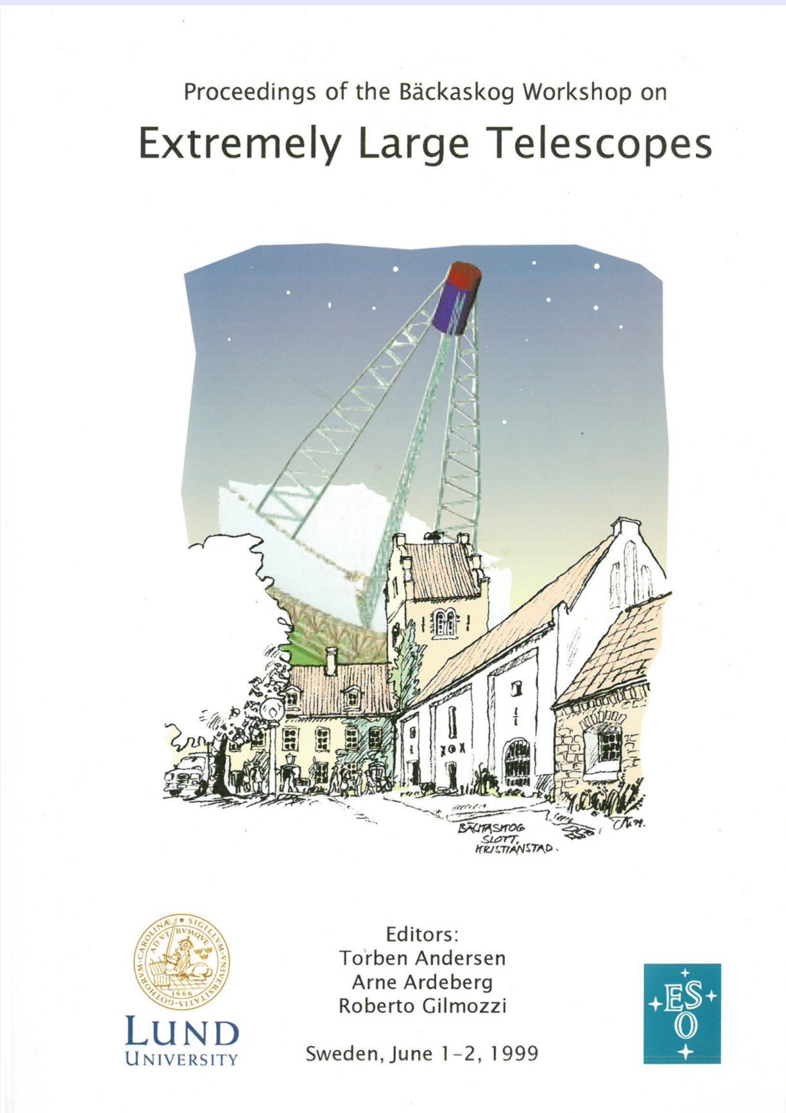
NEAR: New **E**arths in the **A**lpha Cen **R**egion (bringing VISIR as a "visiting instrument" to UT4)

@ MPIA Heidelberg, Oct 12th 2018

Ulli Käufl, ESO on behalf of the NEAR-team

at least: Markus Kasper, Robin Arsenault, Gerd Jakob, Serban Leveratto, Eloy Fuenteseca, Miguel Riquelme, Ralf Siebenmorgen, Michael Sterzik, Gerard Zins, Nancy Ageorges, Sven Gutruf, Arnd Reutlinger, Dirk Kampf, Olivier Absil, Brunella Carlomagno, Olivier Guyon, Pete Klupar, Dimitri Mawet, Garreth Ruane, Mikael Karlsson, Eric Pantin, Kjetil Dohlen ....



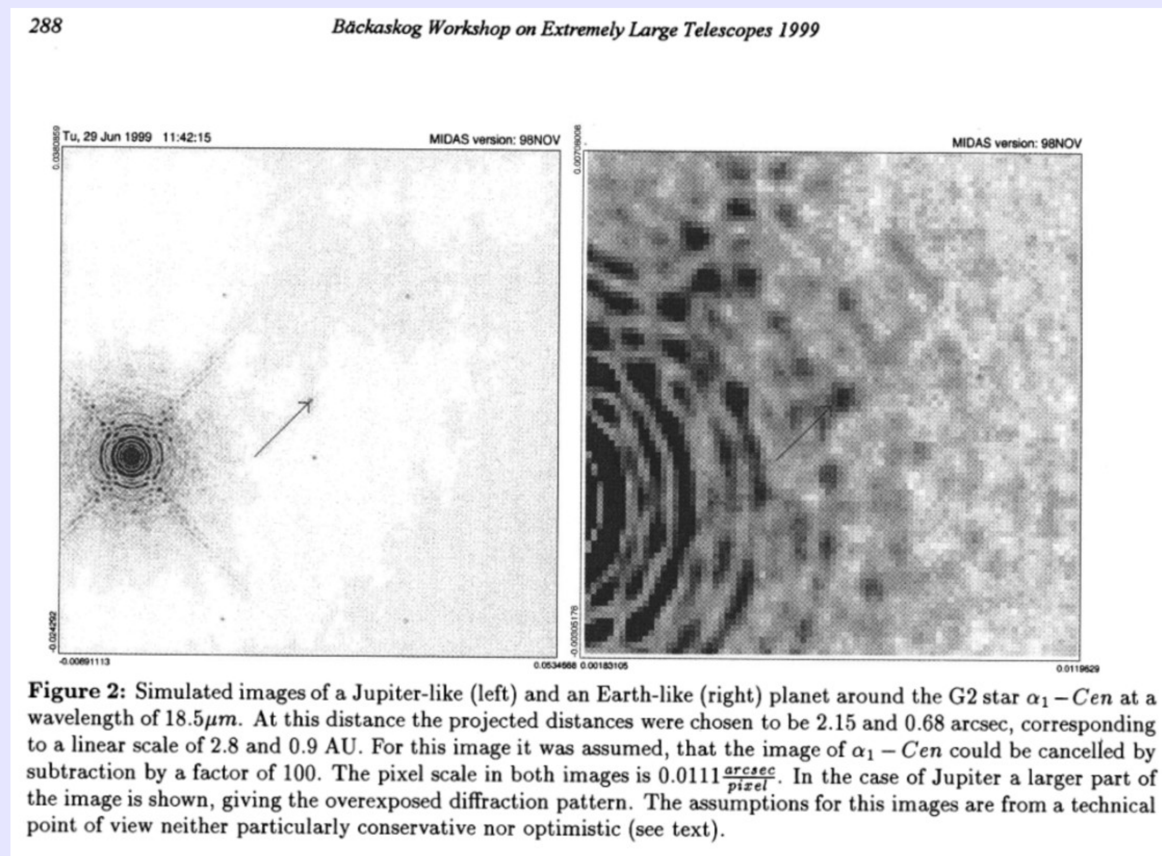
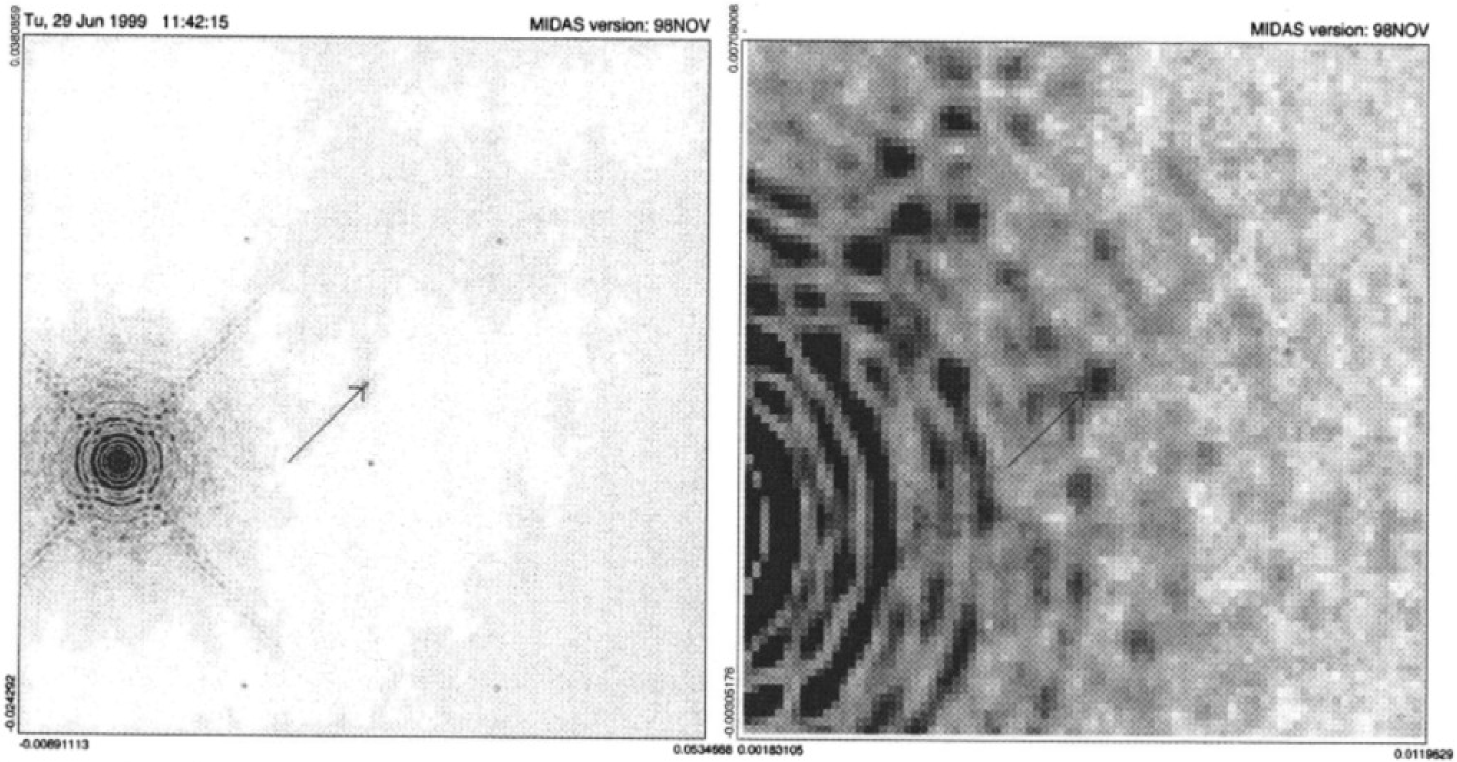


Figure 2: Simulated images of a Jupiter-like (left) and an Earth-like (right) planet around the G2 star $\alpha_1 - Cen$ at a wavelength of $18.5\mu m$. At this distance the projected distances were chosen to be 2.15 and 0.68 arcsec, corresponding to a linear scale of 2.8 and 0.9 AU. For this image it was assumed, that the image of $\alpha_1 - Cen$ could be cancelled by subtraction by a factor of 100. The pixel scale in both images is $0.0111 \frac{arcsec}{pixel}$. In the case of Jupiter a larger part of the image is shown, giving the overexposed diffraction pattern. The assumptions for this images are from a technical point of view neither particularly conservative nor optimistic (see text).

Planets around α-Cen in the last Millenium: the 100m days

288 *Bäckaskog Workshop on Extremely Large Telescopes 1999*



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Planets around α-Cen in the last Millenium

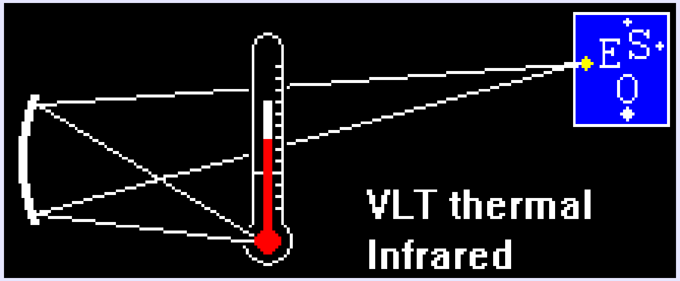
the idea was not followed up immediately for at least the following reasons:

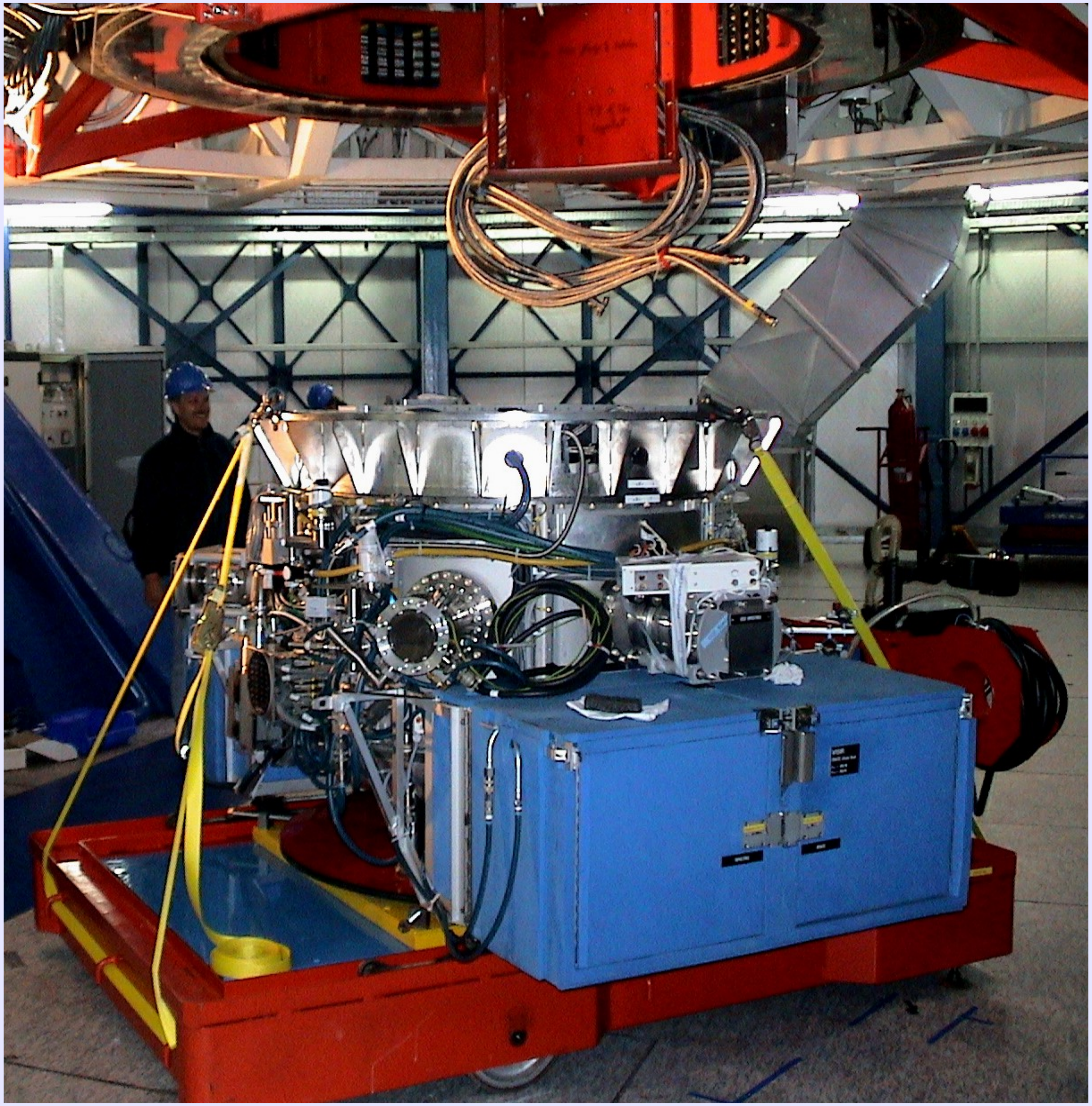
- α-Cen is a close binary (8-27 AU): orbit stability now and during the formation phase?
- no 10/20 μm instrument acceptable for first light of E-ELTs for the first generation of E-ELT science teams ….
- real simulations, polychromatic, ADI, then were beyond the FLOPS easily available
- shape of telescope pupil beyond modeling
- coronagraphy was very basic: occulting disc + Lyot stop

now

- planets around close binaries have been found, albeit they may not be as frequent ...

VISIR at the ESO-VLT in a nut shell:





- built by CEA/Astron 2004 upgraded by ESO 2012
- 10/20 μm imager/ spectrometer (R ~ 500 – 30000)
- sensitivity (BLIP) ~ 2 mJy 10μm imaging ~ 20-200 mJy spectro
- diffraction limited FWHM ~0.3“ sampling 0.045”/pix
- as of Nov 2014/July 2015 back @ VLT-UT3

Why on Earth using VISIR to search for Planets?

