LAGRANGE

The self-coherent camera temporally modulated

– a satisfactory paradox –

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Wavefront measurements from focal plane intensity

Wavefront sensing

- Conventional wavefront sensors

Measure aberrations using light ahead of a coronagraph

- Common-path wavefront sensors

(i) Exploit the post-coronagraphic image

(ii) or the light diffracted by the focal plane mask to infer aberrations to the coronagraphic image

Wavefront sensing using science camera:

- avoids non-common path errors,
- wavefront measurements performed at the same wavelength as science acquisition.

Technique	Modulation used	Real time	Science duty cycle
Modal WFS	no	yes	100%
LDFC	no	yes	100%
MEDUSAE	no	no	$< 100\%$
COFFEE	yes	no	$< 100\%$
QACITS	no	yes	100%
SCC	yes	yes	100%
Pairwise probing	yes	no	$< 100\%$
Speckle nulling	yes	yes	$< 100\%$
Phase retrieval	yes	no	$< 100\%$
Kernel phase	yes	yes	$< 100\%$
Phase shifting interferometry	no	yes	100%
Phase sorting interferometry	no	yes	100%

Jovanovic et al. SPIE 2018

Many approaches have been developed to recover wavefront measurements from focal plane intensity, and fall into two categories:

- **temporal modulation**
- **spatial modulation**

The Self-Coherent Camera – SCC

Spatial modulation technique

➢ Basic principles

(i) Rely on continuous interference between the speckle field and permanent probe,
(ii) decompose the focal plane image into coherent and incoherent components,
(iii) coherent part drives the control of the electric field,
(iv) incoherent part contains astrophysical signal (e.g. planet).

➢ SCC in practice

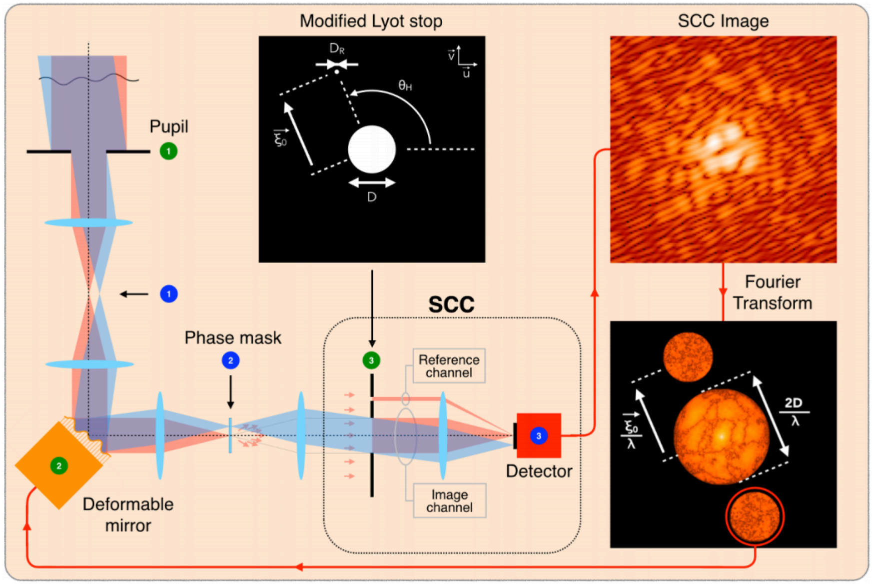
Uses a small off-axis reference hole in the Lyot stop of coronagraph (reference channel)

The electric field in the science image is spatially modulated w/ fringes

A single image is necessary to estimate the electric field, **science duty cycle is 100%**

Electric field is:

- retrieve based on the analysis of the Fourier transform of the science image
- minimized to create a dark hole by deformable mirror actuation



Baudoz et al. 2006 – Galicher et al. 2008

SCC – General formalism

$$I(\vec{\alpha}, \lambda) = |A_S|^2 + |A_R|^2 + |A_P|^2 + A_S^* A_R \exp^{\left(\frac{-2i\pi\vec{\alpha}\vec{\epsilon_0}}{\lambda}\right)} + A_S A_R^* \exp^{\left(\frac{2i\pi\vec{\alpha}\vec{\epsilon_0}}{\lambda}\right)}$$

