Wavefront sensing and control for Gemini Planet Imager's Calibration Unit-2.0

Gemini Observatory Science Meeting, July 26th 2022

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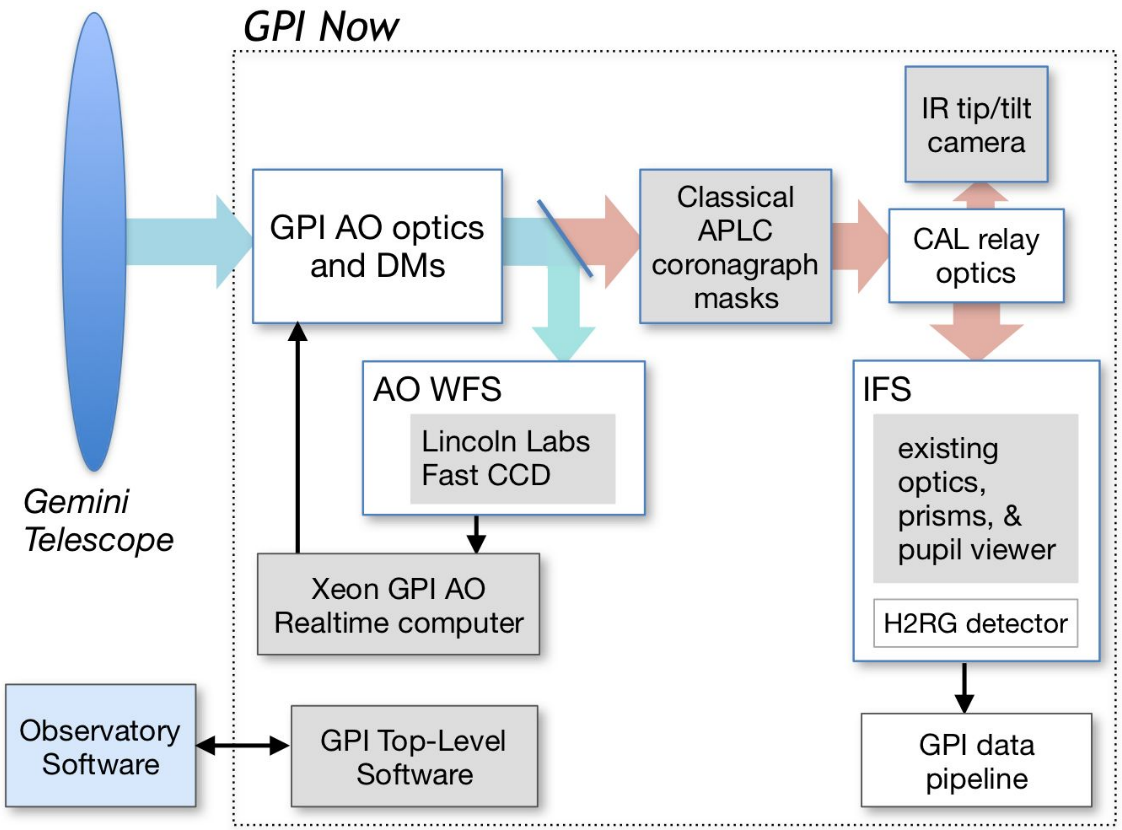
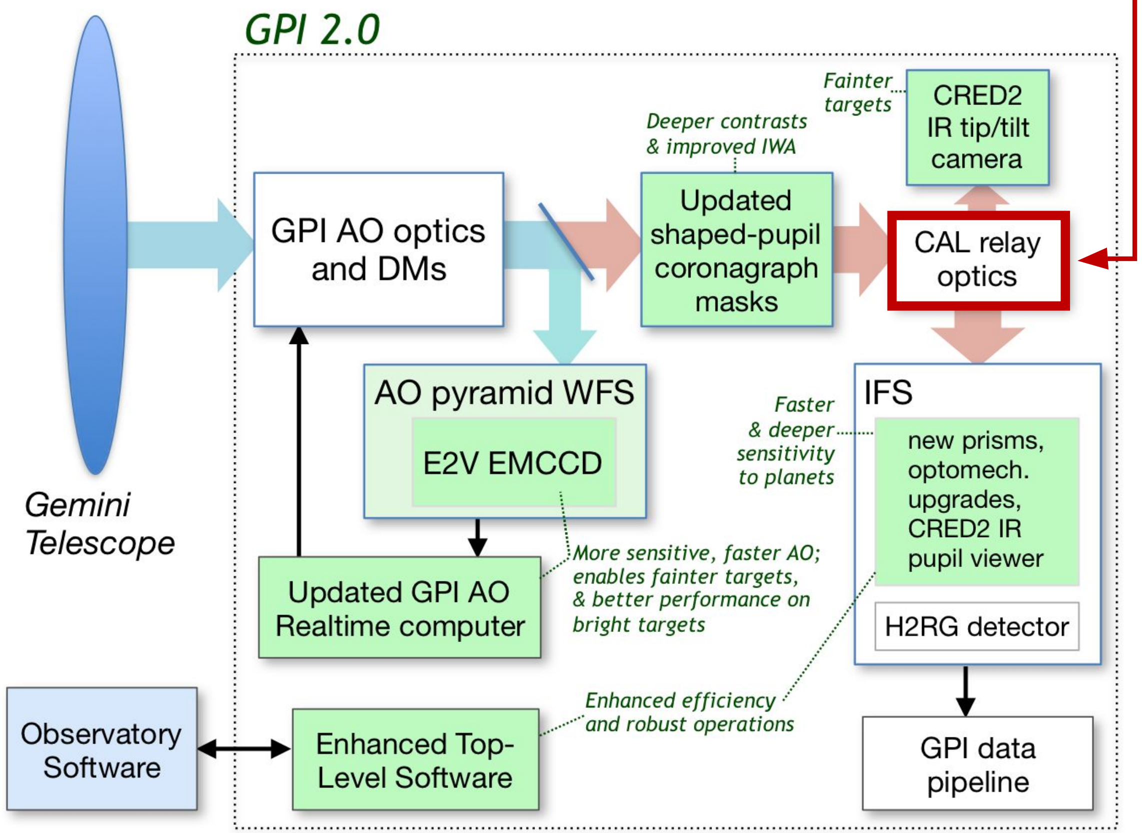
HAA: *Jennifer Dunn, Tim Hardy, André Anthony, Brenda Matthews* **+ *External and International Collaborators***

Gemini Planet Imager (GPI)

Impacted by vibrations

Provide 2nd stage correction of quasi-static speckles and post-AO residuals upstream IFS

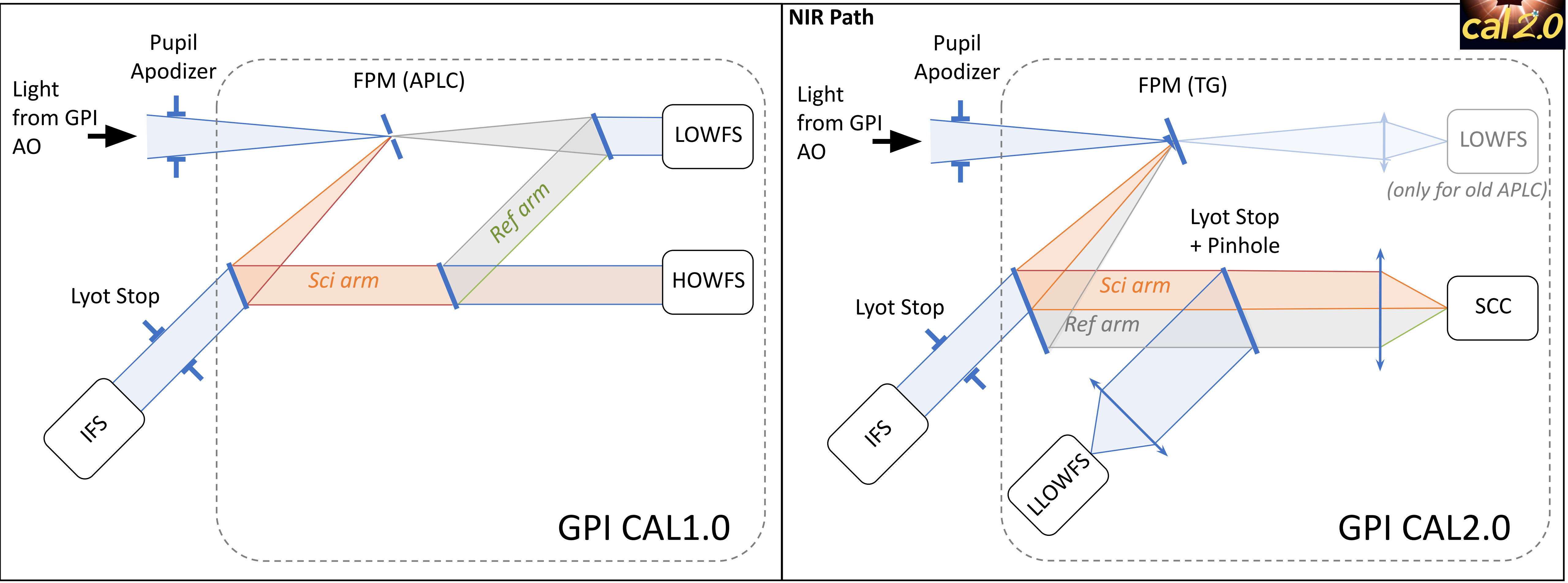




Chilcote et al., SPIE 2020

GPI's Calibration units

- Replace the dual-arm interferometer (HOWFS) with a common-path interferometer (a.k.a. Self-Coherence Camera) more robust to vibration. This requires a new Focal Plane Mask (FPM).
- Expected star/planet contrast gain up to 100x



