High contrast imaging :
The THD2 bench

June 30th, 2021

Raphaël Galicher, Pierre Baudoz, Johan Mazoyer
& THD2 team

cnrs
SORBONNE UNIVERSITÉ
Université de Paris
PSL UNIVERSITÉ PARIS

Outline

THD2 researches and THD2 team

Why THD2 bench?

THD2 testbed
- Main description
- Space-like conditions
- Ground-like conditions

Application at telescopes
- NCPA correction on SDC at Palomar Observatory
- NCPA correction on SPHERE at Very Large Telescope

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THD2 laboratory: high contrast imaging

Leadership in Europe

R&D

Coronagraphy
Bonafous et al. 2016, Delorme et al. 2014,
Patru et al. 2018, Galicher et al. 2020, etc

Wavefront sensing/control
Mas et al. 2012a, 2012b, Mazoyer et al. 2013, 2014,
Galicher et al. 2014, Delorme et al., 2016,
Potier et al., 2019, 2020a, Singh et al. 2019, etc

Data processing
Baudoz et al. 2012, 2013

Deformable mirror
Baudoz et al. 2018a, 2018b, 2018c

Application

Palomar Observatory
Galicher et al. 2019

SPHERE @ VLT
Potier et al. 2020B

CGI for Roman Space Telescope
→ Pierre Baudoz presentation

THD2 team in 2021

Name	Role
Pierre Baudoz	Principal Investigator
Raphaël Galicher	co-PI
Johan Mazoyer	Dark Hole algorithm expertise
Mehdi Kourdourli	PhD Student
Elsa Huby	Coronagraphy expertise
Gérard Rousset	Adaptive Optics Expertise
Anthony Boccaletti	Science & Coronagraph Expertise
Benjamin Roman	Intern on High Contrast
Antoine Teixeira	Intern on High Contrast

We welcome students from undergraduates to postdoc

Name	Role
Simone Thijs	AIT
Olivier Dupuis	Mechanical Design and Integration
Aurélien Pelleau	Optical engineer in Apprenticeship
Manuel Ortiz	AIT
Jean-Michel Réess	Optical design
Pernelle Bernardi	Optical design
Arnaud Sevin	Real Time Computer
Goran Greblo	Computing Engineering
Sudagar Vassin	Computing Engineering
Vartan Arslanyan	Mechanical Fabrication
Sylvain Cnudde	Graphic Design
Cris Dupont	Administrative

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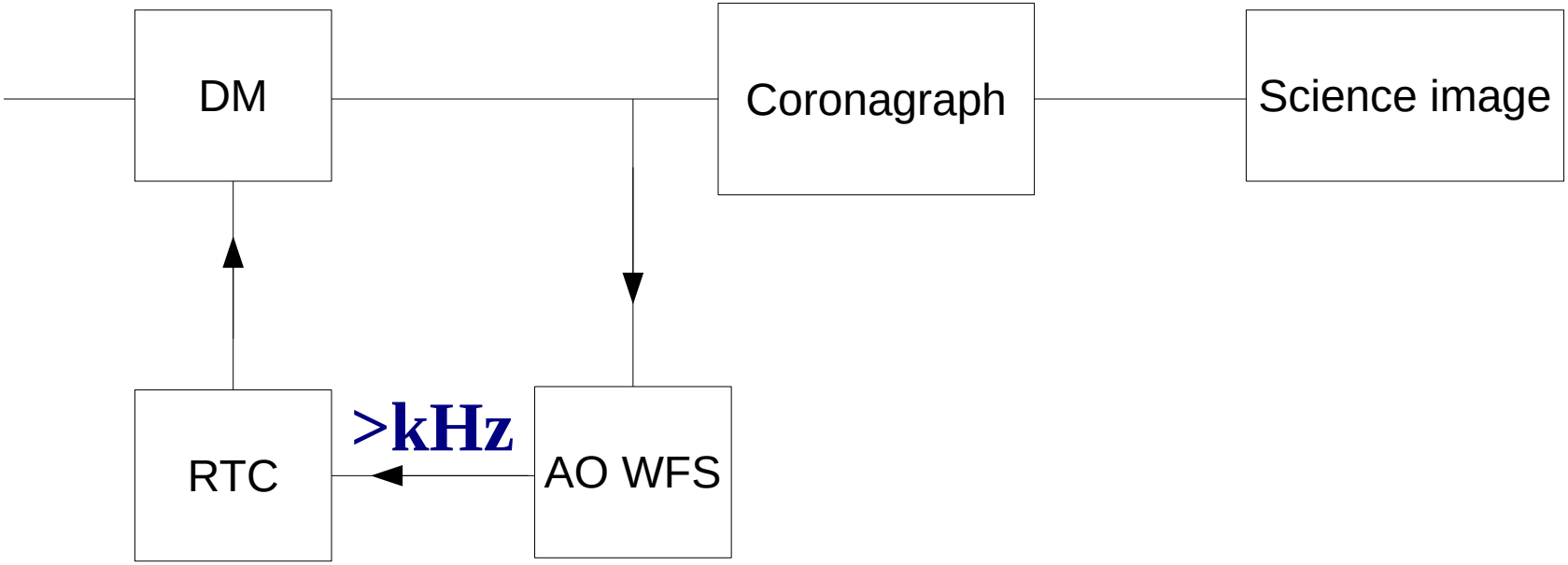
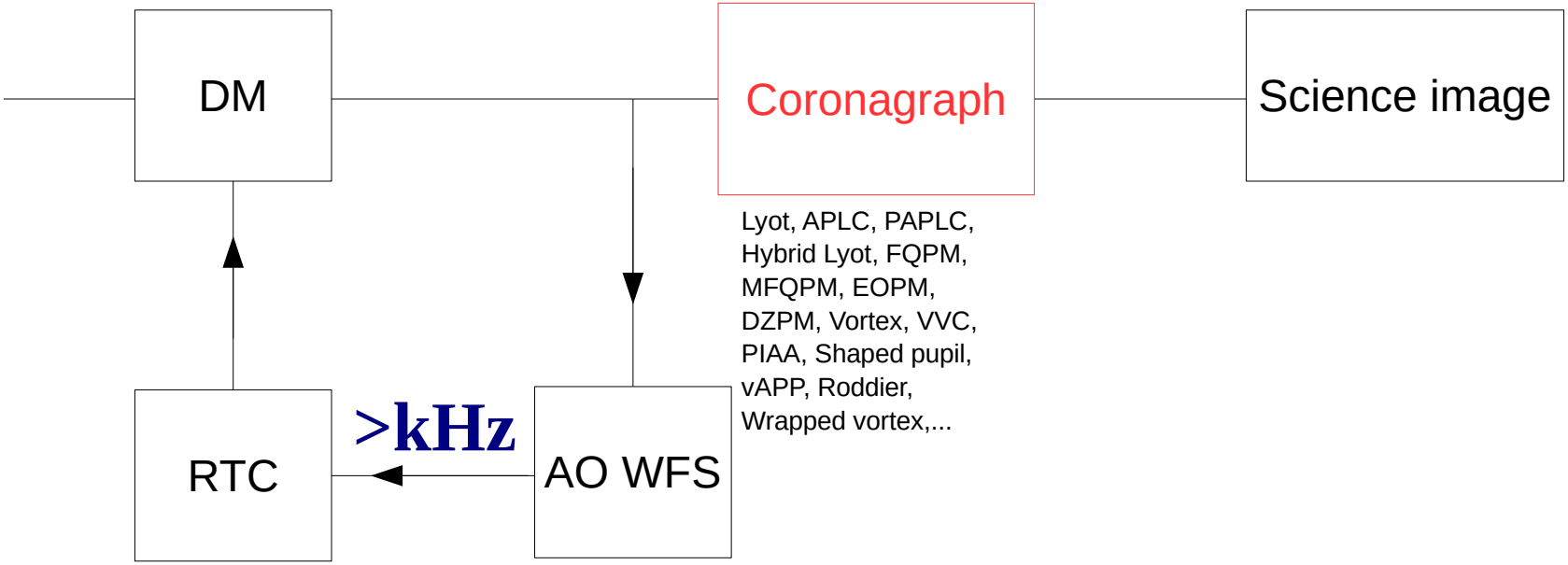
Exoplanet imagers in 2021 on ground