VISIR works in <u>extreme</u> Background Noise Limit (eBLIP):

"*Observing at 10µm has been likened to observing visually through a telescope lined with luminescent panels and surrounded by flickering light as though the telescope were on fire*"

Low & Rieke, 1974

wavelength interval [µm]	*1.9-2.1*	*2.1-2.3*	*2.2-2.4*	*3.3-3.7*	*4.5-5.5*	*9.0-11.0*	*19.0-21.0*
photons per pixel per second	60	440	1050	$1.2\ 10^{6}$	$1.2\ 10^{8}$	$8.4\ 10^{9}$	$5.5\ 10^{10}$

ph/pix/s for Nyquist sampling and standard conditions in ground based astronomy

Why on Earth using VISIR to search for Planets?

physics pro 10µm:

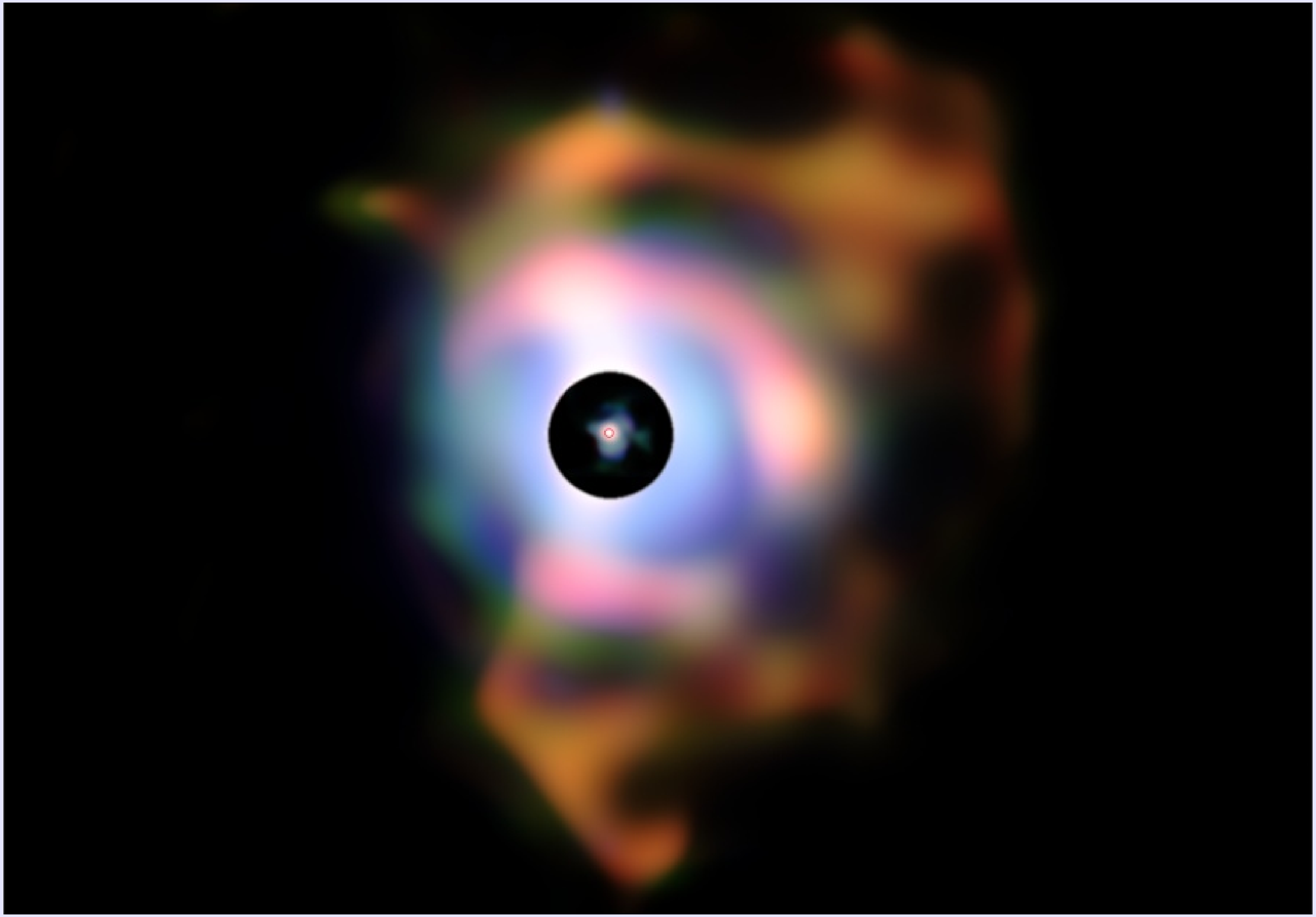
- scattering much less in infrared:
  - Rayleigh scattering α $1/\lambda^4$
  - Mie Scattering α $1/\lambda^{1.3}$
- contrast:
  best possible contrast of a planet in the Jeans-limit ($\lambda \to \infty$)
  $$I_{planet} / I_{star} = D^2_{planet} / D^2_{star} \times T_{planet} / T_{star}$$
  for the Earth – Sun case this yields ~ 4×10^{-6}
- AO much easier the longer the wavelength

physics contra 10µm:

- spatial resolution at diffraction limit: α λ
- thermal background 10^9 ph s^{-1} pix^{-1} => sensitivity!!!

trade off: NIR-xAO, ESO-Sphere vs. VISIR AO … ***VISIR wins***

Examples of “straight imaging” Betelgeuse at 10µm



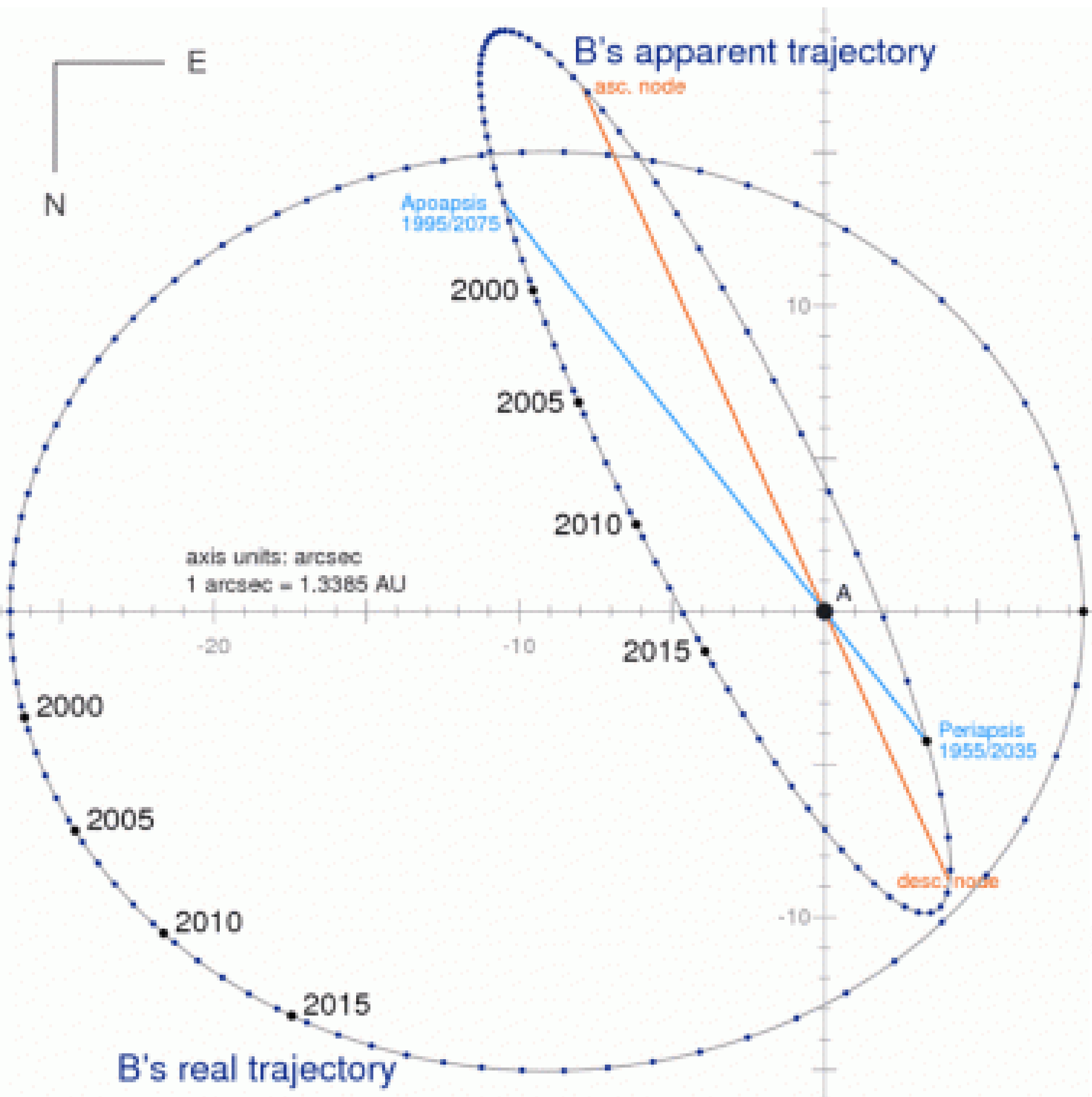
“old” VISIR / Pierre Kervella:

APOD 28.6.2011

inner black circle ~5”

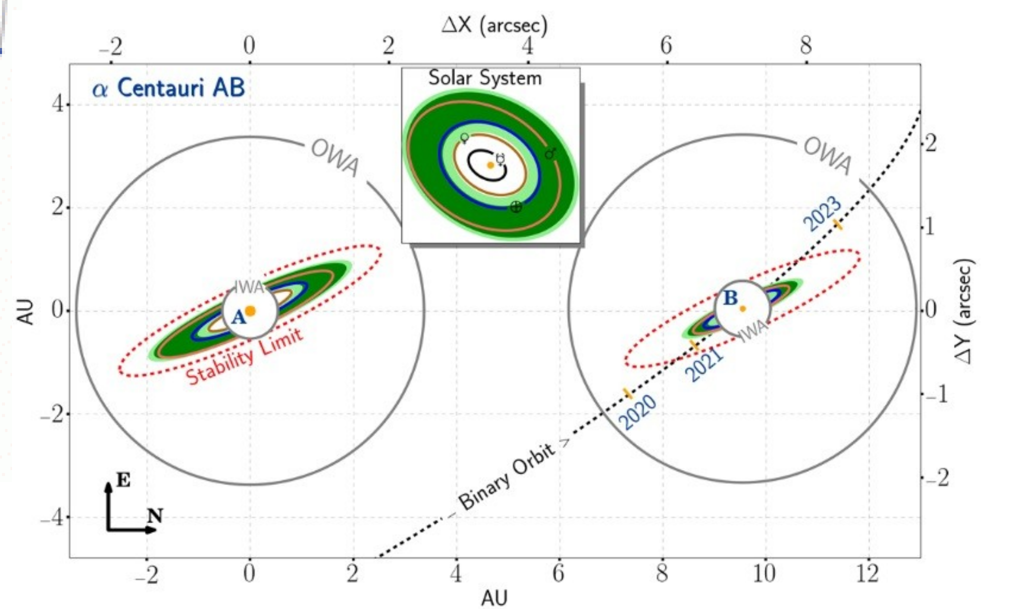
dynamic range > 4dex

αCen A and B

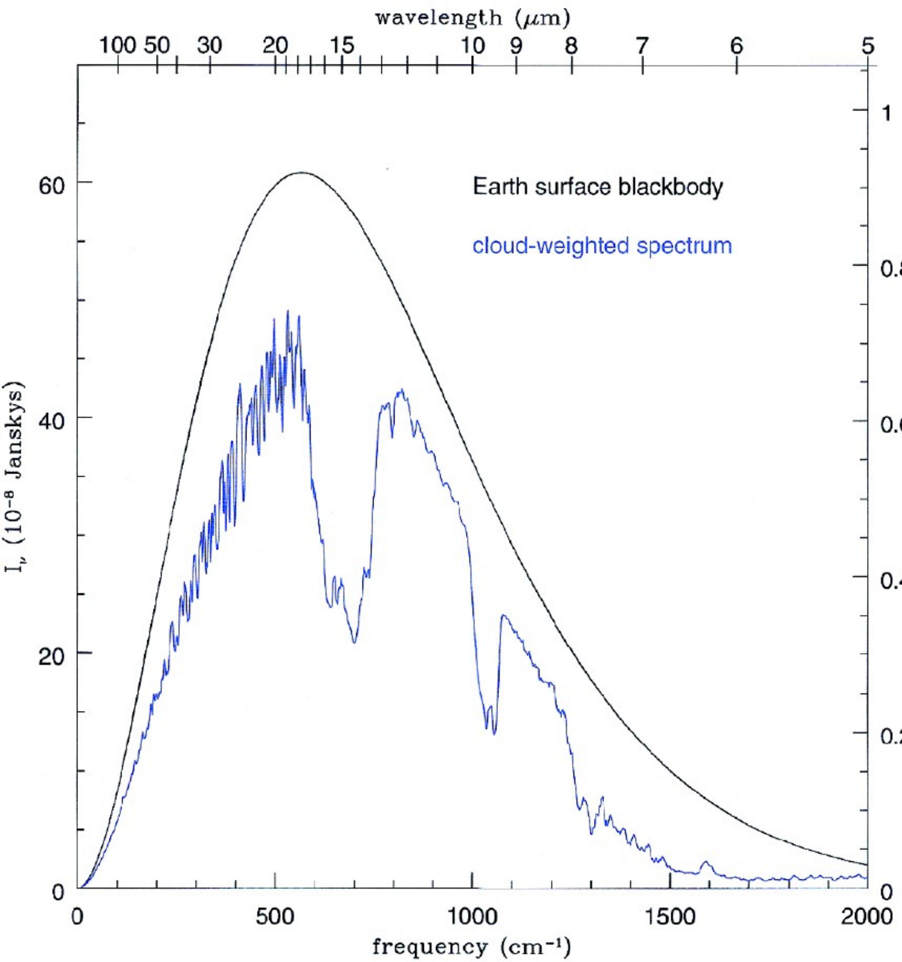


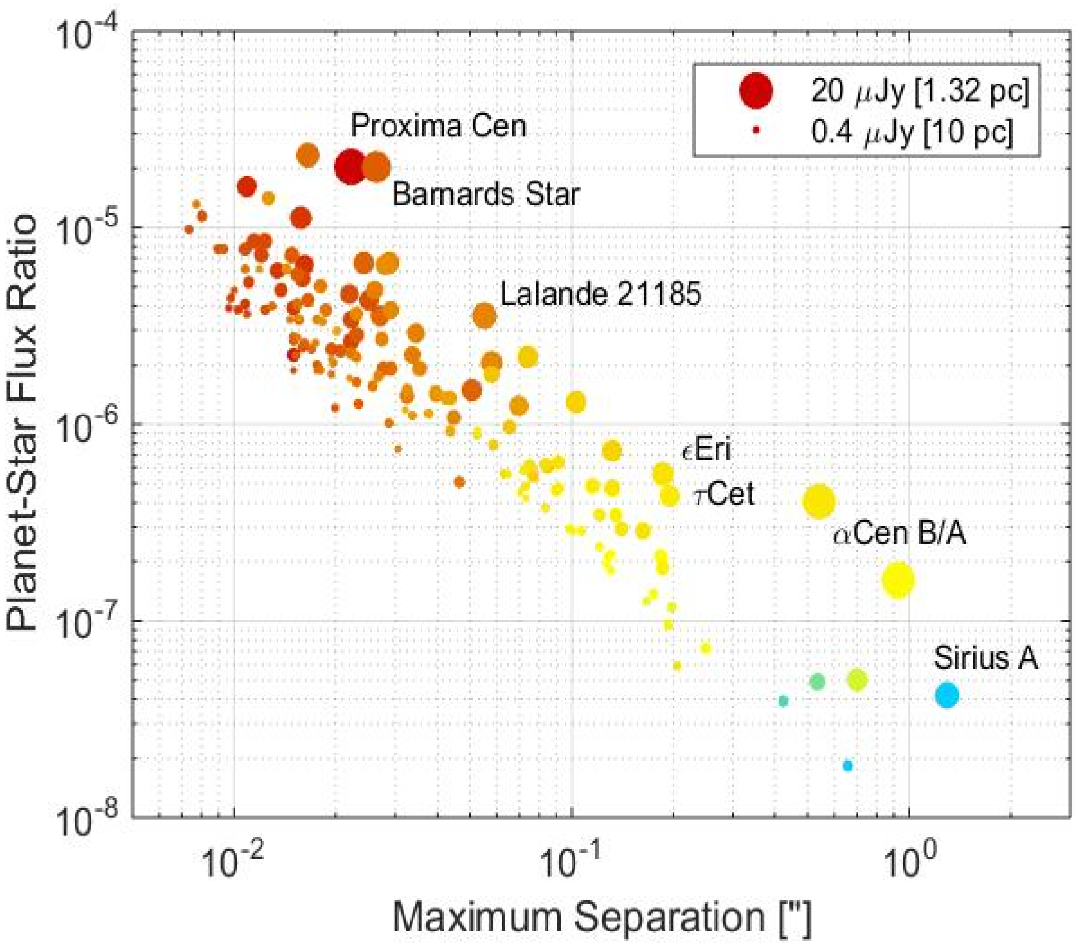
Nearest star system (G2, K1, M6)
1.34 pc or 4.3 Lightyears

Alpha Centauri A	
Mass	1.100[7] $M_\odot$
Radius	1.227[8] $R_\odot$
Luminosity	1.519[7] $L_\odot$
Alpha Centauri B	
Mass	0.907[7] $M_\odot$
Radius	0.865[8] $R_\odot$
Luminosity	0.5002[7] $L_\odot$



αCen, sensitivity and contrast





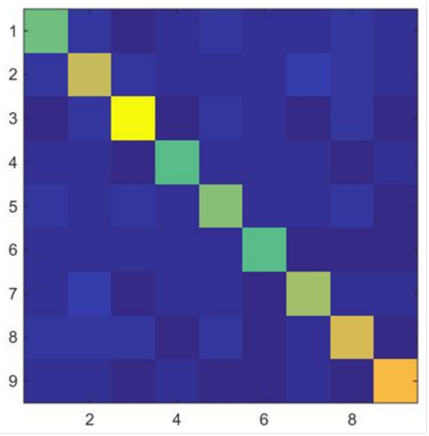
- 2 $R_\oplus$, 1.35 pc: ~80 μJy
- αCen A: ~130 Jy, Ab: ~6x10^{-7} at 3.5 λ/D (10μm, 8-m telescope)
- αCen B: ~60 Jy, Bb: ~1.5x10^{-6} at ~2.5 λ/D

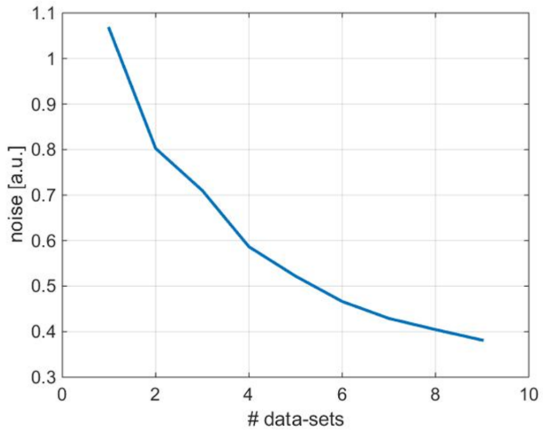
Sensitivity verification

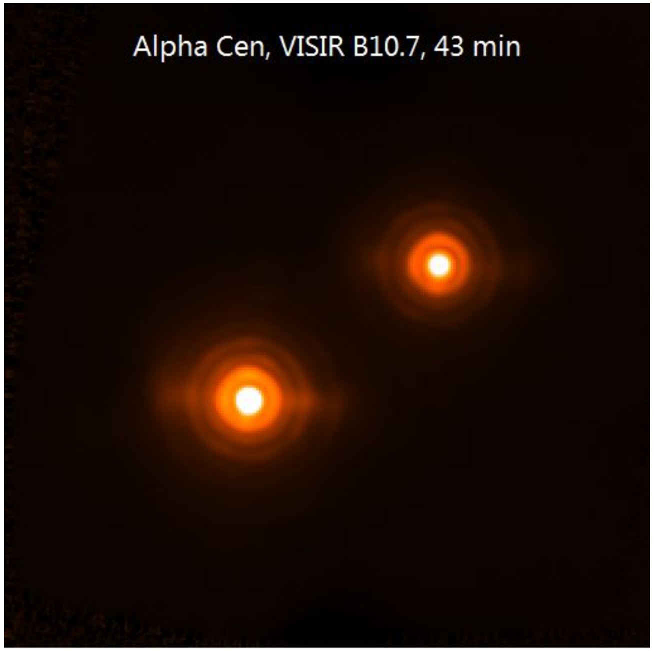
- Programme 098.C-0050(A) (PI Sterzik): Sirius, B10p7 filter, 4 Hz chopping, 9 x ~1hr, Dec 2016 - Mar 2017

Test 1: do multiple observations beat down the noise ?
Pixel intensity statistics over an empty part of the detector show

1. Intensities are spatially and temporally uncorrelated
2. Noise is **reduced**







Test 2: BLIP sensitivity for 100 h observation?
BLIP sensitivity of Sirius data: 1.1 mJy (5σ / h)
Scaling the SNR of classical VISIR to the new NEAR configuration yields:
0.75 mJy (5σ / h) or **75μJy (5σ / 100h)**

imaging planets around $\alpha_{1,2}$ – Cen with VISIR

challenges left:

- VISIR as “visiting instrument” to VLT-UT4 to use the adaptive secondary: AOF
(c.f. 10703-3, Pierre Yves Madec et al.)