CAL 2.0 Team Organization Chart (NRC-led effort)

PI
C. Marois
O. Lardière
B. Gerard

EDI
B. Matthews
Q. Konopacky
C. Marois
TBD PDF

GPI2 team
Q. Konopacky
J. Chilcote
B. Macintosh
D. Sivransky

Collaborators
B. Matthews
R. Dong
E. Nielson
R. DeRosa
P. Baudoz
R. Galicher
G. Ruane
F. Marchis
R. Jensen-Clem
T. Esposito

PM
J. Fitzsimmons

Organizations
OMP
Gemini Obs.
KAUST
NanoFab

Optical
O. Lardière
S. Thibault
B. Gerard
M. N'Diaye

Mechanical
A. Anthony

SAPHIRA/ Electronics
T. Hardy
S. Sivanandam

RTC/Software
J. Dunn
J.-P. Véran
B. Gerard
G. Herriot

Integration
O. Lardière
A. Anthony
S. Thibault
GPI team

Focal plane wavefront sensing & deformable mirror control

FAST
B. Gerard
C. Marois
O. Lardière
W. Thompson

LLOWFS
G. Singh
B. Gerard
C. Marois
O. Lardière

Speckle nulling
D. Sivransky
A. Potier

Phase diversity
M. Lamb

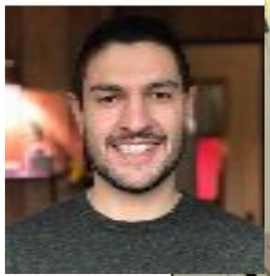
Risk mitigation approaches

Marois et al., SPIE 2020

The NEW-EARTH Lab team (2022)

NRC Extreme Wavefront control for Exoplanet Adaptive optics Research Topics at Herzberg

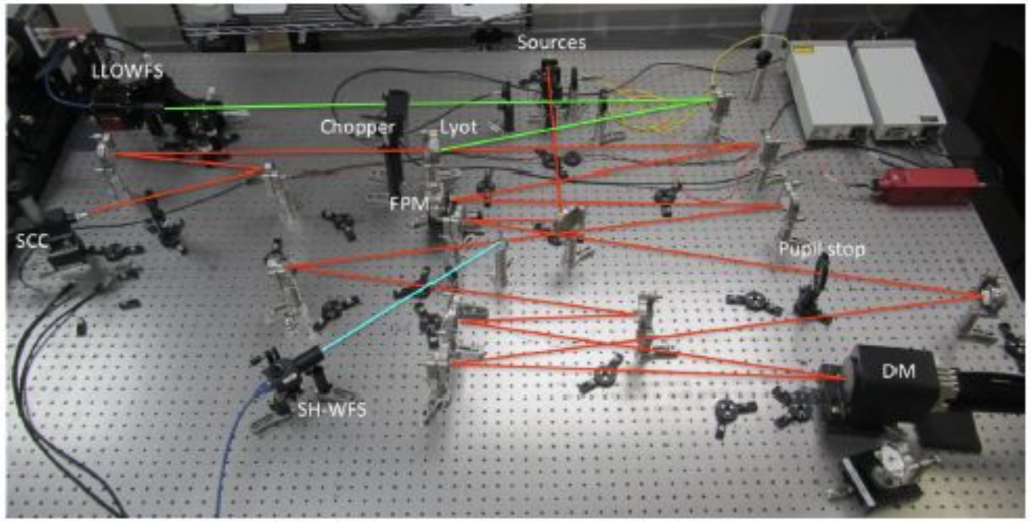
ohnson

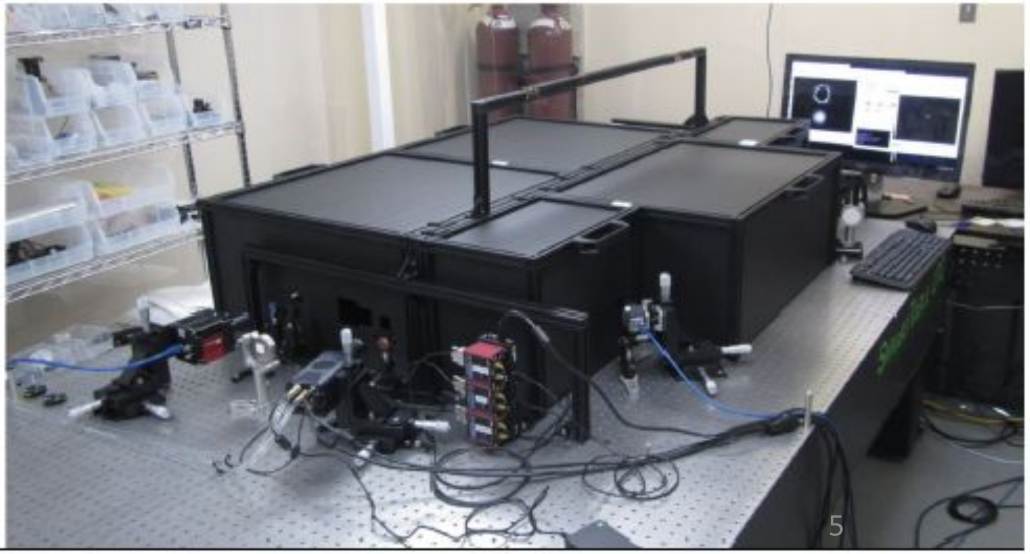


ompson

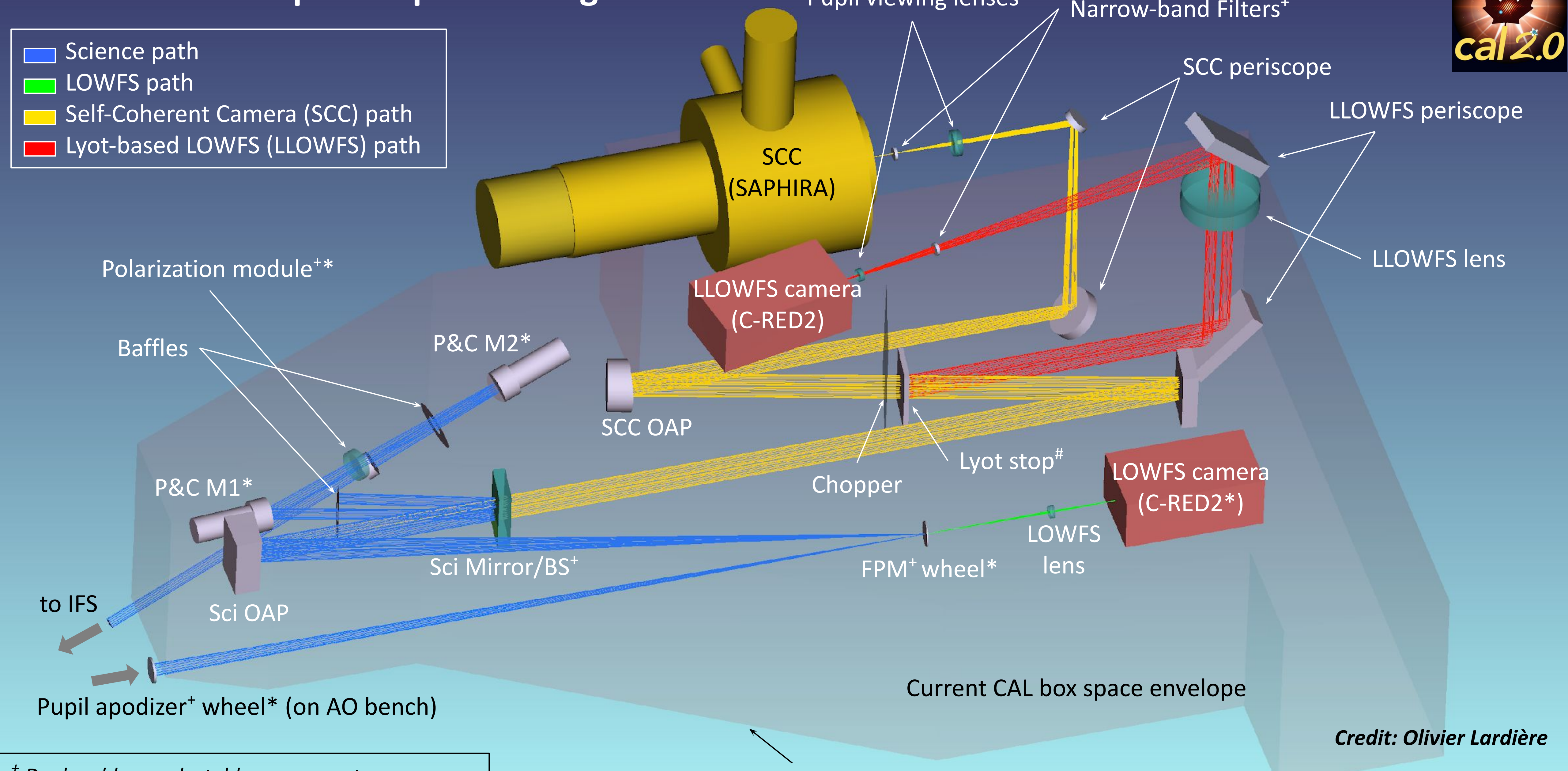
Olivier Lardière

Garima Singh





GPI CAL2.0 Conceptual Optical Design



+ Deployable or selectable component
** GPI's component that can be reused for CAL2.0*
 # On motorized X-Y flexure mount

What causes residual aberrations in post-AO regime?