C = 1e-5 to 1e-3

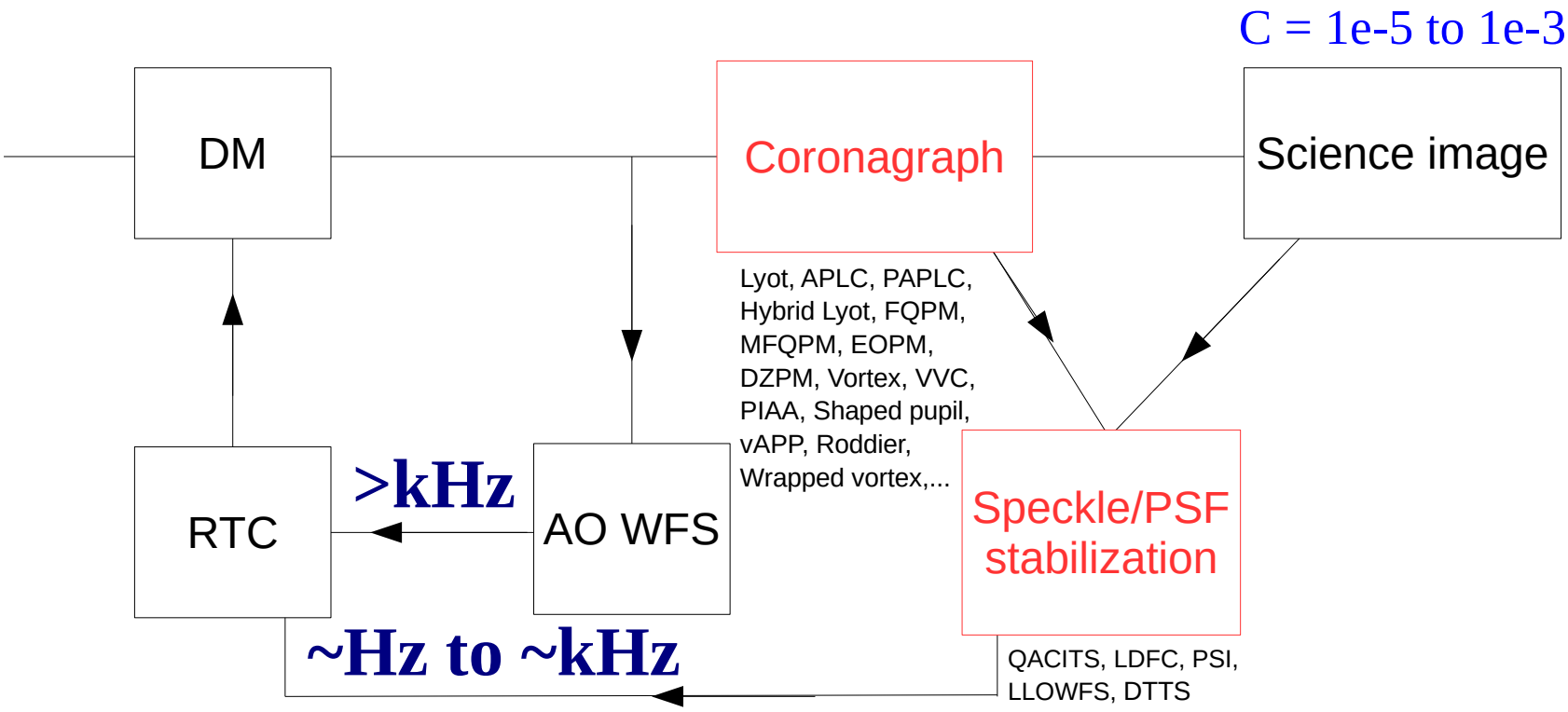


New coronagraphs: segments & broadband

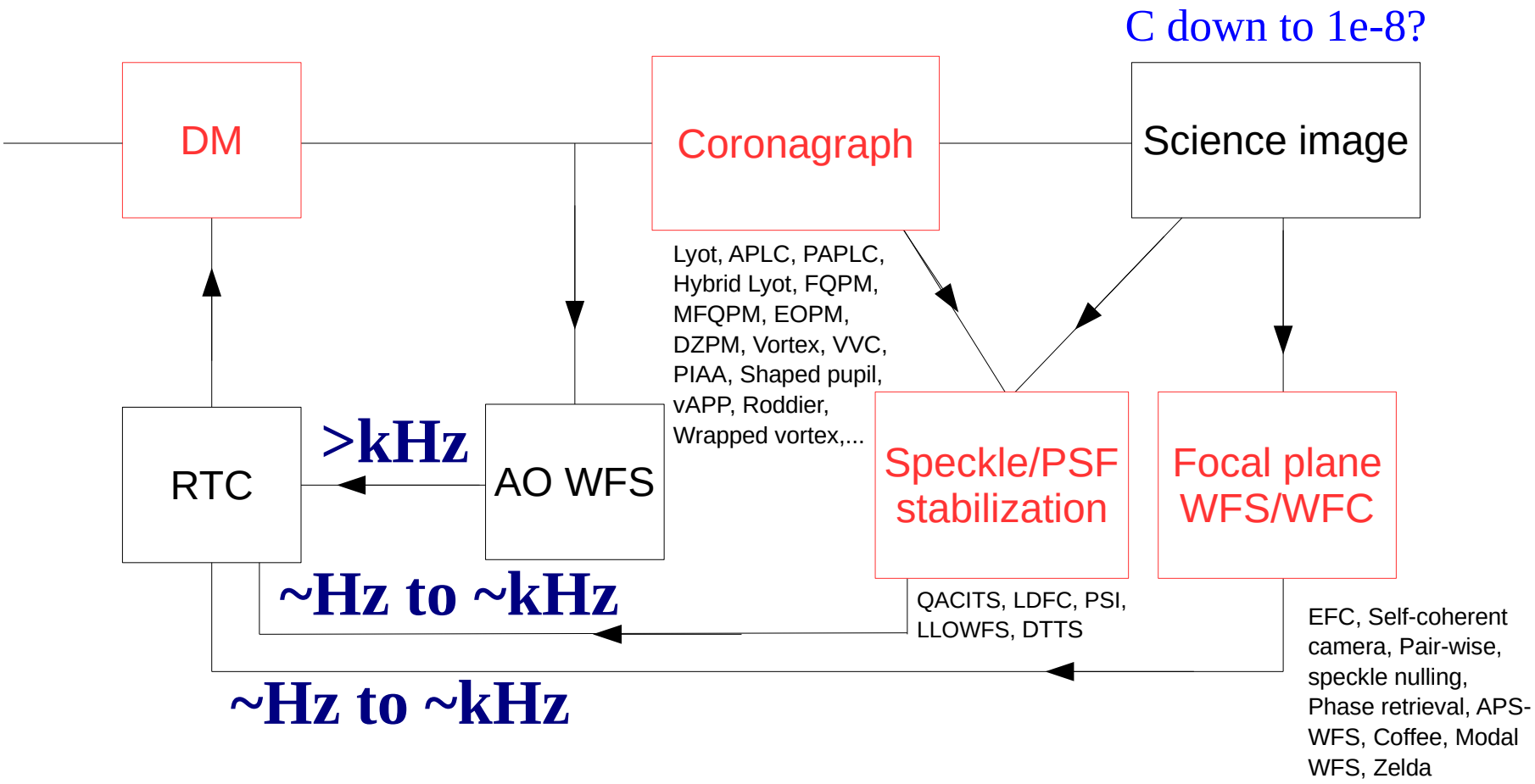
C = 1e-5 to 1e-3



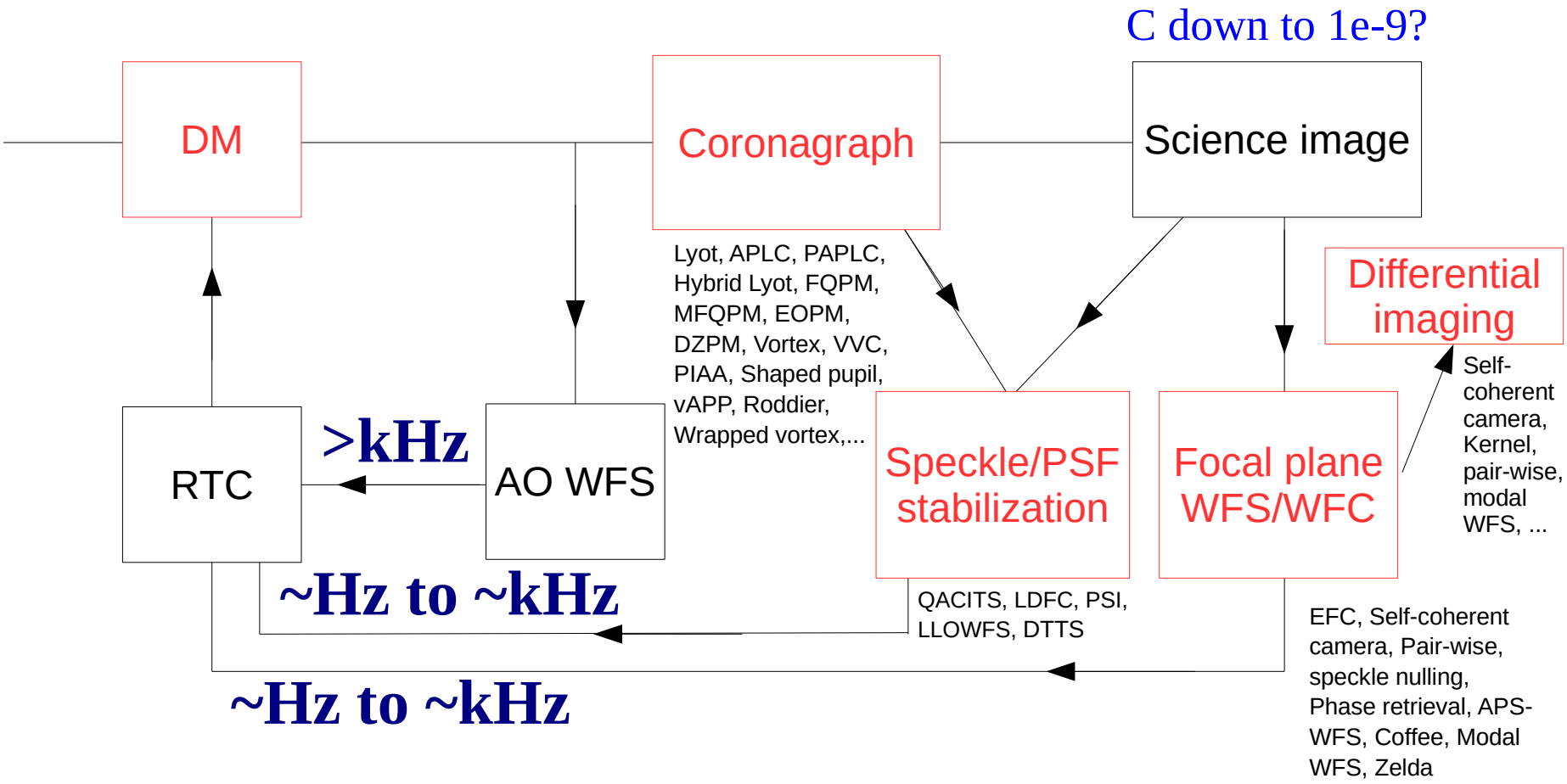