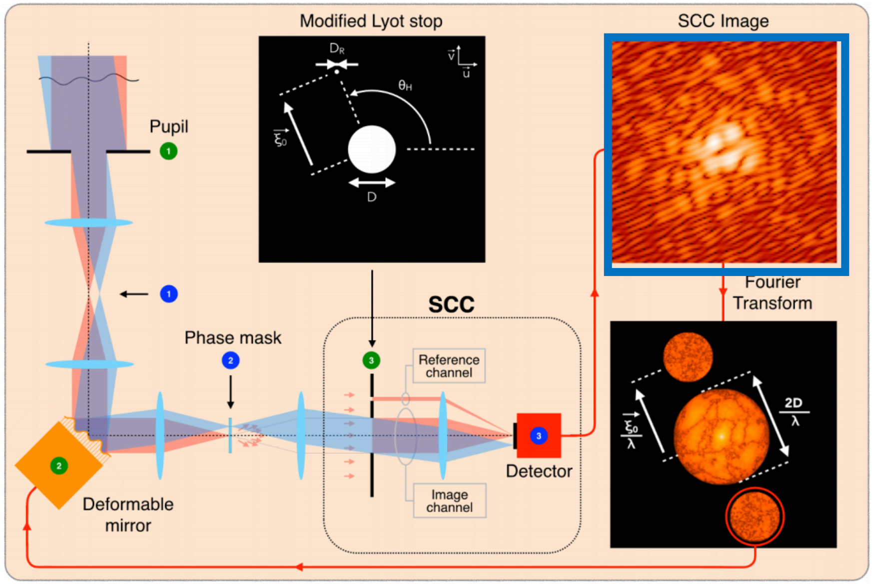
Science image intensity

Stellar residuals

Reference intensity

Planet signal

Spatial speckle modulation through interferences



Baudoz et al. 2006 – Galicher et al. 2008

A_S Electric field (complex amplitude) from the pupil channel (Lyot stop) contribution

A_R Electric field (complex amplitude) from the reference channel (Lyot stop) contribution

SCC – General formalism

$$\mathcal{F}^{-1}[I](\epsilon,\lambda) = \mathcal{F}^{-1}[I_S + I_R + I_P] + \mathcal{F}^{-1}[I_-] \otimes \delta(\boldsymbol{\epsilon} - \frac{\boldsymbol{\epsilon_0}}{\lambda}) + \mathcal{F}^{-1}[I_+] \otimes \delta(\boldsymbol{\epsilon} + \frac{\boldsymbol{\epsilon_0}}{\lambda})$$

$$I_- = A_S^* A_R$$

$$I_+ = A_S A_R^*$$

OTF of the science image

Central peak
[sum of the autocorrelation of the electric field in the pupil channel, and reference channel]

Lateral peaks
[correlation of the electric field in the pupil and reference channels]

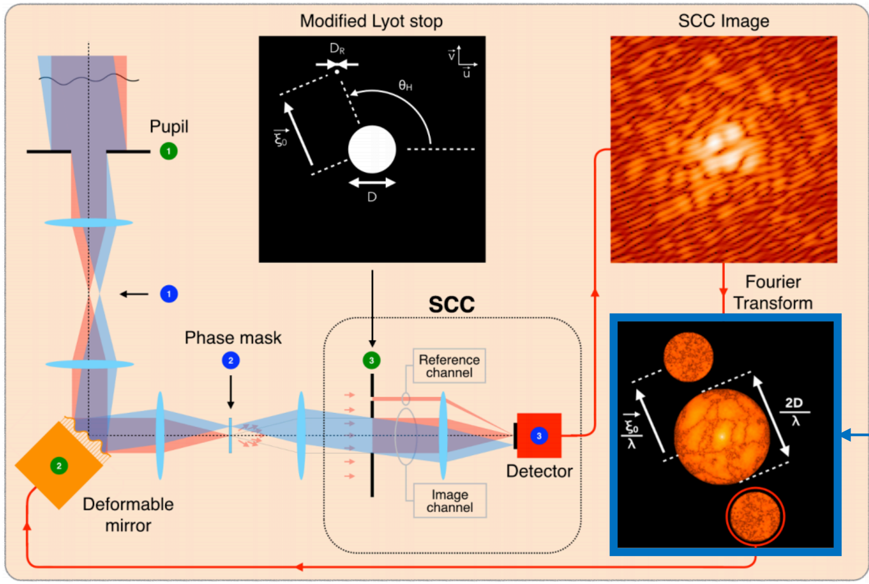
$$\phi_{est} = \mathcal{F}^{-1}\left[\frac{I_-}{A_R^* M}\right](\epsilon,\lambda)$$

Phase errors (imaginary part)

Amplitude errors (real part)

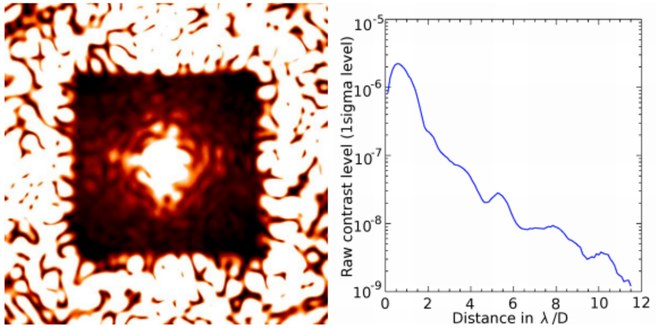
A_S Electric field (complex amplitude) from the pupil channel (Lyot stop) contribution