- improve VISIR, VLT and operations
- use AO and active tracking to increase Strehl
- use dedicated filter and a clean freshly coated telescope
- improve Lyot stop and generally perfect pupil alignment
- use different chopping/nodding schemes
- use the telescope with normal PWV (2.5mm)

- sensitivity: signal from planet with $r = 2 \times r_\oplus$: 80µJy @ $\lambda \sim 12 \mu m$
to be compared with ~ 2.9mJy, 10 σ in 1h achieved for Sirius B

- contrast: ➔Cen A: ~ 6×10^{-7} at 2.8 – 3.8 λ/D
➔Cen B: ~1.5×10^{-6} at ~2 λ/D

imaging planets, extrapolating contrast from SPHERE

sources of non-common path aberrations: compared to SPHERE: few and well understood "training" of AO with very bright stars

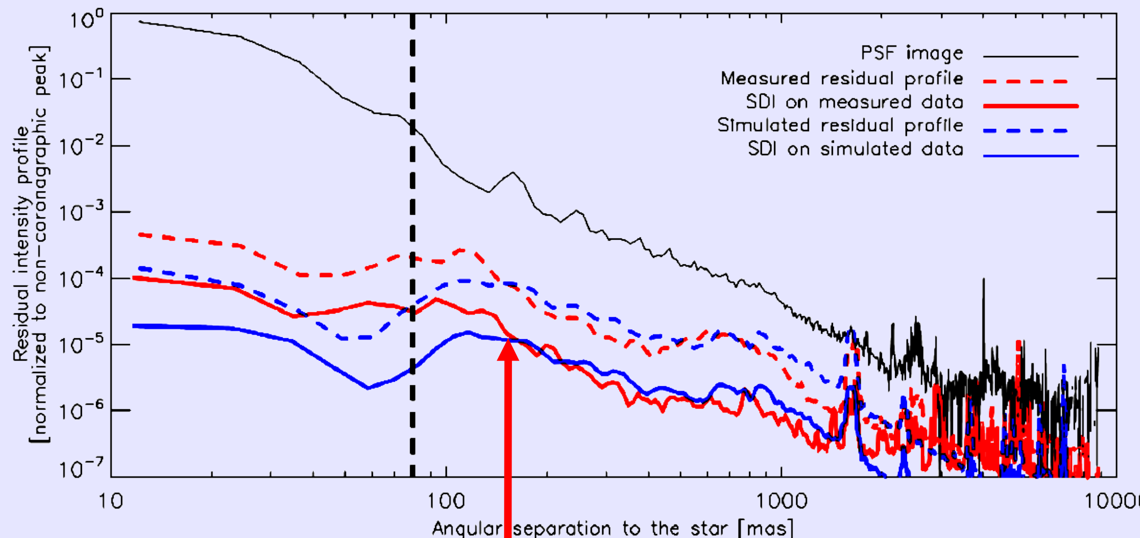


Figure 16. SPHERE H-band coronagraphic detectivity profiles in nominal turbulence conditions. The vertical dashed line indicates the size of the coronographic mask. From Sauvage et al. 2016.

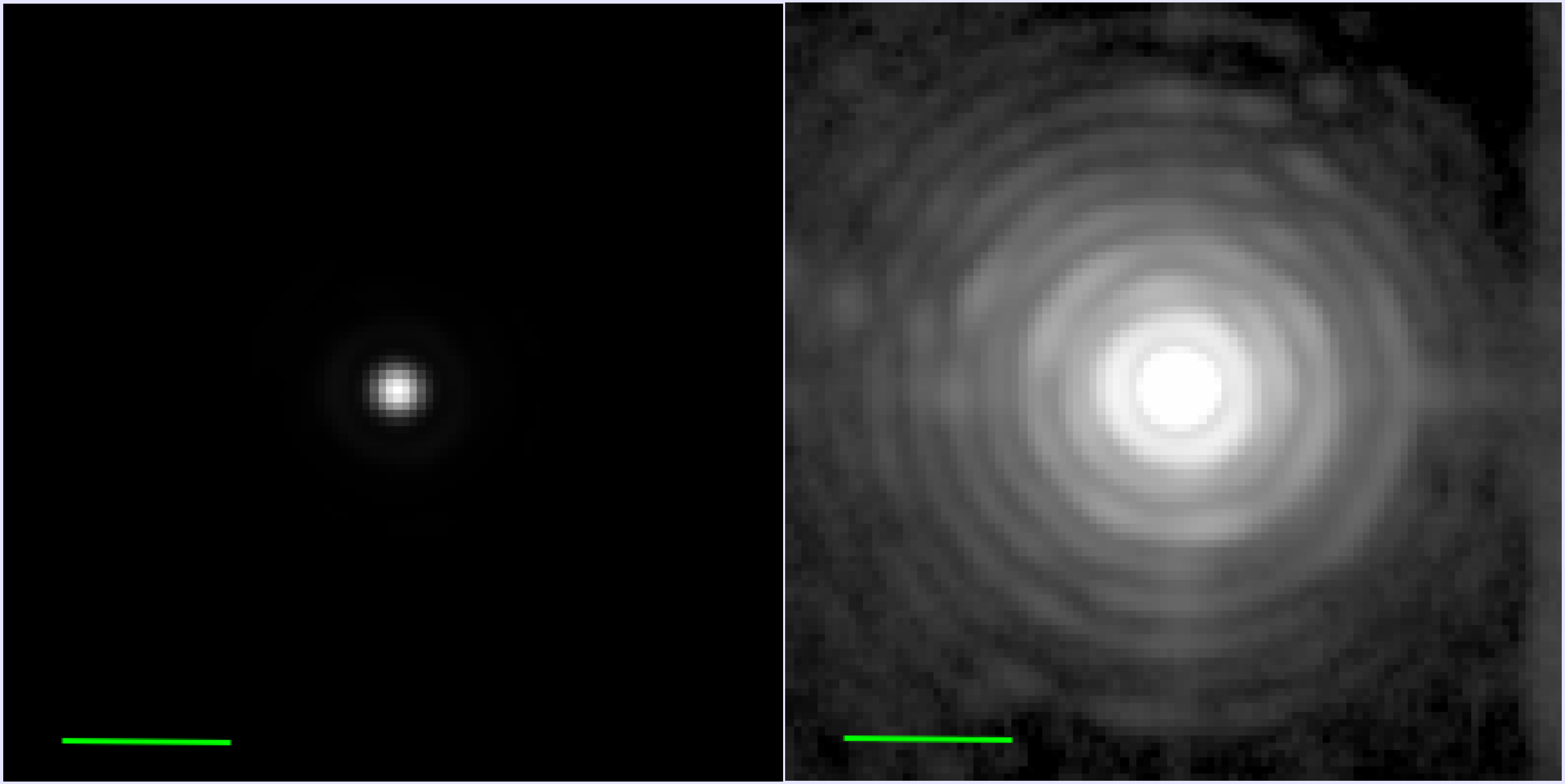
usage of angular differential imaging (ADI)

residual speckle intensities ~ $1/\lambda^2$

conclusion:

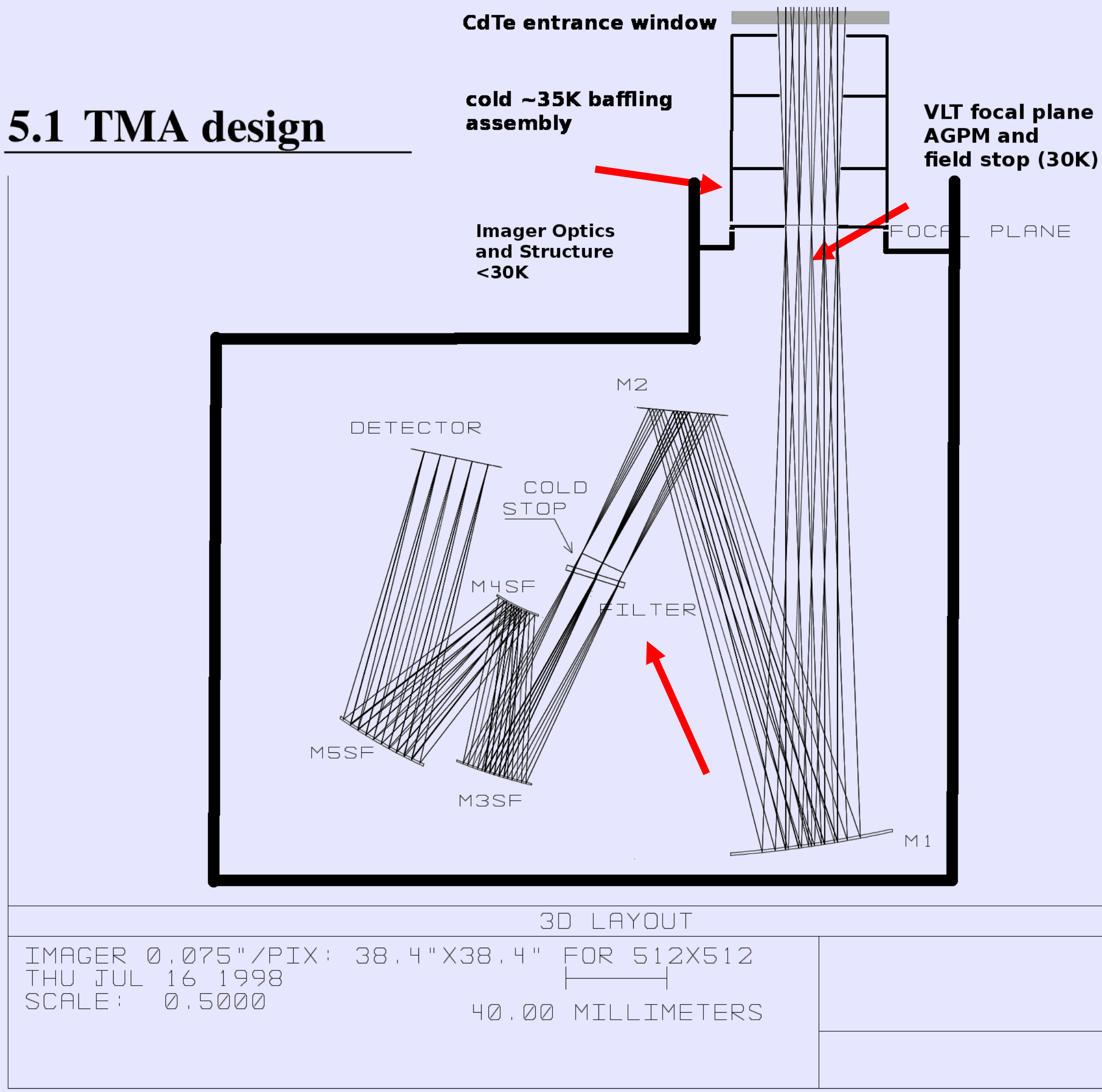
team at ESO is fully convinced, that the detection of a 2-earth diameter planet at $\alpha_{1,2}$ Cen is feasible

VISIR image quality proves potential for high contrast imaging



- left linear, right logarithmic (burst mode, shift and add)
- green bar 1 arcsec, ~11 Airy rings

Location of critical elements in optical path



Schematics VISIR imager 0.045"/pix configuration

- field stop with AGPM and 4-quadrant (4QPM) phase masks
- filter wheel in pupil plane with Lyot stops
- cold baffle limits solid angle at focal plane to ~400 deg^2
- illumination of focal plane with ~10% of a 290 K black body

Waves in Focal Regions: How does phase-shift coronagraphy work?

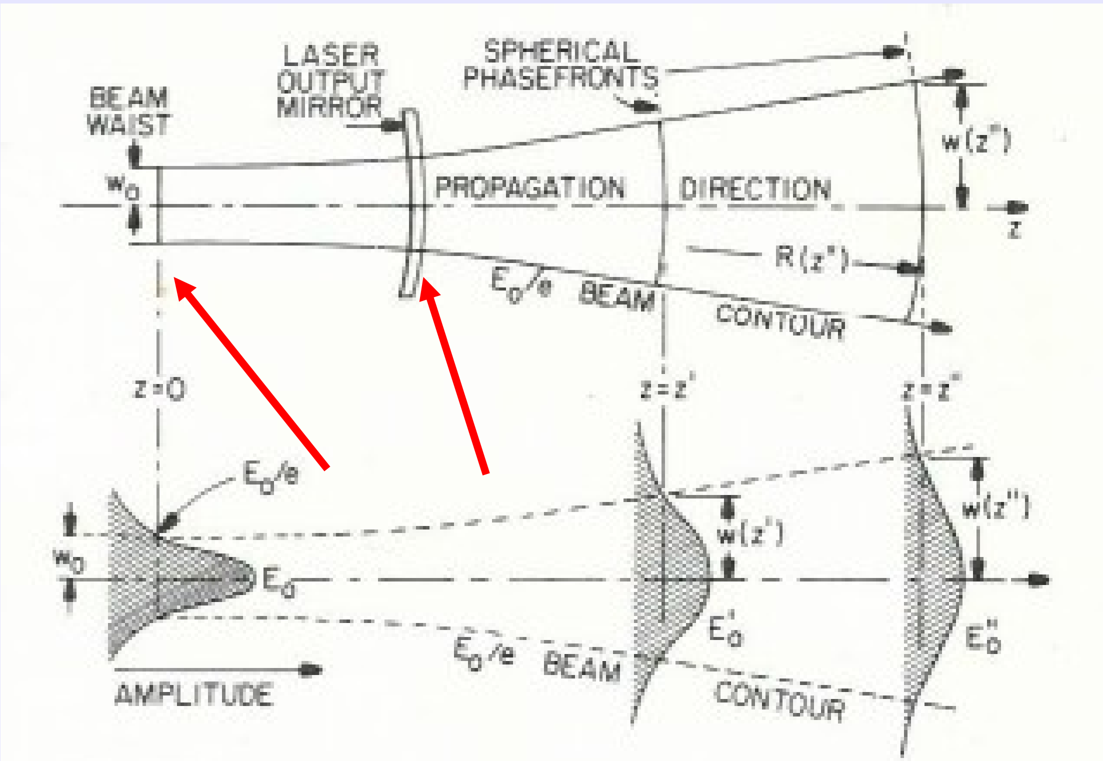


Fig. 12

Radius of Curvature of Wavefront at a Distance z from Beam Waist

$$R(z)=z\left[1+\left(\frac{\pi W_0^2}{\lambda z}\right)^2\right]=z\left[1+\left(\frac{z_R}{z}\right)^2\right] \qquad \text{V.8}$$

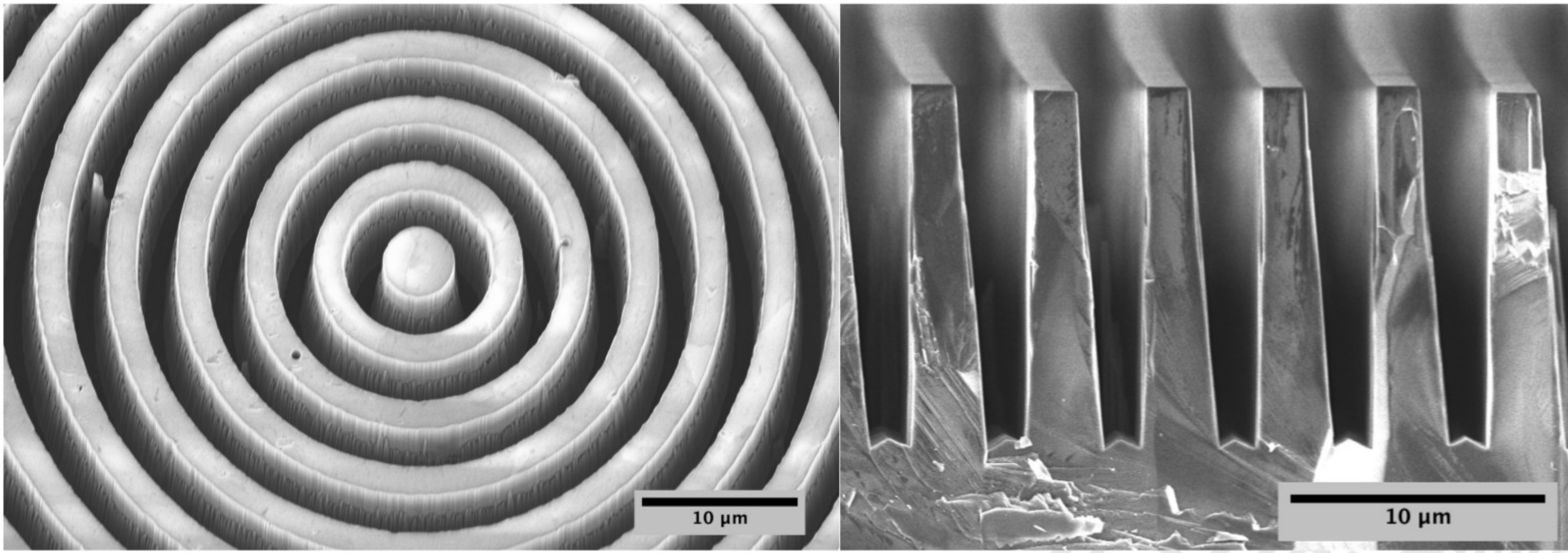
$$= z_R\left(\frac{z}{z_R}+\frac{z_R}{z}\right)$$

Complex Radius of Curvature $\tilde{q}(z)$

It is important to re-call two principles:

- In the focal plane – diffraction limited case any light bundle is a plane wave!!!
- any photon, even in unpolarized light, has a defined polarization state