Cheap upgrade: speckle stabilization



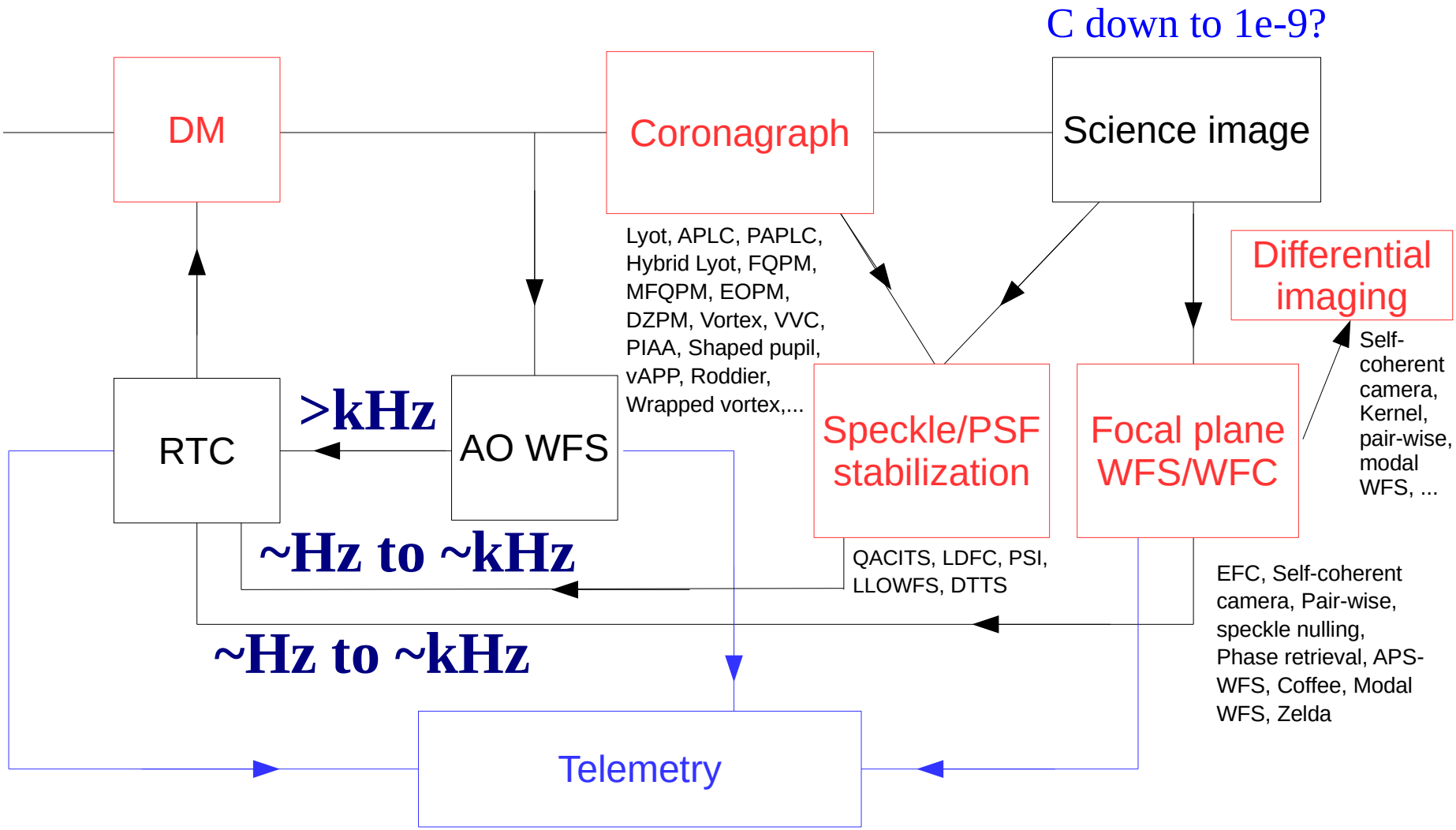
More ambitious: speckle minimization



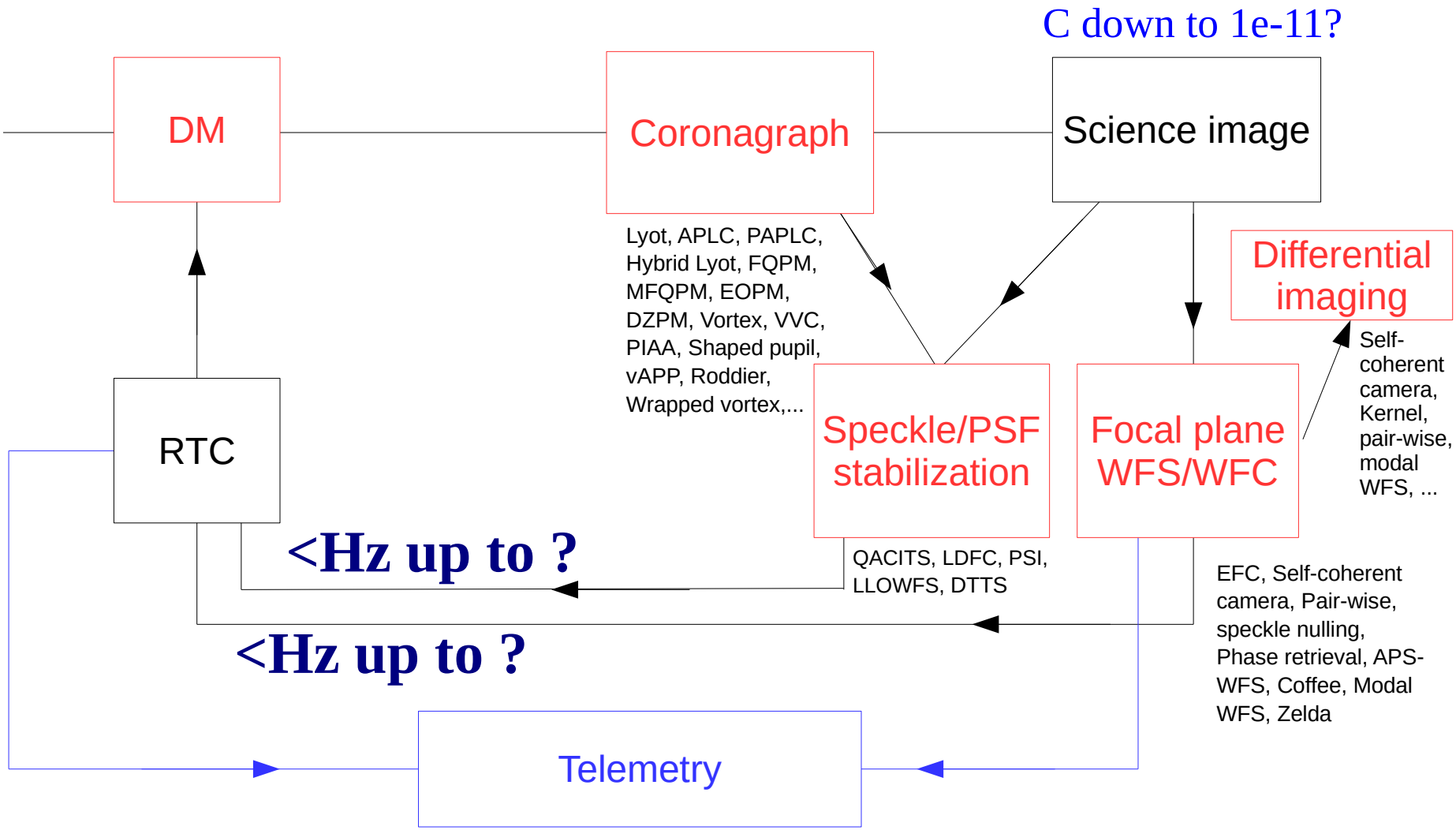
More ambitious: coherence differential imaging