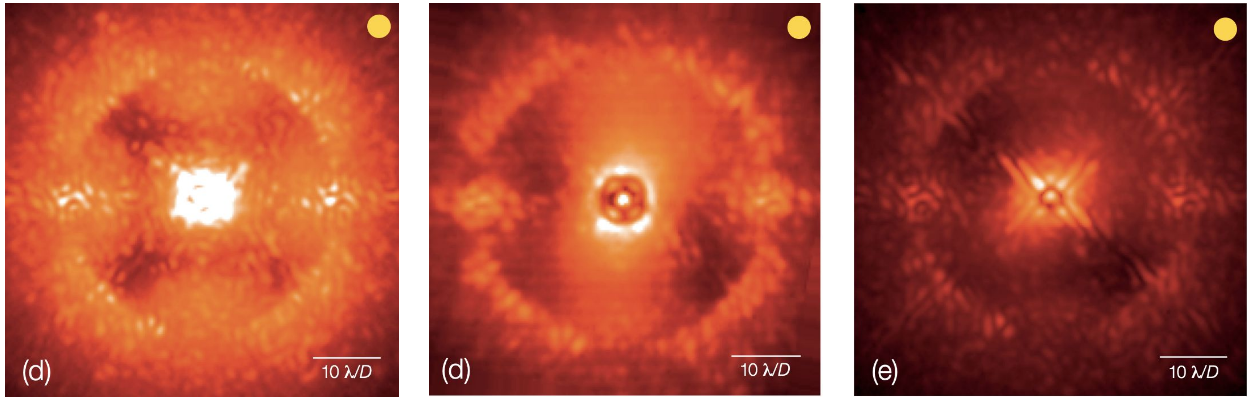
Static defects

- Coronagraph is not perfect, always have residual light due to diffraction, can be mitigated by Apodization.
- Manufacturing defects of a coronagraph
- Optical defects
- Amplitude aberration

Dynamic errors

- **Low-order aberrations**
- **Non-common path aberrations (NCPA)**
- Post-AO residual halo
- Aliasing
- Fitting-error
- Low-wind effect
- Wind driven halo

Raw on-sky image (SPHERE/VLT)

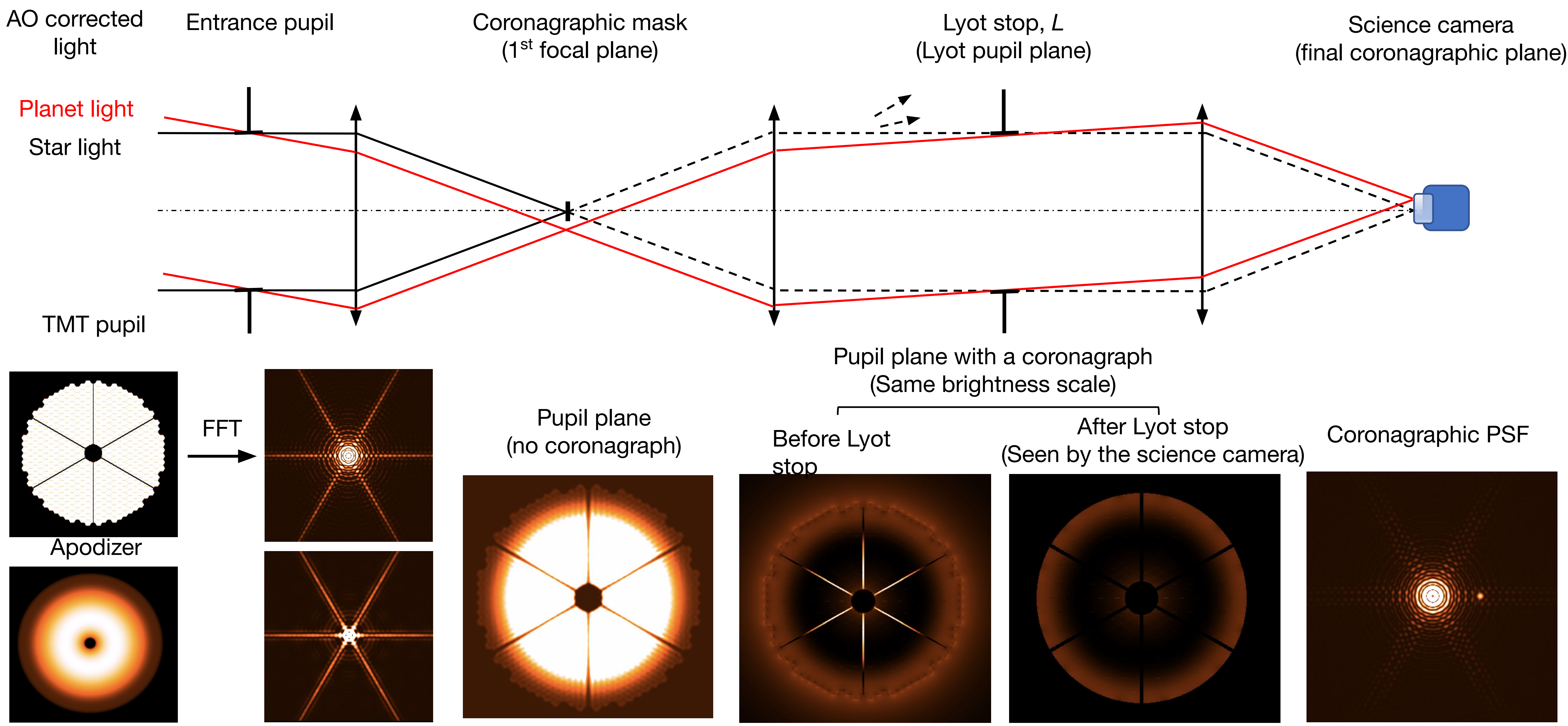


Cantalloube et al 2019

State-of-the-art raw contrast limit:- 10^{-4} – 10^{-5} at > 5 λ/D at NIR wavelengths (Self-luminous young extrasolar giant planets around nearby young stars).

Optical layout of a coronagraphic system

* PSFs are not at same brightness scale



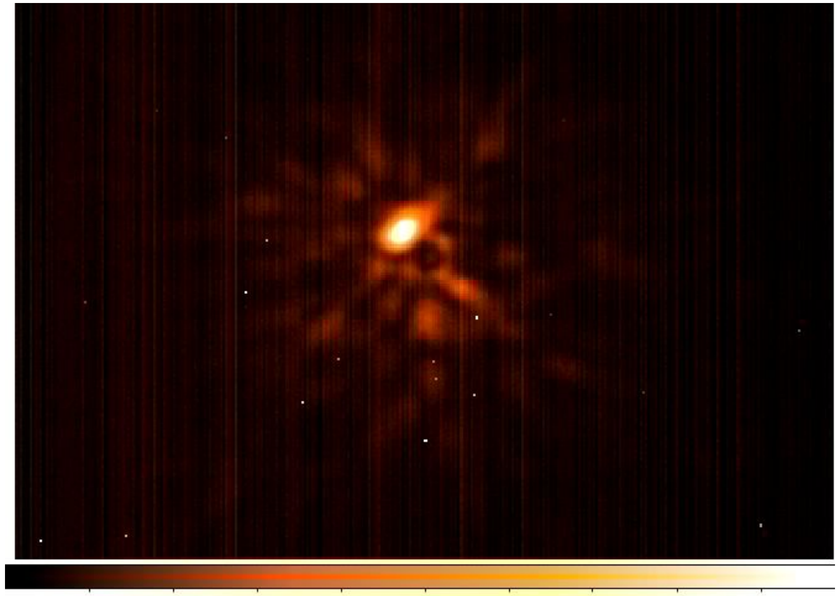
What causes residual aberrations in post-AO regime?

Low-order aberrations

Causes: Temperature variations, thermal distortions, optical/mechanical vibrations, alignment errors due to telescope motors and chromatic errors.

