The Evanescent Wave Coronagraph (EvWaCo)

Development status

Université de Nice Sophia Antipolis, Nice, 2nd February 2018

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The Evanescent Wave Coronagraph

1. **Introduction**
2. **The coronagraphic mask**
3. **The setup and results**
4. **Conclusions and next steps**

The Evanescent Wave Coronagraph

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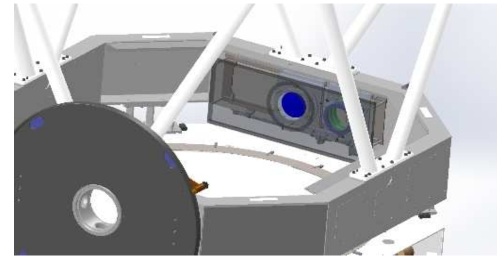
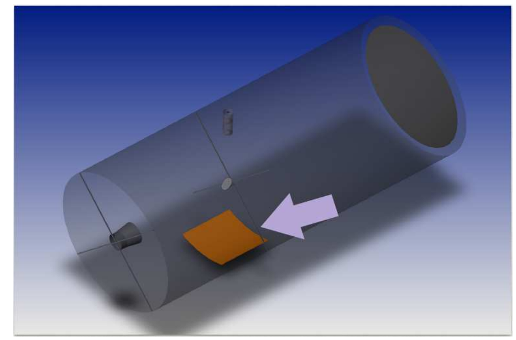
Optical technologies development at NARIT

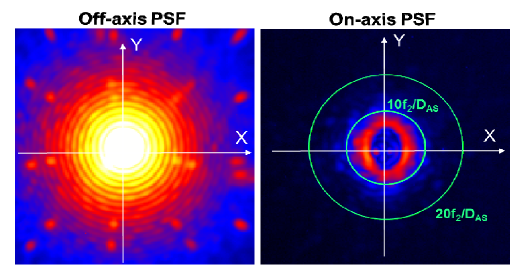
Spectroscopy



- Low Resolution Spectrograph Design and development
- High Resolution Spectrograph Design and development
- Fourier Transform Spectrograph: Development of FTS systems for astronomical and civil applications.

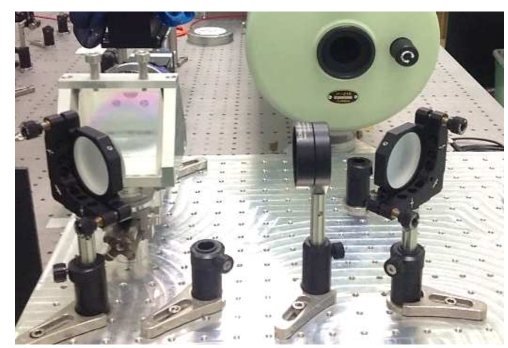


Telescope design



- Focal Reducer design and development
- TNT optical alignment and performance optimization
- Medium-size Telescope Design and development

Coronagraphy and Adaptive Optics

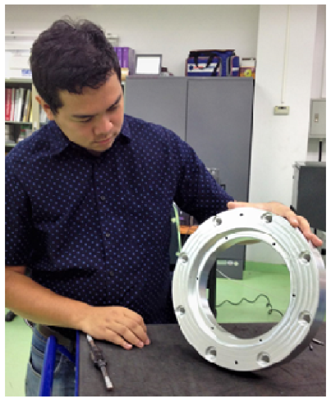


- The Evanescent Wave Coronagraph project
- Adaptive optics for the Thai National Telescope

Optical technologies development at NARIT

Team and facilities

Dr C. Buisset
Researcher
Team Leader



Mr A.Prasit
Expert in Mechanical
and System Engineering

Mr W. Wanajaroen
CMU Student
Telescope design

Ms A. Alagao
Research Assistant
Coronagraphy

Ms E. Lhospice
Research Assistant
High Res. Spectrograph

Ms P. Choochalerm
NARIT Scholarship
High Res. Spectrograh

Ms J. Paenoi
KMITL Student
Low Res. Spectrograh

Ms P. Artsang
SUT Student
FTS project

And…

Assoc. Prof T. Lepine
Researcher and Lecturer, Lab HC and IOGS
Support to Optical Laboratory Projects

Optical technologies development at NARIT

Optical Laboratory facilities:

- Optical and mechanical design software: ZEMAX Optics Studio and Solidworks
- Integration, Alignment and Test current facilities: Large reference mirror, wavefront sensor, alignment telescope, stable sources, etc…

High precision mechanical workshop:

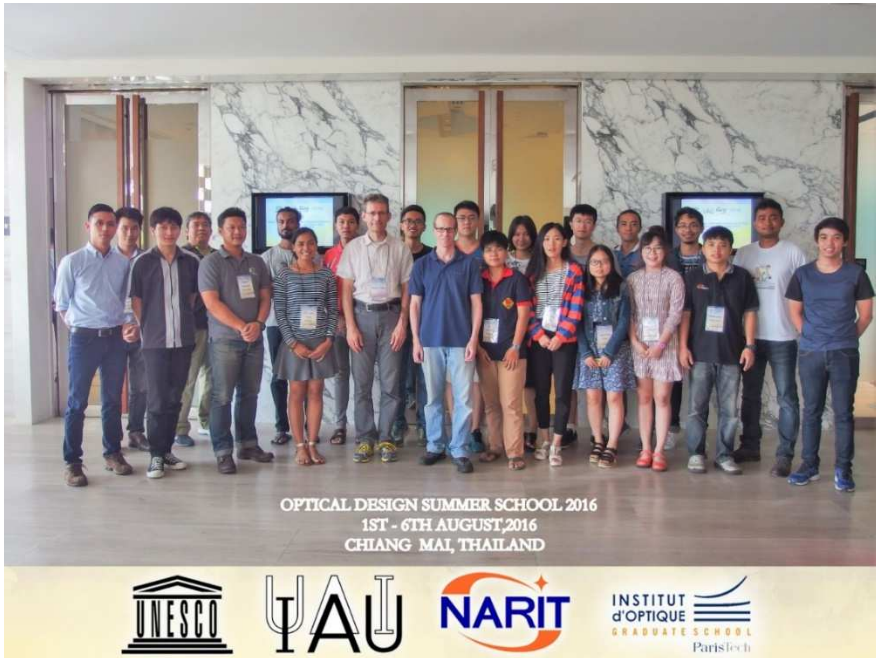
- Coating vacuum chamber for large optics up to D ≈ 2 m.
- 1 CNC machine: 4 axis, precision better than 30 µm, max dim = 40 cm x 80 cm
- 1 Coordinate Measuring Machine, precision better than 3 µm

Optical technologies development at NARIT

- **Thai National observatory (TNO):**
  - ✓ NARIT main observing facility, located near Doi Inthanon summit (Chiang Mai, Thailand), altitude 2,457 m, latitude 18.57 N, longitude 98.48 E
  - ✓ Median seeing condition: $\alpha_{S,Median} \approx 0.9''$. Seeing max $\alpha_{S,Max} < 2''$
  - ✓ Principle instrument: Thai National Telescope (TNT), 2.3 m Ritchey-Chretien Telescope mounted on 1 alta-azimuthal mount

The Optical Design Summer School

- **2 international workshops organized in August 2016 and 2017 dedicated to optical design of imaging instruments by using ZEMAX software. Duration: 6 days.**
- **Invited Lecturer:** Assoc. Prof. Thierry Lépine (IOGS, France).
- 25 students/year from Thailand, China, India, Philippines, Sri Lanka, Malaysia, Russia and Indonesia → Successful and unique event, very good feedbacks from the attendees.
- **Next workshop:** "ODSS 2018" in August 2018 (To Be Announced on NARIT website).

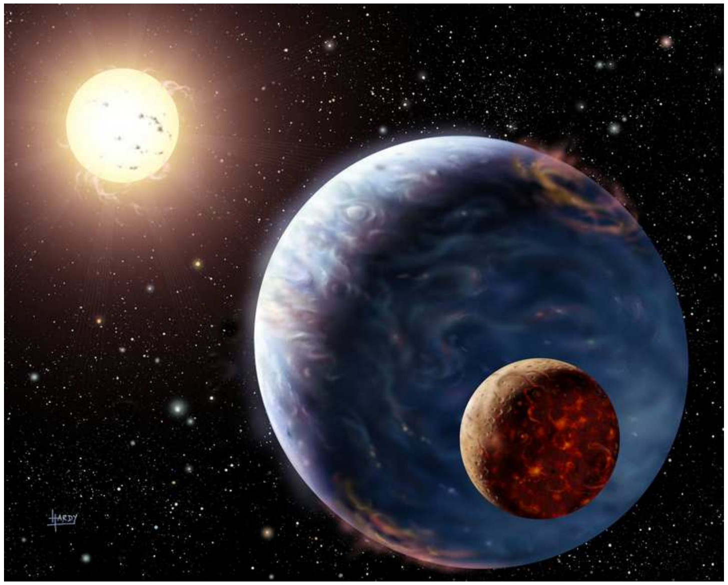


The Evanescent Wave Coronagraph

Coronagraph main science case: analyze of star close environment

- **Characterize planets and their host system:** orbital motion, spectroscopy of planetary atmospheres or planet disk interactions
- **Stellar systems inner regions probing:** to understand formation & evolution of rocky planets within the primordial and debris disk.

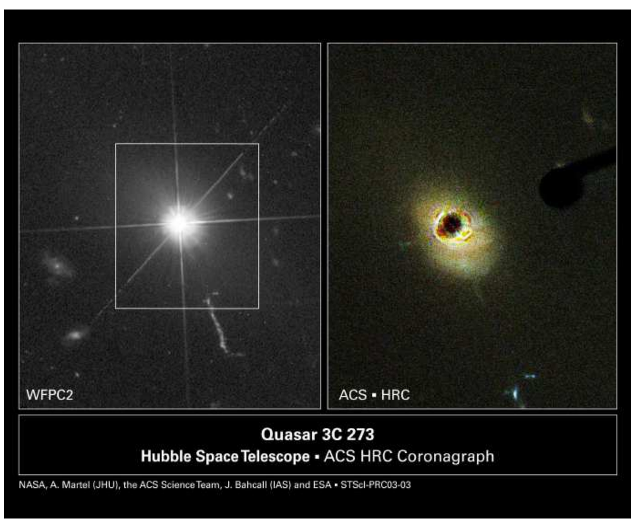
→ Ultimate Goal: **Direct detection and characterization of earth-like exoplanets with Extremely Large and Space Telescopes**

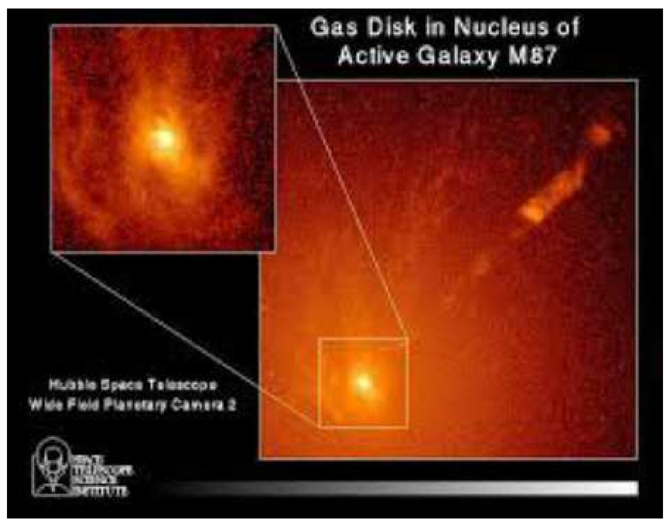


The Evanescent Wave Coronagraph

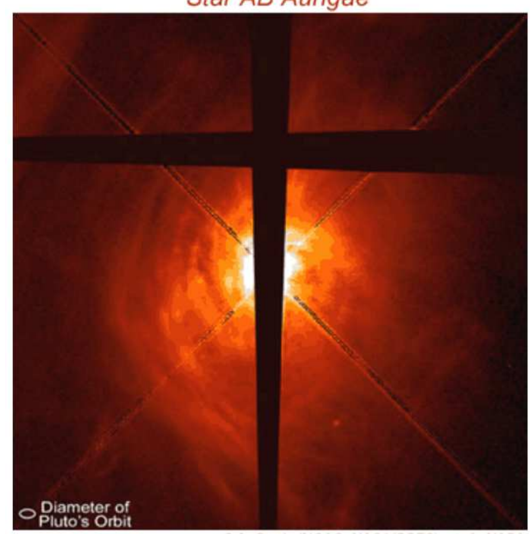
Other science cases: Cosmic Origins Science[1]

