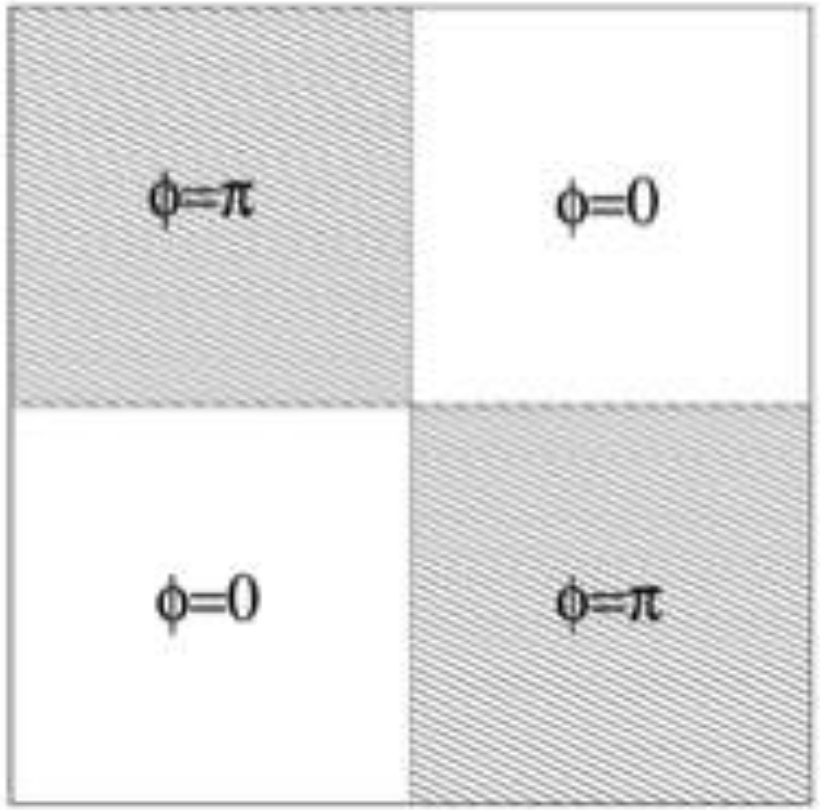
Selected for JWST/MIRI




**VLT aperture**

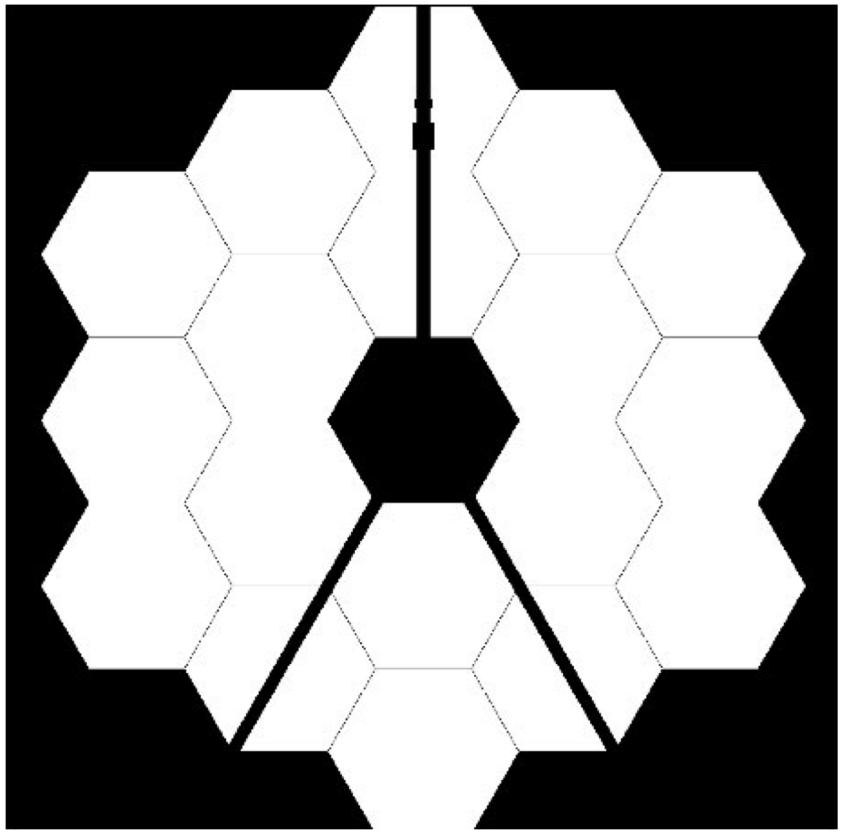
**SPHERE first light in 2014 (hardly used since the first light)**