A_R Electric field (complex amplitude) from the reference channel (Lyot stop) contribution

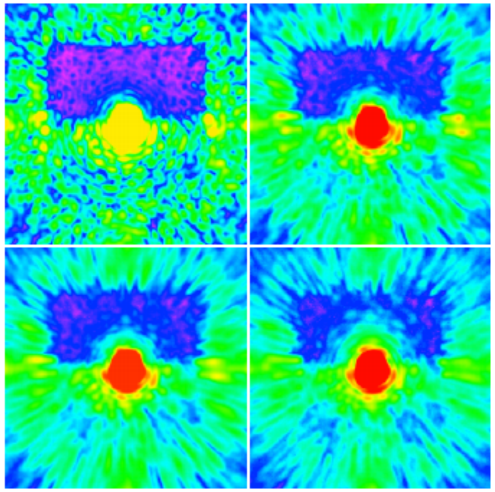


Baudoz et al. 2006 – Galicher et al. 2008

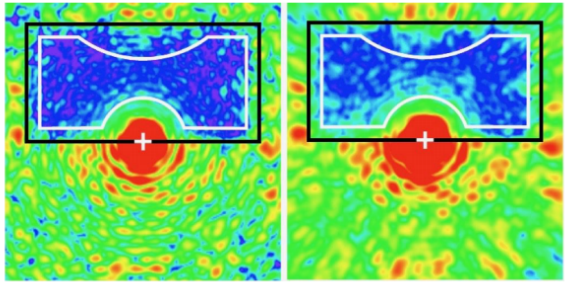
SCC – [few] Laboratory and on-sky results



Lab. result - THD bench (LESIA)
Full dark hole in monochromatic light (785 nm) with 2 DMs
Dark hole 16 x 16 λ/D

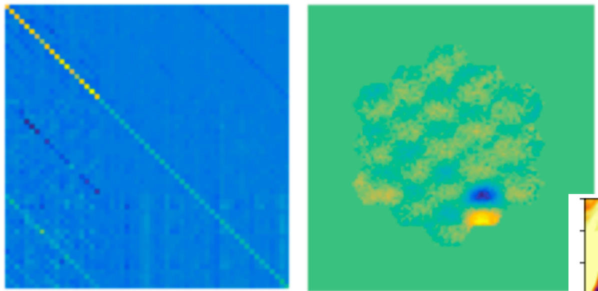


Lab. result - THD bench (LESIA)
DZPM + SCC in broadbands
(30, 200, 250, and 250 nm)

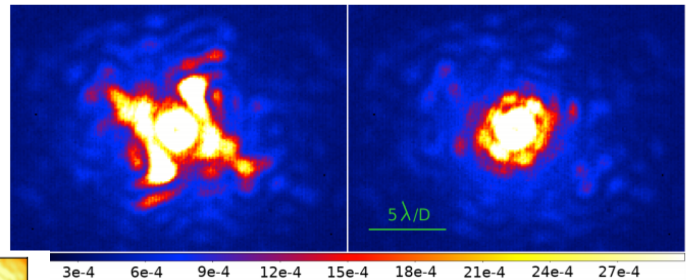


Lab. result - THD bench (LESIA)
Half dark hole in monochromatic light (650 nm)
and broadband (12.5%) Dark hole 10.5 x 24 λ/D

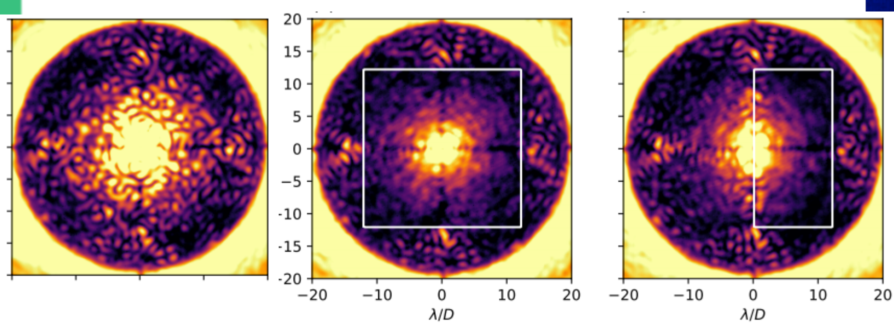
...
Mazoyer et al. 2013
Mazoyer et al. 2014
Delorme et al. 2016 a, b
Martinez, Janin-Potiron et al. 2018
Galicher et al. 2019 (under press)
Singh et al. 2019 (under press)
...