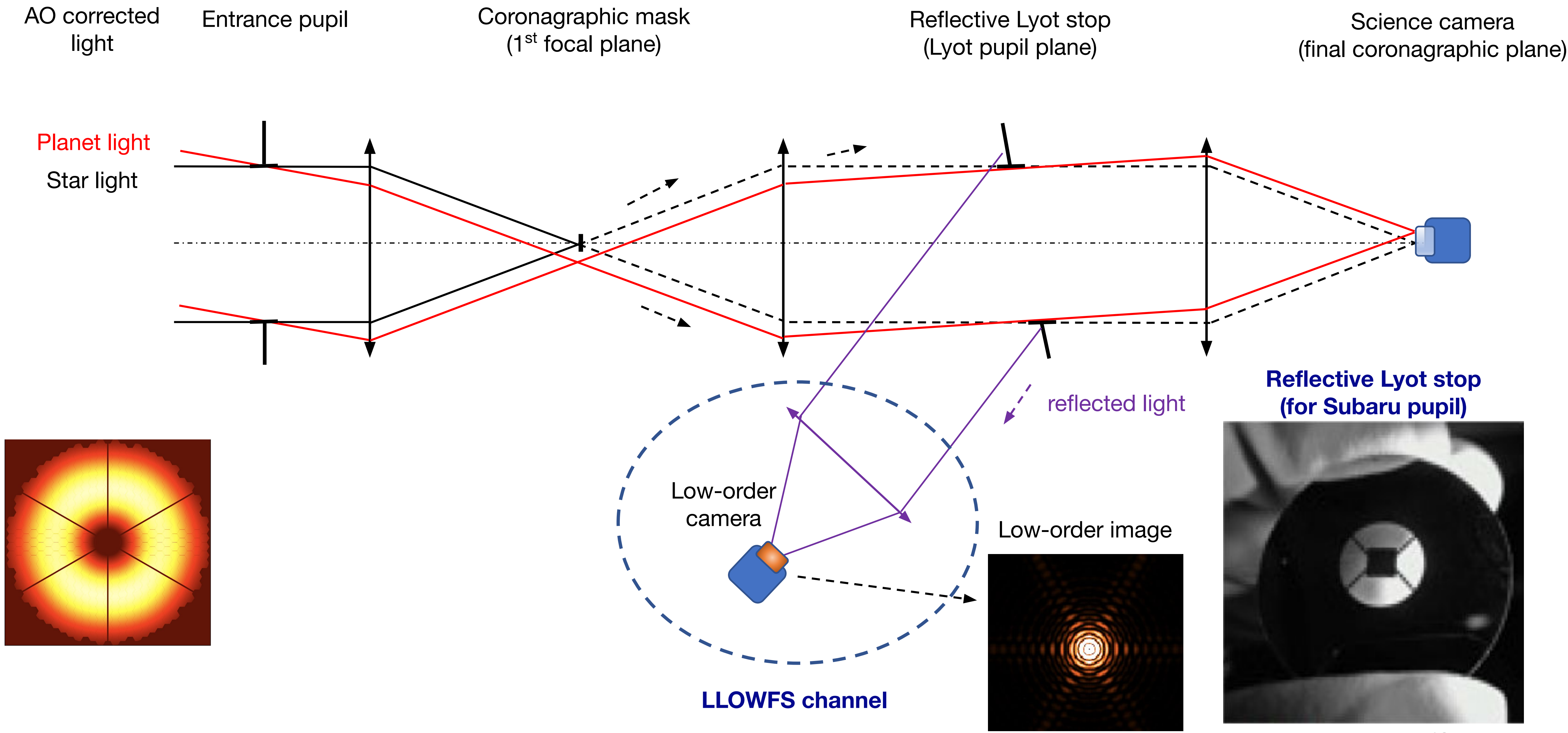
Effects: Starlight leak around a coronagraphic mask, prevent detection at small angles.

On-sky, no low-order corrections (SCExAO/Subaru), PIAA coronagraph



Lyot-stop low-order wavefront sensor (LLOWFS)

Singh et al 2014 and 2015



What causes residual aberrations in post-AO regime?

SCExAO
Subaru Coronagraphic Extreme Adaptive Optics

Low-order aberrations

Causes: Temperature variations, thermal distortions, optical/mechanical vibrations, alignment errors due to telescope motors and chromatic errors.

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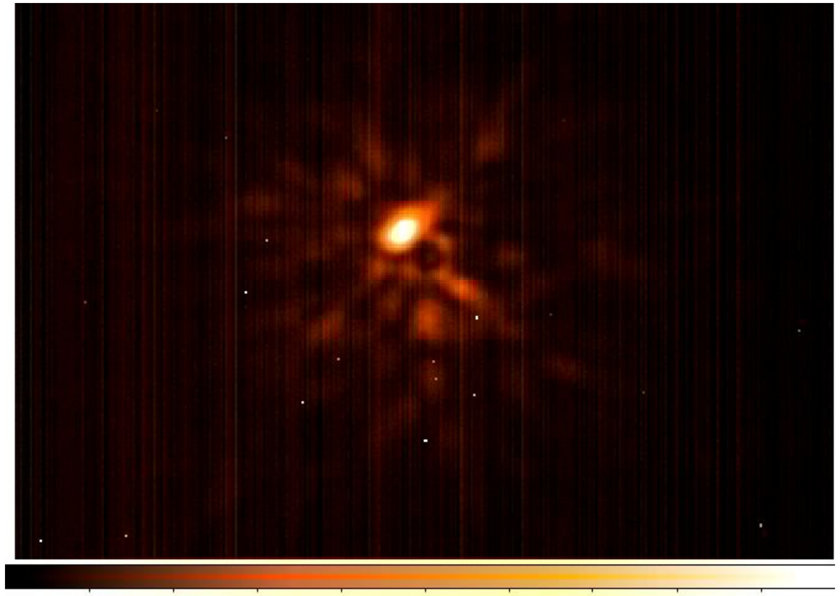
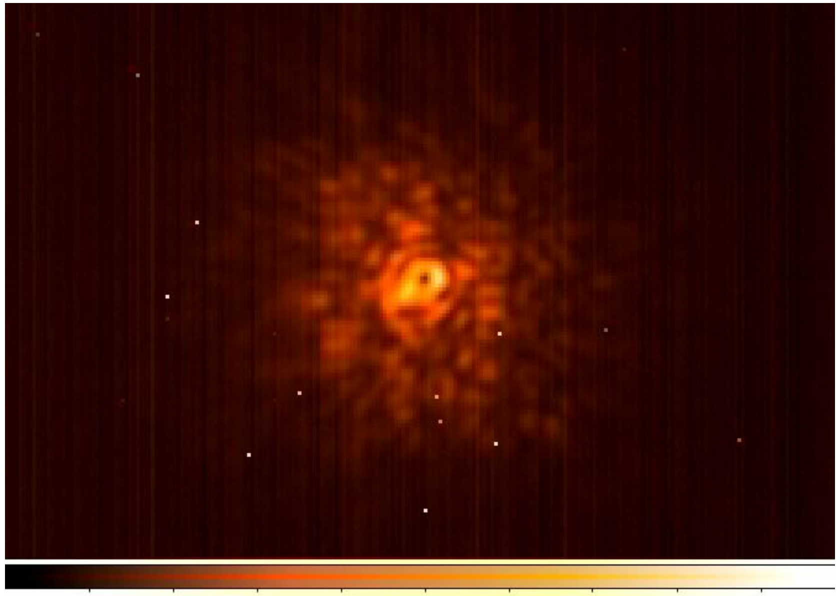
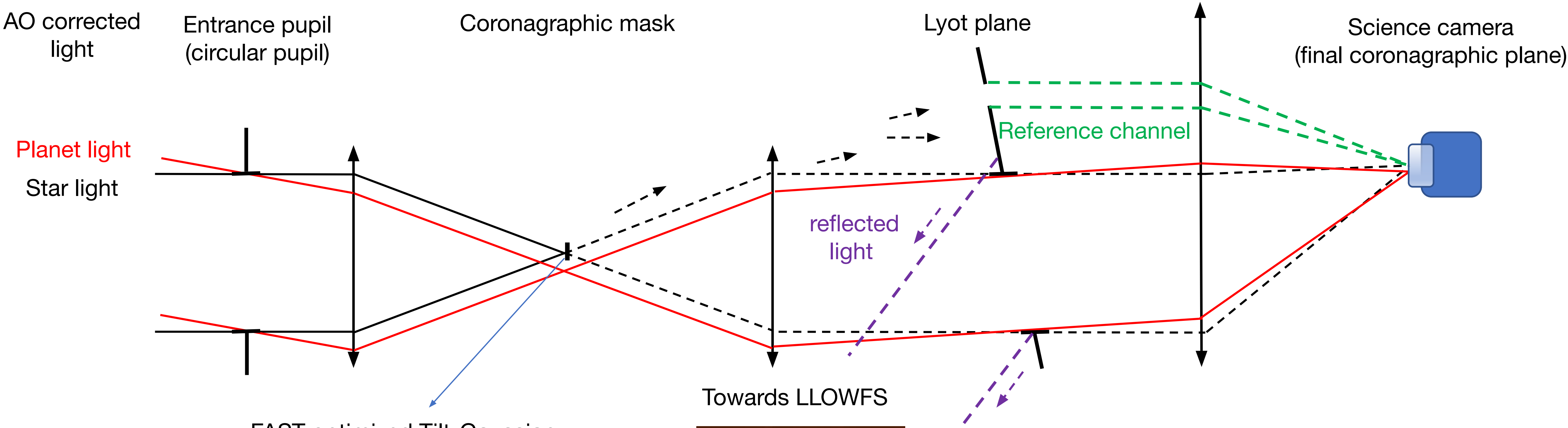
On-sky, no low-order corrections (SCExAO/Subaru), PIAA coronagraph



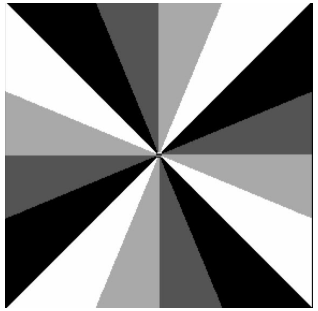
On-sky, LLOWFS loop closed on 10 modes Singh et al. 2017