# The need for active control




**4 quadrant phase mask coronagraph (Rouan et al. 2000)**

Selected for JWST/MIRI



**JWST aperture**

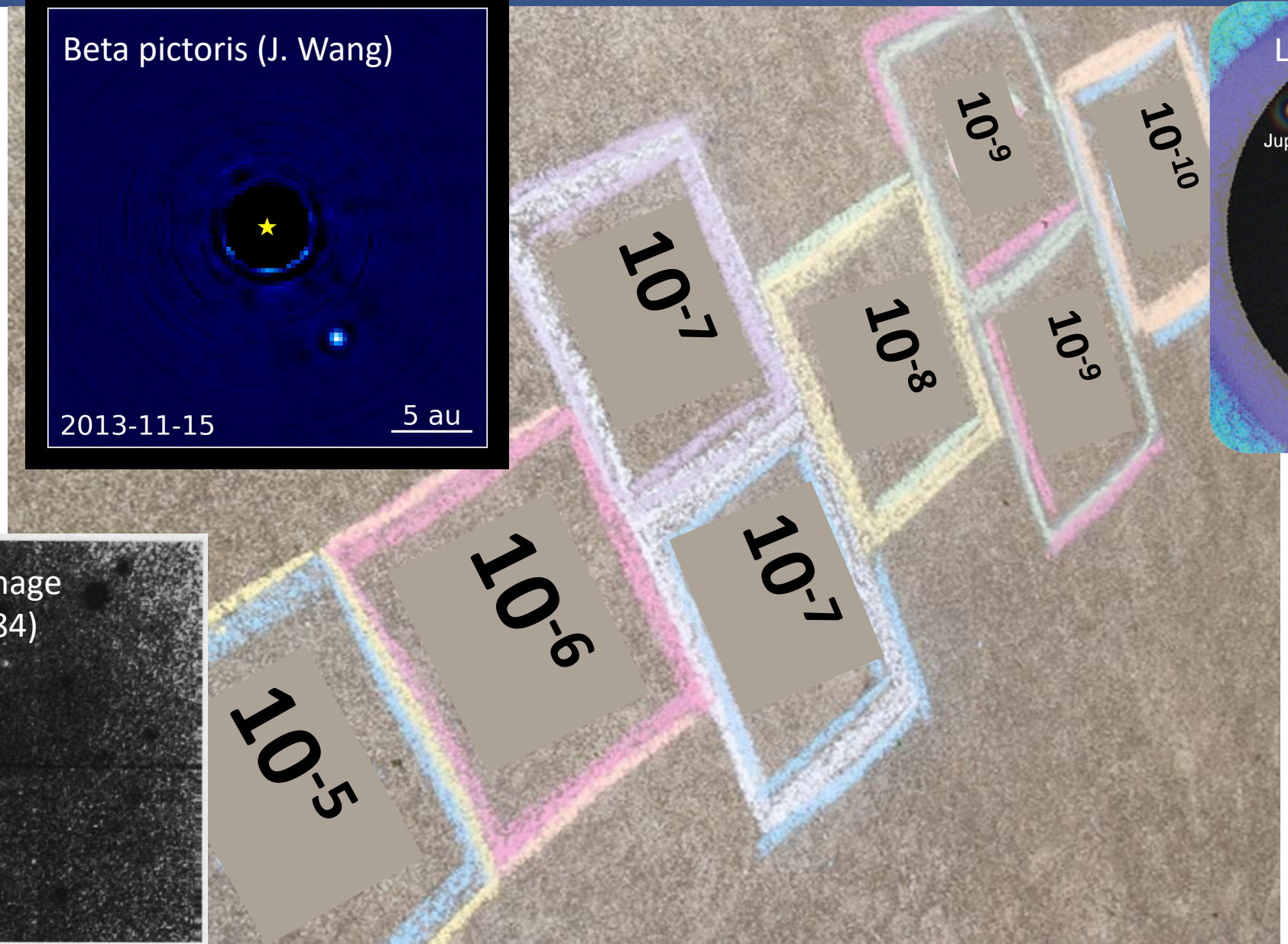
**State of the art in 2006**

**Launch in 2021**

# Thank you !


Beta pictoris (J. Wang)
2013-11-15
5 au

Beta Pictoris first image
(Smith & Terrile 1984)
25 arcsec
500 AU


10-5
10-6
10-7
10-7
10-8
10-9
10-9
10-10

LUVOIR-like simulation
N'diaye , Pueyo et al.
Jupiter
Earth
Venus
1 AU