Nanostructuring of diamond



In 2012

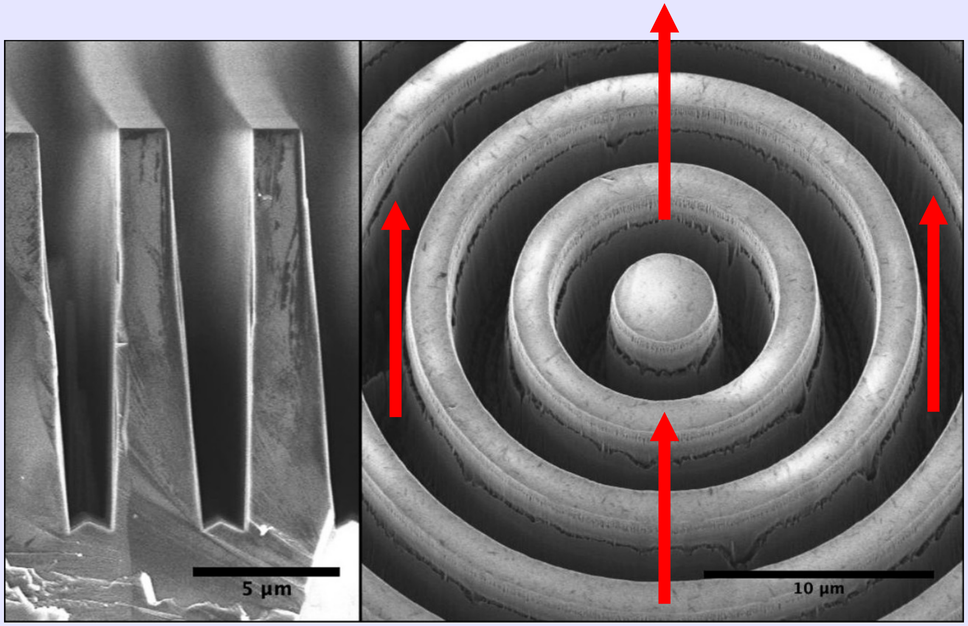
specification
- 4.6 µm period
- 1.84 µm line width at top
- 13.86 µm depth
- 2.75° angle of sidewalls

achieved
- 4.6 µm
- 1.83 ± 0.02 µm
- 13.8 ± 0.2 µm
- 2.75° ± 0.2°

P. Forsberg and M. Karlsson
Diamond and Related Materials
34 (2013).

UPPSALA
UNIVERSITET

AGPM:
Annular Groove Phase Mask

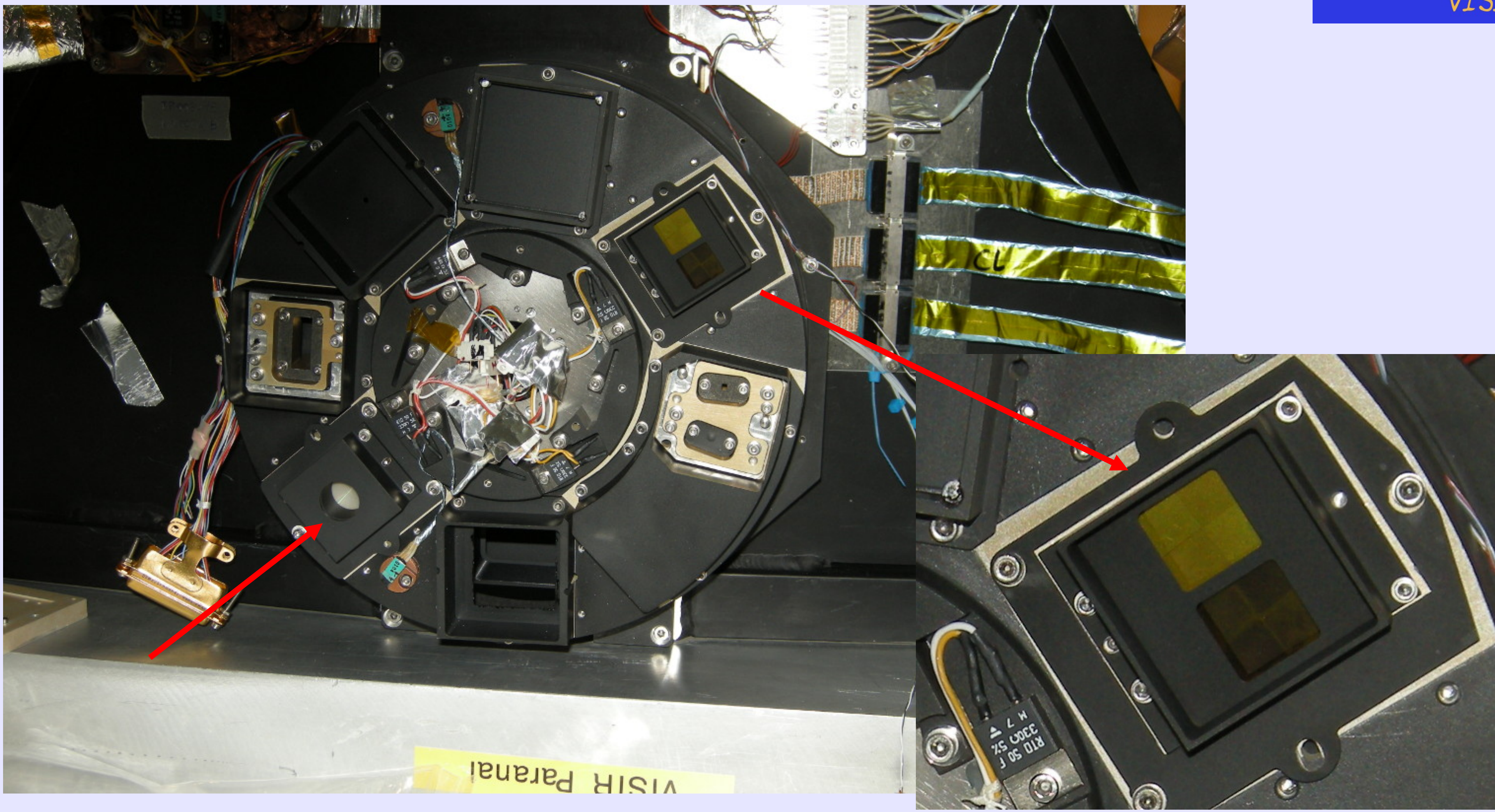


and the BEST it is to 1st order achromatic,
see SPIE paper [10702-28]
in *High-contrast Imaging*
Around the world: status and prospects with the infrared vortex coronagraph,
Olivier Absil et al. 2018

Sub-wavelength structure etched into synthetic diamond

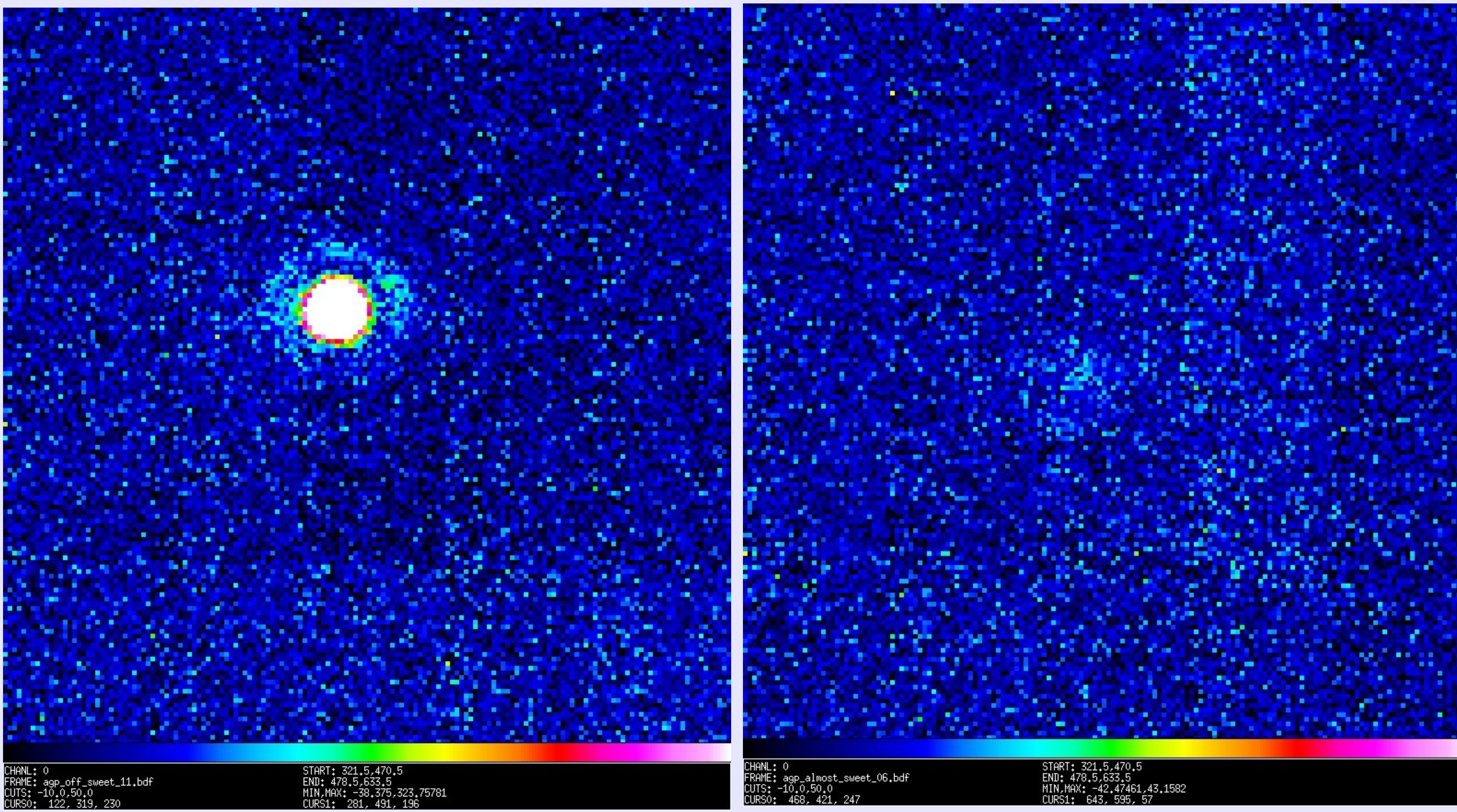
- produces extinction for a well centered electric field
- Very small inner working angle of ~10 mas
- Successfully prototyped 2011/2012
- NEAR will receive an improved version via *Breakthrough Initiatives*

Coronagraphy in VISIR: the phase masks



- the phase masks on the VISIR aperture wheel
- annular groove (AGPM) and 4 quadrant (4QPM) phase masks

“lab testing” of the 2011 VISIR annular groove phase mask



- VISIR star simulator: left sweet spot touches Airy ring right, star on sweet spot, attenuation ~100

VISIR AGPM results on sky

- examples from 1st early science verification with VISIR AGPM (Feb. 2016)
- data taken under rather adverse conditions (mediocre seeing, high humidity and telescope problems)
- intermediate images stored every ~100millisec, frame selection
- tracking issues of the VLT not yet corrected for axis and pupil
- please note WR104 is a new challenge for centering algorithms like QACITS

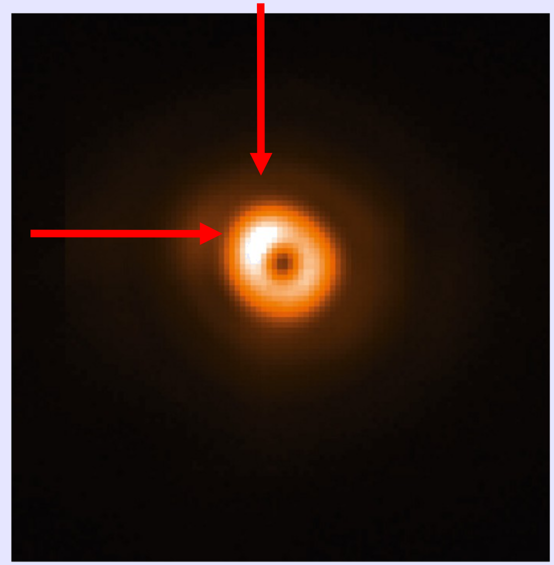


Figure 4. The mid-infrared extended dust emission around the Wolf–Rayet star WR104 is revealed by the VISIR coronagraphic annular groove mask.

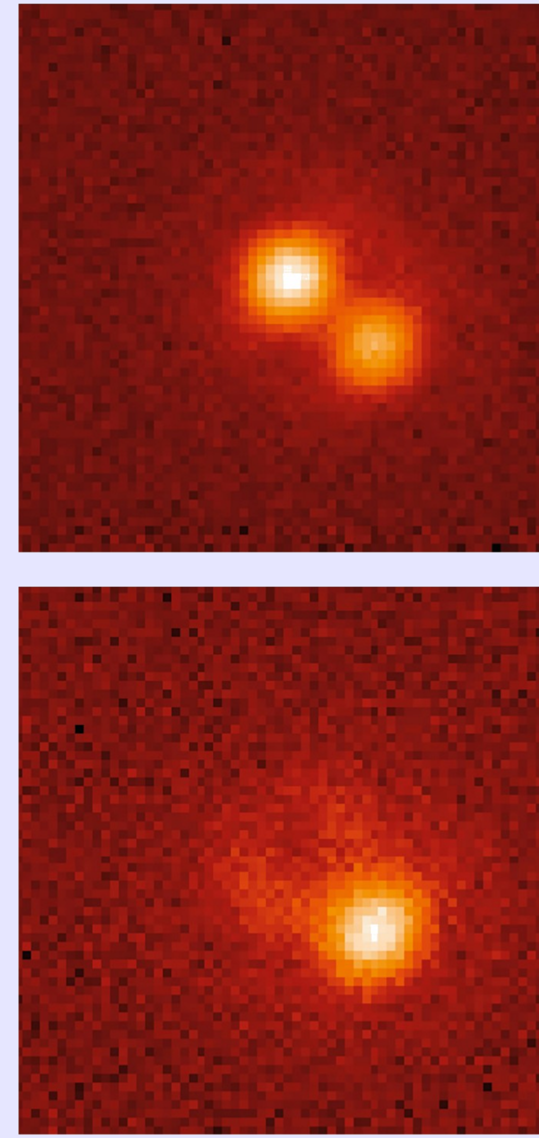


Figure 5. Demonstration of the AGPM coronagraph on the visual binary star η Oph (HR 6378) with the broad 12.4 μm filter. The upper image shows the binary without the annular groove phase mask, and the lower image with the coronagraph occulting the left-hand star.

Coronagraphy vs PSF subtraction

- annular groove masks produce a point-symmetric λ/2 phase shift around the sweet spot

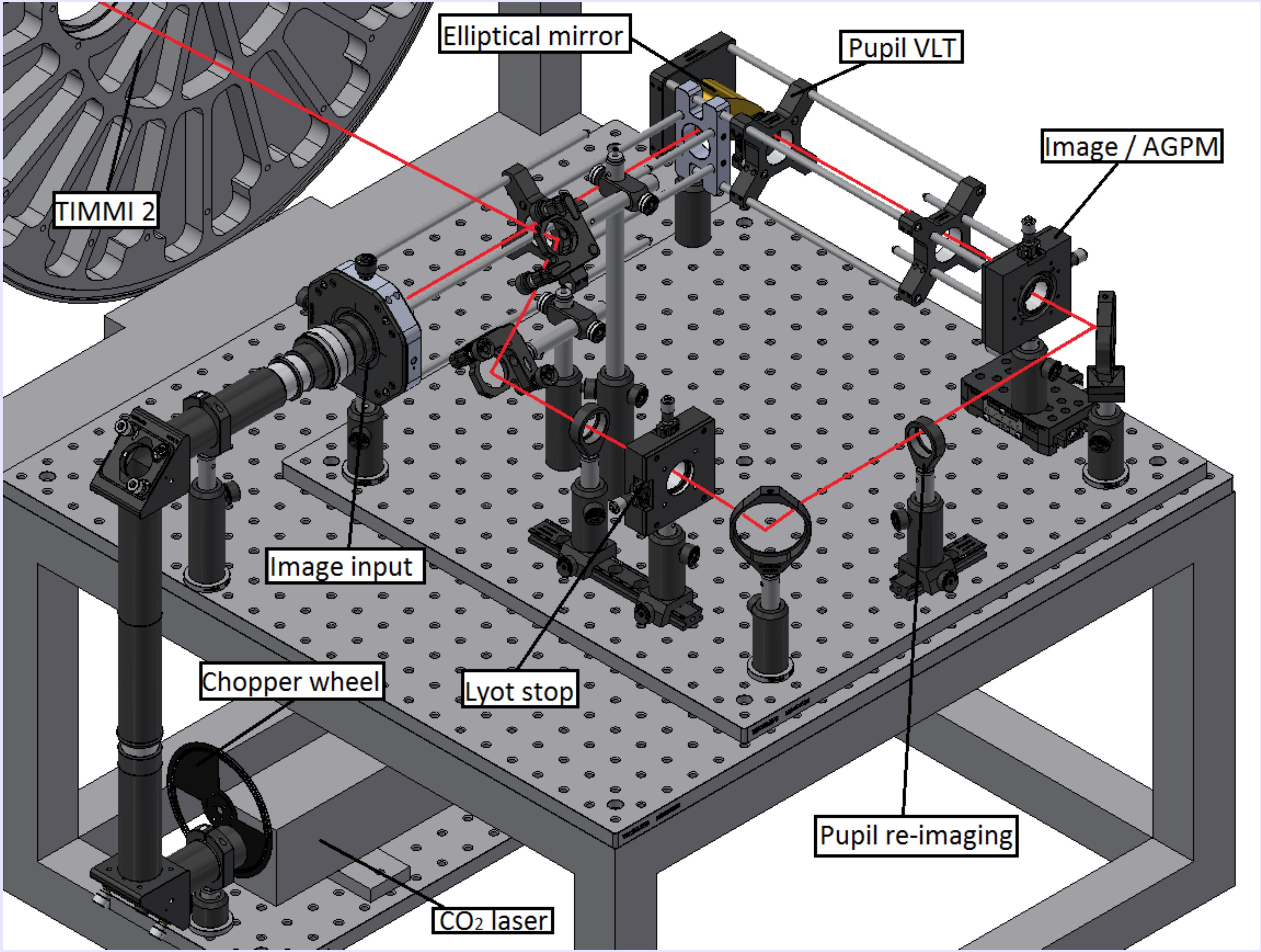
- extinction requires matched wavelength and full spatial coherence:
  => thermal background is not attenuated
  => compared to a classic occulting disc no “black spot” in the center:
  such a disk would produce 63 ghost images and would
  in general severly affect the image cosmetics

- relatively easy to operate and to keep star aligned

- extinction ratio AGPM: >> 100

- <u>non-negative process</u>, contrary to PSF subtraction:
  naïvely comparing performance of both methods I used to argue that in the extreme BLIP a coronagraph has not advantage over PSF-subtraction …