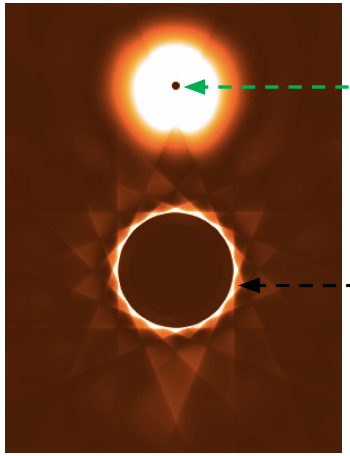
LLOWFS on the NEW-EARTH Lab



FAST optimized Tilt-Gaussian Vortex (TGV) mask
Gerard et al., 2018, 2019, 2020



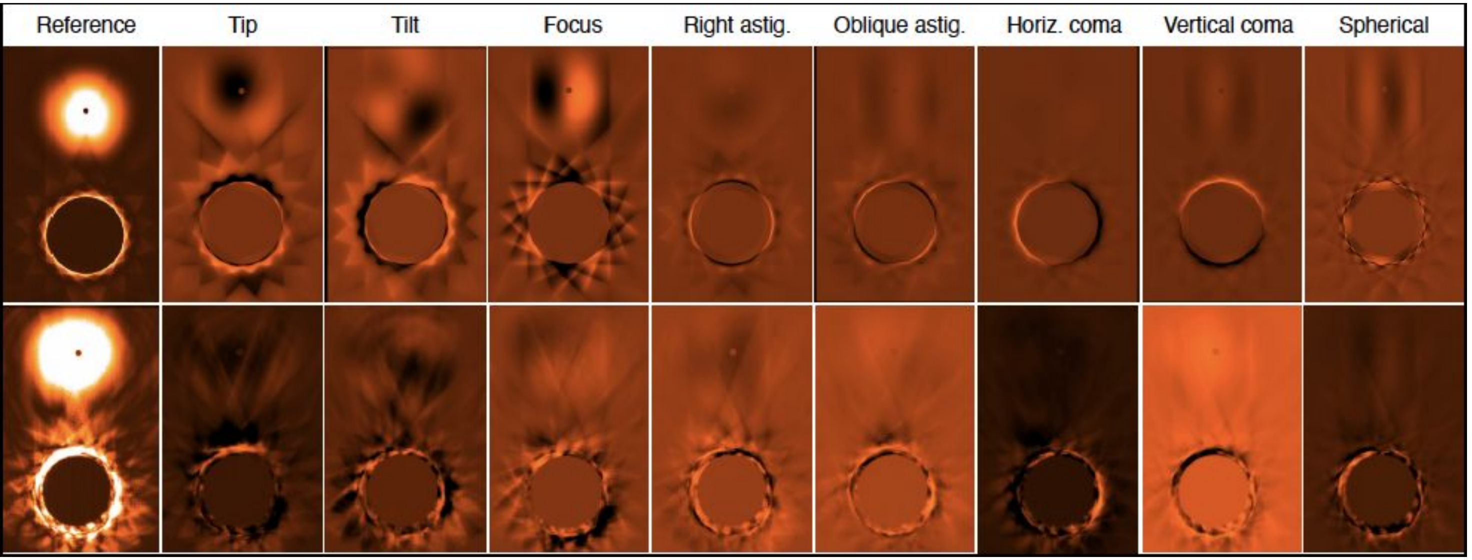
Fabricated by KAUST
(Fresnel design)



Pupil-plane LLOWFS sensing

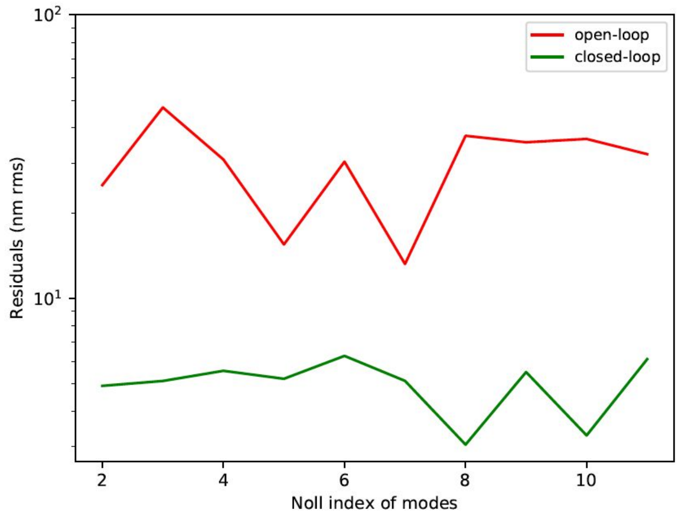
Singh et al., SPIE, 12185-192, 2022

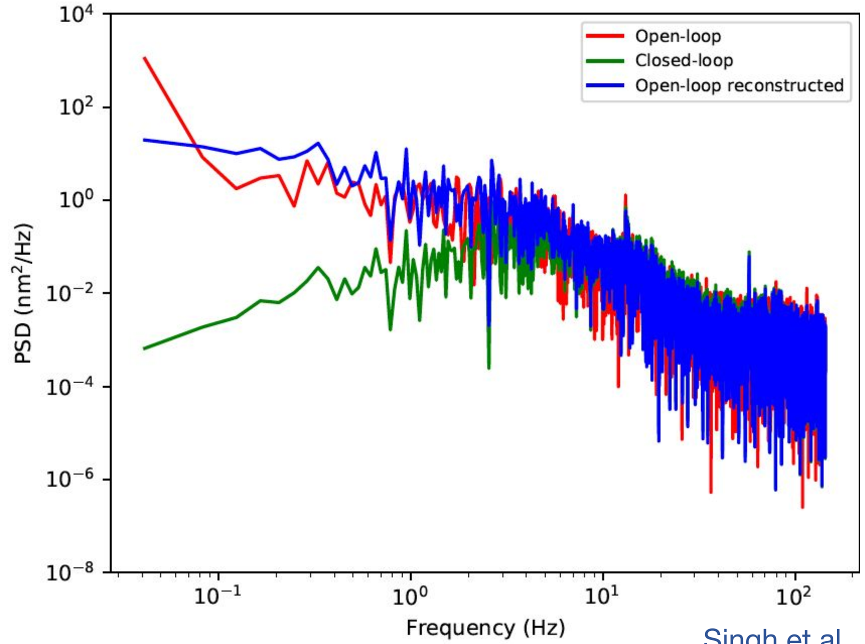
NEW-EARTH Lab results with LLOWFS (with modal gain optimization)

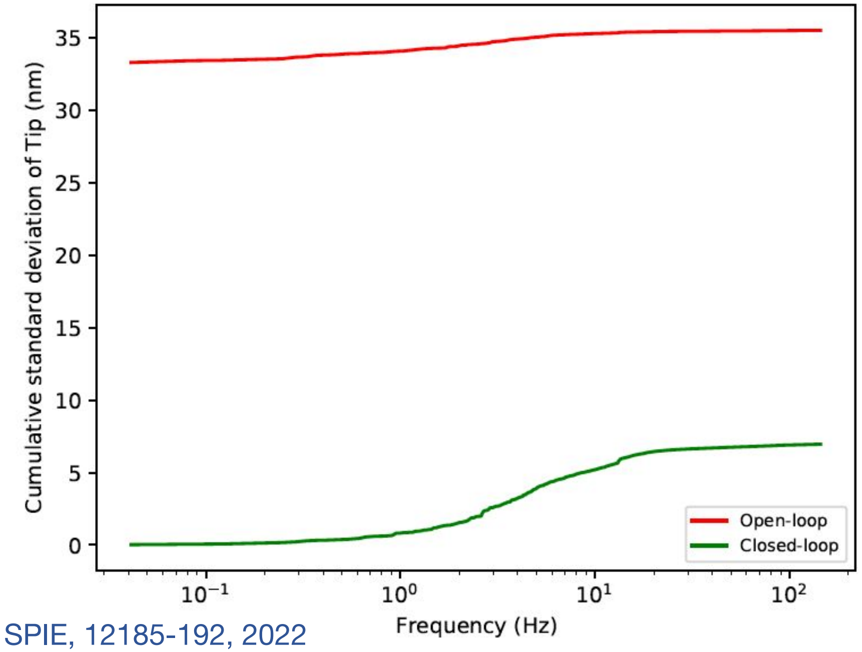


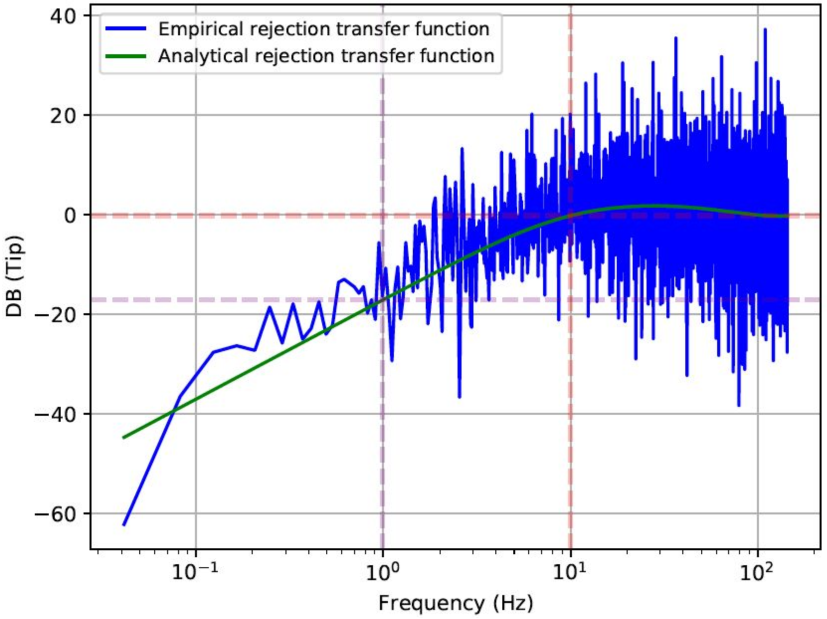
(Singh et al., SPIE, 12185-192, 2022)

Under GPI 2.0 residuals
1” seeing, 151 nm RMS, V_{mag} 8









Singh et al., SPIE, 12185-192, 2022

What causes residual aberrations in post-AO regime?