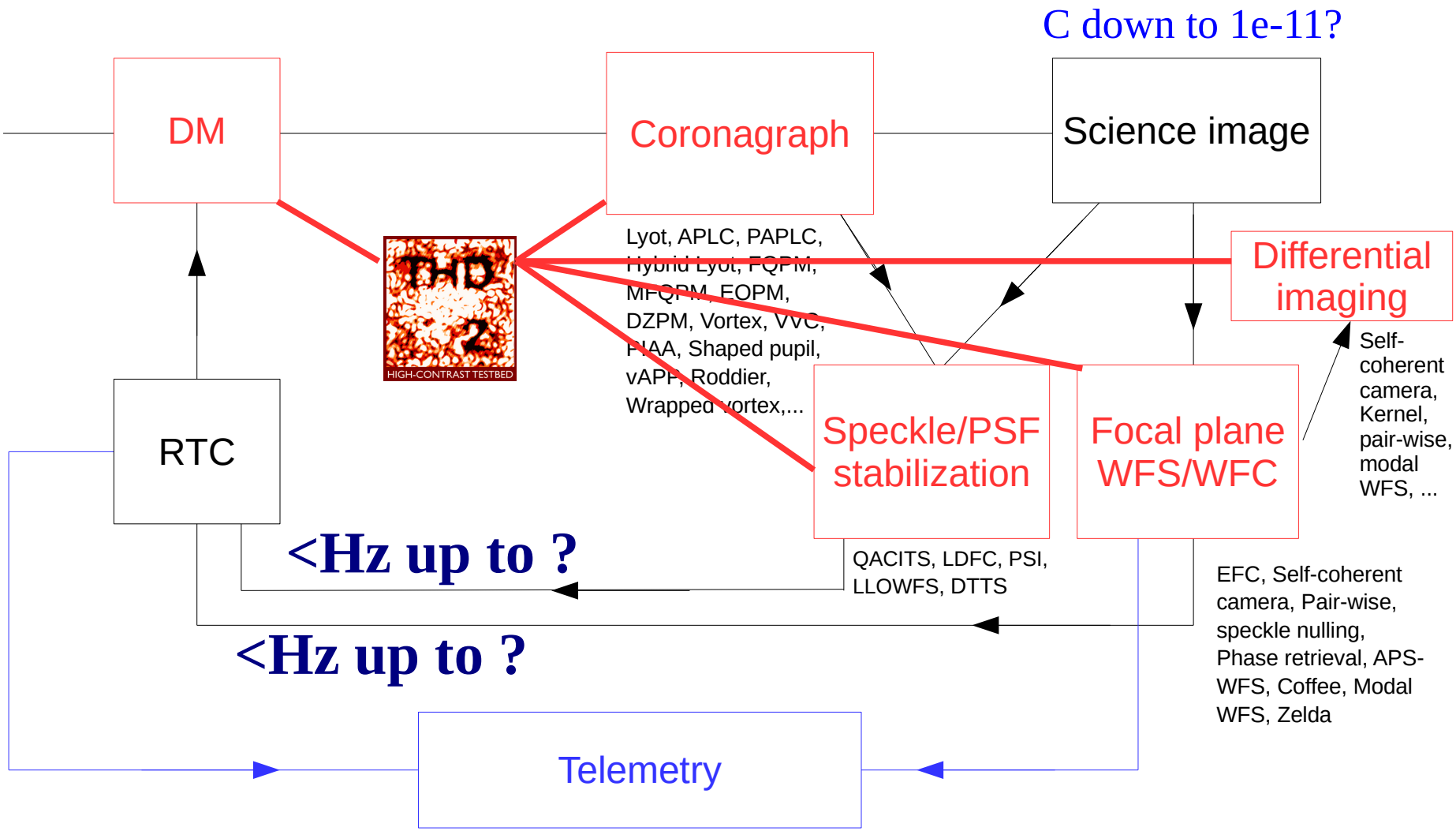
Complete ground-based instrument



Complete space instrument



Complete space instrument



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THD and THD2 testbeds

Objectives

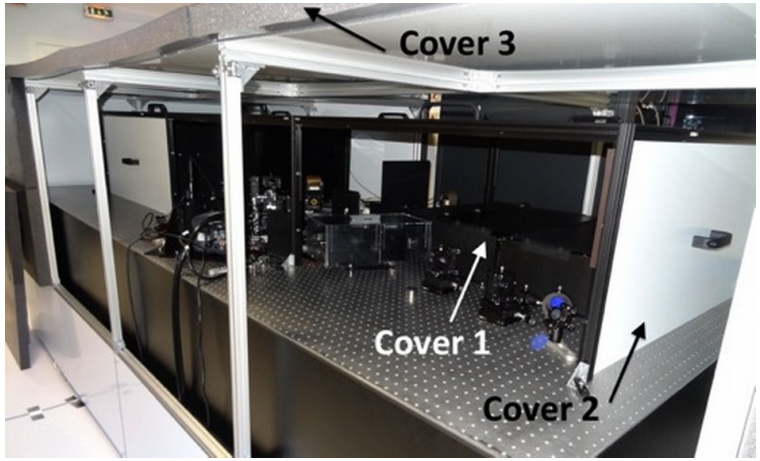
Unique in Europe

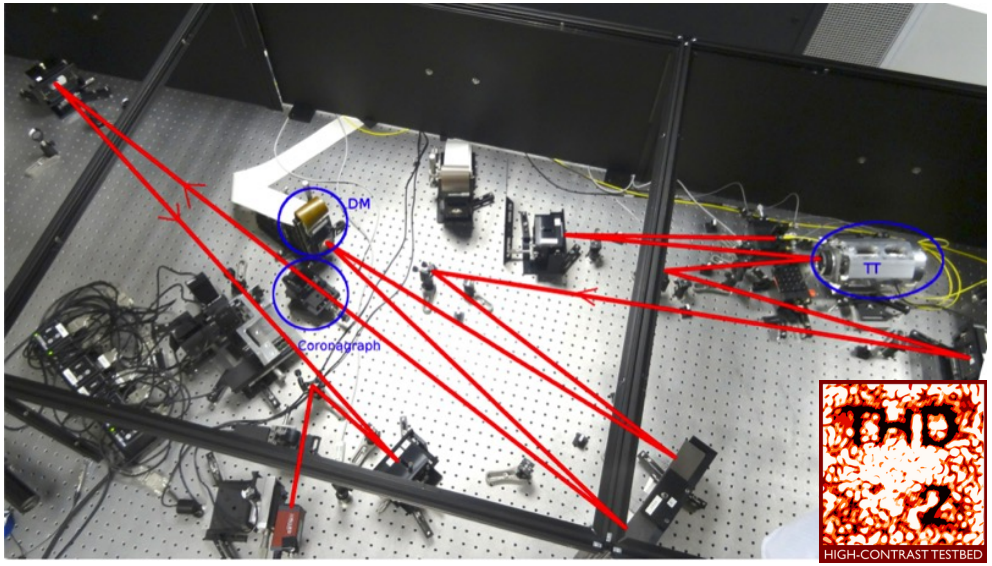
R&D : Compare & associate high contrast imaging techniques

2008 : THD → 1 deformable mirror

2015 : THD2 → 2 deformable mirrors

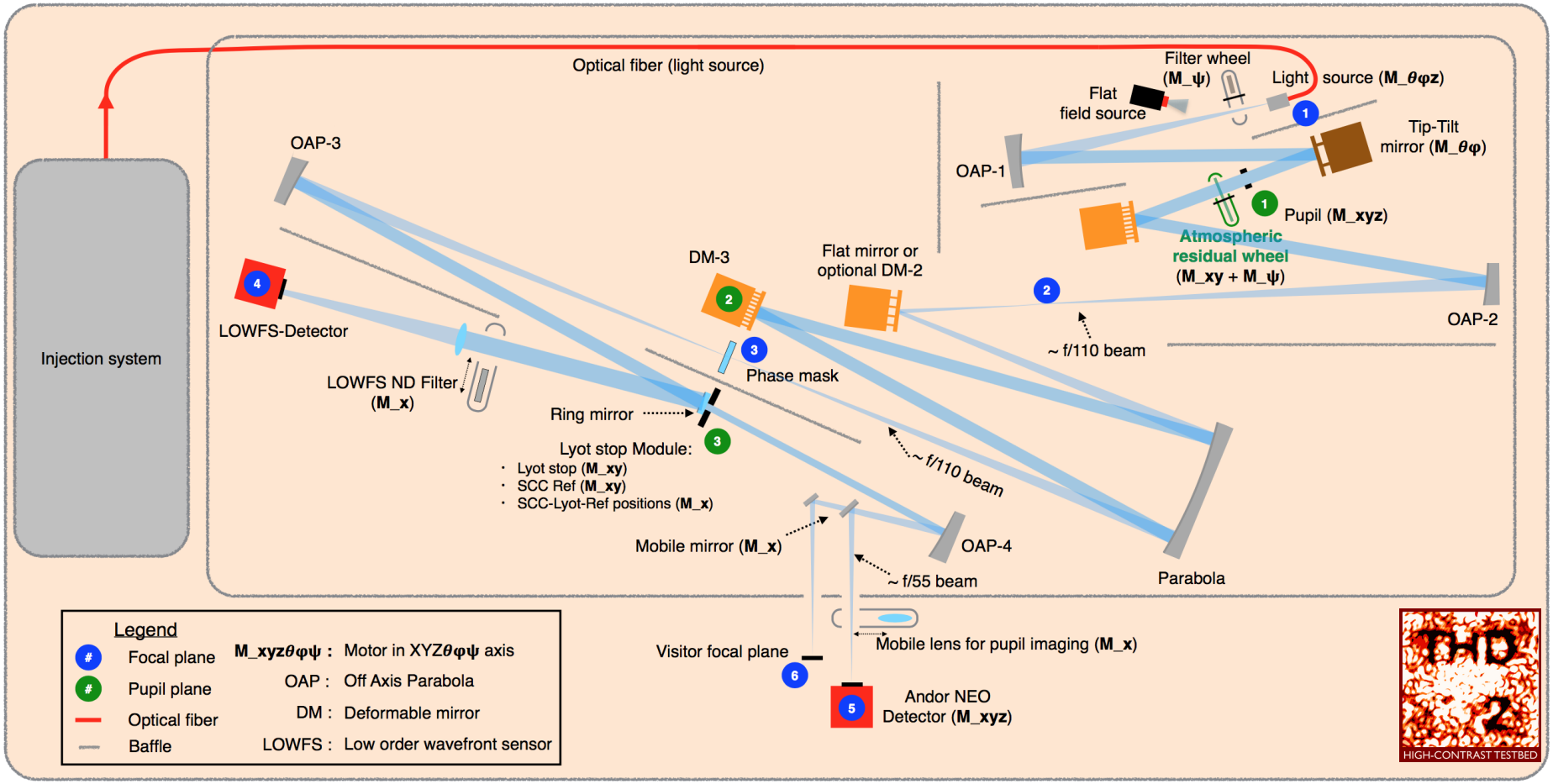
clean room, temperature control ~0.1°C, three covers, >20 motors, 2 filter wheels, polarizers, ...





THD2 optical design

450nm to 950nm ; 2 DMs ; 1 TT mirror ; space/ground simu



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THD2 main components

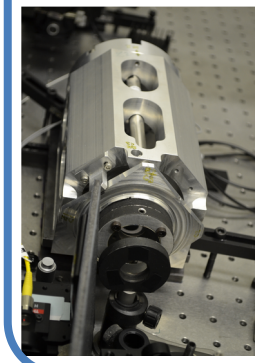
Source unit : visible light from monochromatic to large bandwidth > 300 nm

- Broadband (450nm to 950nm) supercontinuum source + filter wheel
- Laser diodes @ 638nm, 705nm and 785nm
- Flat-Field source @ 650 nm
- Fluxmeter, Spectrometer

Active mirrors

Tip Tilt mirror

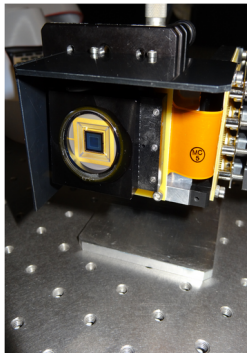
SPHERE prototype



3 Deformable Mirrors

34x34 actuators

12x12 actuators



32x32 actuators

Cameras & Sensors

Science + Self-Coherent Camera

- 100 Hz
- 3 e- RON

Low-order wavefront Sensor

- 500 Hz
- 18 e- RON

Calibration & Housekeeping

Recording simultaneously : **images** from cameras, **applied controls** to active mirrors, **total flux and spectrum of input light**, **temperature** & **humidity** sensors (≈ 10 sensors), working configuration, …

THD2: Numerous techniques & collaborations

Coronagraphic components	Advancement	Collaboration
Four quadrant phase mask	●	GEPI (France)
Multi-FQPM	●	GEPI (France)
Apodized Dual zone phase mask	●	LAM (France)
Eight octant phase mask	09/2015 →	Hokkaido Univ. (Japan)
Vector vortex	●	NAOJ (Japan) & LESIA (France)
Six level phase mask	●	GEPI (France) & Shanghai Univ. (China)
Wrapped vortex	●	LESIA (France)
Gaussian TT mask	●	Univ of Victoria (Canada)
Phase apodized pupil Lyot coronagraph	●	Leiden Observatory (Netherlands)
Wavefront sensing/control	**Advancement**	**Collaboration**
Monochromatic & polychromatic SCC	●	LESIA (France)
Amplitude and phase correction	●	LESIA (France)
Coronagraph & phase diversity (Coffee)	2016 →	Onera (France)
Chromatism correction, optimization of algorithms, system study	●	SRON (Netherlands) & LESIA (France)
Pair-wise and electric field conjugation	●	LESIA (France)
Zelda technique	2017 →	LAM & LESIA (France)