- **Quasars & AGN:** Host galaxies, Central black holes, Accretion disks, Bulges, spiral arms, Mergers,…
- **Young stars:** Accretion disks, Outflows, jets, Protoplanetary disks
- **Evolved stars:** Debris disks, Ejecta, symmetries, LBVs η Carinae, WR star





Star AB Aurigae



C.A. Grady (NOAO, NASA/GSFC), et al., NASA

D. Ebbets, K. Sembach, S. Neff, Cosmic Origins Science Enabled by the Coronagraph Instrument on NASA's WFIRST/AFTA Mission, 2014

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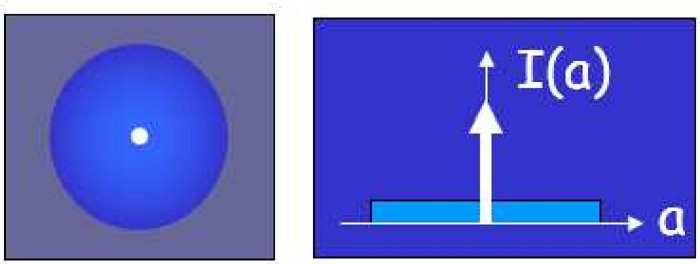
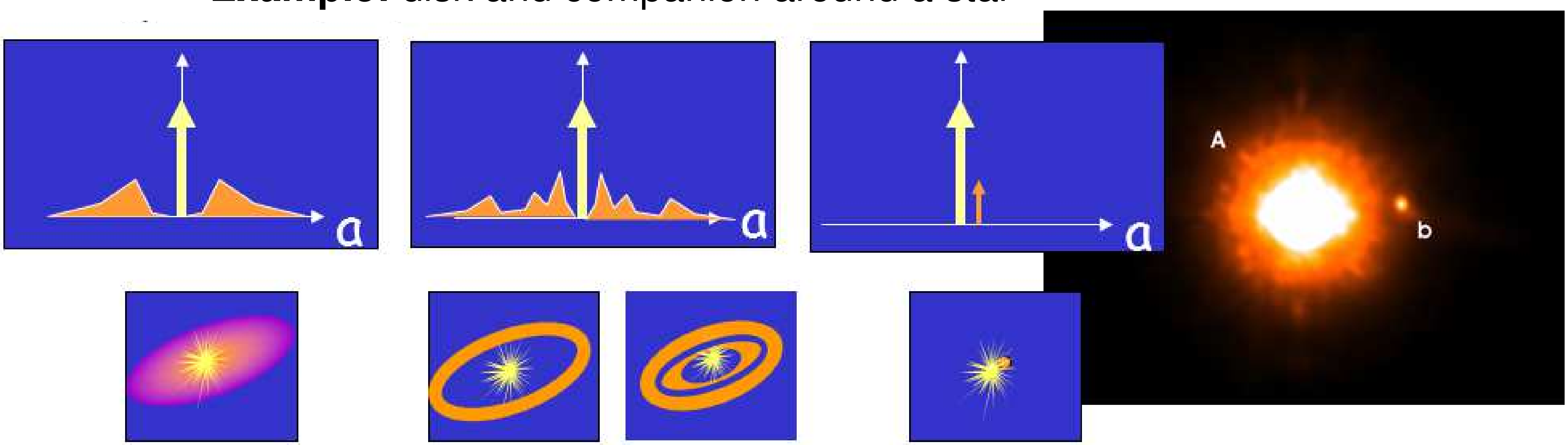
Specific Constraints linked to exoplanet direct detection

- Standard science need (adapted from Rabbia, ITHD 2003 & IOGS 2007)



Central object: point-size, unresolved object located on the Line-of-sight

- **Example:** disk and companion around a star



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Specific Constraints linked to exoplanet direct detection

- **Photometric dynamic:**

  Management of the huge ratio between the star and the companion flux

- **Angular resolution :**

  Capability to separate 2 very close sources

- **Photometric sensitivity:**

  Capability to detect the faint flux emitted by the companion

The Evanescent Wave Coronagraph

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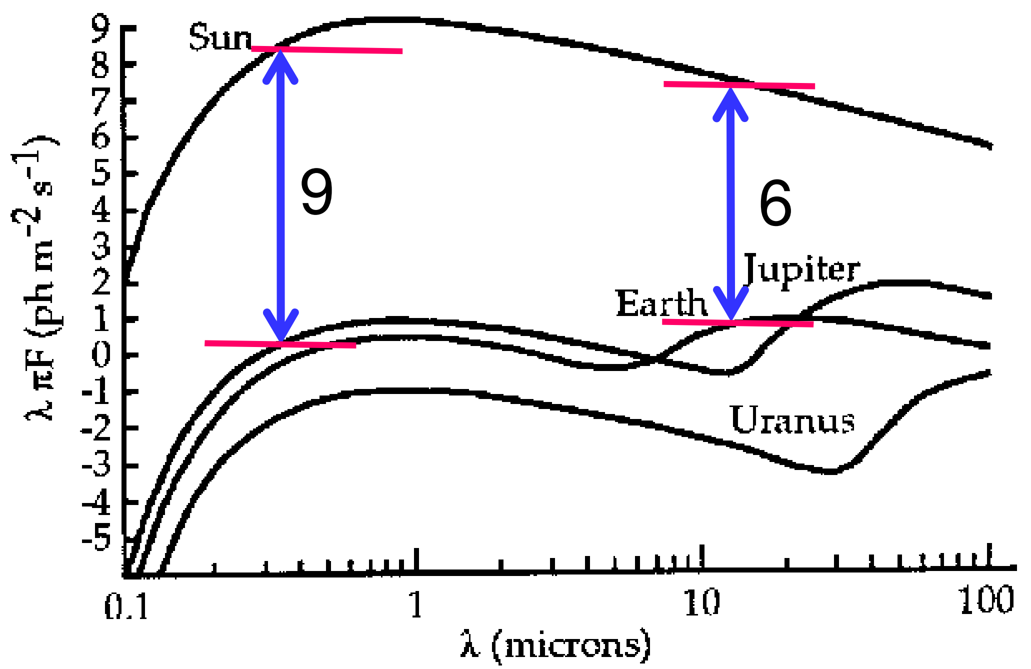
The Evanescent Wave Coronagraph

Specific Constraints linked to exoplanet direct detection

- **Photometric dynamic:**
  - ✓ **Key parameter:** R_{Flux} = Star Flux / Companion Flux
  - ✓ **“Hot Jupiters”: $R_{Flux} \approx 10^4 – 10^5$**
  - ✓ **Earth-like exoplanets:** $R_{Flux} \approx 10^9$ in visible and 10^6 in Thermal IR



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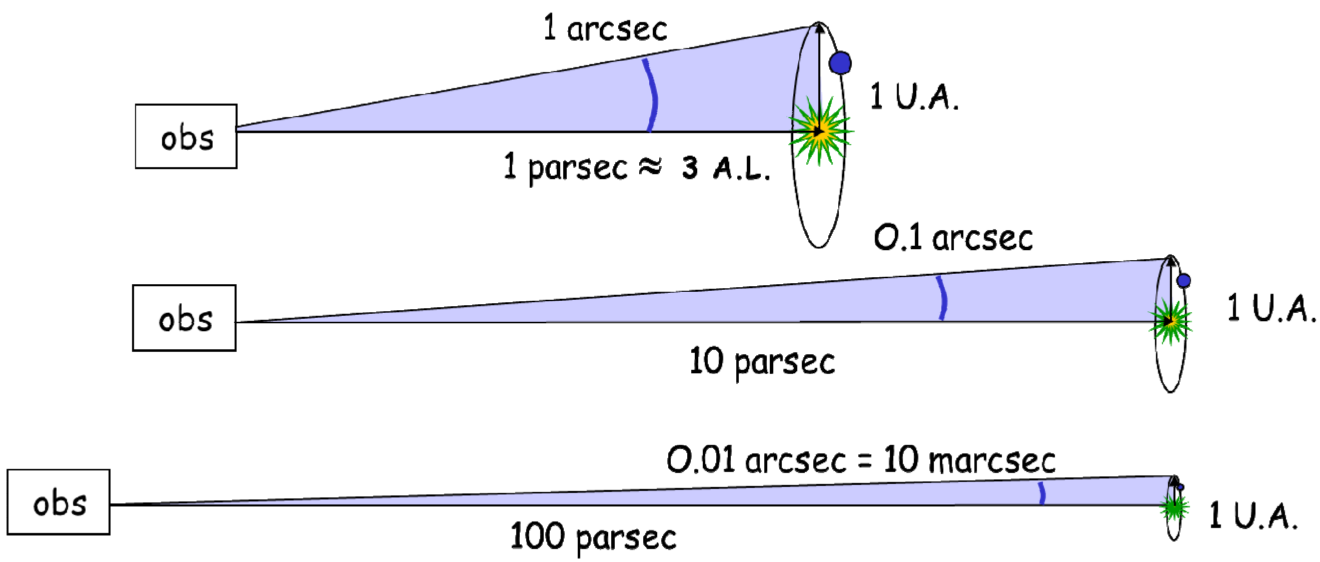
Specific Constraints linked to exoplanet direct detection

- **Angular resolution:**

✓ **1 arcsec : 5.10^{-6} rad:** angular diameter of 1 garden pea placed at 1 km



✓ **Rayleight criteria:** separation must be larger than ≈ λ / Tel. Diameter

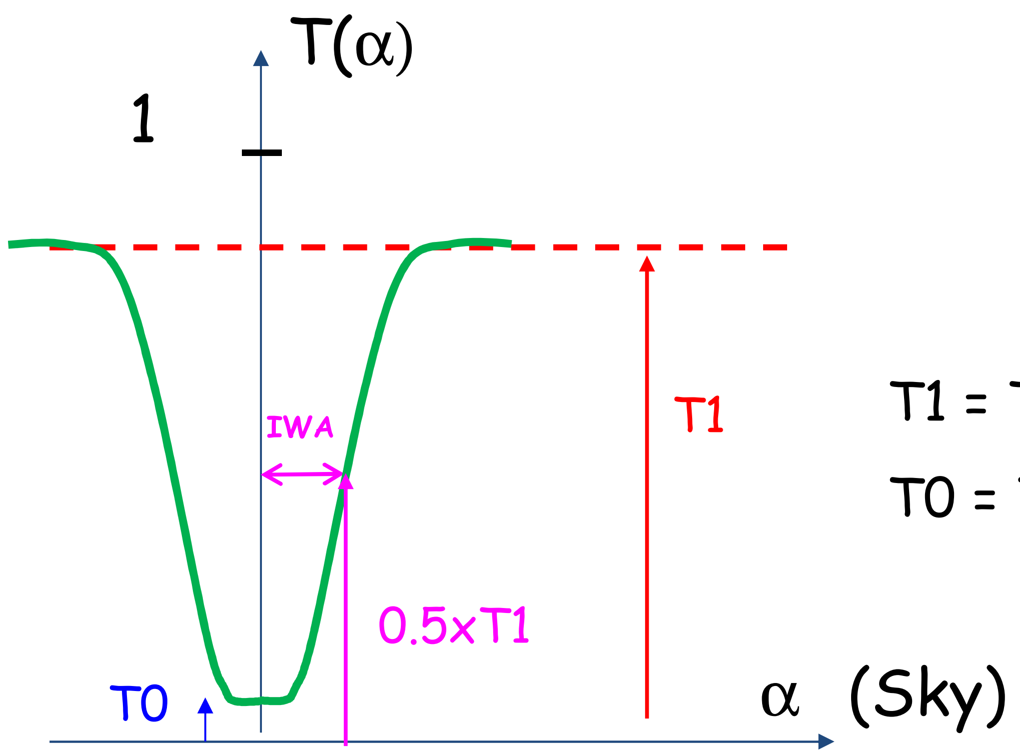
λ (µm)	**0.6**	**2.2**	**11**
Required D (m) pour 100 marcsec	≈ **1**	≈ **40**	≈ **200**