Non-Common Path Aberration (NCPA)

Smooth halo: AO-induced fast varying speckles that average out. Add photon noise on the planet detection.

+

Static speckles: evolution lifetime > complete sequence of images (typically 30min-1h).

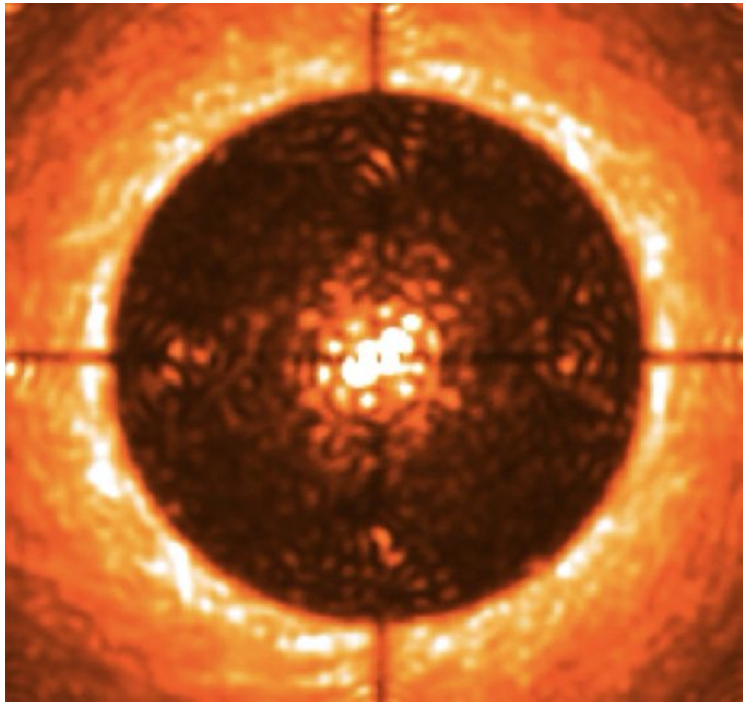
Can be calibrated a posteriori using observing strategies like angular/spectral differential imaging.

+

Quasi-static speckles: vary slowly during the observing sequence.

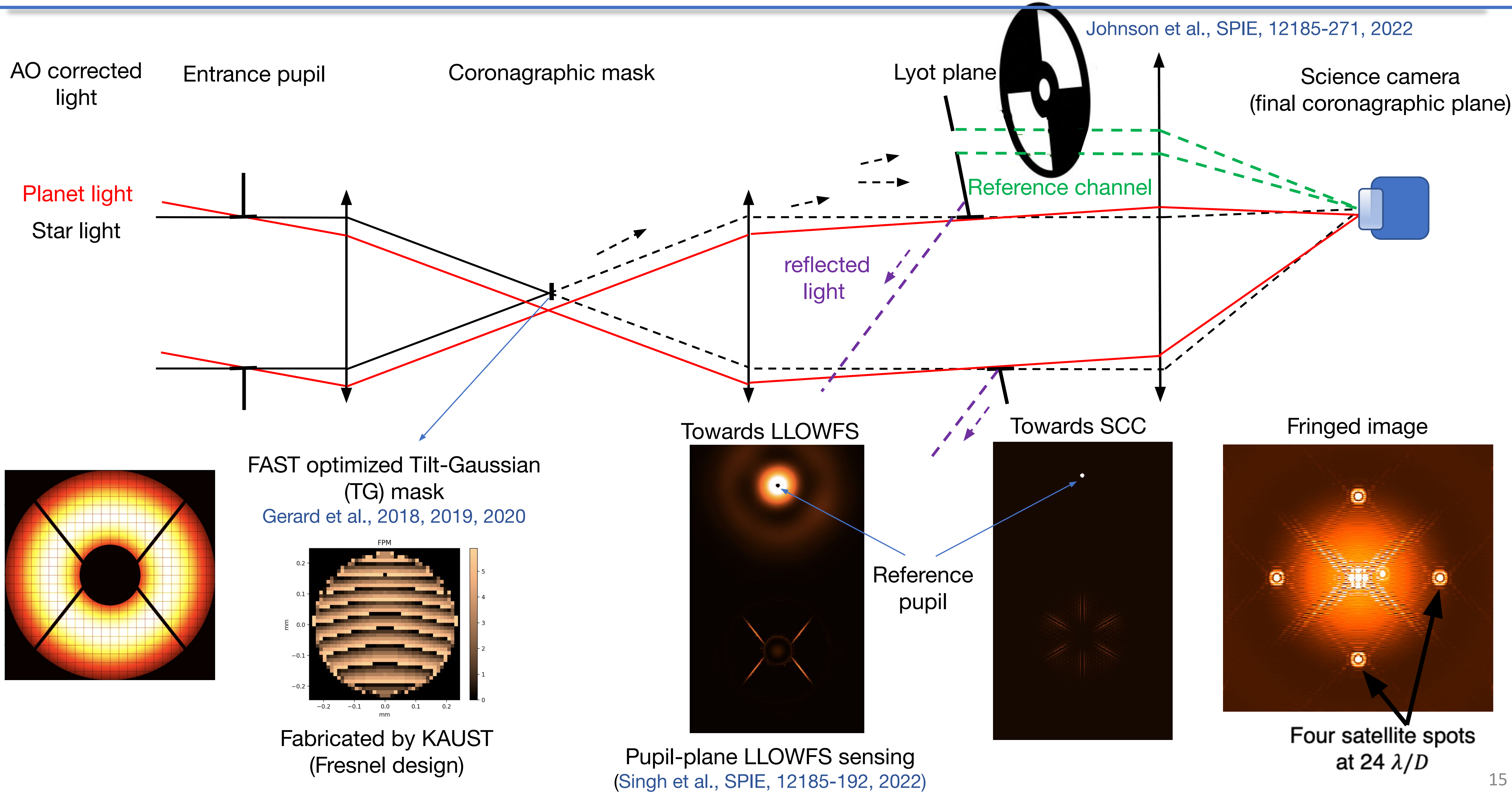
NCPA which evolve during science acquisition cannot be calibrated, and leave behind evolving speckles in the images.

Post-AO laboratory image (18s) on THD2/Paris



Self Coherent Camera (SCC)