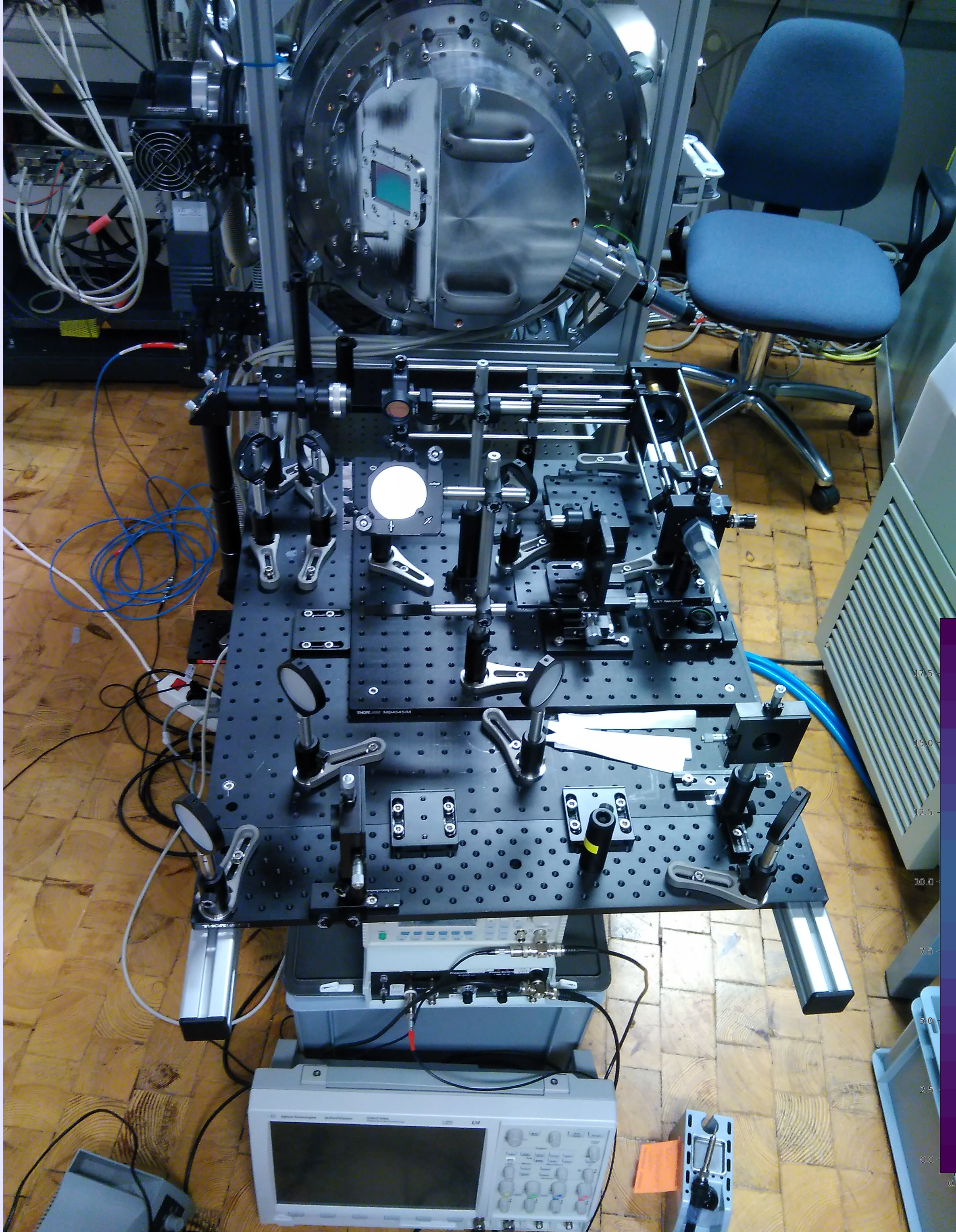
“lab testing” of the 2018 VISIR new annular groove phase mask



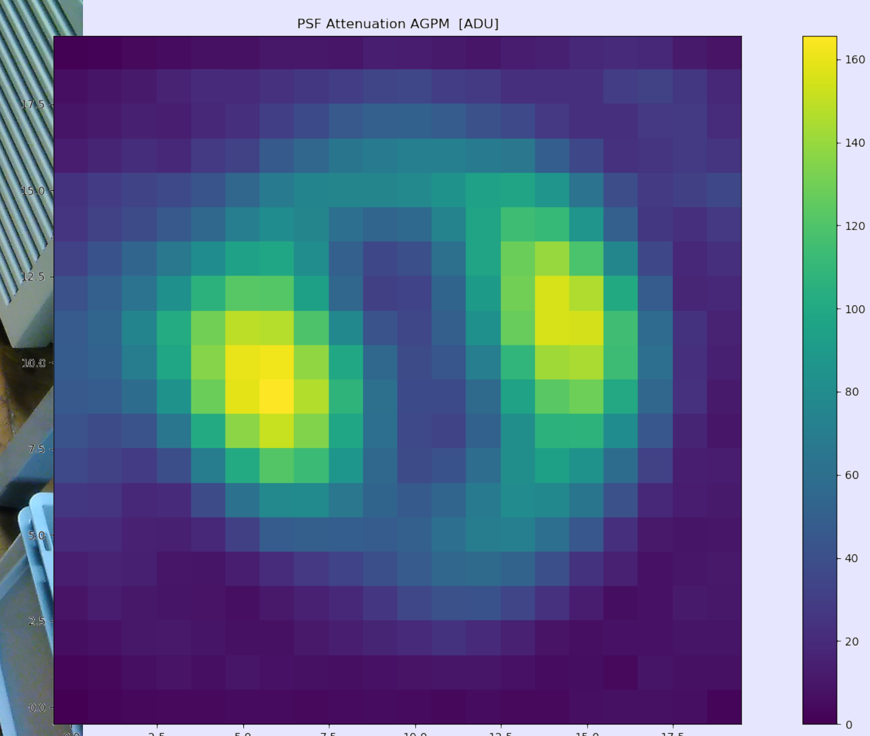
TIMMI2 Test Bench, the laser

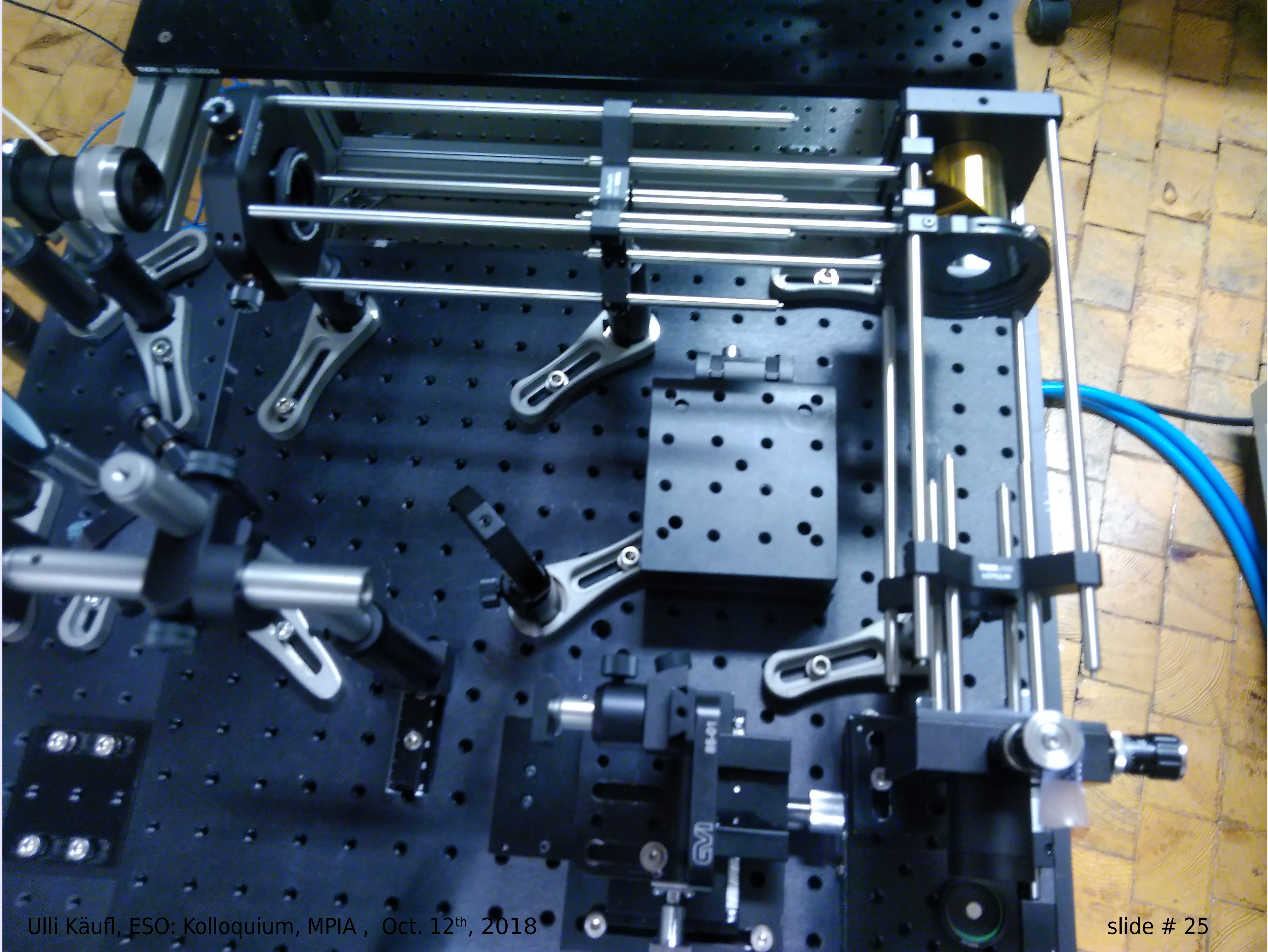
- Access Lasers, model 4LG ~10kEUR
- 100-200mW on ~40 lines between 9.3-10.8 µm
- RF excited =>long shelf life
- can be water cooled
- compact: 317x76x64 mm
- beam waist 2.4mm
  divergence 5.5mrad (f# ~ 180)
- Gaussian beam
- power stability 1-10%
- note:
  1) 1mW ~ 5 x 10^{16} ph/s
  2) lab background ~ 10^{8} - 10^{9} ph/s
  3) 100mW is good power for alignment with visualization cards

L4G



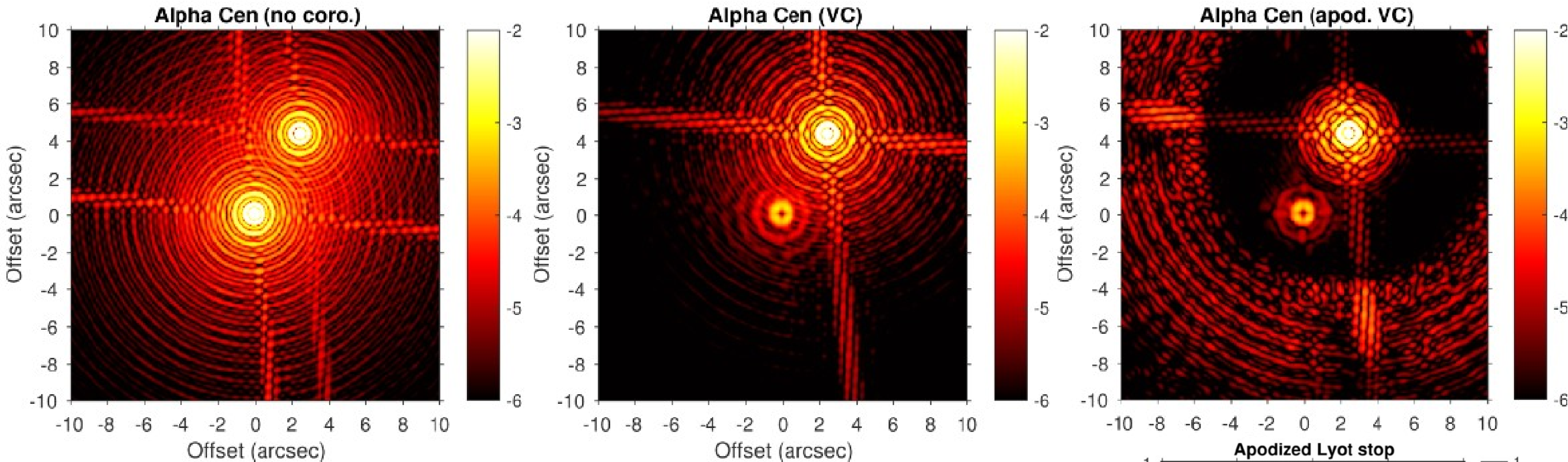
- the real set-up as it was last Monday
- still work to do ….



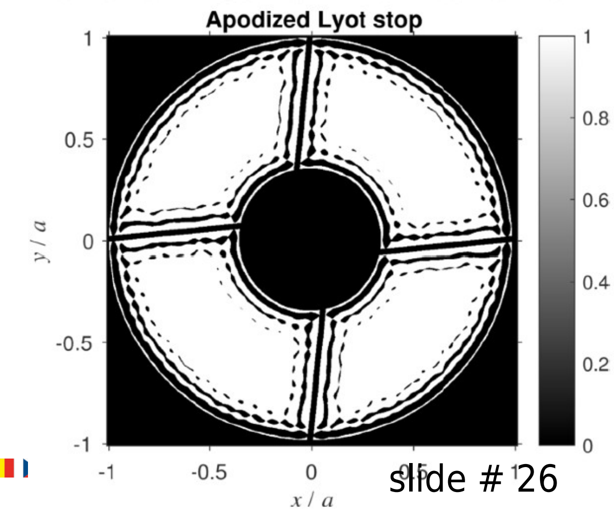


AGPM Lyot stop

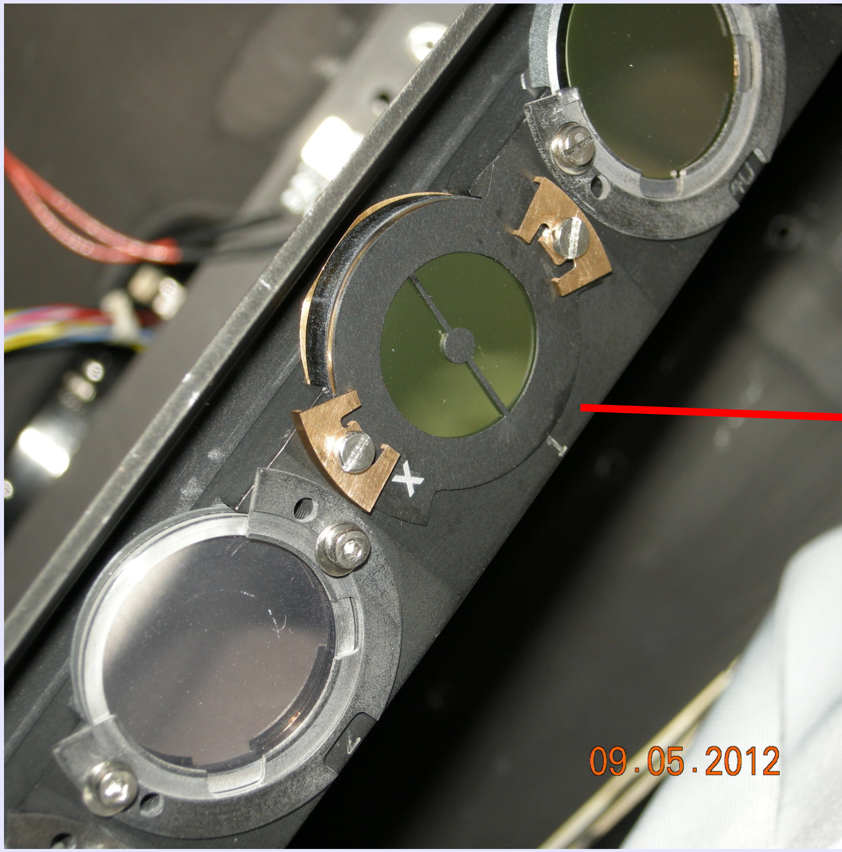
- Must suppress Airy rings of binary component, which is not centered on the AGPM

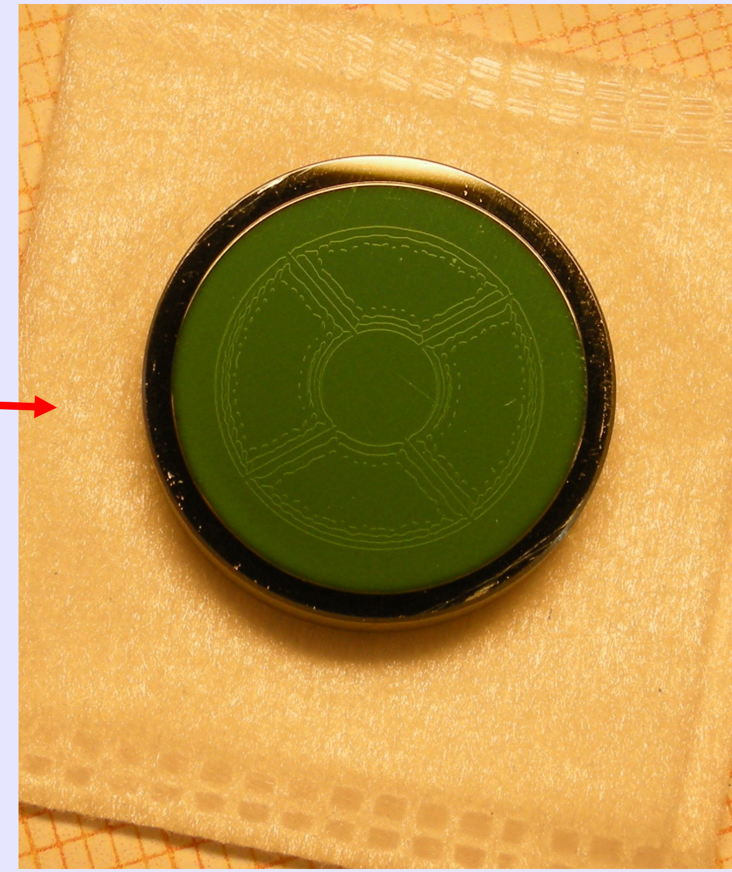


- Simulations and design by G. Ruane (Caltech)