The Evanescent Wave Coronagraph

Specific Constraints linked to exoplanet direct detection

- **Inner working angle:**

Specify in units of lambda/D the range of angles that the coronagraph effectively works with >50% planet transmission of the (Collected flux)

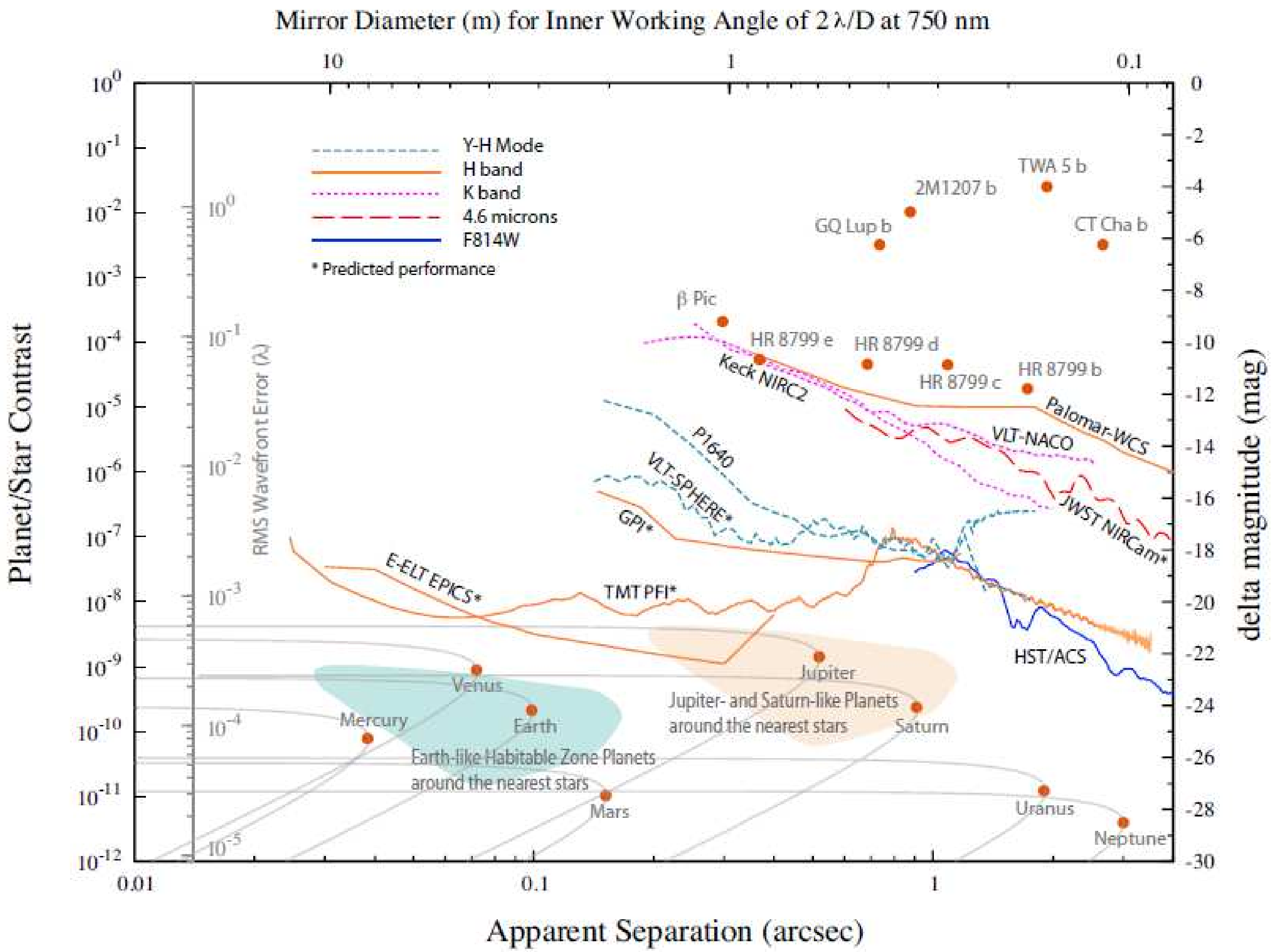


T1 = T(α > IWA) ∝ collected flux

T0 = T(α =0) ∝ Attenuated flux

The Evanescent Wave Coronagraph

Specific Constraints linked to exoplanet direct detection

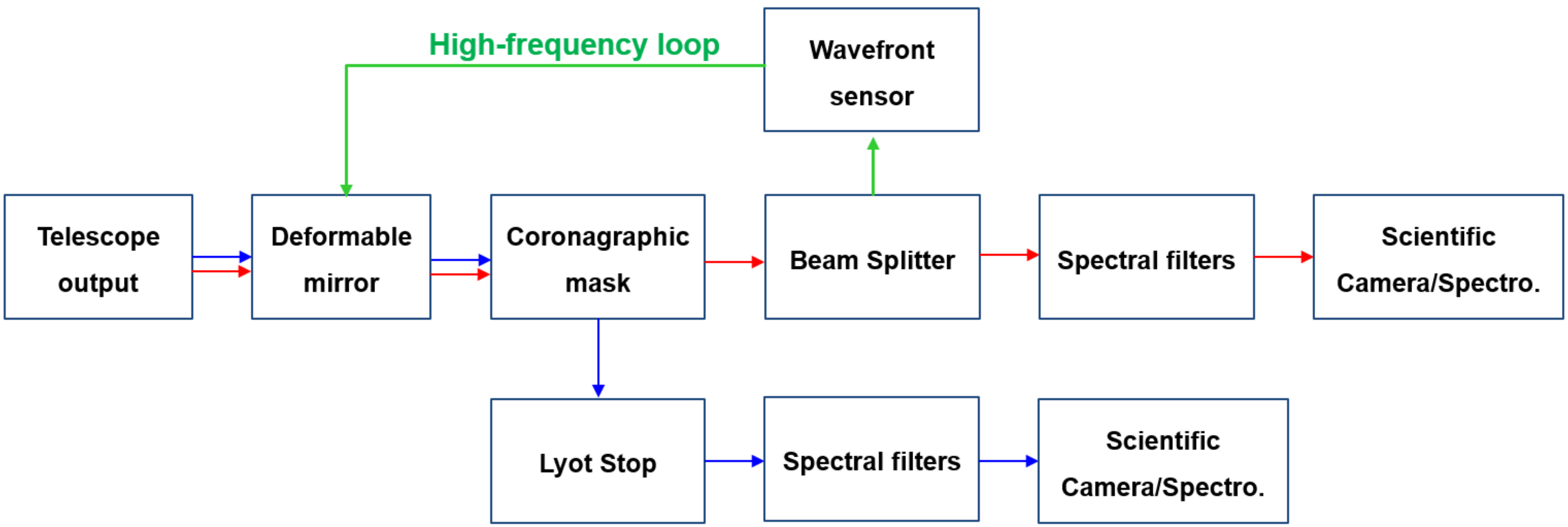


D. Mawet et al., "Review of small-angle coronagraphic techniques in the wake of ground-based second-generation adaptive optics systems ", Proc. of SPIE Vol. 8442, 844204, 2012

The Evanescent Wave Coronagraph

Project Objective

- **To develop a full instrument for large telescopes that comprises its own adaptive optics setup** → 2 outputs: " Star channel" and "Companion channel"
- **Star channel:** central object stabilized and corrected from atmosphere degradation
- **Planet channel:** image of the environment of the star with a high contrast on a camera to enable the detection of faint companions



The Evanescent Wave Coronagraph

Development and on-sky test of 1 prototype with the 2.4 m TNT

- **Objective:** to demonstrate state-of-art performance with a simplified and cost-effective prototype involving new technologies for the occulting mask.
- **Preliminary Specifications:**

Performance	Specifications
Spectral bands	I (Optional: R and V)
Aperture	TNT sub-pupil, 1m diameter
Strehl Ratio	SR > 0.7 at $\lambda = 800$ nm and magnitude m = 9 and s ≈ 1''
Inner working angle	< 3 λ/D at $\lambda \approx 800$ nm
Raw Contrast	$C < 10^{-4}$
Deformable mirror Number of actuators	192 (16 actuators along pupil diameter)
Close-loop Frequency	> 1kHz
Wavefront sensor technology	Shack-Hartman wavefront sensor, 16 x 16 microlenses

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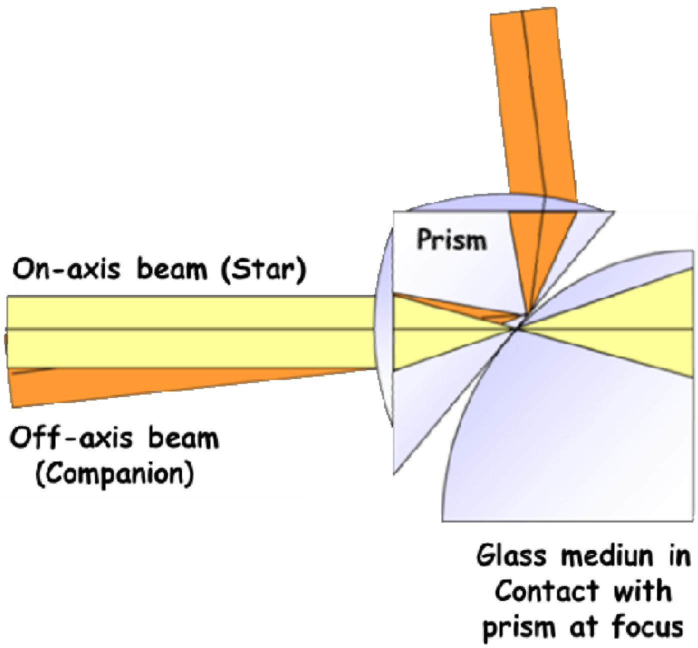
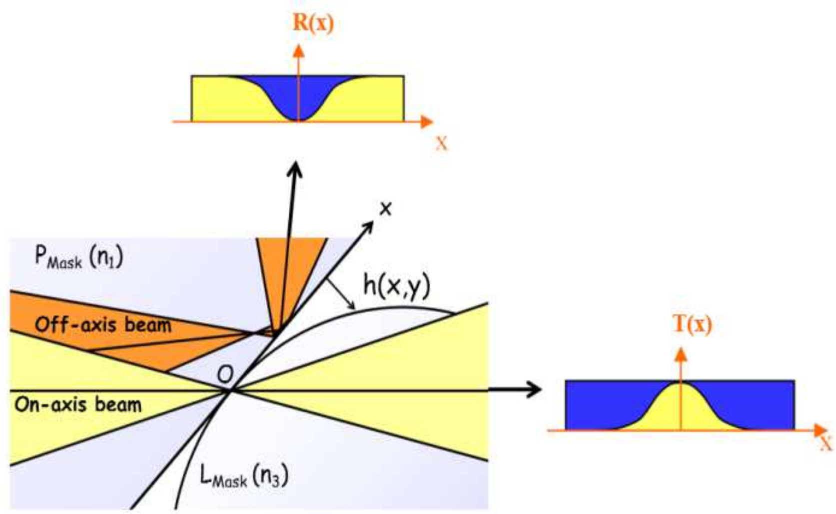
EvWaCo occulting mask Principle: Proposed by Dr Y. Rabbia in 2003

- **On-axis beam (Star):** Focused on the oblique face of 1 prism on total reflection
- **1 Glass medium placed in contact at Focus level** → On-axis beam transmitted by Frustration of the Total Internal Reflection (tunneling effect)
- **Off-axis beam:** Total reflection due to air thickness with appropriate shape of glass medium → Separation of Star and Companion beams





Y. Rabbia, "Shared constraints and specific characters in Very High Dynamics Imaging", in Proceedings of Astronomy with High Contrast Imaging, C.Aime and R. Soummer Ed., EAS Publication Series 8, pp. 65-78, 2003.