Lab. result - SPEED bench (Lagrange)
Cophasing interaction matrix



On-sky result (Palomar telescope) on Br-γ
NCPA correction MGS vs. SCC



Lab. result - THD2 bench (LESIA)
Post-AO + static aberrations (left),
full dark hole (middle) and half dark hole (right)
(after 5 iterations)

SCC – Reference properties and limitations

The SCC Lyot stop – the problem of the reference channel

- Size (d_R) and separation (ϵ_0) of the reference channel are highly constrained

$$\gamma = \frac{D_L}{d_R}$$

- Dark hole -

$$\gamma \geq \frac{N_{act}}{1.22 \times \sqrt{2}}$$

$$d_R \leq 1.22 \times \sqrt{2} \frac{D_L}{N_{act}}$$

Mazoyer et al. 2014

- Cophasing -

$$\gamma \geq 4N_{seg} + 2$$

$$d_R \leq \frac{D_L}{4N_{seg} + 2}$$

Janin-Potiron et al. 2016

$$\epsilon_0 = \beta\,(1.5 + 0.5/\gamma)\,D_L$$

$$\beta > 1$$

Galicher et al. 2010

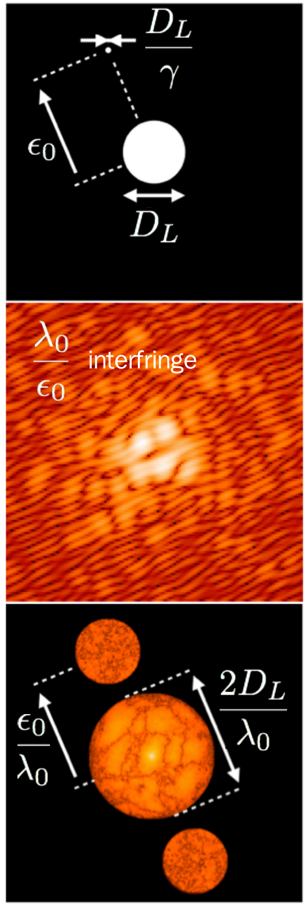
FTO lateral and central peaks would overlap otherwise

$$\epsilon_0 > 1.5 \times D_L$$

SCC Lyot stop

SCC image

SCC OTF



- Typical values lead to low S/N in the reference (Lyot stop) and small-size interfringe (detector)

SCC – Reference properties and limitations

The SCC Lyot stop – the problem of the reference channel

- Conventional SCC limitations

- Exploitation limitations

Low S/N in the reference channel imposes long-time exposure measurements:

  - Precludes fast-living atmospheric aberrations from the correction
  - Quasi-static aberrations correction if S/N is sufficient (Lab. Ok, On-sky more difficult)

- Design limitations

High sampling requirements of the detector to resolve the fringes

Downstream optics must be sufficiently large to capture the reference beam (diameter > 3 D_L)

- Solutions

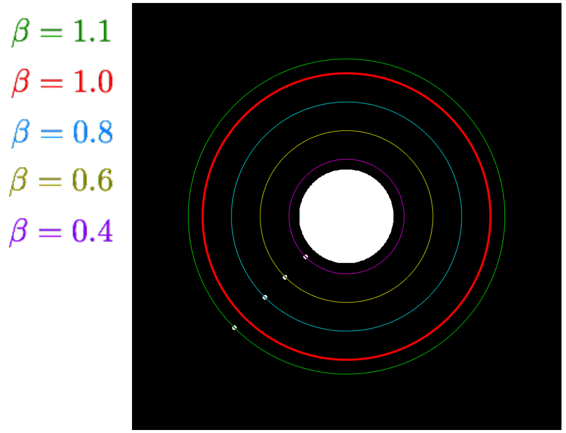
- Modify the focal plane mask to maximize the light captured by the reference channel

  Gerard et al. 2018 [FAST ATMOSPHERIC SCC]

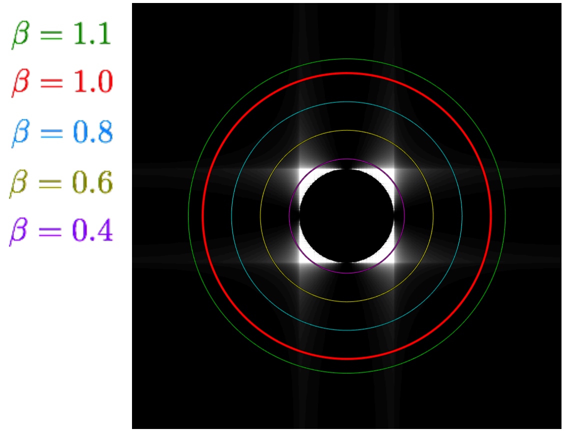
- Make the SCC working with the reference channel where it should not be: in the pupil boundaries

  Martinez 2019 [FAST-MODULATED SCC]

SCC Lyot stop



Intensity in the Lyot plane (FQPM)