New filters and Lyot stops for VISIR

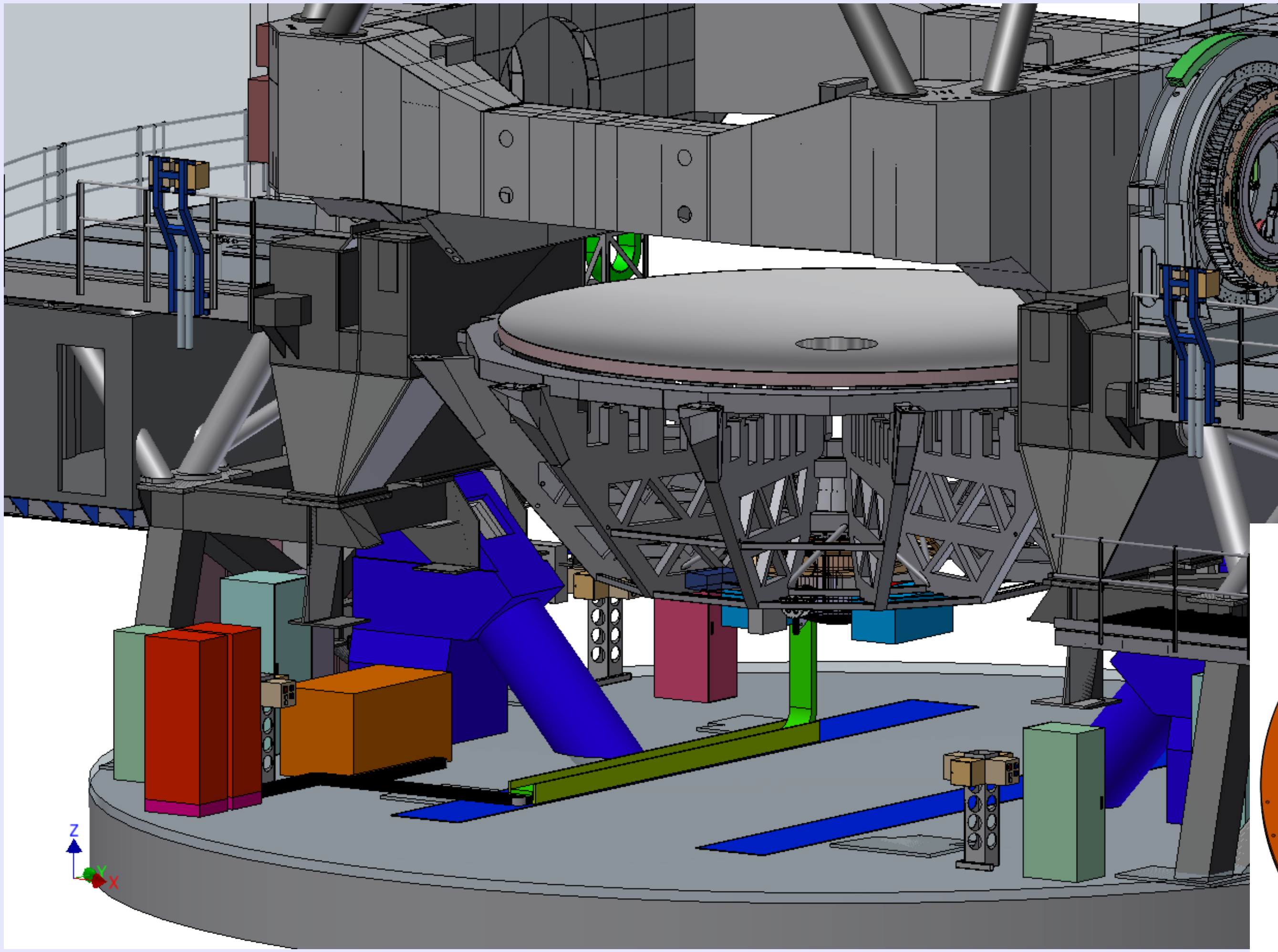




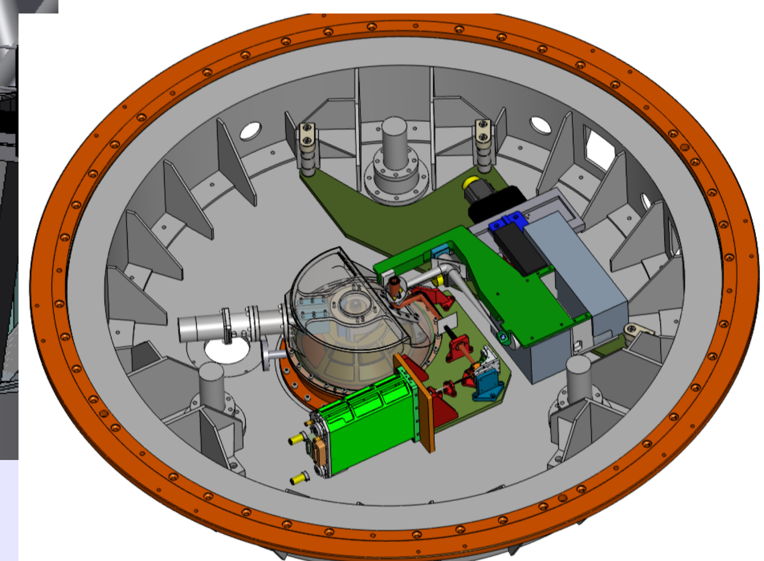
Challenge: Fabrication of integrated Lyot stop and filter to

- allow for precise centering of Lyot stop with reference to VLT pupil
- fit the design space

VISIR at UT4 Cass, consolidated mechanical design

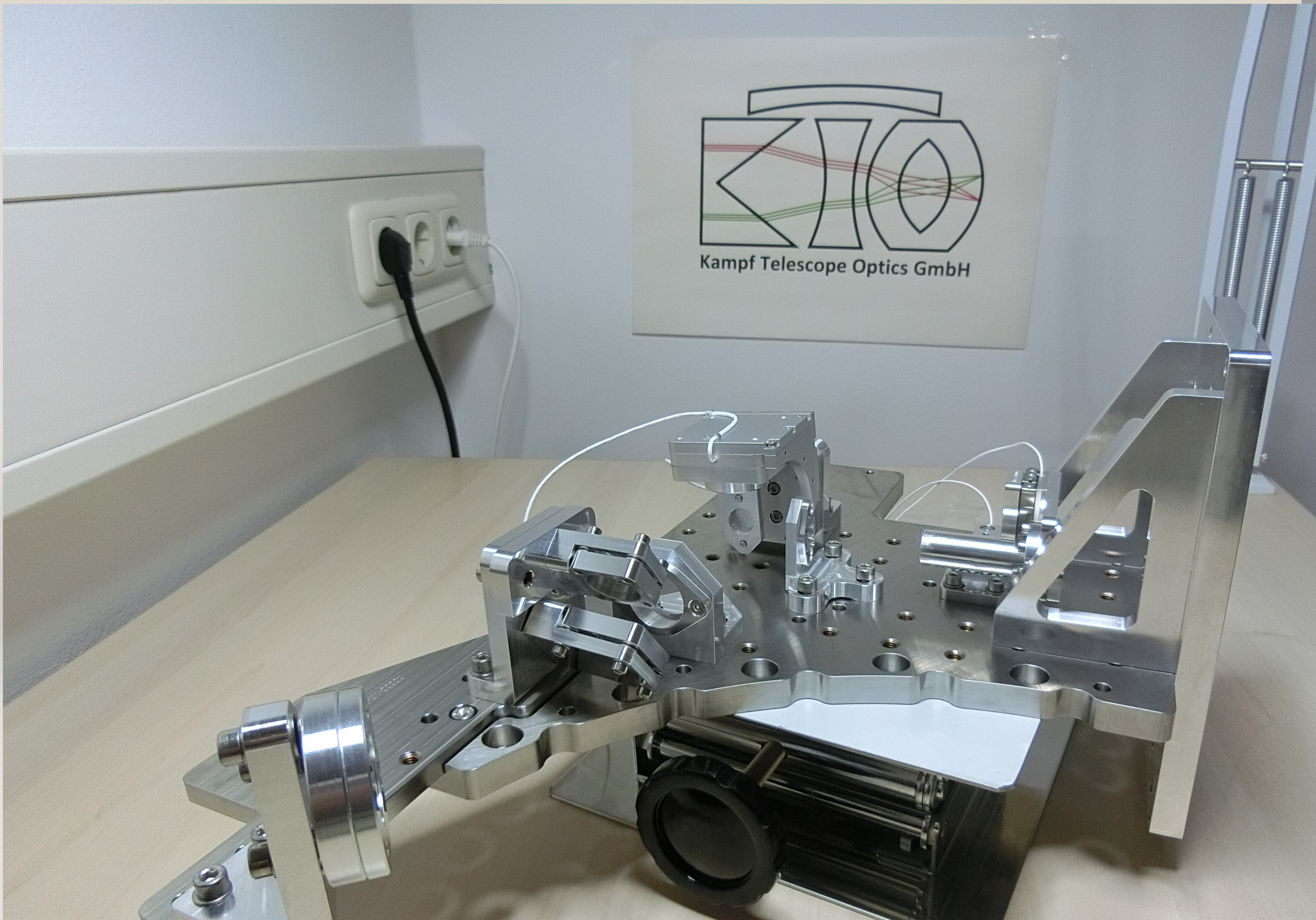


- Main rack as in UT3
- He compressors on Azimuth
- He lines and cables routed from M1 cell (not through wrap)
- Test cables long enough
- Weight neutral
- btw. this was VISIR base line design at FDR

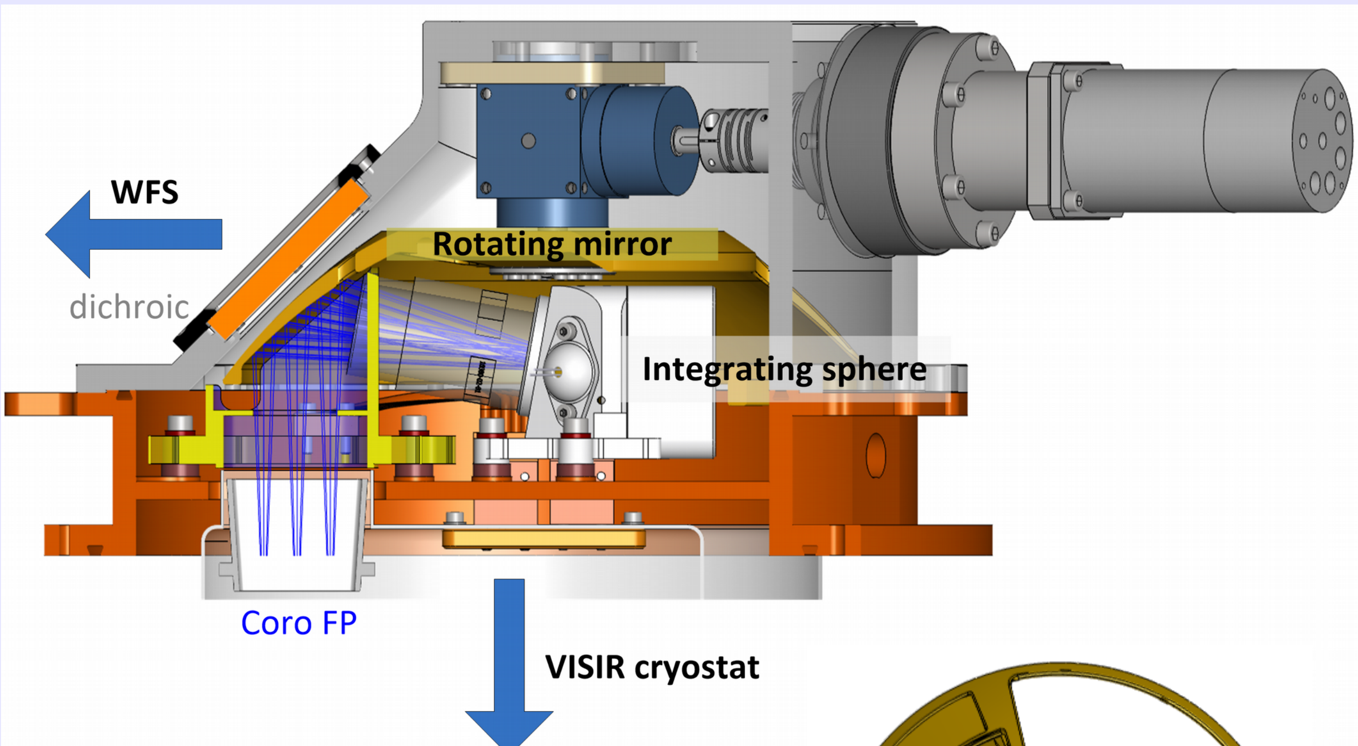


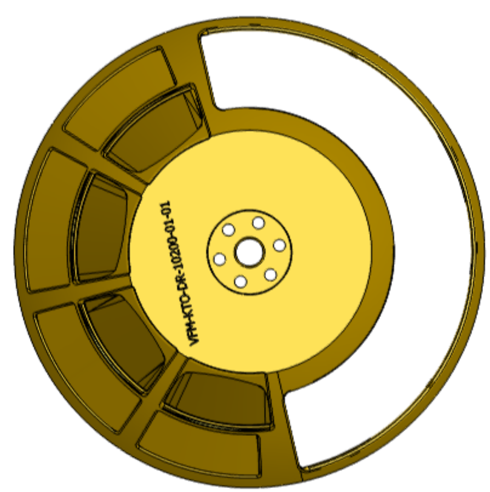
VISIR Flange Module (VFM)
Subcontracted to KT Optics, Munich

- **Compatibility with VLT tracking etc experimentally veryfied!!!**

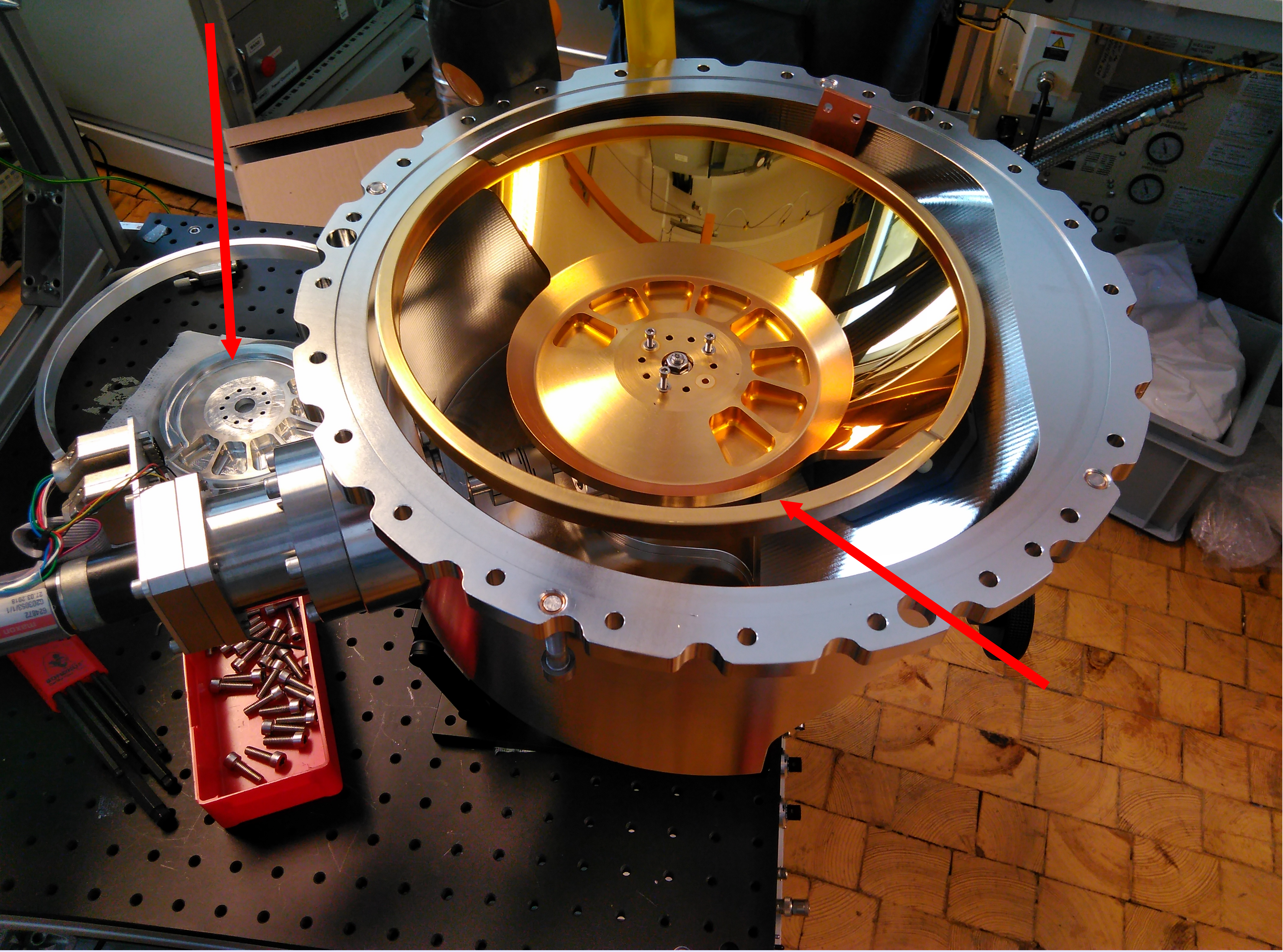

Kampf Telescope Optics GmbH

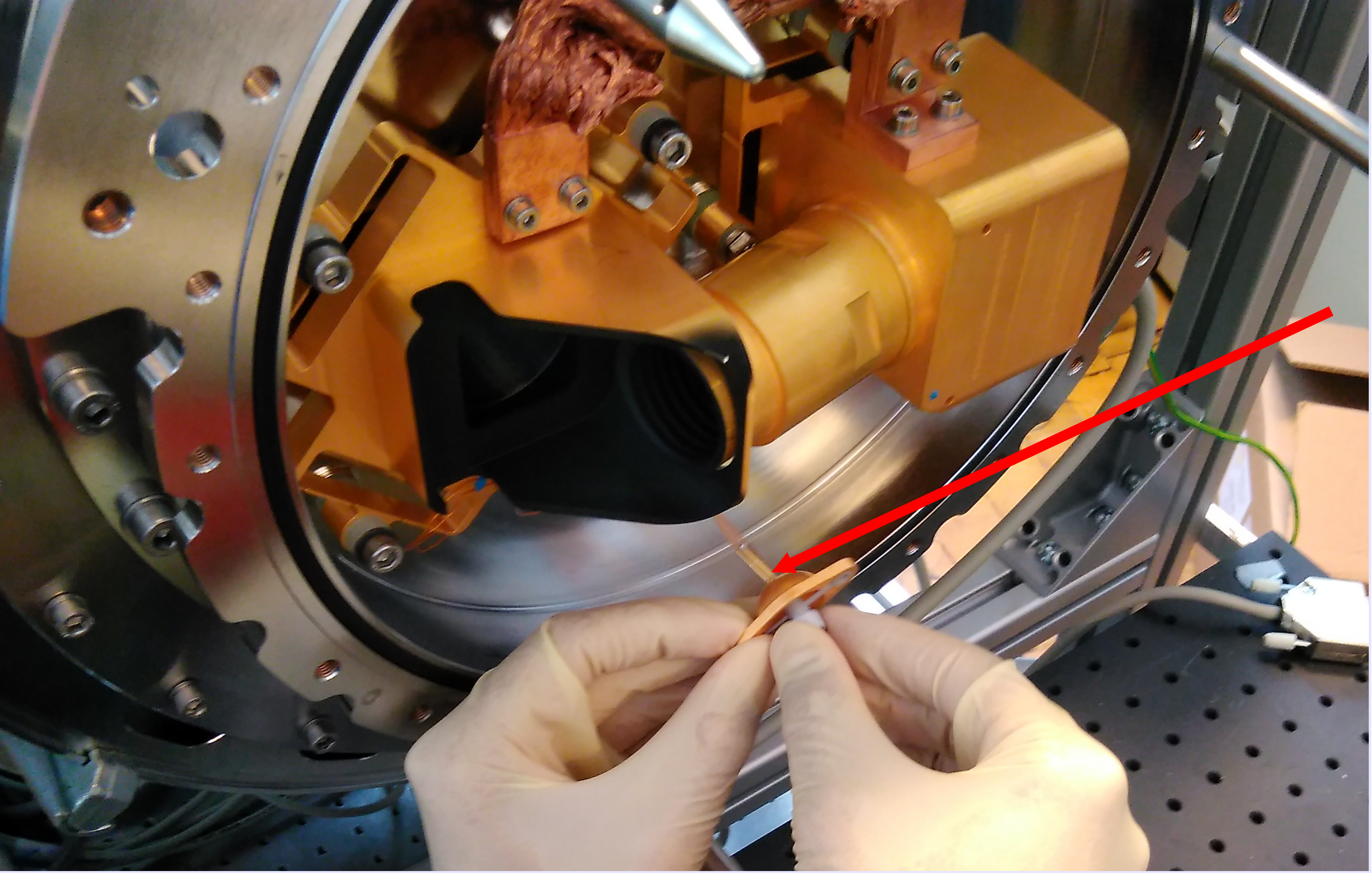
Vacuum Optics Unit (Internal chopper, Dicke Switch)