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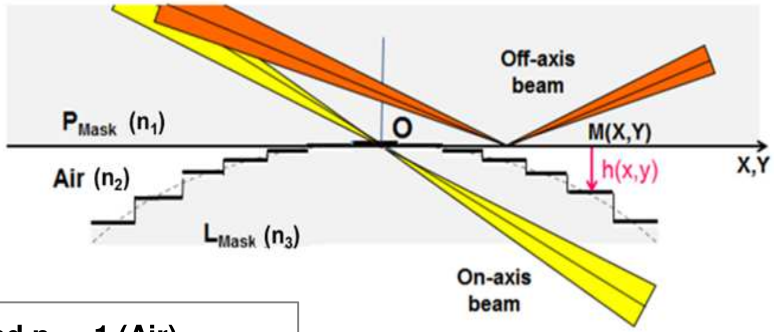
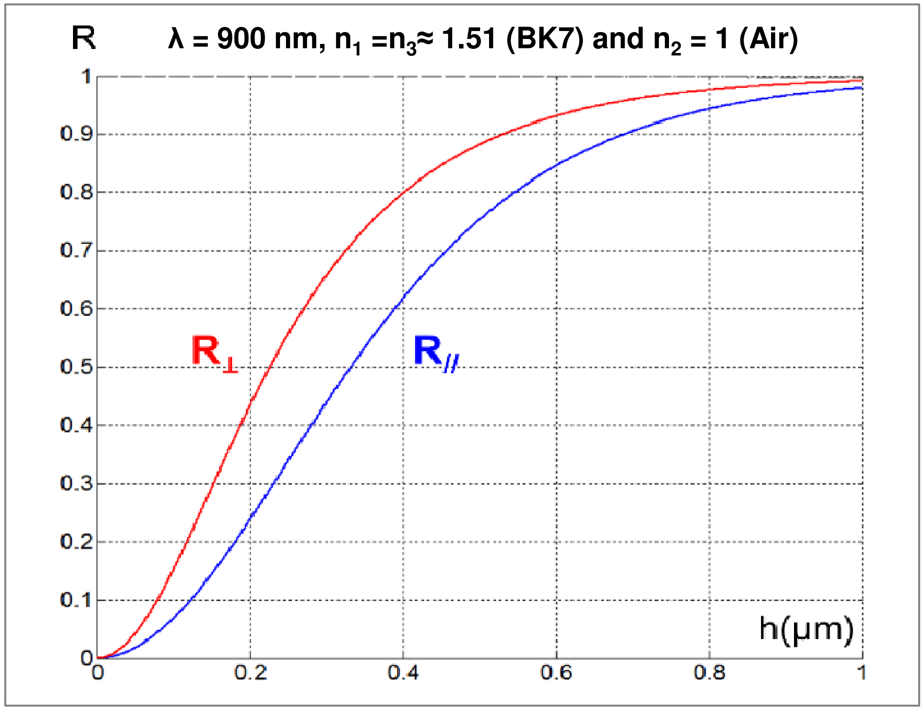
EvWaCo Model:

✓ **Mask Reflection coefficient calculated by applying locally the FTIR reflection coefficient:**

$$R(x,y,\lambda)=1-\frac{1}{\alpha\sinh^2\left[\left(2\pi h(x,y)/\lambda\right)\left(n_1^2\sin^2\phi_1-n_2^2\right)^{1/2}\right]+\beta}$$





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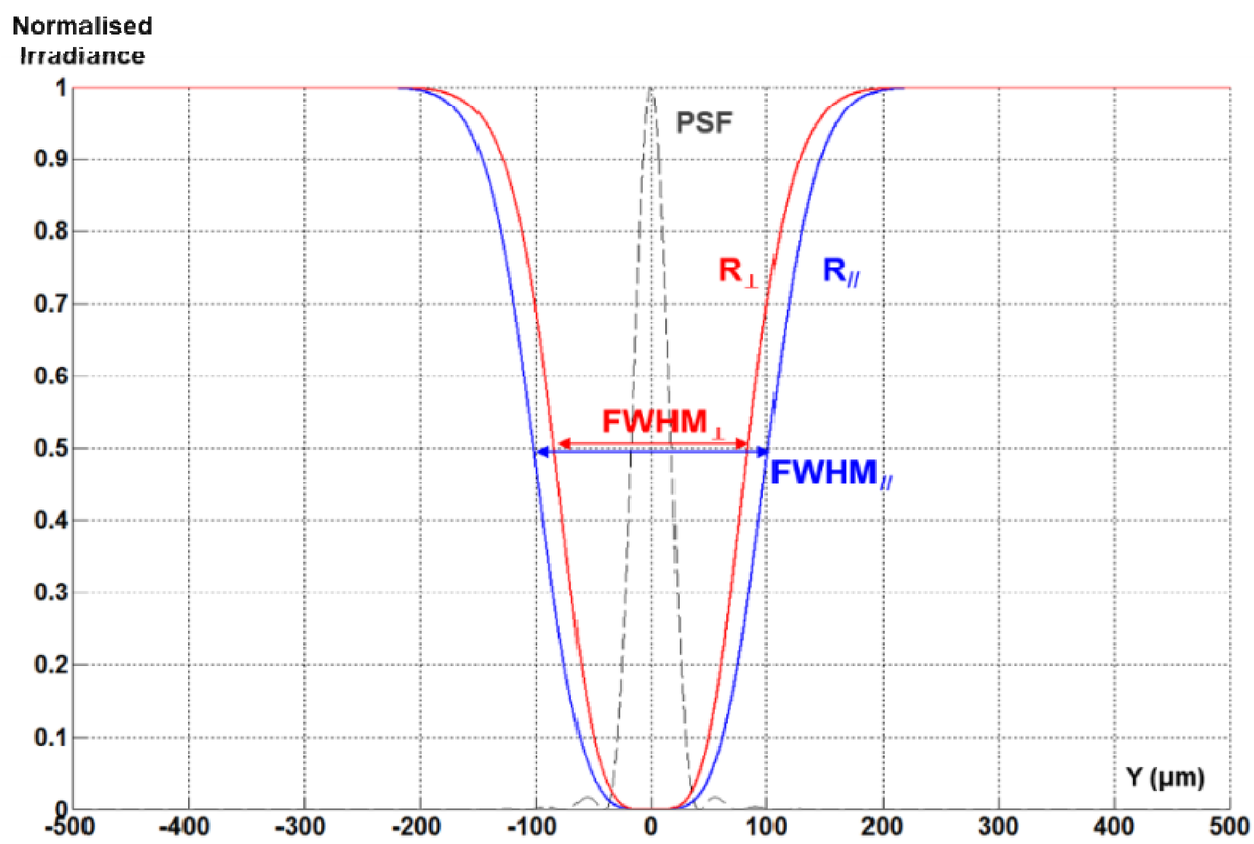
EvWaCo mask theoretical reflection coefficients:

- **Glass medium:** spherical lens of curvature RC = 15.5 mm → $h(x,y) \approx \left(x^2+y^2\right)/2.RC$
- **Mask FWHM ≈ 200 µm** → Coronagraph Inner Working Angle = Few element of resolutions



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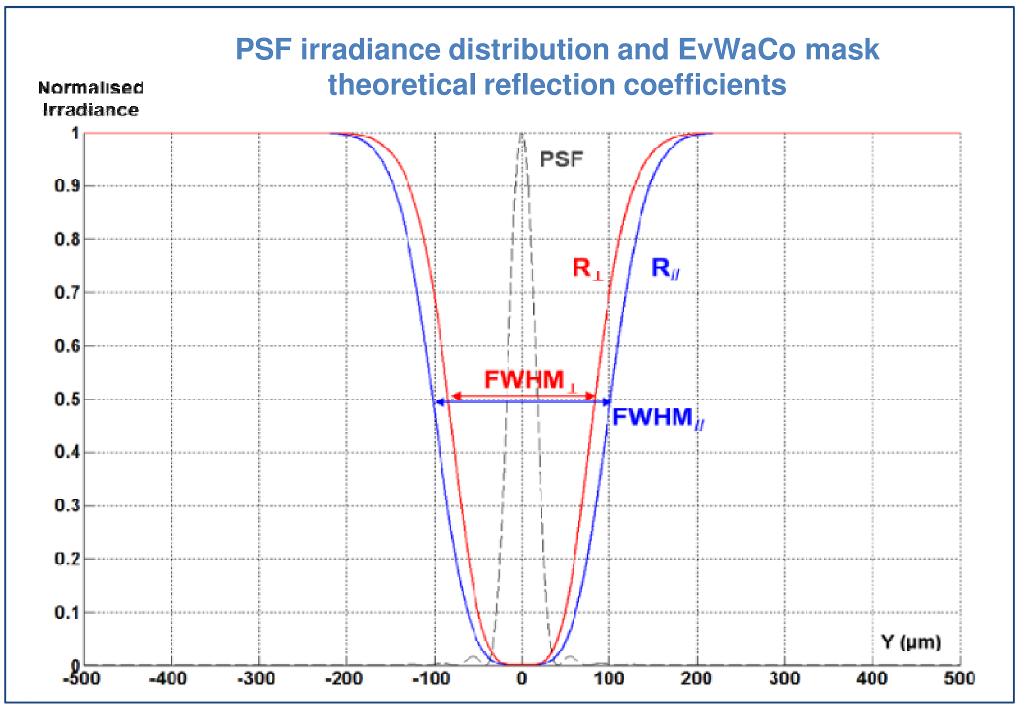
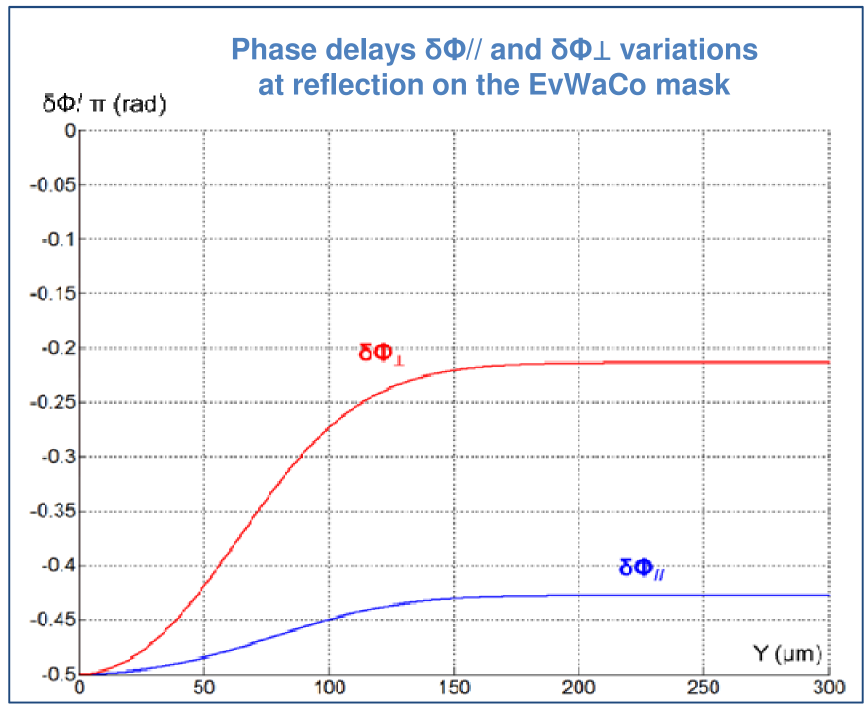
EvWaCo mask polarization effects:

- **Difference of mask FWHM wrt polarization:** $FWHM_{//} \approx 200$ µm and $FWHM_{\perp} \approx 168$ µm
- **Phase variation along the mask:** $-\pi/2 < \delta\Phi_{\perp} < -\pi/5$ rad and $-\pi/2 < \delta\Phi_{//} < -0.45\,\pi$

→ Mask slightly polarizes the reflected wave and that the contrast depends on the polarization

→ Encouraging results obtained in unpolarized light, indicates that the impact on the performance is likely to be negligible.