SCC – Breaking the rules

The ideal SCC design

➢ SCC theory dictates that $\beta > 1.0$

The reference channel cannot be placed in the vicinity of the pupil channel

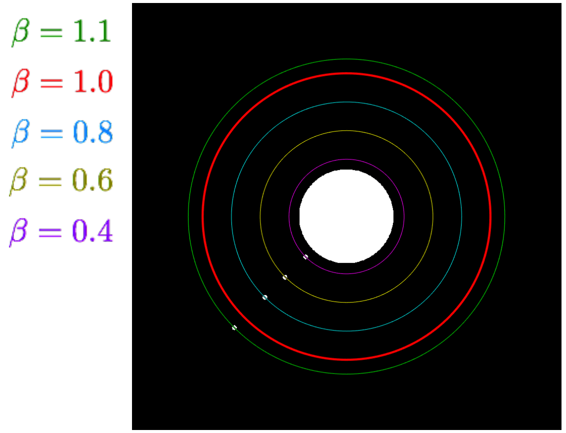
The maximum diffracted energy from the coronagraph is in the vicinity of the pupil channel

➢ SCC with $\beta = 0.4$

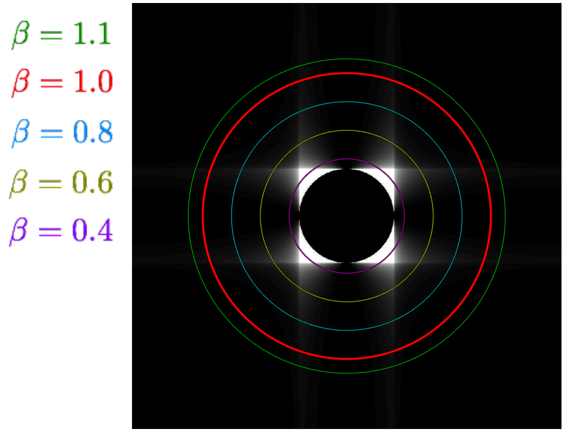
It would:

- solve the S/N issue for long-time exposure measurements (quasi-static aberrations),
- make possible short-time exposure measurements (fast-living aberrations),
- relax the requirement on the fringe sampling on the detector (fringes would be larger),
- suppress the optical design constraint of the downstream optics (a sever shortcoming).

SCC Lyot stop



Intensity in the Lyot plane (FQPM)



Fast-modulated self-coherent camera

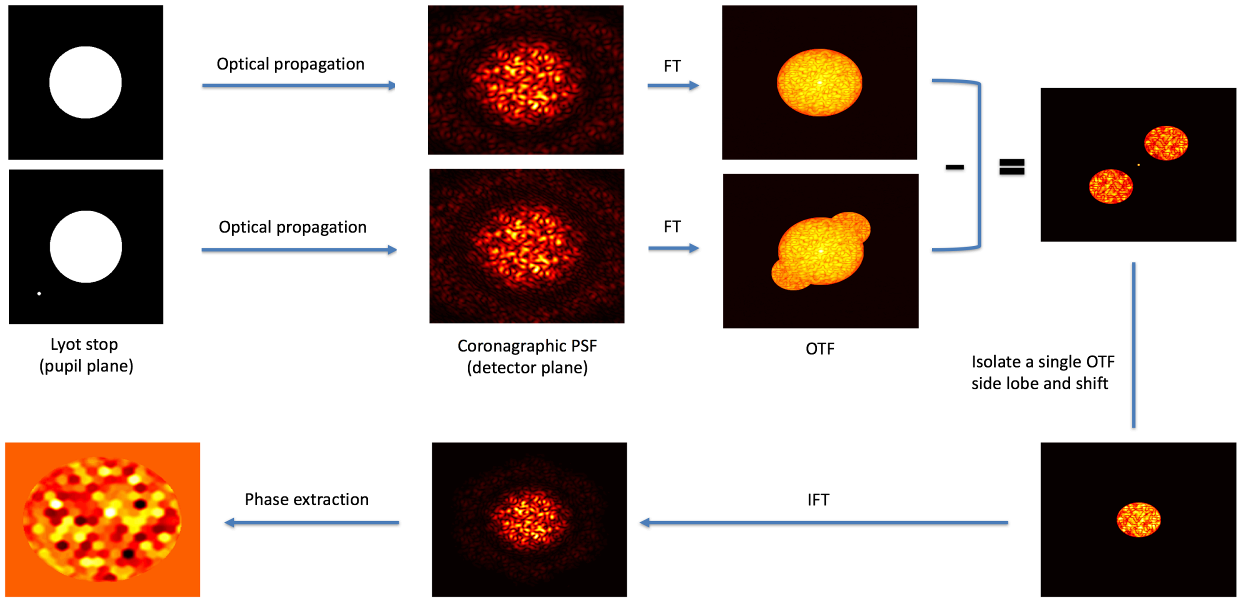
General principle

Two SCC images are recorded sequentially

- One image with the reference channel opened (fringes)
  - ➢ The three peaks in the OTF overlap
- One with the reference channel closed (no fringes)
  - ➢ Only the central peak is present in the OTF