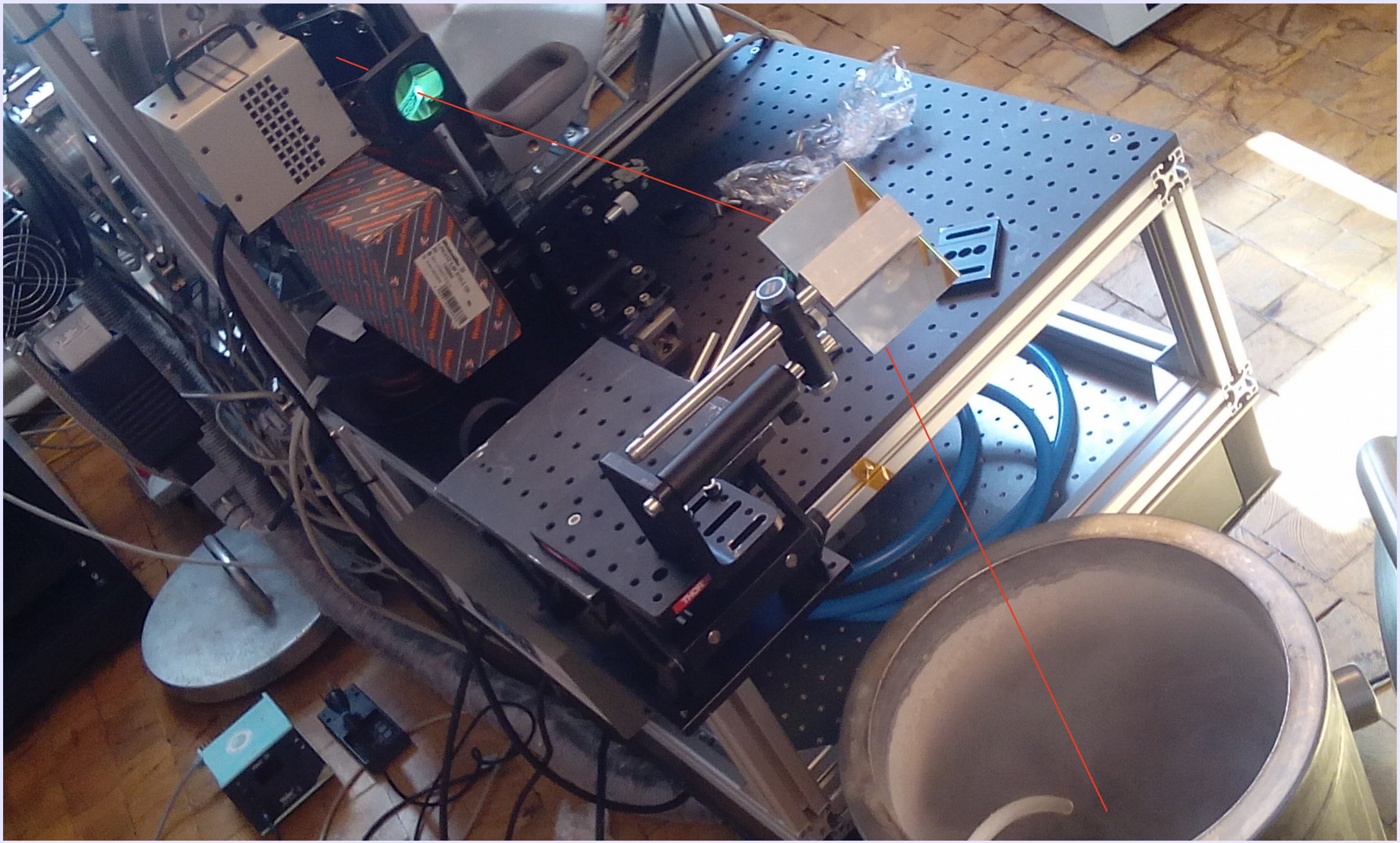


- Internal chopping
- Not seen by AO
- Robust ELFN rejection
- 50% efficiency
- f_{chopp} up to 10Hz
- color temperature of artificial sky ~290 K

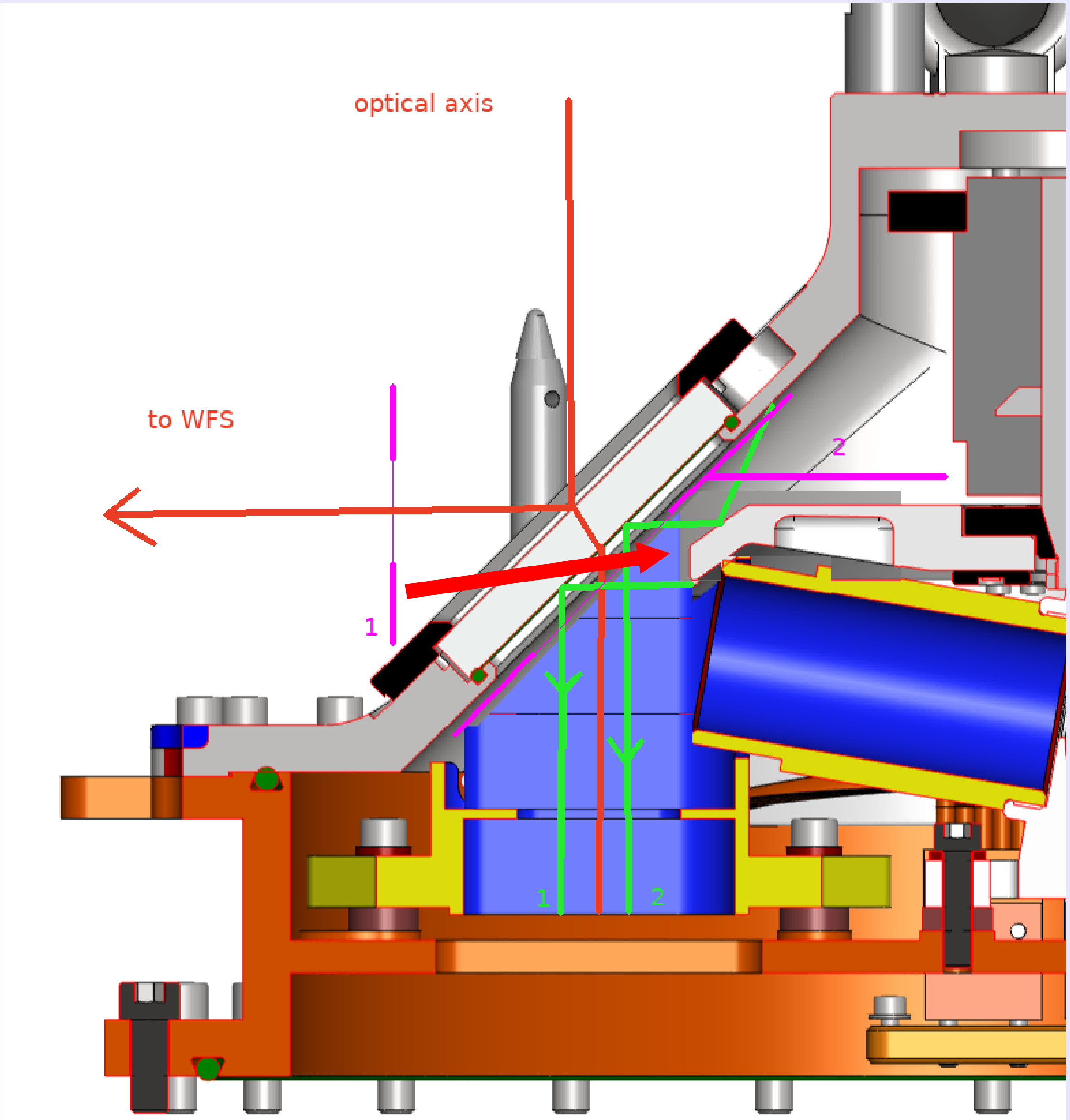




The New Chopper, Dicke Switch under test in the lab



The New Chopper, Dicke Switch under test in the lab: serious problems ...



Challenge: Dicke switch should have been cryogenic but ...

- difficult to baffle
- there are parasitic light paths ...
- #2 green could be suppressed by baffles
- # 1 green needed a new D-mirror

lesson learned:

- there are too many 10 µm photons and they find their way


THOR
THOR

Dicke Switch: success with modifications

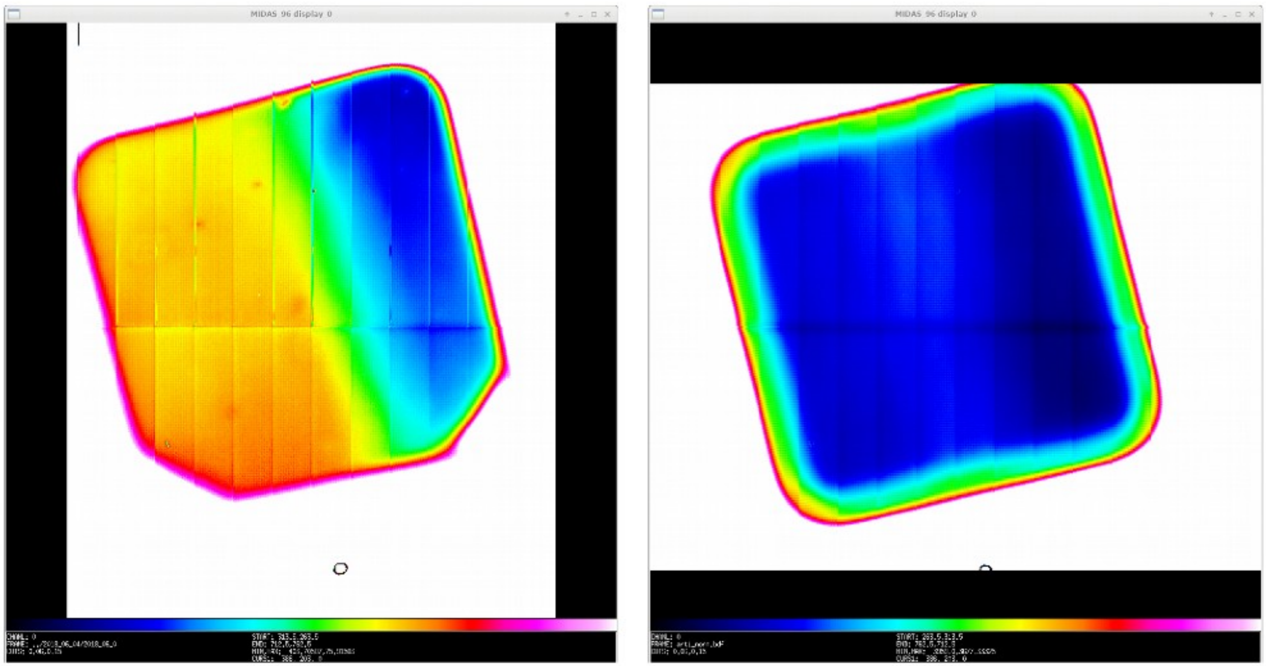


Figure 5: The left part is "artificial sky" with the configuration of June 2018, while the right image shows an image of the artificial sky in the July 2018 configuration. Both images are normalized to the background measured from the lab and plotted with the same cut levels (lo-cut 6%, high cut 15%). While a dramatic improvement is visible also the new configuration is still not flat. Still the variability of the sky signal and its impact on observations now appears acceptable (see discussion in text).

modifications:

- D-shaped mirror with sharp edge
- cold baffle at dichroic

- further reduction with final D-shaped mirror polished and guilded expected
- all components, especially cold baffle at dichroic will be substantially colder in VISIR

Dicke Switch: more noise ?

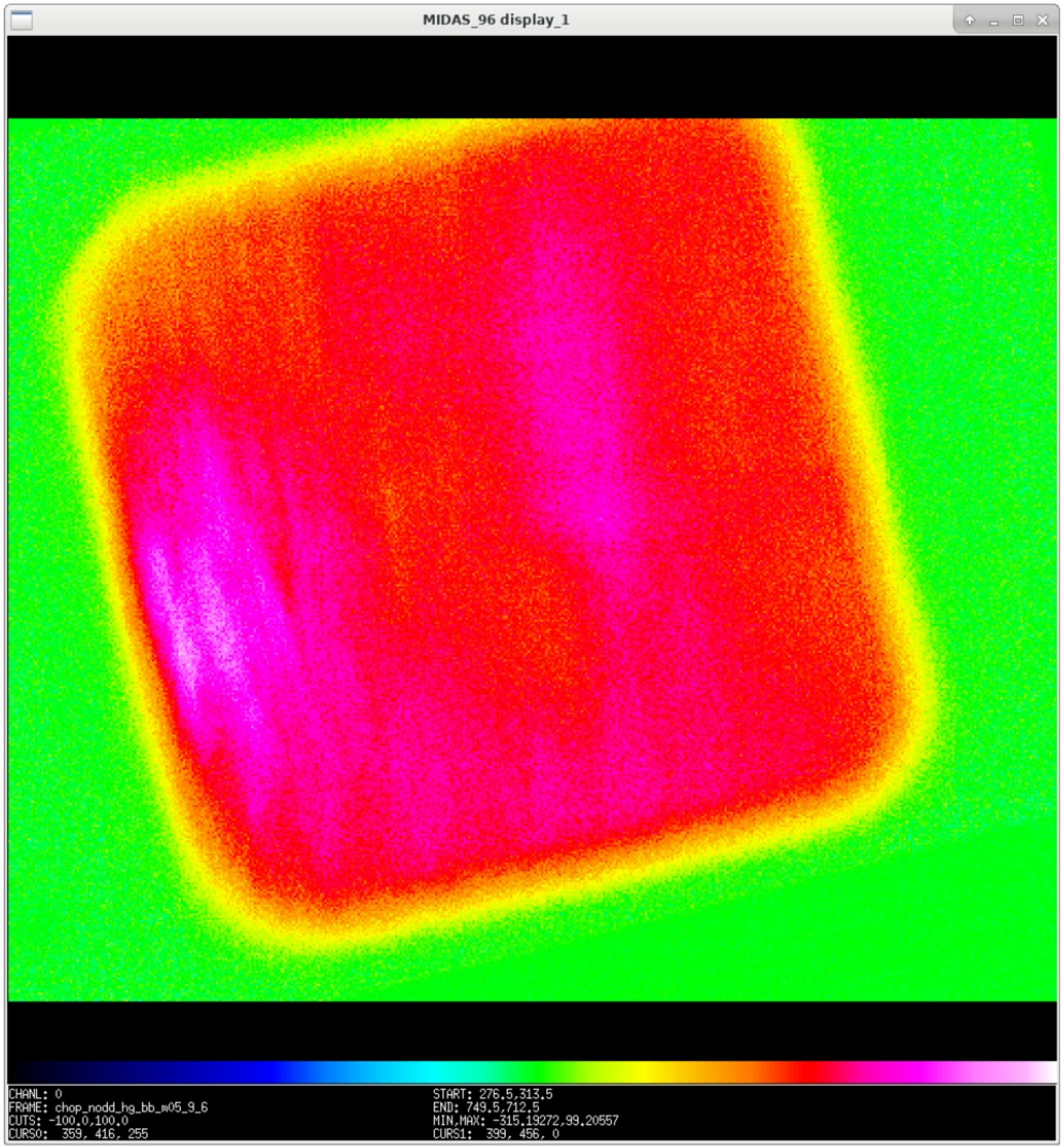
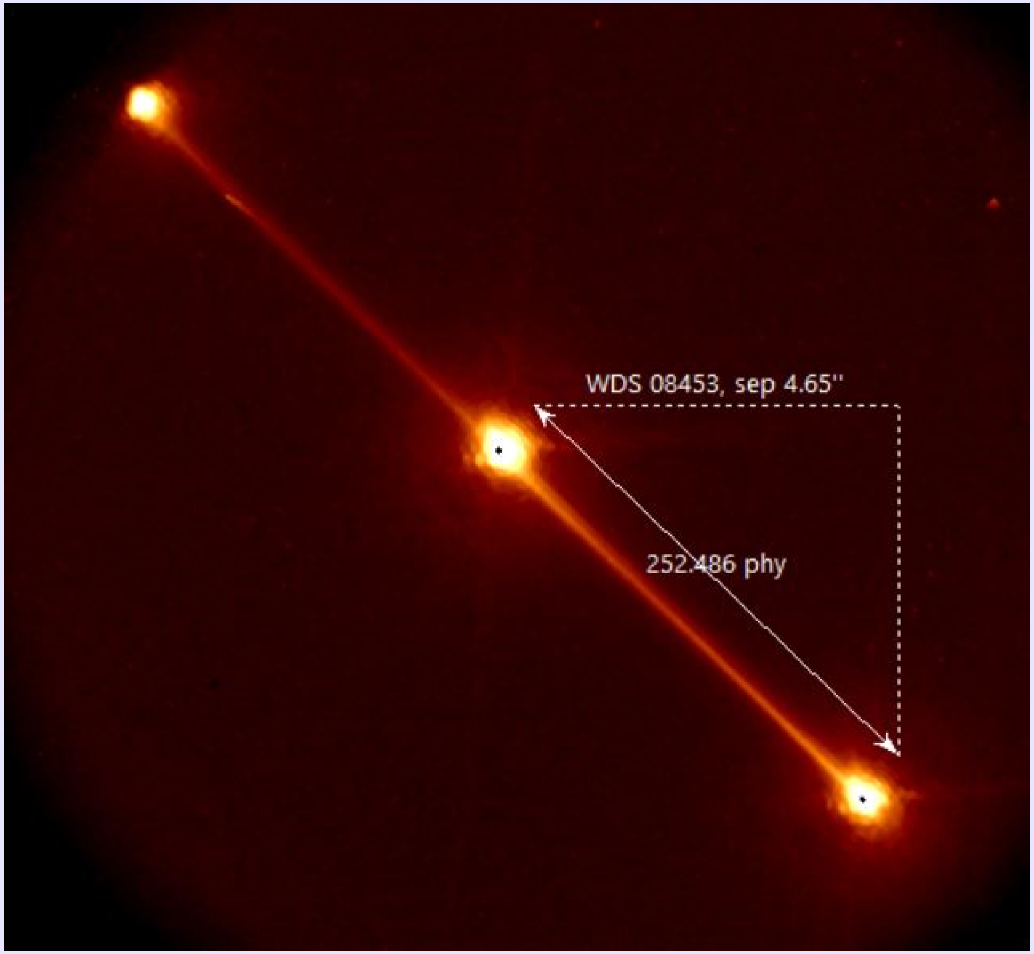


Figure A2_2: Chopped and simulated nodded exposure with 9.6 Hz chopping, "selfie"-mode vs. internal black body, normalized to the laboratory background (=1). Cuts are -100 to +100 ADU. The internal black body was set to -5C. Inside of the FOV of the instrument the residual "sky background" is now almost perfectly flat.