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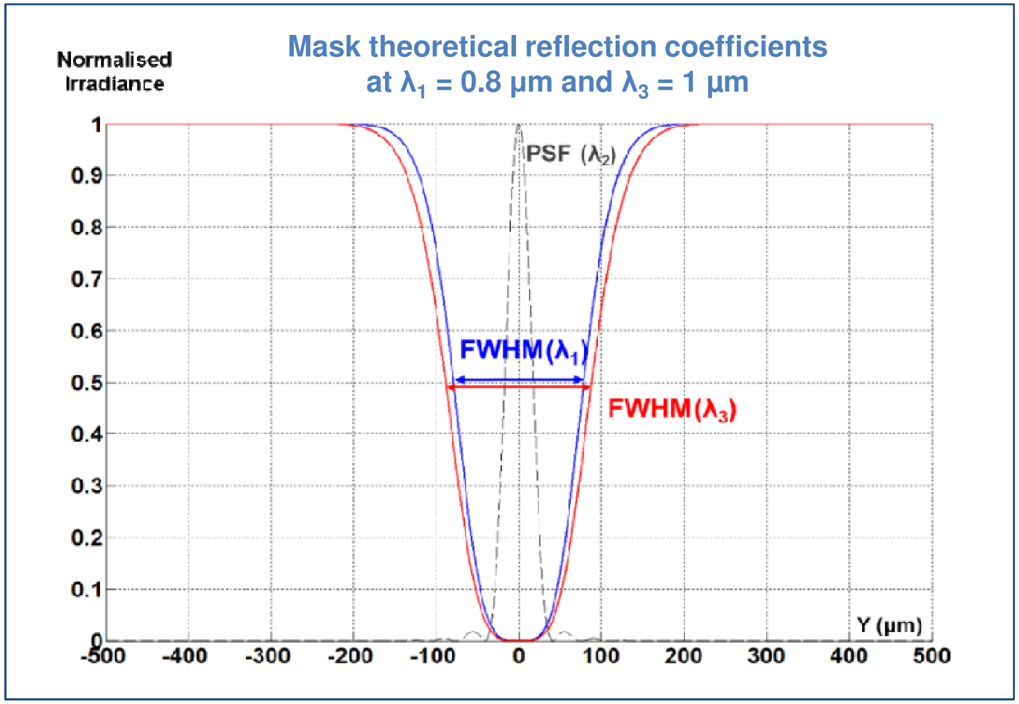
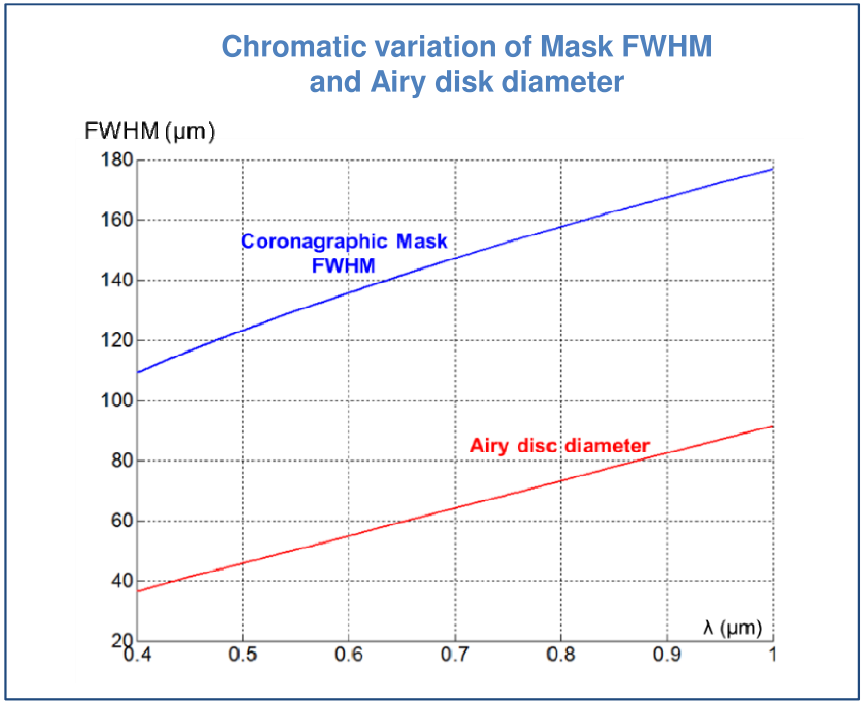
EvWaCo Chromatic variation of the mask reflection coefficient:

- **Mask FWHM increases almost linearly with λ over the full spectral band [0.4 µm, 1 µm].**

→ Self-adaption capability of the mask active area with respect to the wavelength and a quasi-achromatization of the mask response





The Evanescent Wave Coronagraph

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2. The coronagraphic mask

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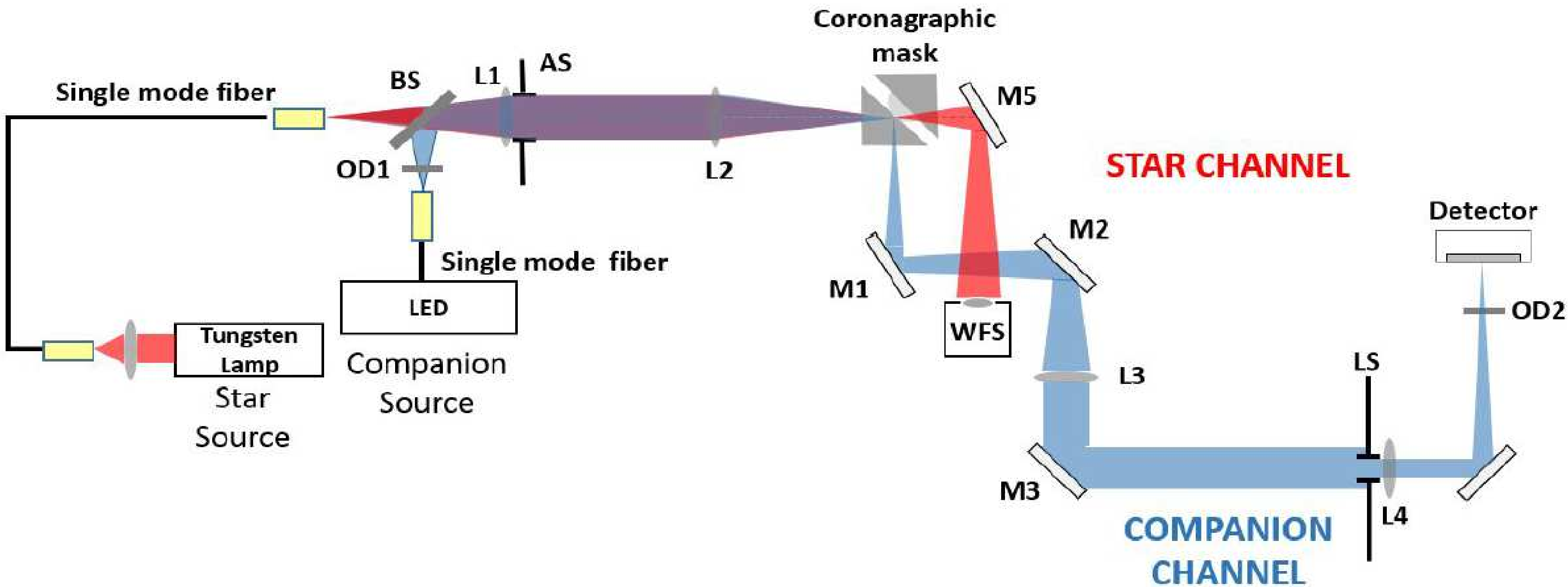
The Evanescent Wave Coronagraph

The setup and results

- Source: Quartz Tungsten Halogen Lamp + I-band filter, $\Delta\lambda/\lambda \approx 22\%$
- 1 Lyot Stop placed in Exit pupil plane, Diameter = Pupil Diameter x 0.78 → T > 60 %
- Detector: APOGEE U9000, pixel size = 12 µm, cooled at the temperature T_{CCD} = -14°C



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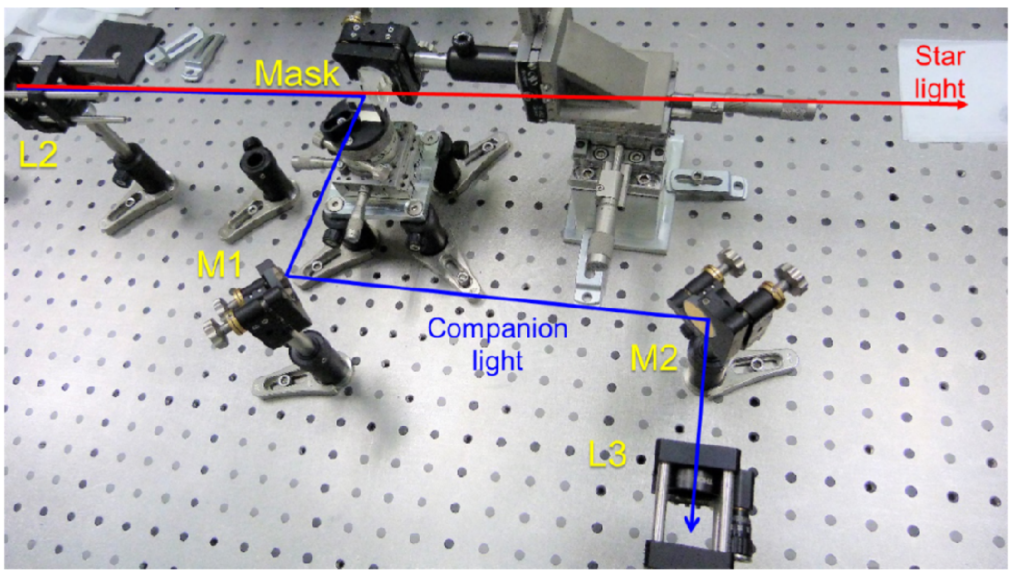
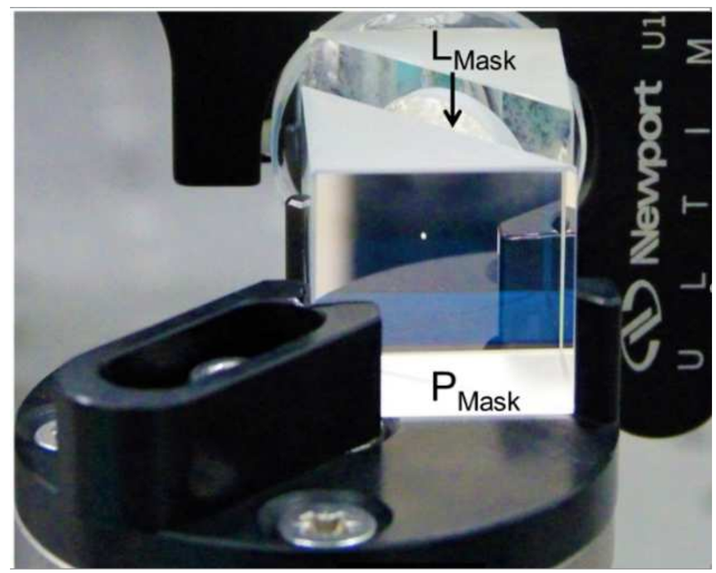