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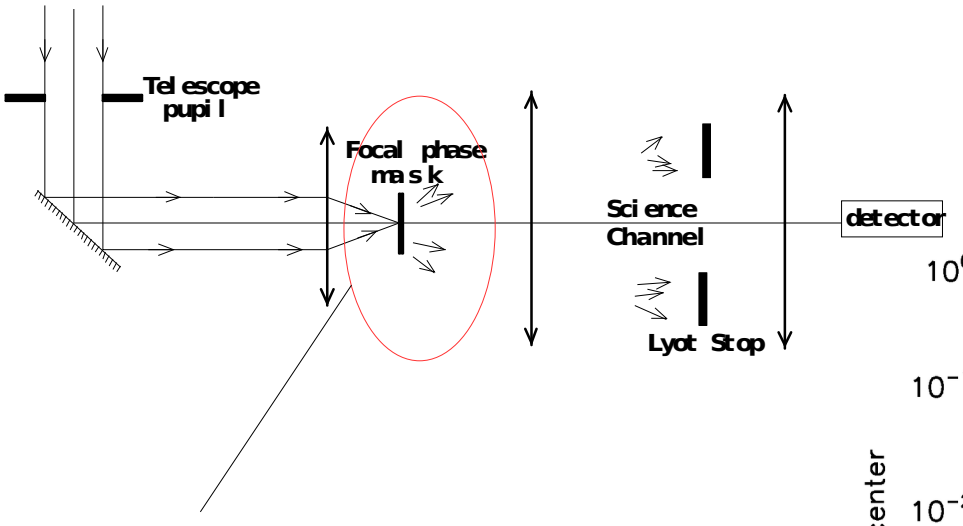
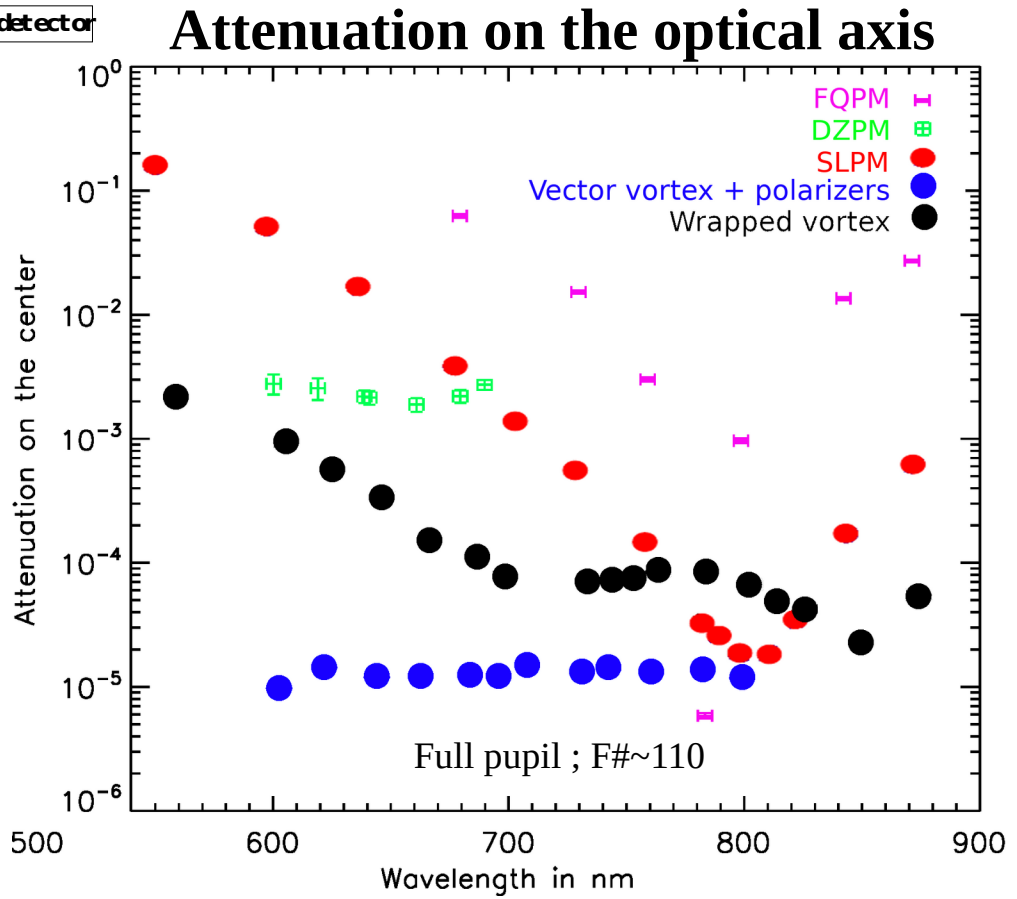
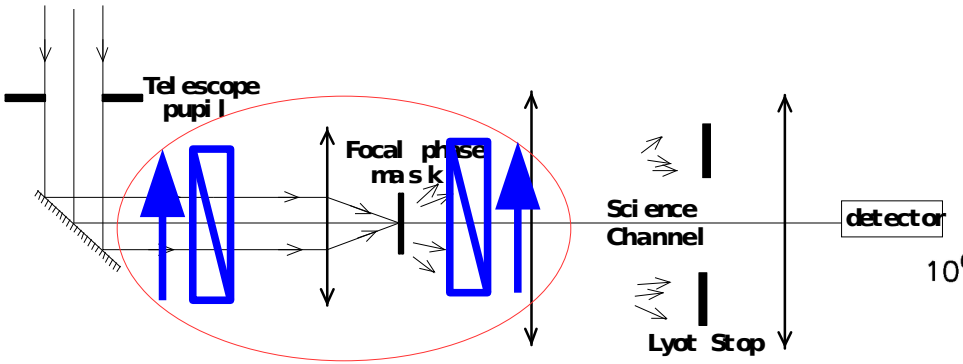
THD2: Coronagraphs (1/2)



Four quadrant phase mask (FQPM)
Dual zone phase mask (DZPM)
multi-FQPM (cascade of FQPM)
Six level phase mask (SLPM)
Eight octant phase mask (EOPM)
Vector vortex phase mask
Wrapped vortex



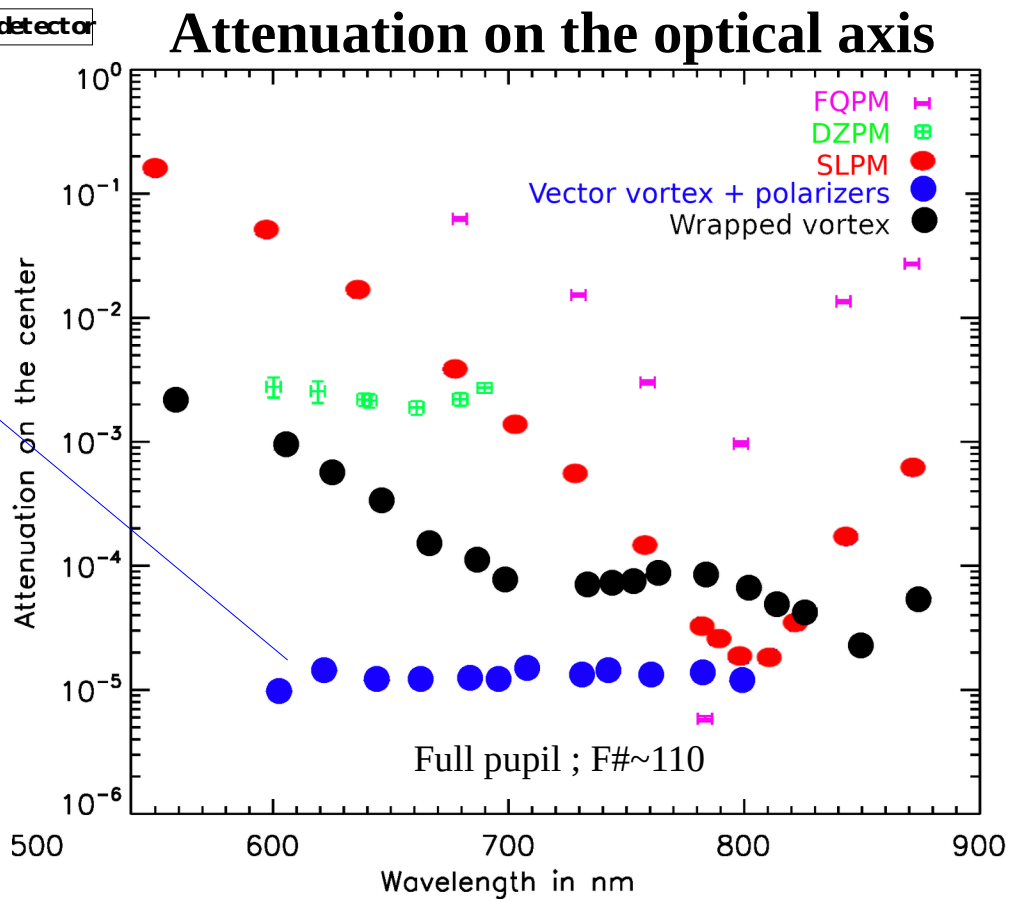
THD2: Coronagraphs (2/2)



Vector vortex + circular polarizers

Good performance but
+ 5 optics → stability!
+ λ/4 achromatic plate

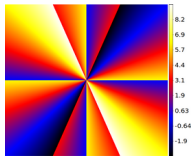
Article in Prep

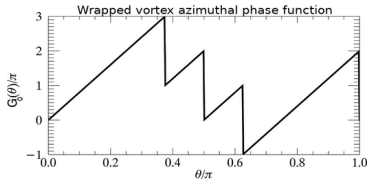


THD2: Half dark hole & chromaticity (1/2)