Dicke vs sky chopping

- chopping and nodding with artificial sky yields almost flat noise map
- no additional noise from Dicke switching
- increase of chopping frequency from 3-4 to 10 Hz reduces the Excess Low Frequency Noise (ELFN) of the Aquarius detector by a 30-50%

Chopping Alternative: Using the tip-tilt capability of the VLT active M2



Contract with deformable secondary (DSM) supplier (Microgate) to increase tip tilt stroke

- Successful on sky testing with a K-band camera
- Stroke just enough to have α Cen A or α Cen B alternatively on the coronagraphic spot
- Duty cycle of >90% at 10 Hz

NEAR Structure and Milestones

Structure

- NEAR is hosted within the ESO Technology Development Programme
- NEAR is supported by a grant and hardware from the Breakthrough Initiatives
- NEAR is awarded 100hs of observing time

Schedule

- Jan-April 2018: Preparation of Garching test setup ✔
- Early 2^{nd} Q18: VFM Delivery by KTO @ ESO ✔
- 2^{nd} Q18: Test of VFM and AGPM (ULg deliverable to BTI) in ESO InfraRed Test Facility (ex TIMMI 2) ⇲
- 4Q18: Preparation work on UT4
- Late 2018 shipping / Early 2019: VISIR re-furbishment in NIH, commissioning
- Mid 2019: NEAR observing Campaign

NEAR, an Experiment by ESO and the Breakthrough Initiatives: Conclusions

- the combination of the VLT-AOF with an AGPM in VISIR will deliver a close to perfect high contrast imager!
- VISIR with AO – as visiting instrument to the ESO AOF – has the potential to image Earth-like planets in the α-Cen system
- while exo-planets will largely be the domain of future E-ELTs the VISIR AGPM could also allow for in depth unique investigations of matter very close to bright stars:
  disks, ejecta, accretion phenomena ….

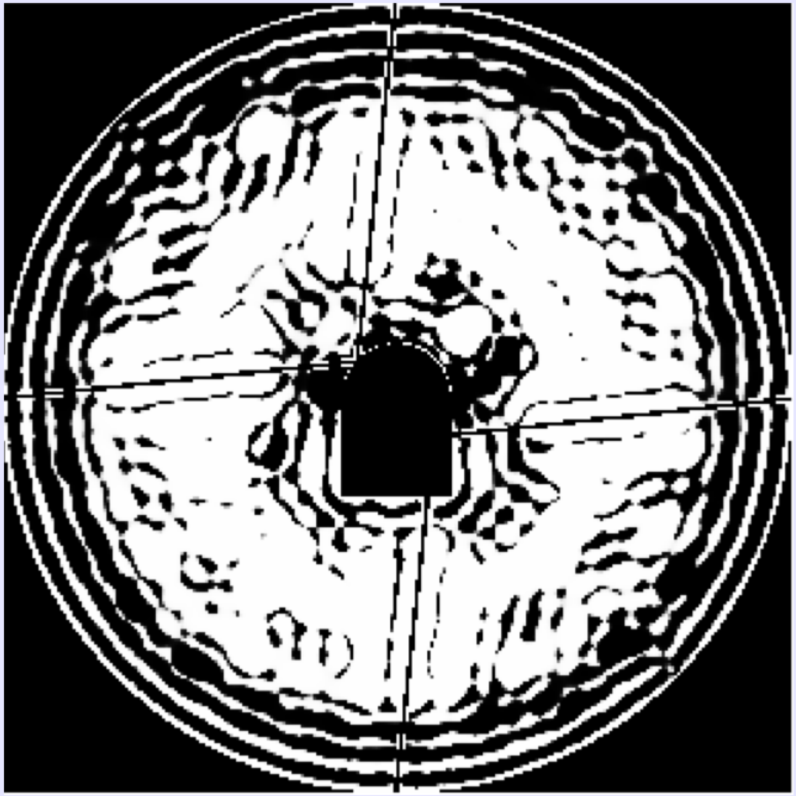
AND

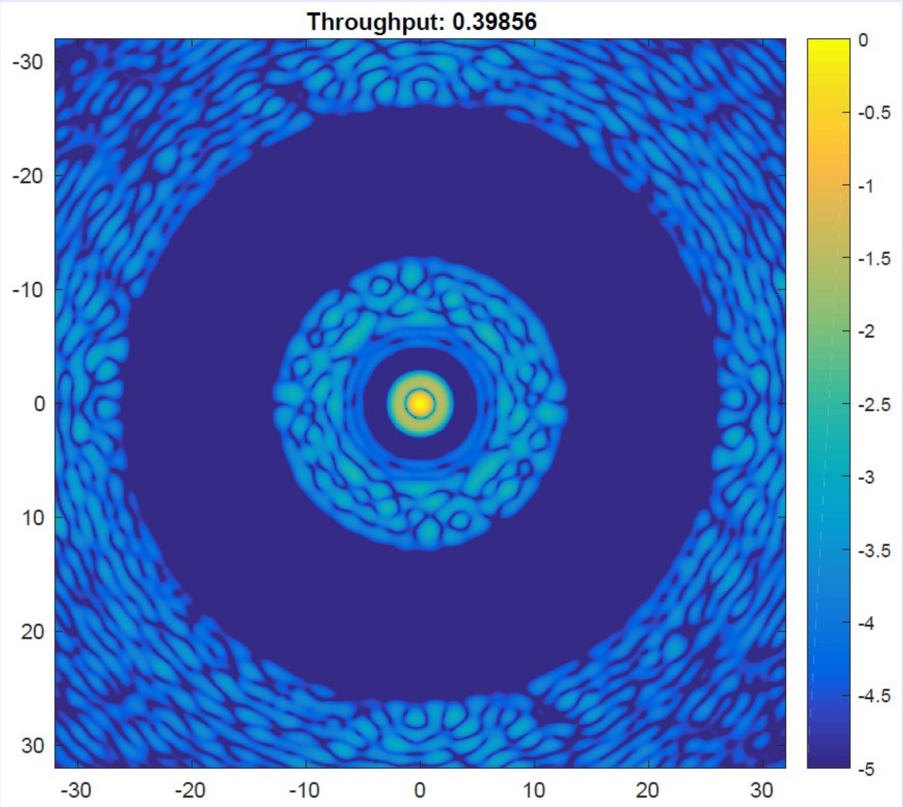
- Dicke switch recommended for E-ELT METIS


DON'T PANIC

Risk mitigation: Coronagraph

- Baseline: AGPM
- Risks: centering requirement 10 mas, one sweet spot only, need high-contrast between 13-23 λ/D because of binary
- Mitigation: Shaped Pupil (A. Carlotti, IPAG), design in progress





beyond coronagraphy: photon angular momentum

shining light through a vortex with a phase step of n*λ produces light with photon angular momentum equal n * ħ !

in astronomy light passing a rotating black hole can acquire such photon angular momentum (e.g. D. Hetharia et al. 2014)

left, from G. Anzolin et al. (2008), shows how starlight after a phase shifter – here a fork - focuses differently

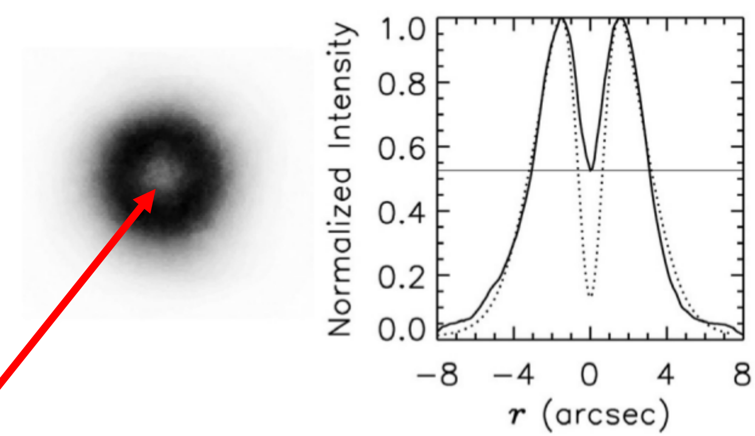


Fig. 6. *Left*: the narrow-band OV of α Boo obtained by summing the selected frames (see text). The intensity is displayed in a squared greyscale. *Right*: profile of the OV across the direction perpendicular to the dispersion (solid line). The dotted line represents the numerical simulation of an $\ell = 1$ OV produced by a PSF modelled as described in the text, with a spectral range of 300 Å. The thin solid line indicates the observed intensity in the central dark region.

Risk mitigation: NCPA

- Baseline: Pre-cal of NCPA, dichroic of superb optical quality
- Risks: Thermal deformation of dichro, optical drifts
- Mitigation: ZELDA Zernike WFS (N'Diaye et al. A&A 2013, 2016)
- Status: Procurement launched with team at LAM, delivery 03/2018
- needs also to fix the defocus of pupil imager which has developed

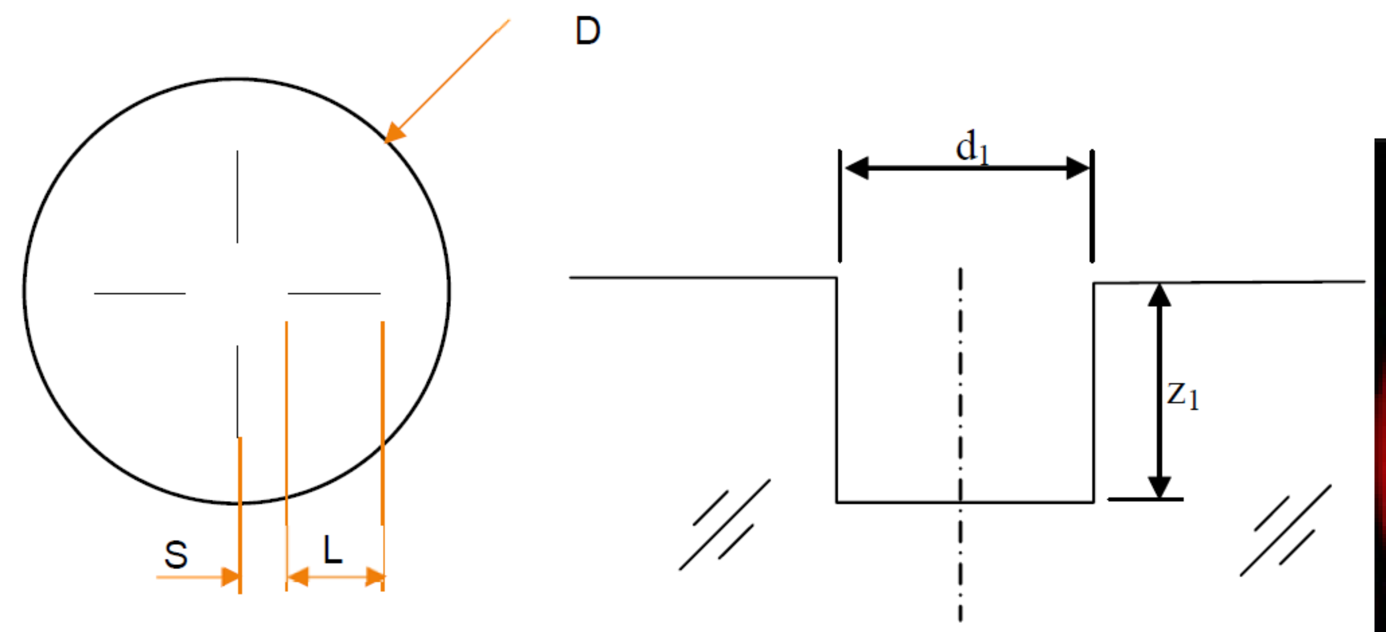
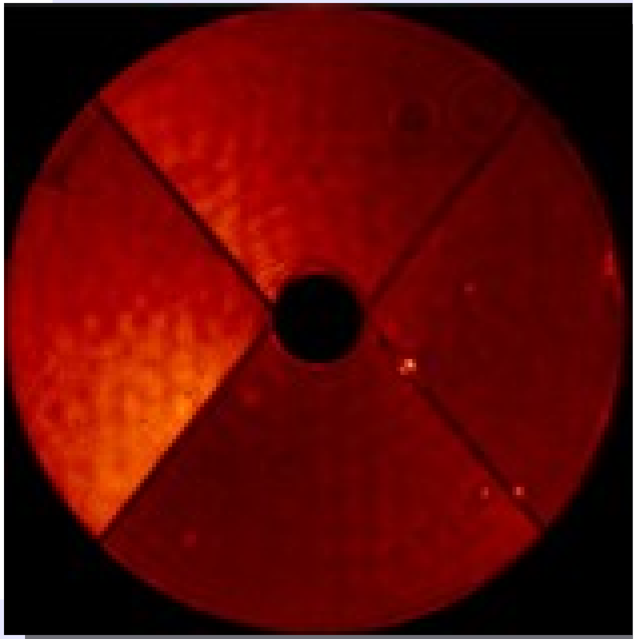


Figure 1: Substrate layout (left) and definition of the mask parameters (right).

implemented in SPHERE

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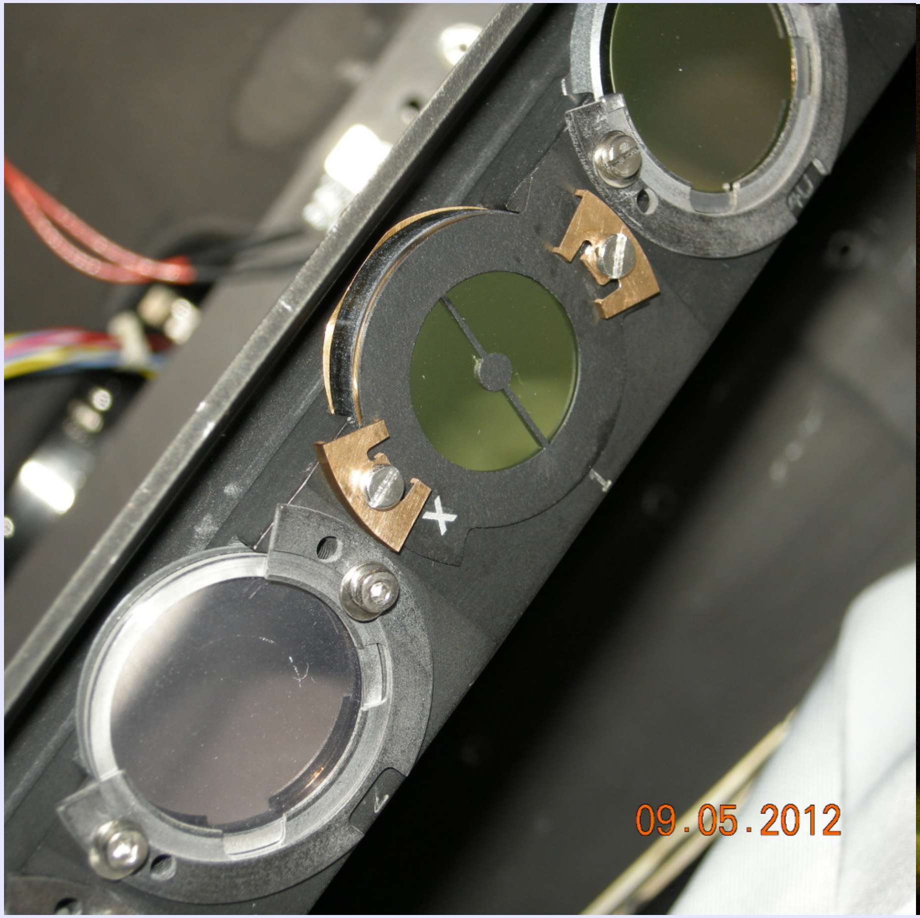
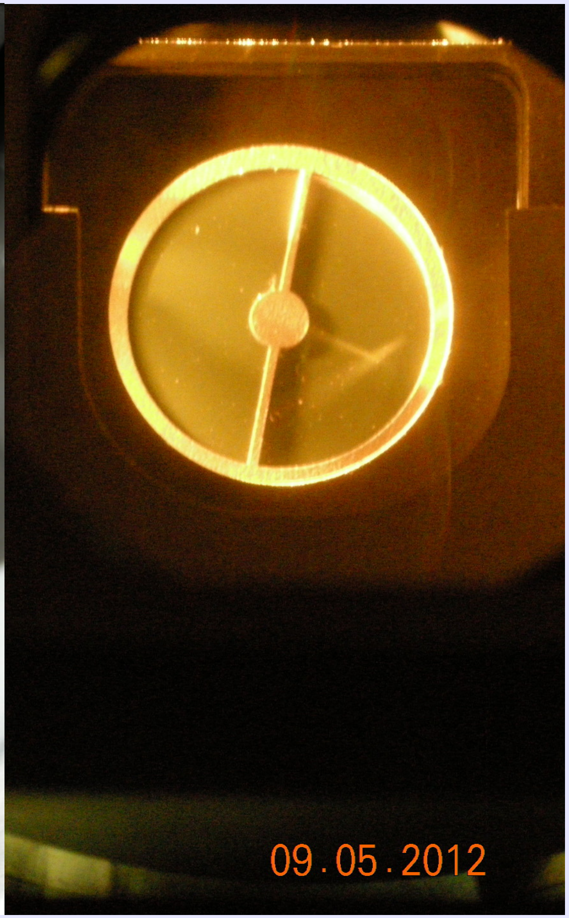
Lyot stop at filter wheel





Lyot Stop in VISIR
cold pupil combined with dedicated filters

- individually mounted and centered for each dedicated filter
- centering a bit tricky
- geometry not yet optimized
- interesting filters may also be used without stop

- with standard digital camera focused to ∞ in focal plane alignment of Lyot stop with instrument cold pupil can conveniently be checked