Baudoz et al. 2006; Galicher et al. 2010, Mazoyer et al. 2013



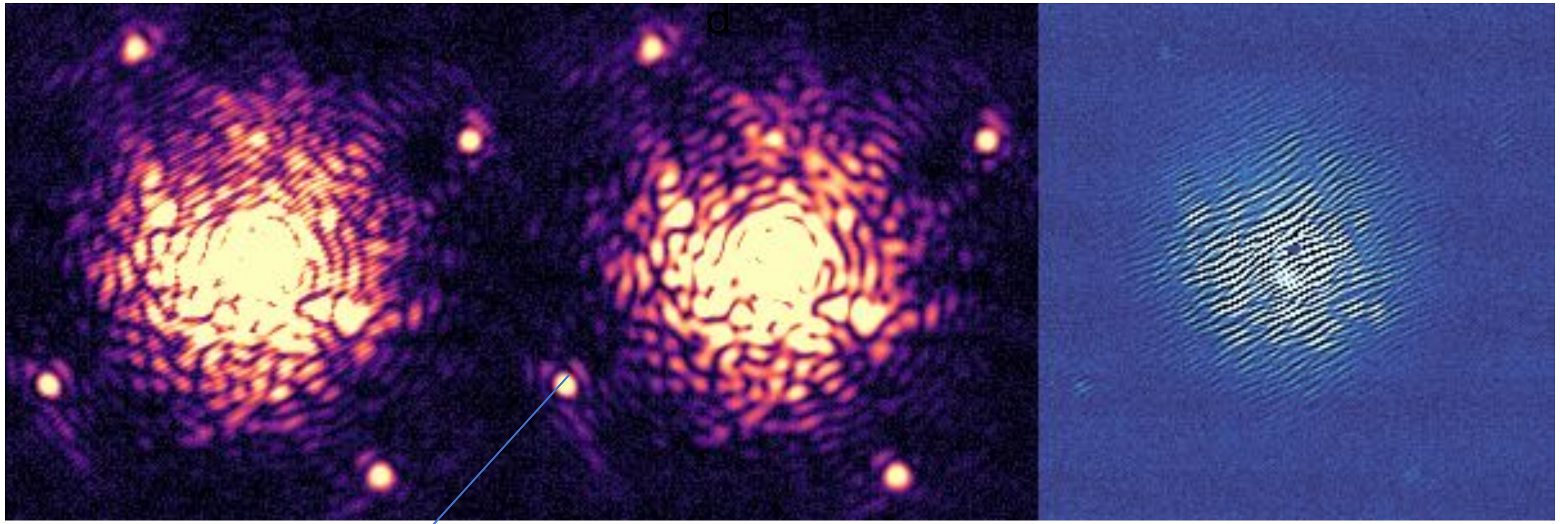
NEW-EARTH Lab results with SCC

Fringed

Un-fringe
d

Fringed – Un-fringed

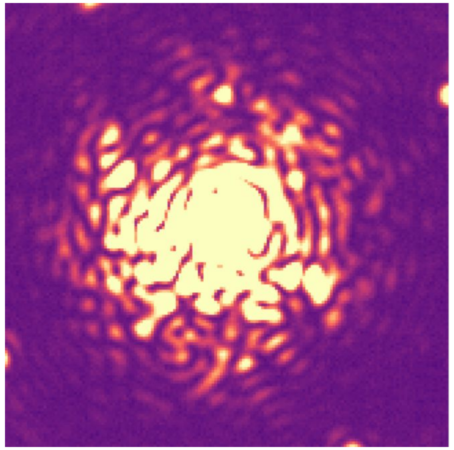
W. Thompson
& NE team



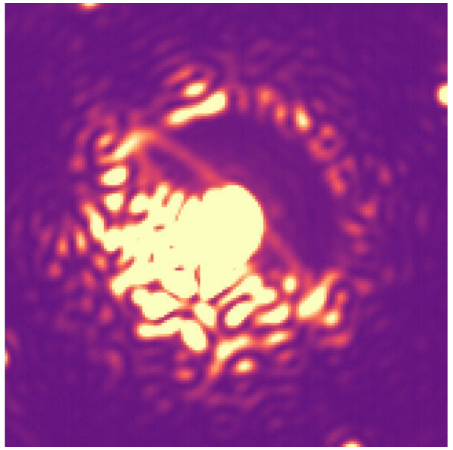
SCC loop running at 200 Hz on a fairly bright simulated source

W. Thompson,
C. Marois

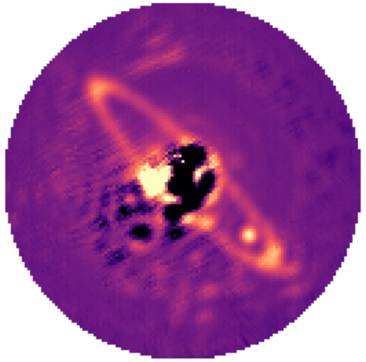
No SCC



With SCC



SCC +
Coherent Differential imaging



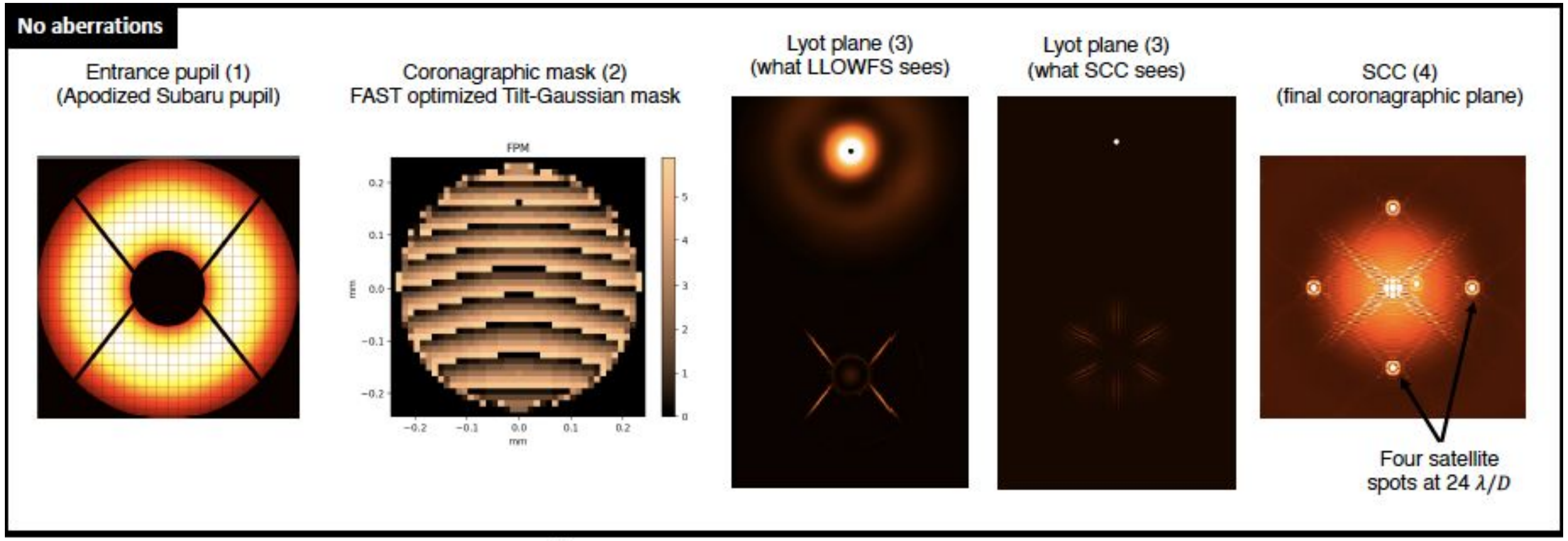
Lab data (narrowband)

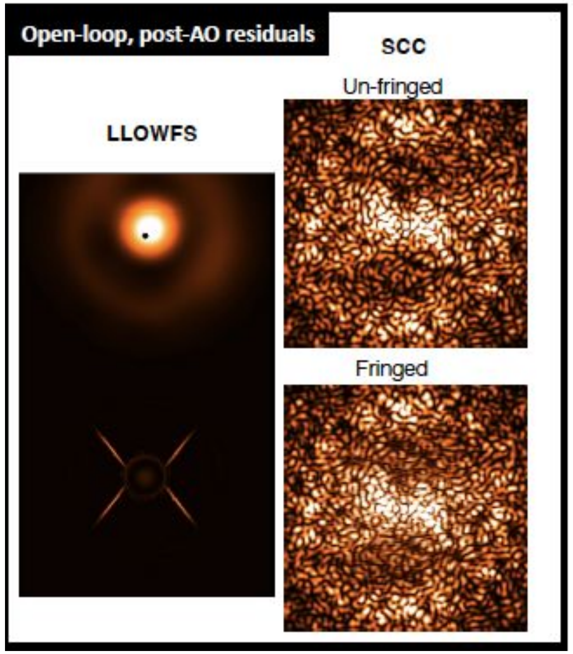
Obtaining a raw contrast of **5×10^{-7} beyond 5 λ/D** at 1.3 μm (Thompson, W. et al., SPIE proceeding, 12185-84, 2022)

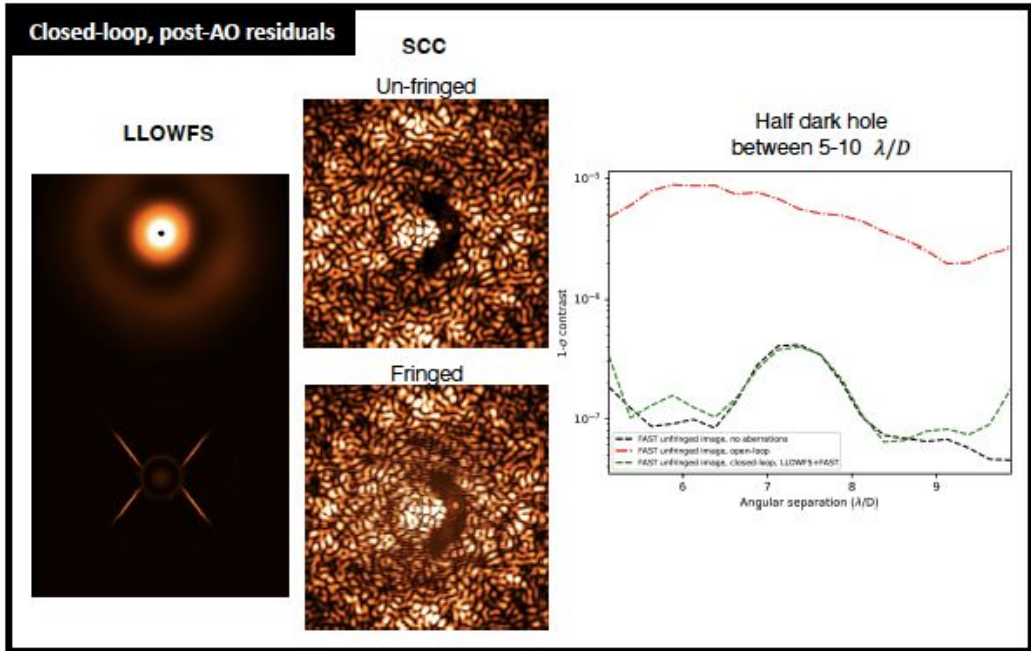
Extra 20-40x gain with CDI!

Limited by camera & DM stroke resolution; some incoherent light

Expectations with CAL 2.0 (Simulations with SPIDERS instrument/Subaru)







Singh et al., SPIE, 12185-192, 2022

Bandwidth / Modes	DC (<1Hz)	Low (1→ 50Hz)	Mid (50→ 250Hz)	High (250→ 1000Hz)
Tip/Tilt/Focus	SCC	LLOWFS		PWFS
mid+high order	SCC		PWFS	

Table 1. Closed-loop FAST WFS control authority, split by spatial modes (rows) and temporal bandwidth (columns).