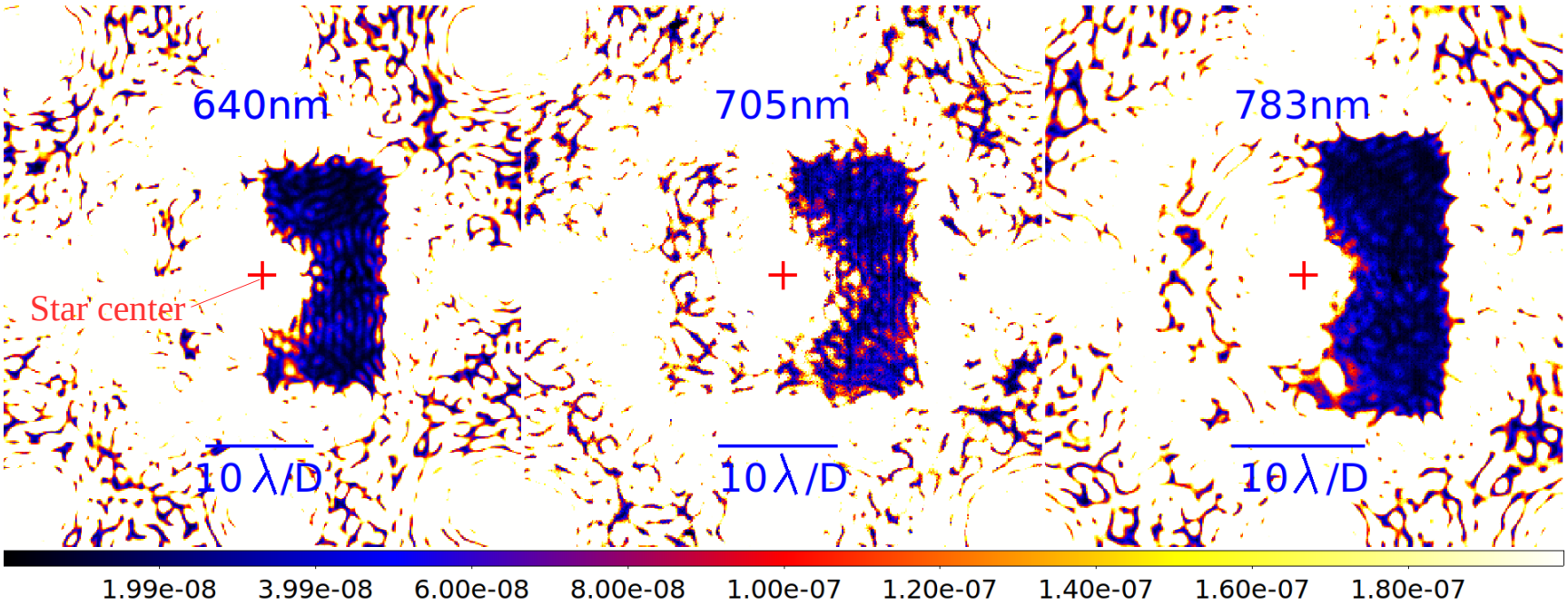
Coronagraph = wrapped vortex

>20 % bandpass





Full pupil ; F#~110



Galicher et al. 2020

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THD2: Half dark hole & chromaticity (2/2)

Coronagraph = wrapped vortex

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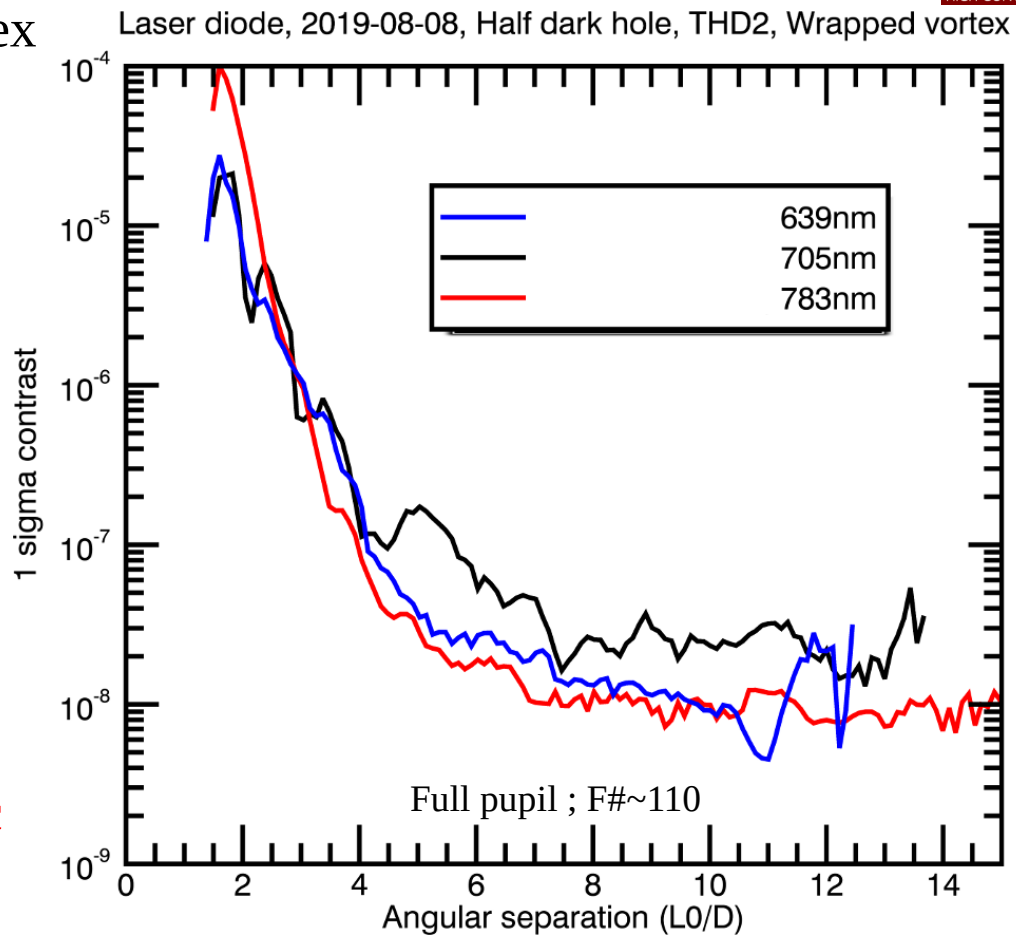
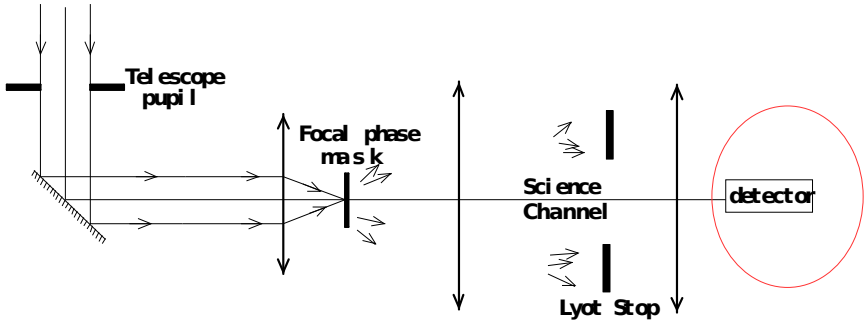


Contrast optimized since 2019
in monochromatic light
→ to be done in polychromatic

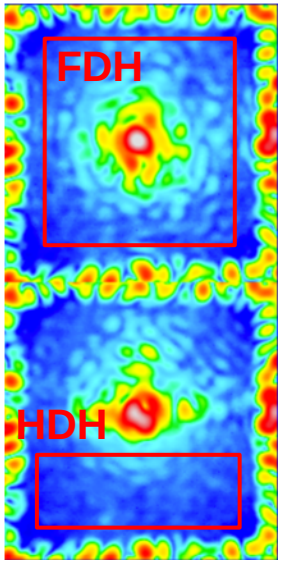
Galicher et al. 2020

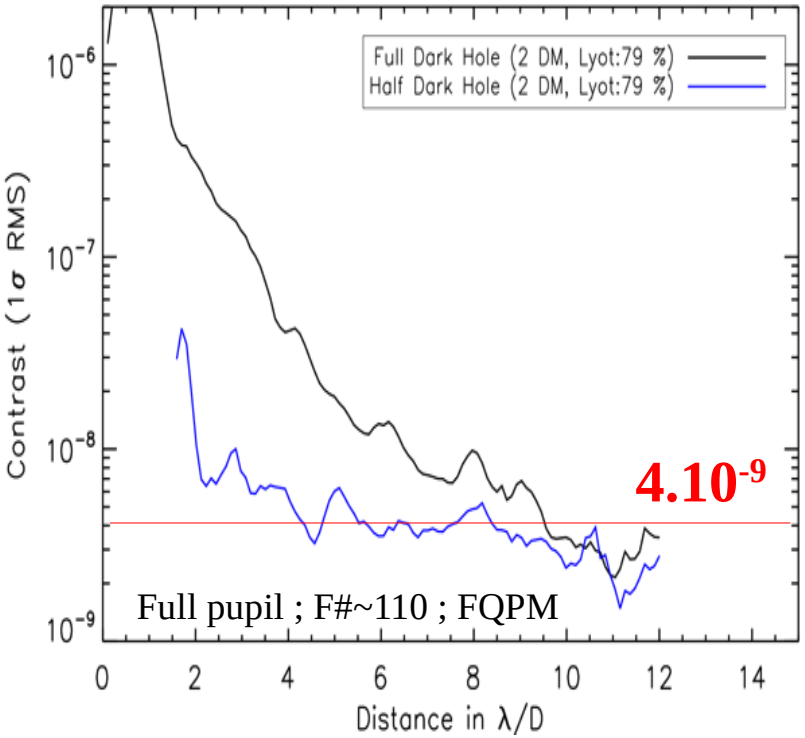
THD2: Focal plane wavefront sensor/control (1/2)

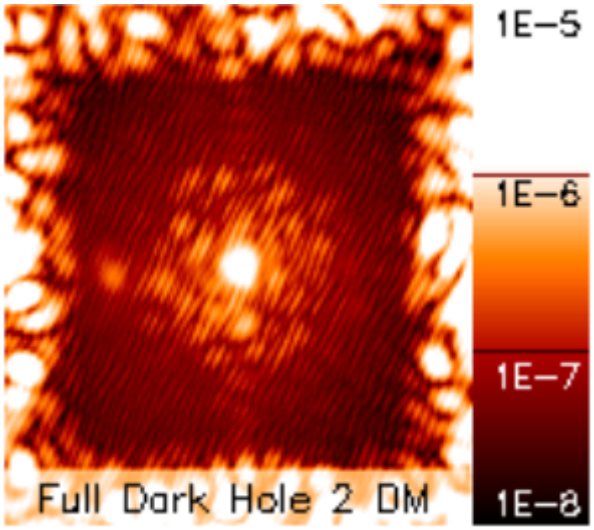


Spatial modulation
→ self-coherent camera

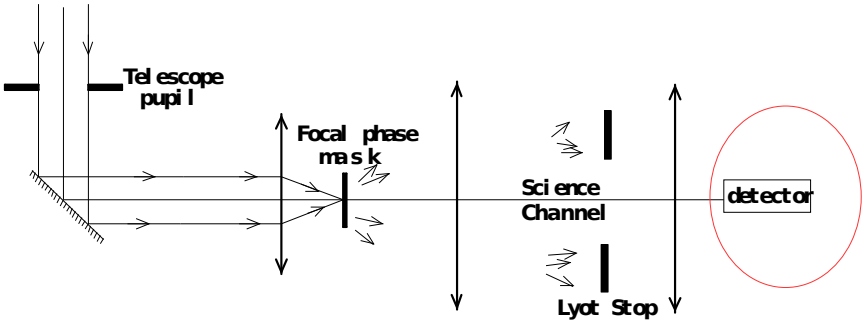
7.10^{-9} for >2 λ/D
4.10^{-9} for >4 λ/D