➢ recovering and isolating the lateral peak is possible

➢ Both images are subject to same aberrations and noises (same detector pixels)



Martinez A&A (2019)

Requirements

➢ Motorized Lyot stop

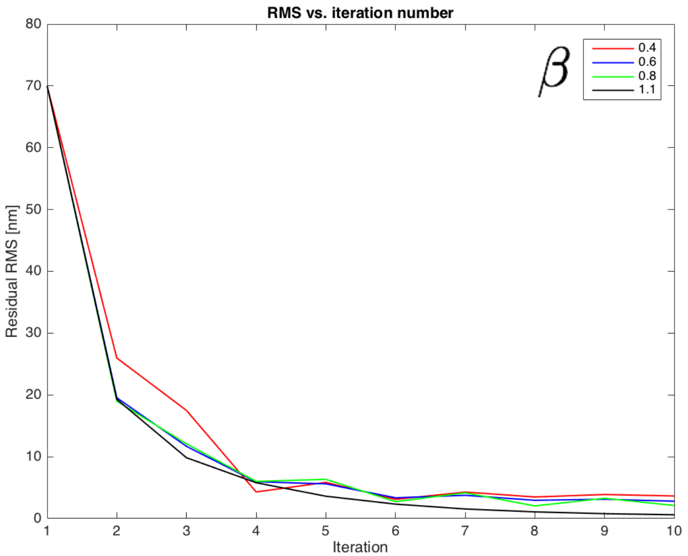
A modulator on the reference hole to close/open the channel at an adequate rate considering integration time and speckle lifetime

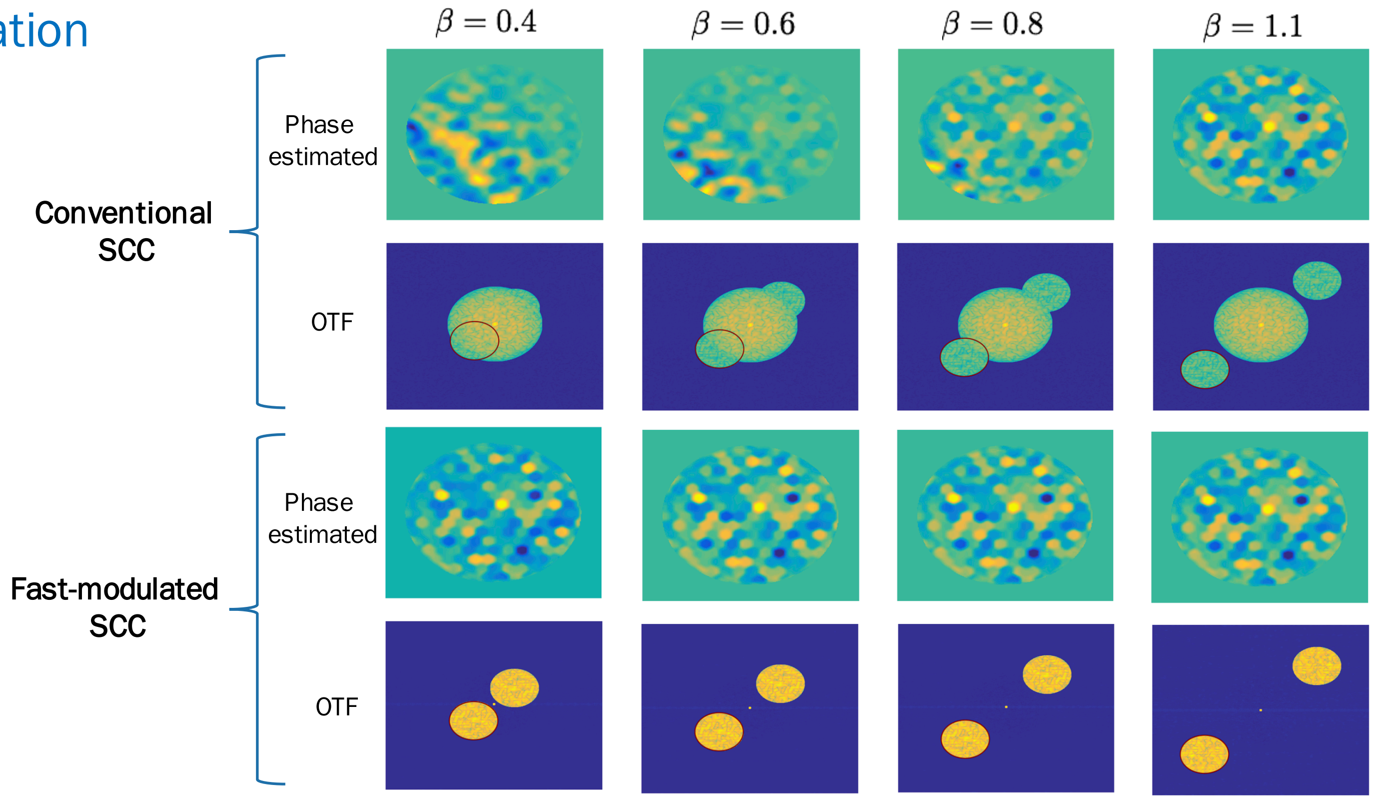
➢ Fast-modulation Fourier filtering algorithm - Nothing but simple