Marois et al., SPIE 2020 and 2022
Lardiere et al., SPIE, 12185-156, 2022
Thompson, W. et al., 12185-84, 2022

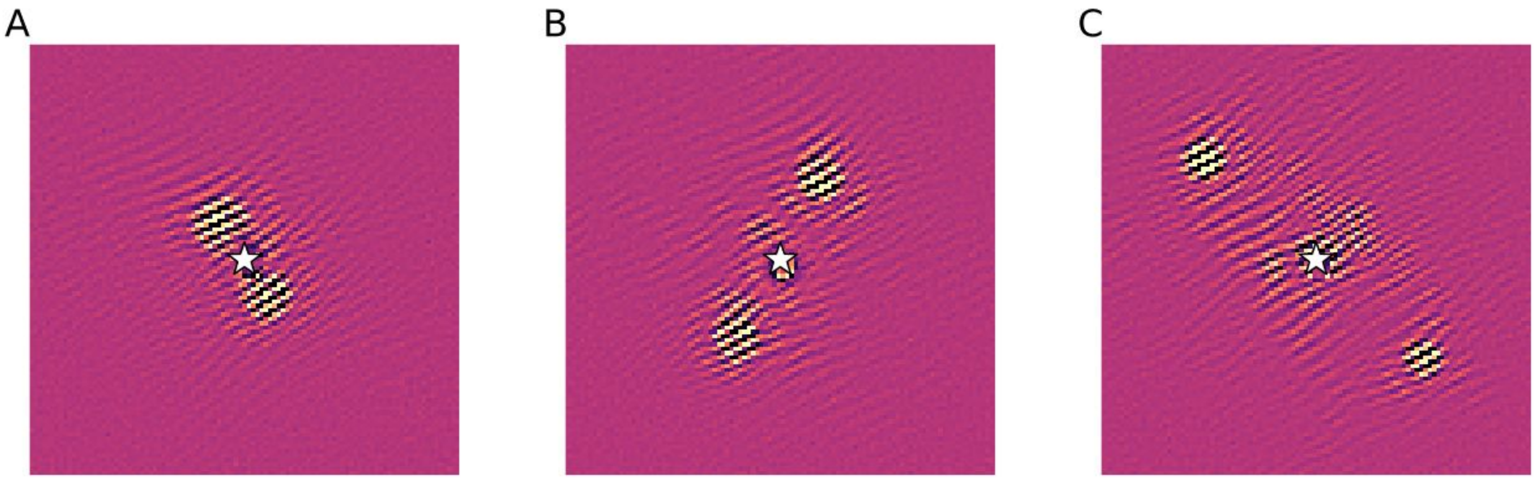
Conclusion

- CAL 2.0 could provide the first estimates of the commonality of true Jupiter analogues.
- A 300-star survey with CAL 2.0 is expected to detect 39 planets.
- Enable detection and atmospheric characterization of lower-mass, closer-in, colder and/or older exoplanets.
- CAL 2.0 will also enable new science within Solar System. Non-coronagraphic imaging at ~0.85μm, high Strehl ratio (>30%) and an angular resolution of 10 mas will enable detections of surface features (craters etc.)
- Improved face-on disk imaging with deeper contrast.
- Direct imaging with the CAL2.0 will enable direct measurements of flux ratio, separation, and position angles of new binaries too close for current systems.

Fig. 23. Project milestones and timelines.

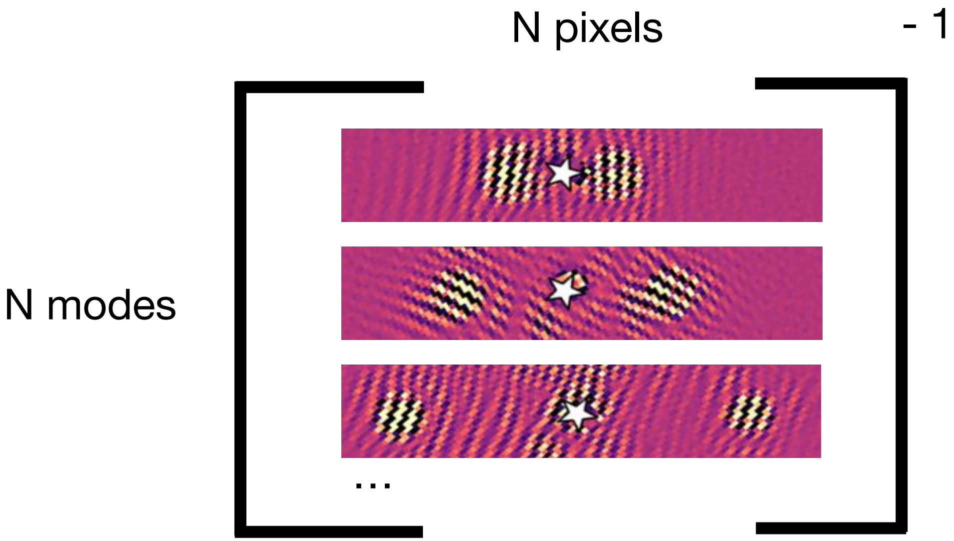
Back-up slides: Closing the loop with SCC

1. Capture sinewave interaction matrix



Isolate only the fringes:
(push fringed – push unfringed) – (pull fringed – pull unfringed)

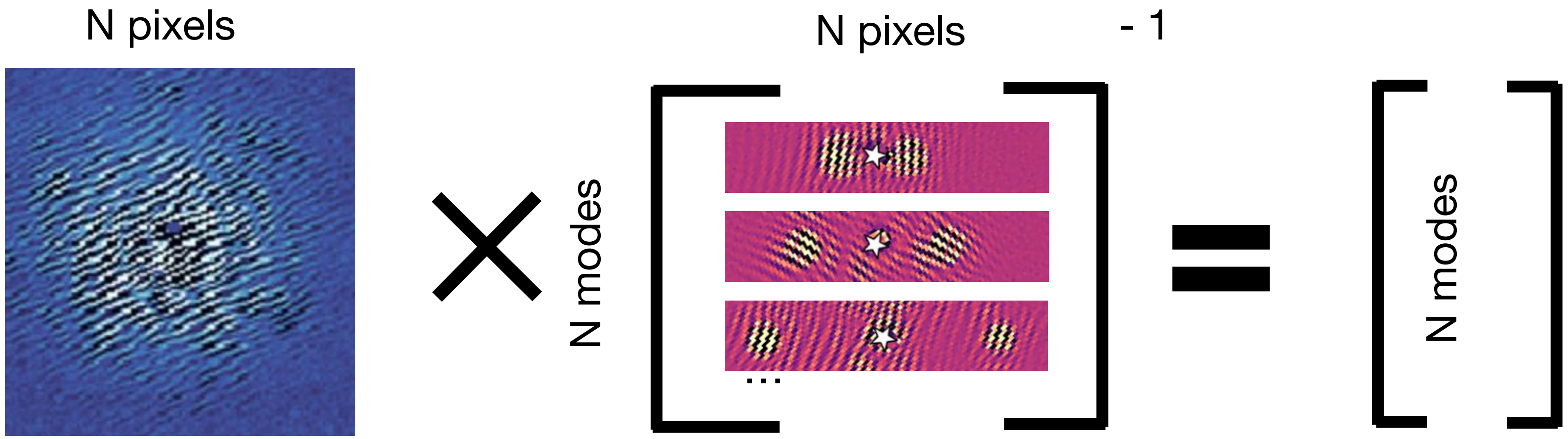
2. Invert matrix with Tihkonov regularization:



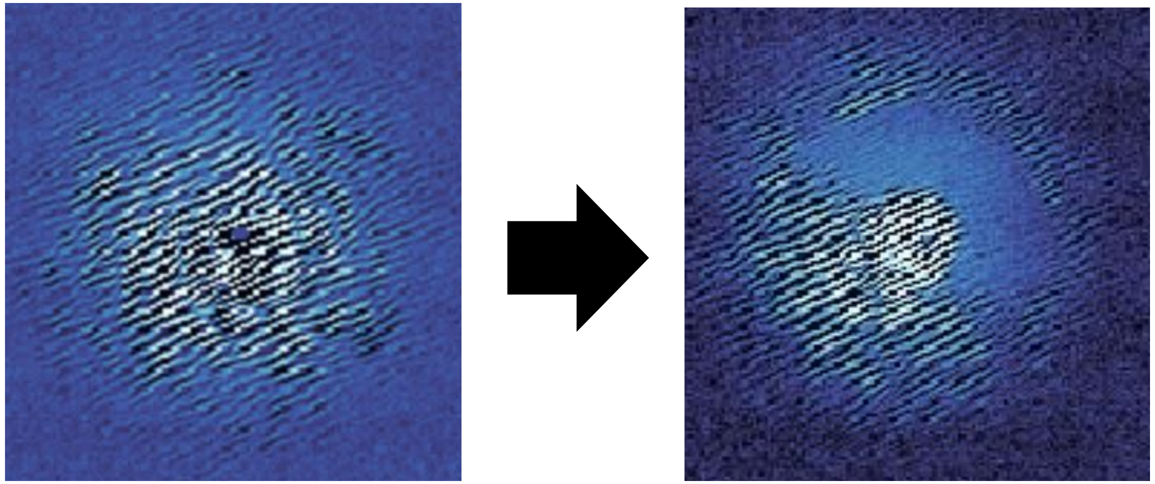
Credit: William Thompson

Back-up slides: Closing the loop with SCC

3. To extract modal coefficients, just multiply by the differential image:



4. Iterate



Credit: William Thompson