THD2: Focal plane wavefront sensor/control (2/2)



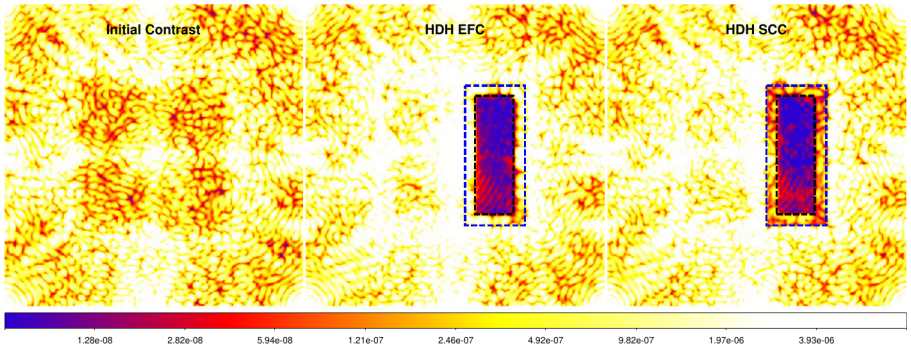
Temporal modulation

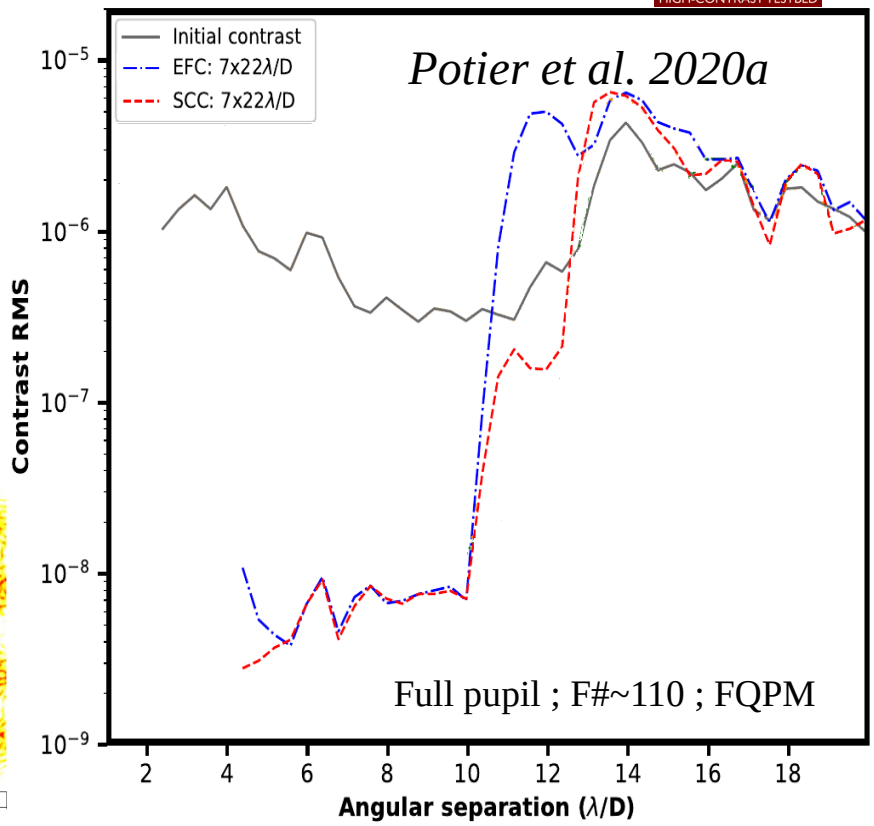
Pair-wise and electric field conjugation

Spatial modulation

Self-coherent camera

Before correction





First comparison of FP WFS @ 5e-9 contrast

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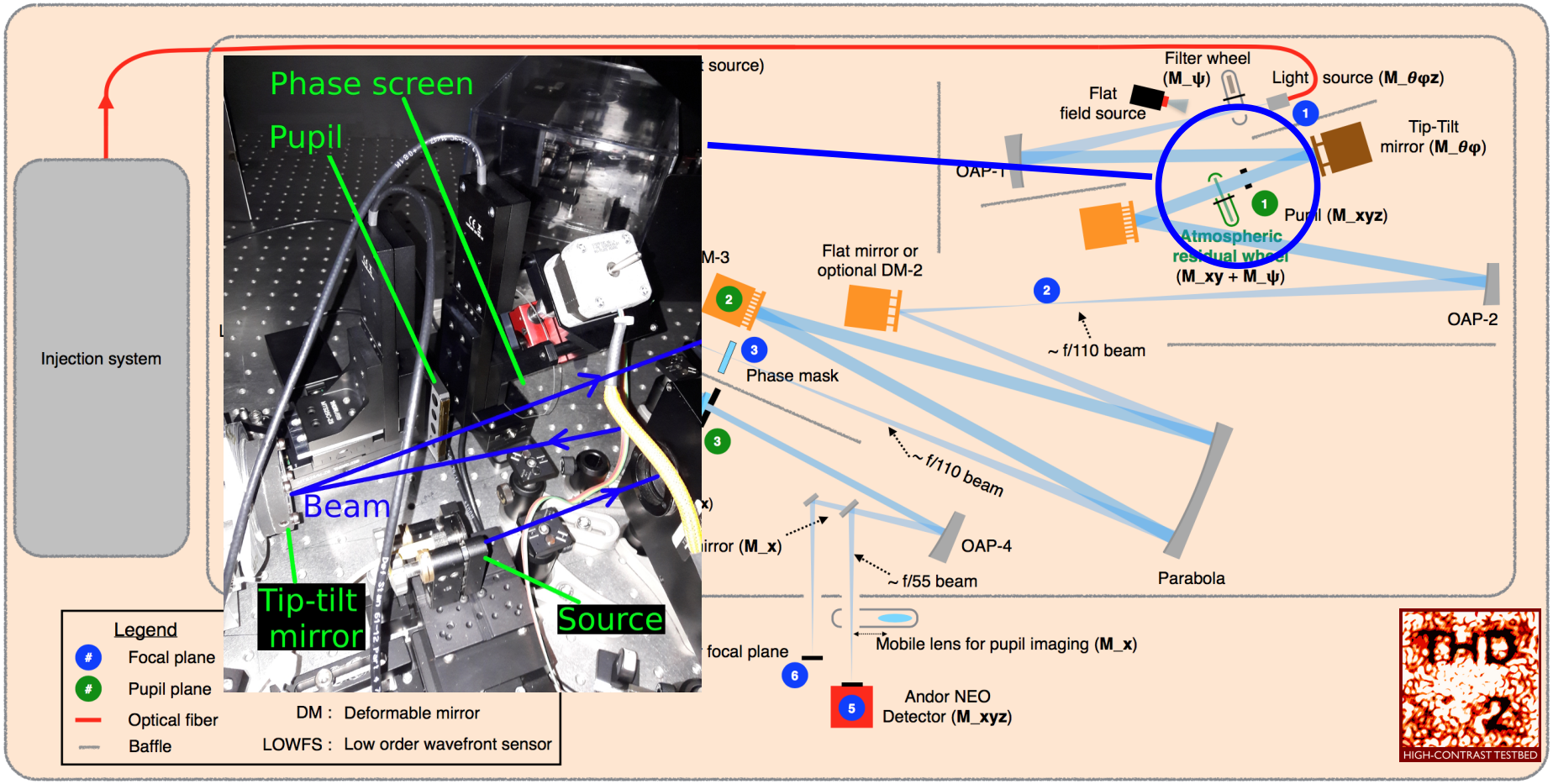
THD2 : Ground configuration

Atmosphere wheel : good AO perf at SPHERE/VLT



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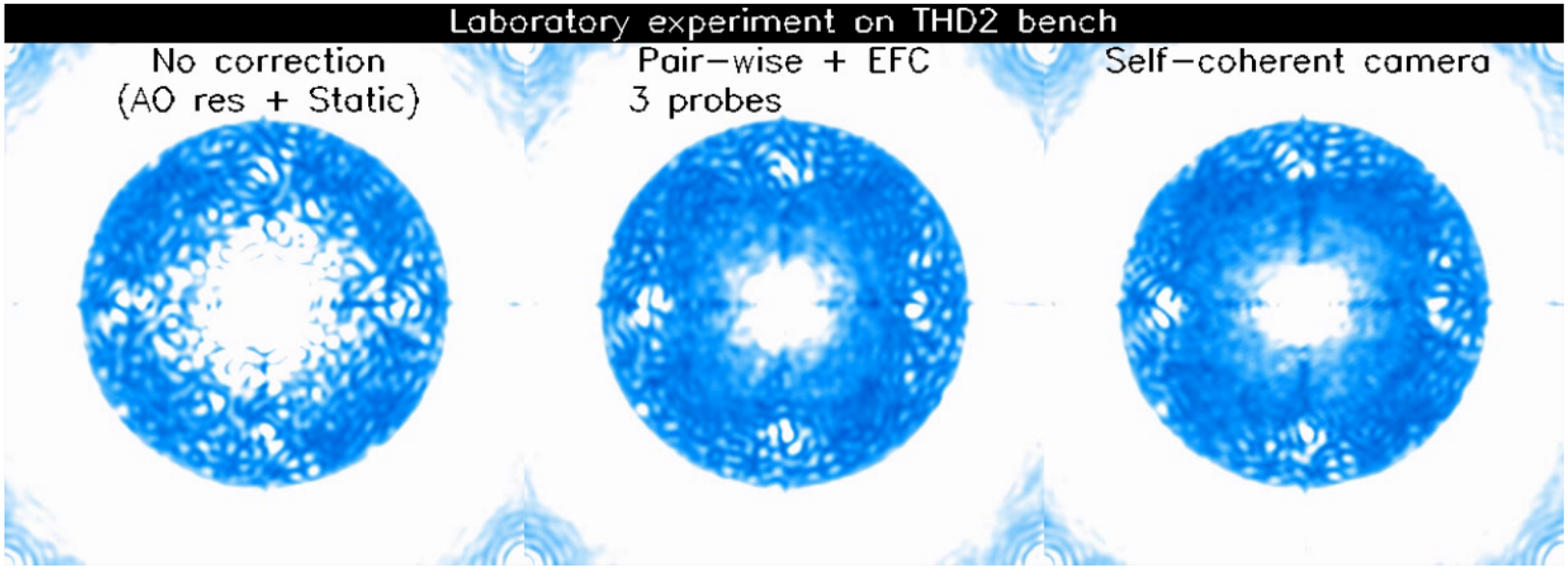
THD2: FPWFS in ground configuration

Correction of quasi-static speckles behind a turbulence AO halo.