Fast-modulated self-coherent camera

Cophasing simulations for illustration

- Segmented pupil with 169 segments
- Piston and tip/tilt misalignments tested
- No dynamical errors nor noises





Martinez A&A (2019)

The SPEED testbench
➢ a playground to test the fast-modulated SCC

SPEED facility

High-contrast imaging at small IWA

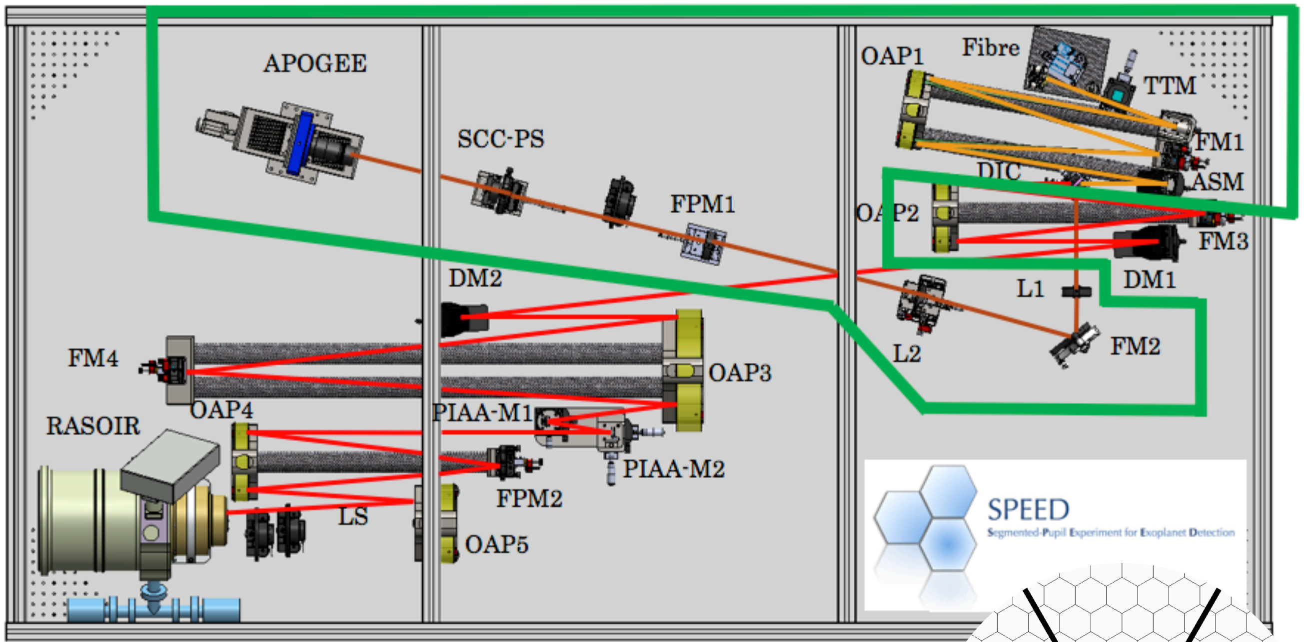
- ELT pupil and constraints
- Multi-DM wavefront control and shapping
- Small IWA coronagraph (PIAACMC)

The visible path of the bench is dedicated to

➢ Cophasing the primary mirror (SCC-PS)