The Evanescent Wave Coronagraph

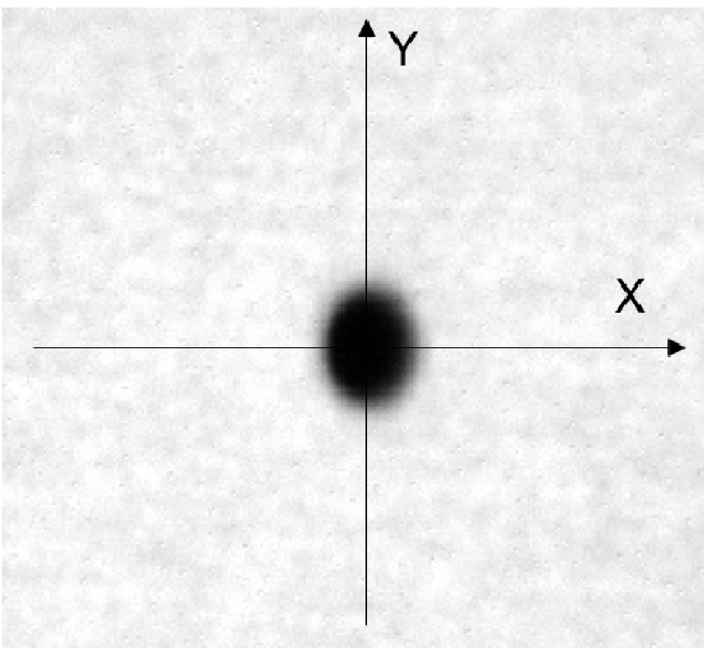
Spatial variation of the mask reflection coefficient

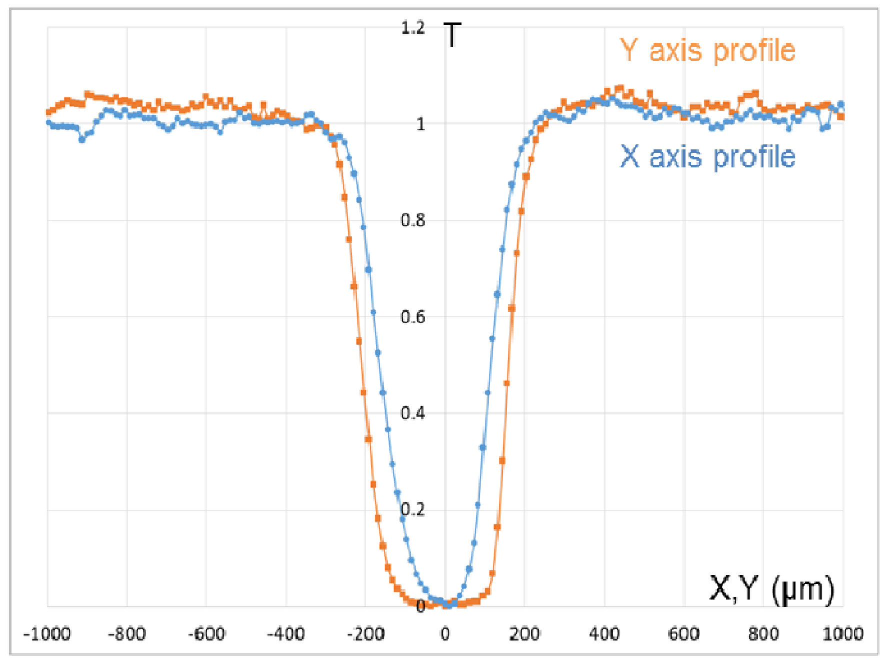
- Mask reflectivity measured by placing a white screen between the optical fiber exit end and L1 + Screen illuminated with 1 optical fiber + Lyot Stop removed from setup.

→ Flat-field illumination of the coronagraphic mask

- Mask FWHM along the X and the Y axes: FWHMX ≈ 280 µm and FWHMY ≈ 380 µm

→ Good agreement with theoretical prediction with enlargement ≈ 200 µm attributed to the pressure applied by L_{Mask} on P_{Mask}.



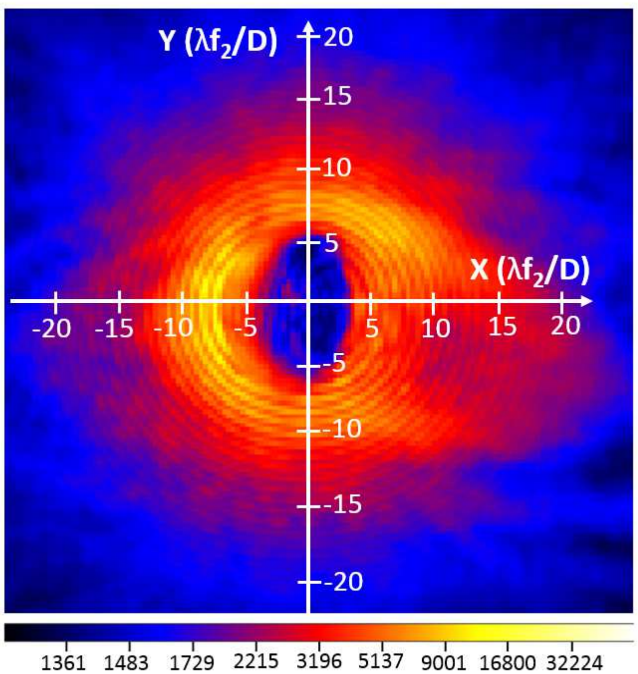


The Evanescent Wave Coronagraph

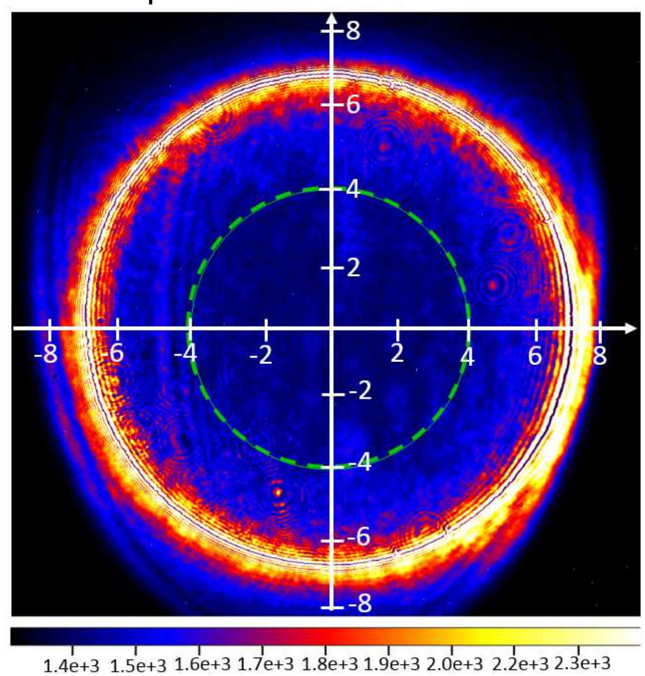
On-axis PSF profile and pupil irradiance distribution without a Lyot stop

- Source: LED, central wavelength λ ≈ 780 nm Δλ/λ ≈ 3%, unpolarised.
- On-axis PSF: Peak attenuation > 10^5. Asymmetric and non-uniform irradiance → attributed to system optical aberrations, presence of contaminants in the mask, and stray light.
- Pupil irradiance distribution: most part of the energy is concentrated at the pupil edges, forming a fine annular shape → characteristic of a band-limited coronagraph.

On-axis PSF Irradiance distribution



Pupil Irradiance distribution

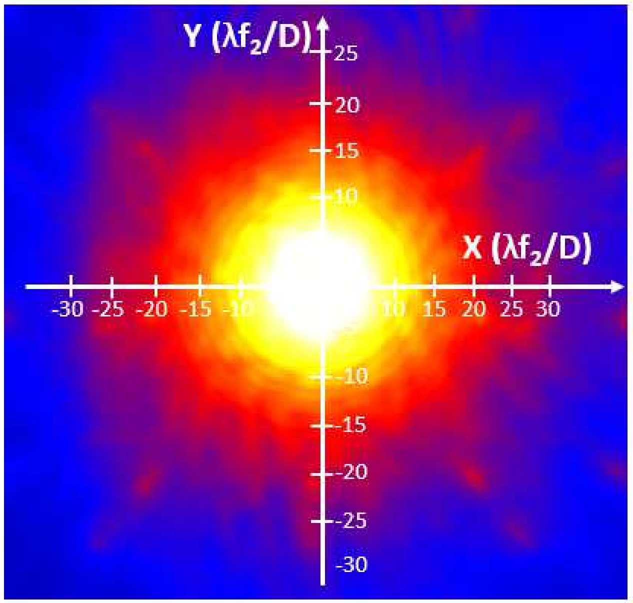


The Evanescent Wave Coronagraph

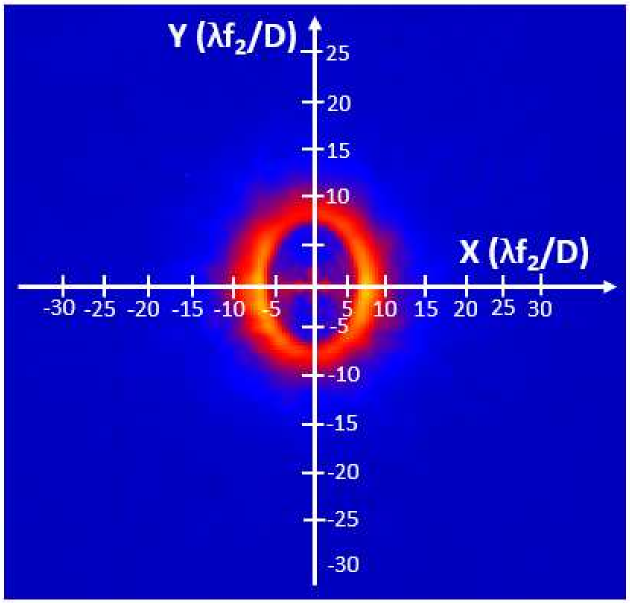
On-axis and off-axis PSF profiles with a Lyot stop