- **temporal modulation** → pair-wise and electric field conjugation
- **spatial modulation** → self-coherent camera

Singh et al. 2019



First lab comparison of FPWFS in ground conditions

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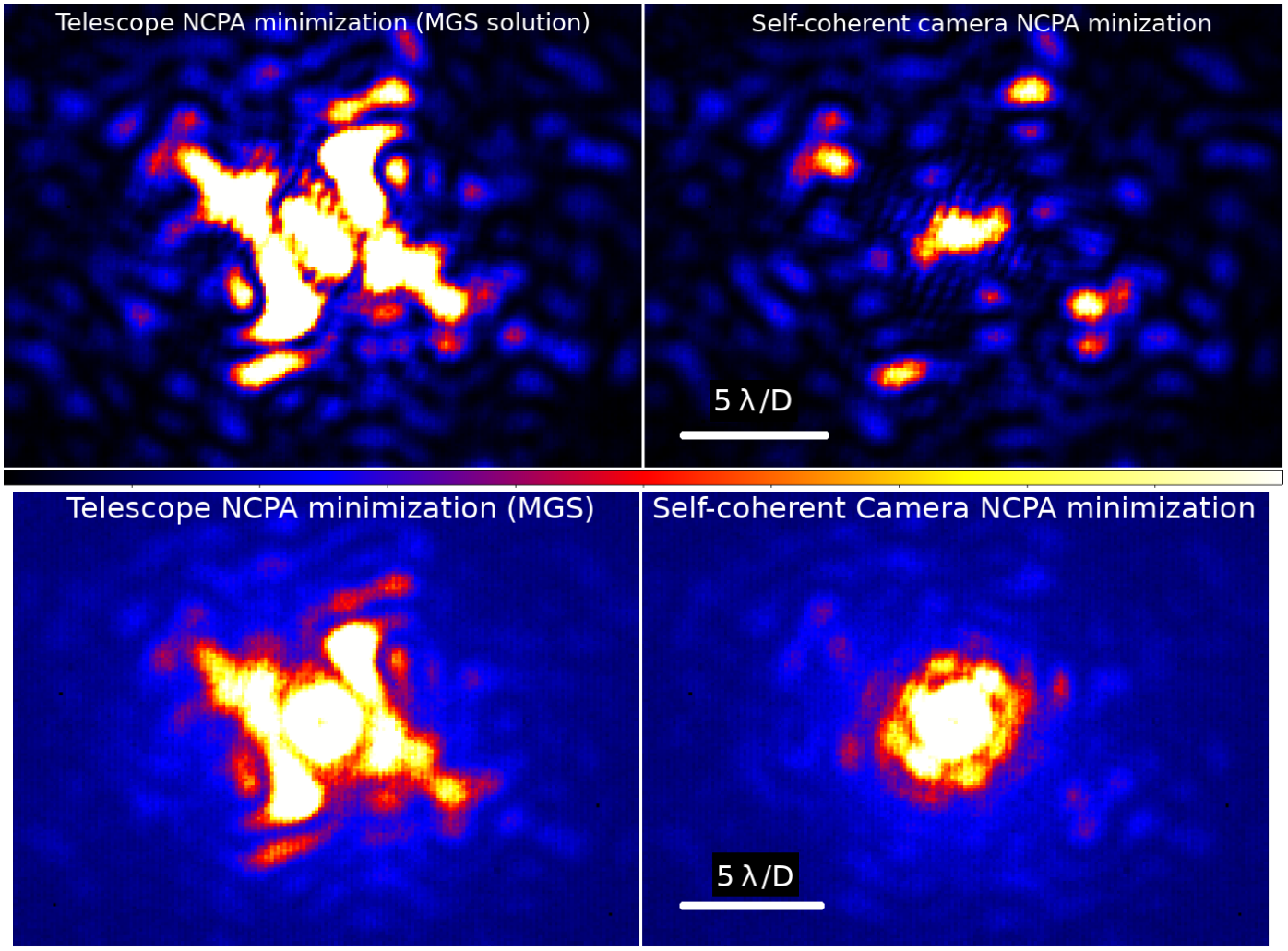
Self-coherent camera (SCC) at Palomar

Galicher et al. 2019



Internal source

On-sky

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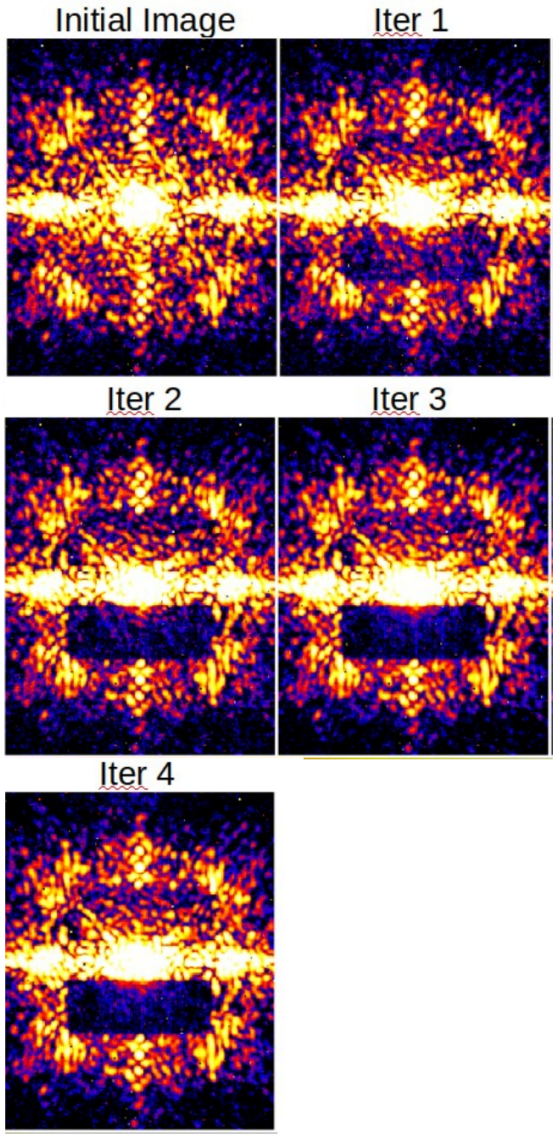
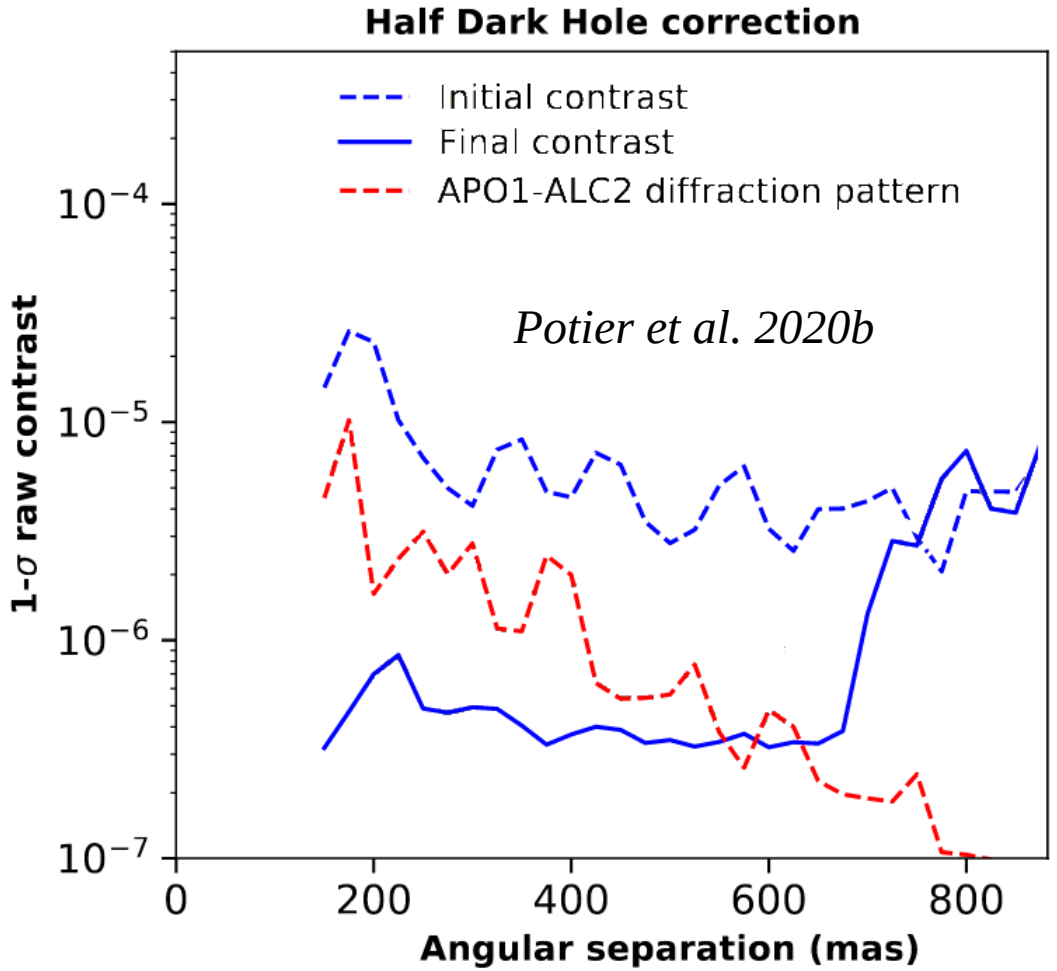
Pair-wise/EFC on SPHERE





Conclusions

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THD2 bench

Comparison/optimization of high contrast imaging for space and ground instruments

→ 10 coronagraph masks

→ 3 wavefront sensing and control

Space configuration

$<5.10^{-9}$ at 3λ/D

→ **Hardware upgrade for the Nancy Grace Roman Space Telescope**

→ Preparation of Luvoir/Habex missions

Ground configuration

→ **Application to Sphere/VLT** (in progress)

→ New coronagraphs (FPWFS friendly)

Thank you