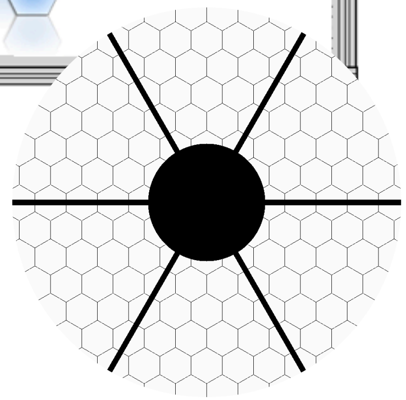
Janin-Potiron et al. A&A 2016

➢ Compare cophasing (fine phasing) sensors



https://lagrange.oca.eu/en/lag-speed-home

❖ The SCC and fast-modulated SCC will be tested for cophasing optics



SPEED telescope pupil

The SPEED testbench
➢ a playground to test the fast-modulated SCC

SPEED facility

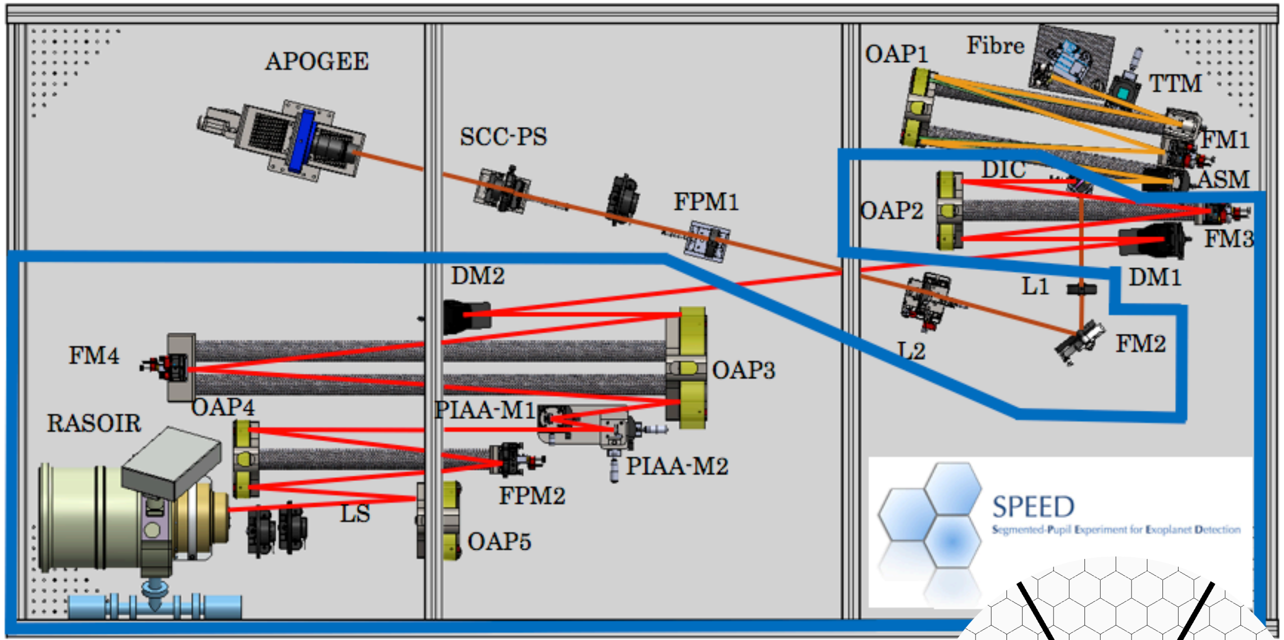
High-contrast imaging at small IWA

- ELT pupil and constraints
- Multi-DM wavefront control and shapping
- Small IWA coronagraph (PIACMC)

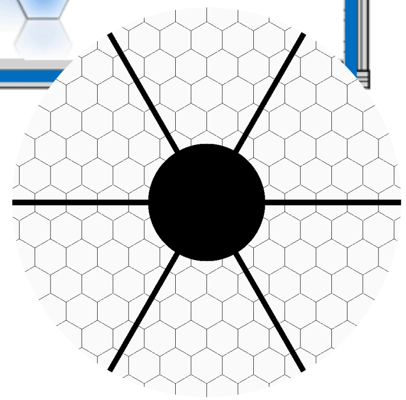
The NiR path of the bench is dedicated to

➢ Wavefront shapping (2-DMs)

➢ High-contrast imaging



https://lagrange.oca.eu/en/lag-speed-home



SPEED telescope pupil

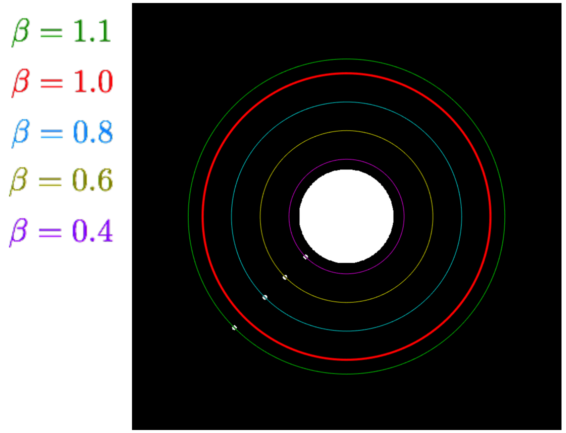
❖ **The SCC and fast-modulated SCC will be tested for active optics (dark hole)**

Conclusion

➢ SCC with unauthorized β values are possible, with major advantages:

- versatility by accessing short- and long-time exposure measurements
- relax the requirement on the fringe sampling on the detector (fringes would be larger),
- suppress the optical design constraint on the downstream optics for new instruments,
- easy installation in existing instruments,
- make the SCC compatible with any type of coronagraph.

SCC Lyot stop



➢ ...but the fast-modulated SCC adds some ***temporal modulation*** where ***spatial modulation*** was the key point...

Likely a satisfactory paradox in many situations, e.g.:

- PIAACMC unlikely compatible with conventional SCC
- Conventional SCC and existing instruments are not compatible by optical design