- Source: Quartz Tungsten Halogen Lamp + I-band filter, $\Delta\lambda/\lambda \approx 22\%$, unpolarised
- 1 Lyot stop placed in Exit pupil plane, Lyot Stop diameter = Pupil Diameter x 0.78
- Inner working angles: $IWA_X \approx 6\ \lambda.f_2/D_{AS}$ and IWAY $\approx 8\ \lambda.f_2/D_{AS}$
- Contrast: $C \approx$ few 10^{-6} between 10 and 20 $\lambda f_2/D_{AS}$; Best contrast value: $C \approx 2.10^{-7}$ at $X \approx 20\ \lambda.f_2/D_{AS}$

Off-axis PSF



On-axis PSF



Visualization Level: 1200 (low), 30000 (high), Combination Technique: Median of 101 images

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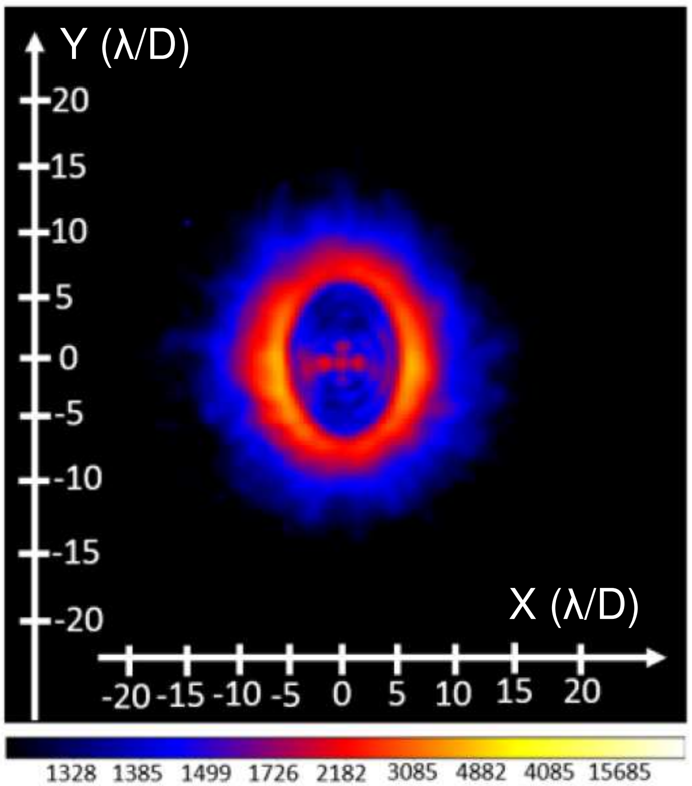
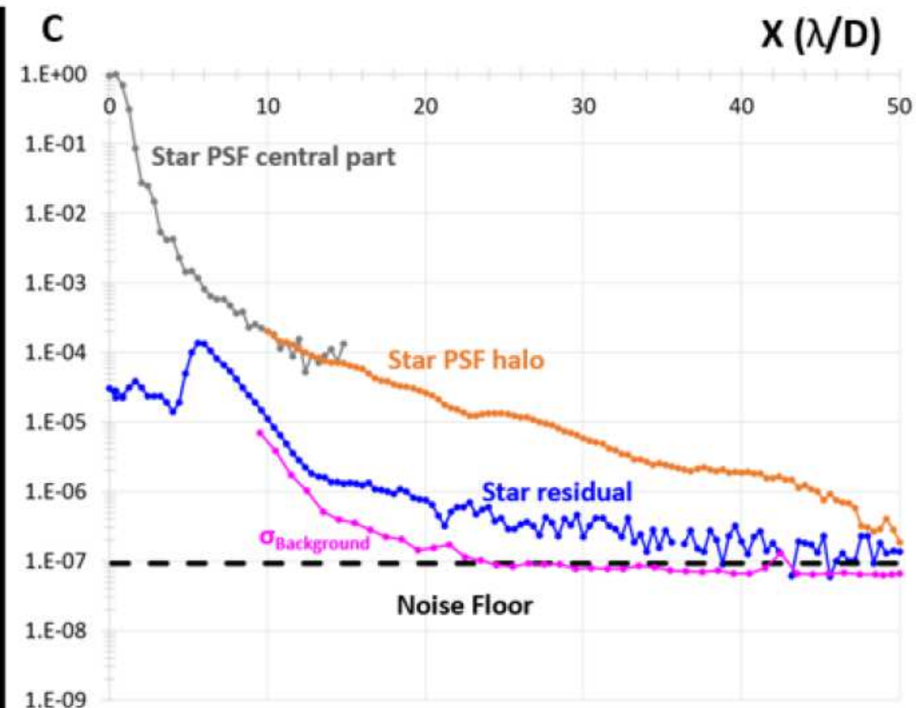


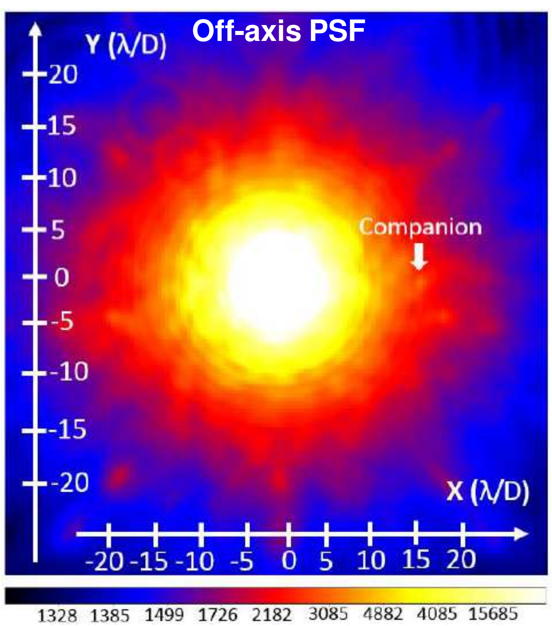


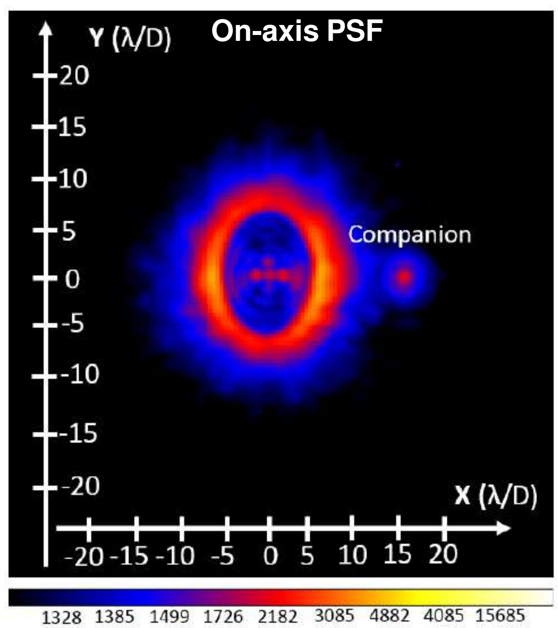
The Evanescent Wave Coronagraph

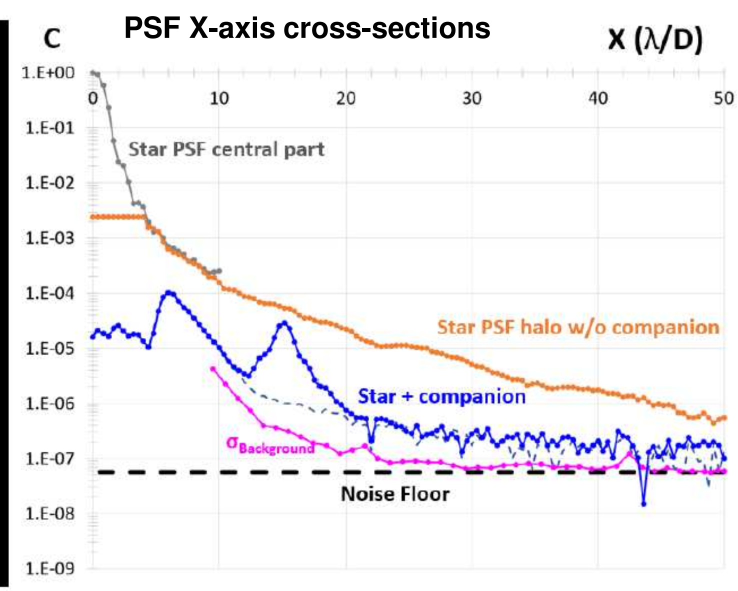
Example of companion detection – 15 λ/D distance from Mask center

- Source: Quartz Tungsten Halogen Lamp + I-band filter, Δλ/λ ≈ 22%, unpolarised
- Companion placed at distance equal to15 λ/D from star center
- Ratio between star and companion peak irradiance: $I_{Star}/I_{Companion}$ ≈ 30 000

→ Companion clearly detected with a Signal to Noise Ratio ≈ 75





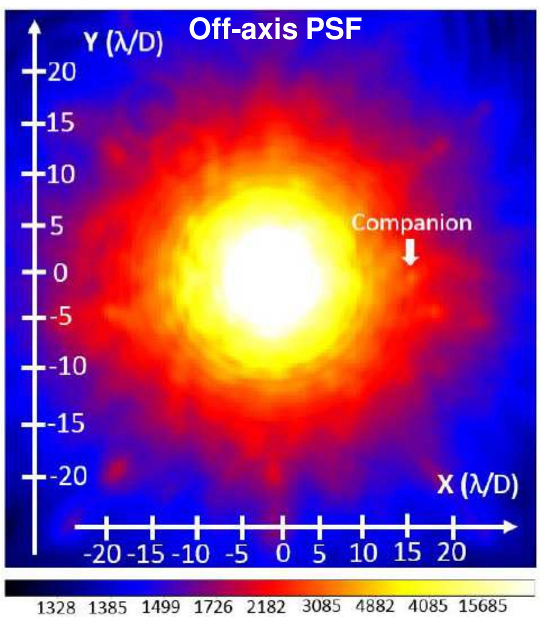


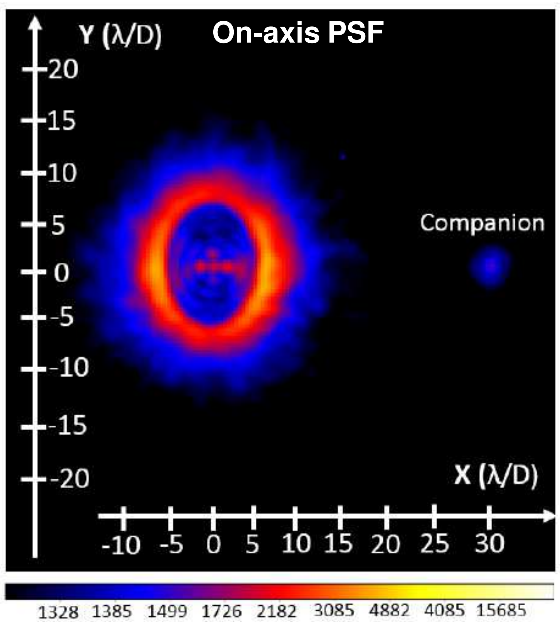
The Evanescent Wave Coronagraph

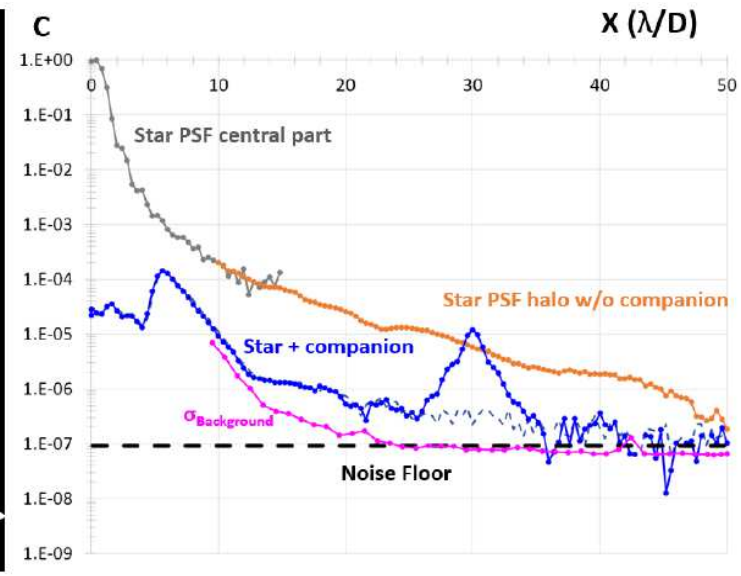
Example of companion detection – 30 λ/D distance from Mask center

- Source: Quartz Tungsten Halogen Lamp + I-band filter, Δλ/λ ≈ 22%, unpolarised
- Companion placed at distance equal to 30 λ/D from star center
- Ratio between star and companion peak irradiance: $I_{Star}/I_{Companion} \approx 100\ 000$

→ Companion clearly detected with a Signal to Noise Ratio ≈ 125



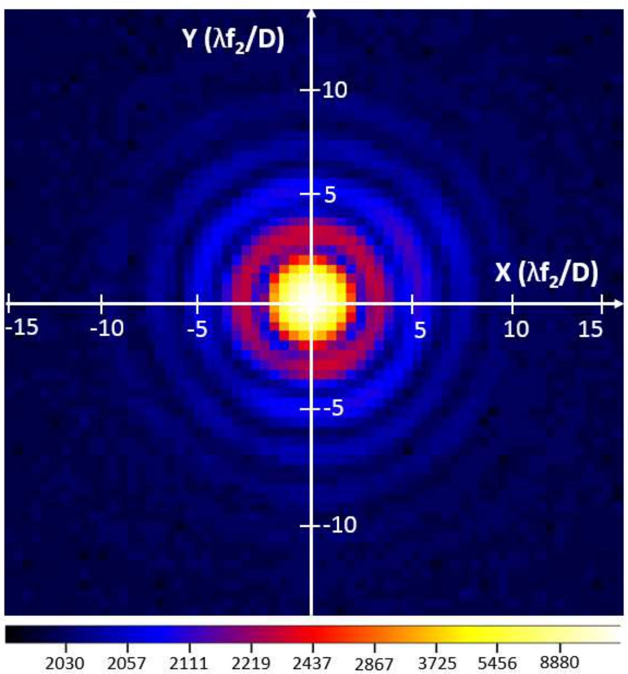


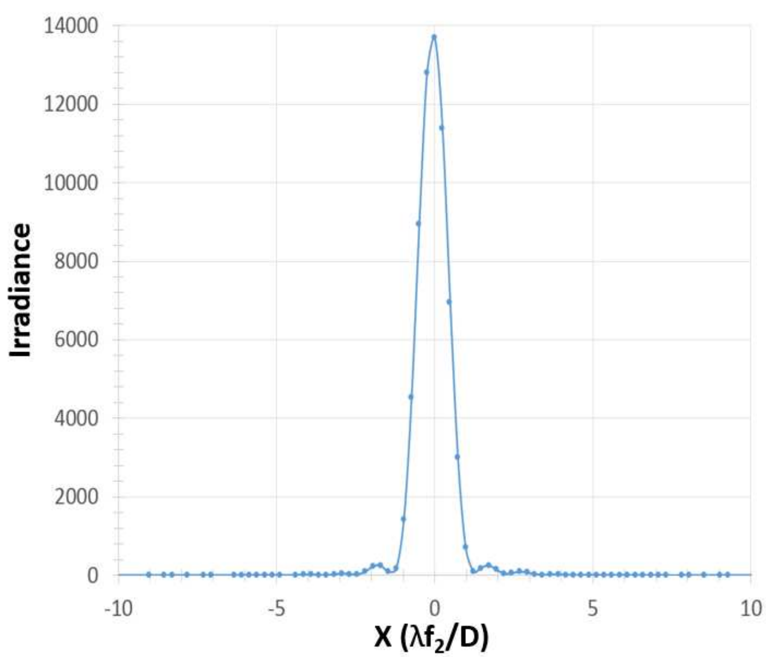


The Evanescent Wave Coronagraph

Star channel PSF and WFE measurement

- CMOS camera + Lenses installed on the star channel to image the on-axis PSF
- PSF profile: very good optical quality, minor residual aberrations induced by star channel optical components surface and alignment errors
- Beam orientation at pupil level measured with accuracy better than 4'' → compliant with required accuracy to get reproducible contrasts.

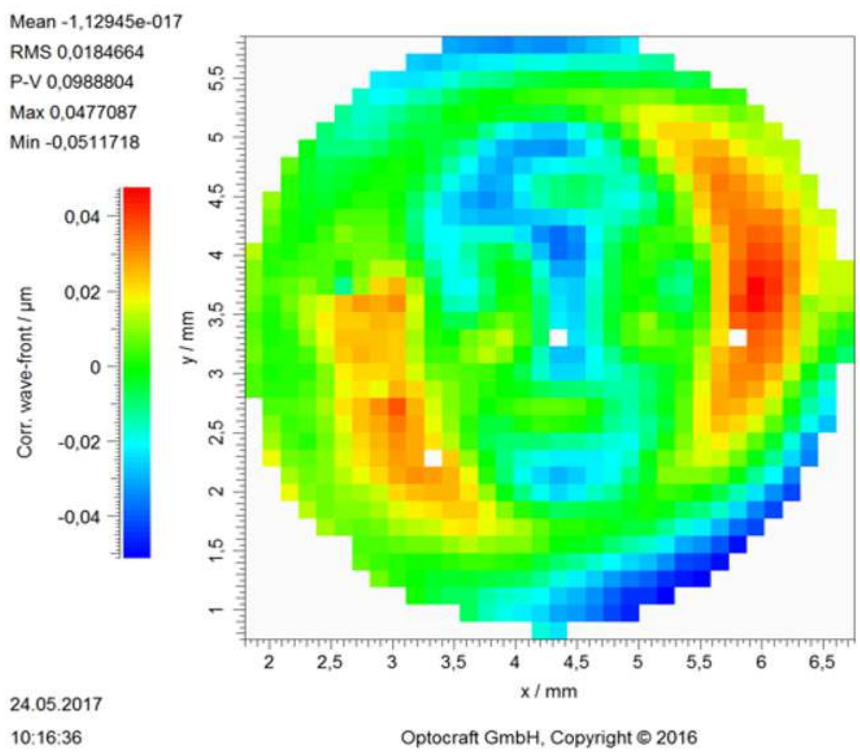




The Evanescent Wave Coronagraph

Star channel PSF and WFE measurement

- 1 WaveFront Sensor (WFS) placed on the beam transmitted by the mask calibrated with 1 optical fiber placed in front of the WFS
- Result: WFE (λ = 780 nm) ≈ 20 nm RMS (Tip-Tilt-Focus removed) → Illustrate the possibility to measure the wavefront low aberrations on the star channel.



The Evanescent Wave Coronagraph

1. Introduction

2. The coronagraphic mask

3. The setup and results

4. **Conclusions and next steps**

The Evanescent Wave Coronagraph

Conclusions

- Encouraging results have been obtained by using off-the-shelves components: $C \approx 10^{-6}$ at a distances 10–20 λ/D from PSF center in unpolarized light, $\lambda \approx 900$ nm and $\Delta\lambda/\lambda \approx 6\%$.

- We have demonstrated the capability to detect a planet of relative peak irradiance $I_{Planet}/I_{Star} \approx 3.\ 10^{-5}$ at 15 λ/D from PSF center with SNR > 75

- Encouraging feedback from the instrumental and from the scientific community → Open the possibility to move toward the development of a full prototype for the Thai National Telescope.

The Evanescent Wave Coronagraph

Next step: Prototype Design, development and on-sky tests

✓ 2018 – 2020 : Prototype design, manufacturing and integration/alignment

- Coronagraph optical design finalization, definition of the pupil apodization to reach specified Contrast and IWA performance.
- Procurement of the optical components, Mechanical design and manufacturing.
- Development and test of the Adaptive Optics control loop.
- Prototype alignment and tests in NARIT Optical Laboratory.

✓ 2020 – 2023: On-sky tests and full characterization.

- Integration and commissioning of the prototype on the TNT.
- On-sky test and validation of the performance in operational conditions.
- Prototype full characterization and identification of potential optimizations to reach state of art performance after processing.

The Evanescent Wave Coronagraph

- **Back-up slides**

The Evanescent Wave Coronagraph

Raw contrasts obtained with SPHERE

- Extracted from “Very Large Telescope SPHERE User Manual, PDM-ESO-254263, VLT-MAN-SPH-14690-0430, Issue P99.0, Sept. 2016”:

SPHERE User Manual
PAGE : 26 / 101

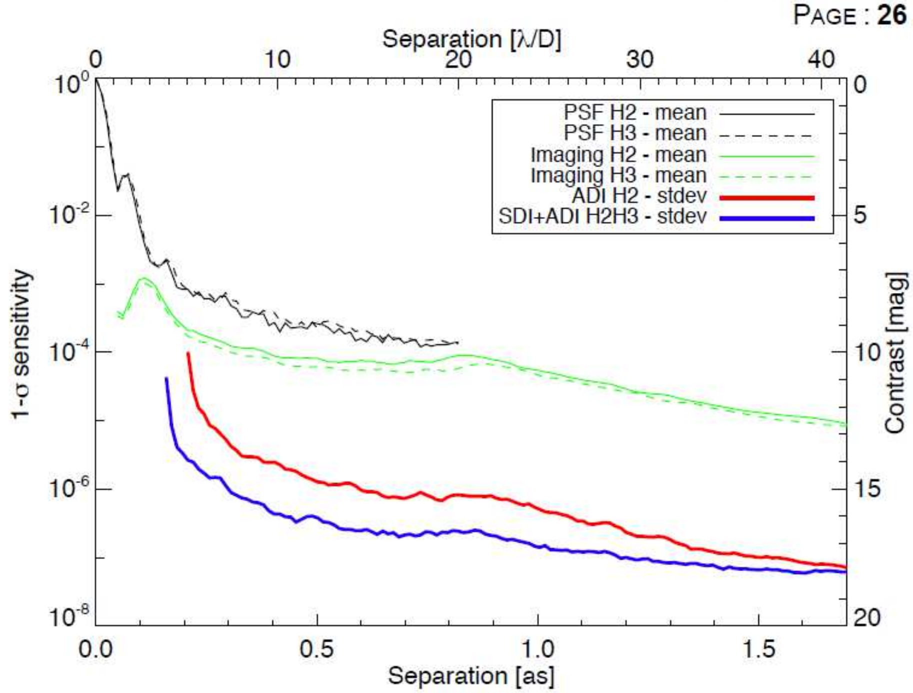


Figure 13: IRDIS DBI H2H3 contrast curves obtained on-sky for a bright target (H=0.2), in average conditions (seeing ~1.0”), with an ADI field rotation of 30 degrees. The plot shows the PSF profiles (black) and coronagraphic profiles (green) in the H2 and H3 filters, the 1σ contrast curve for ADI on the H2 data (red), and the 1σ contrast curve for SDI+ADI on the H2 and H3 data. For the ADI and SDI+ADI analysis, the algorithm throughput is taken into account and compensated, assuming a T8 spectral-type for the planet in SDI.

The Evanescent Wave Coronagraph

Signal to Noise Ratio Computation

- Annular area used to calculate the background noise standard deviation: $\sigma_{Background}$
- At D = 15 λ/D from mask center, $\sigma_{Background} \approx 4.10^{-7}$