

PhD Defense
21st September 2015
Space Telescope Science Institute, Baltimore

on

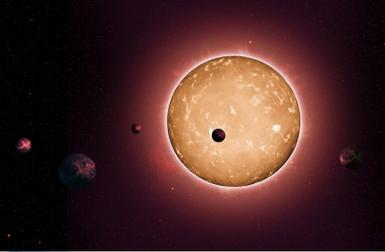
**Low-order wavefront control and calibration for
phase-mask coronagraphs**

by

Garima Singh

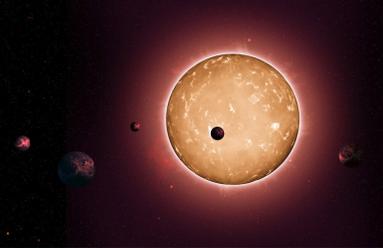
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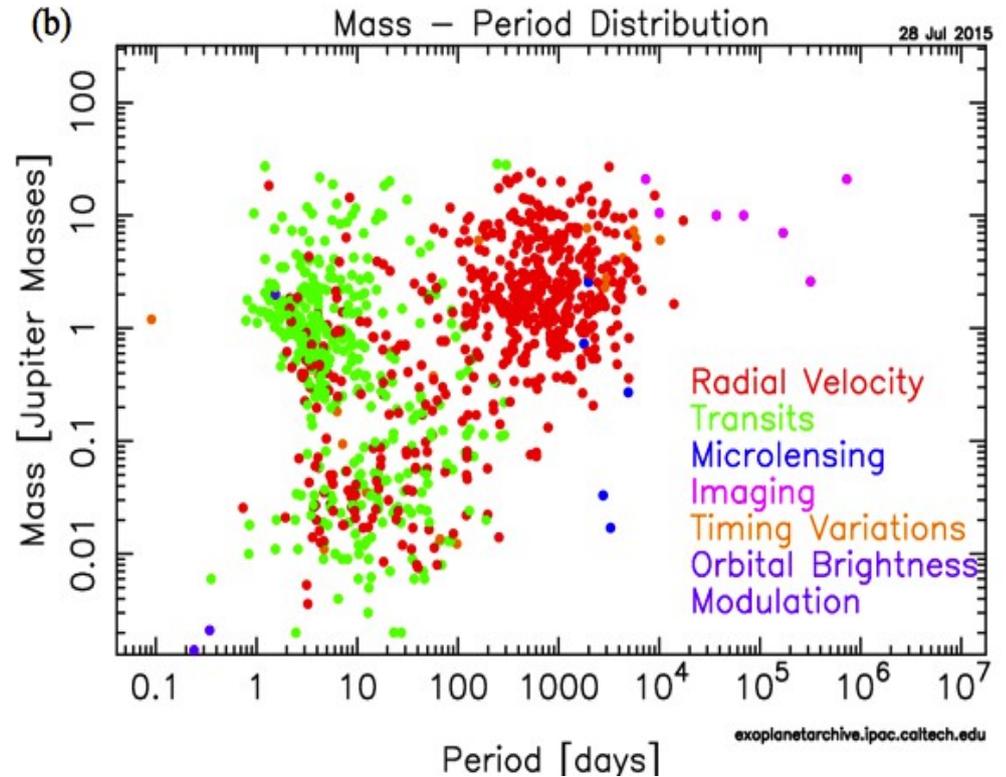
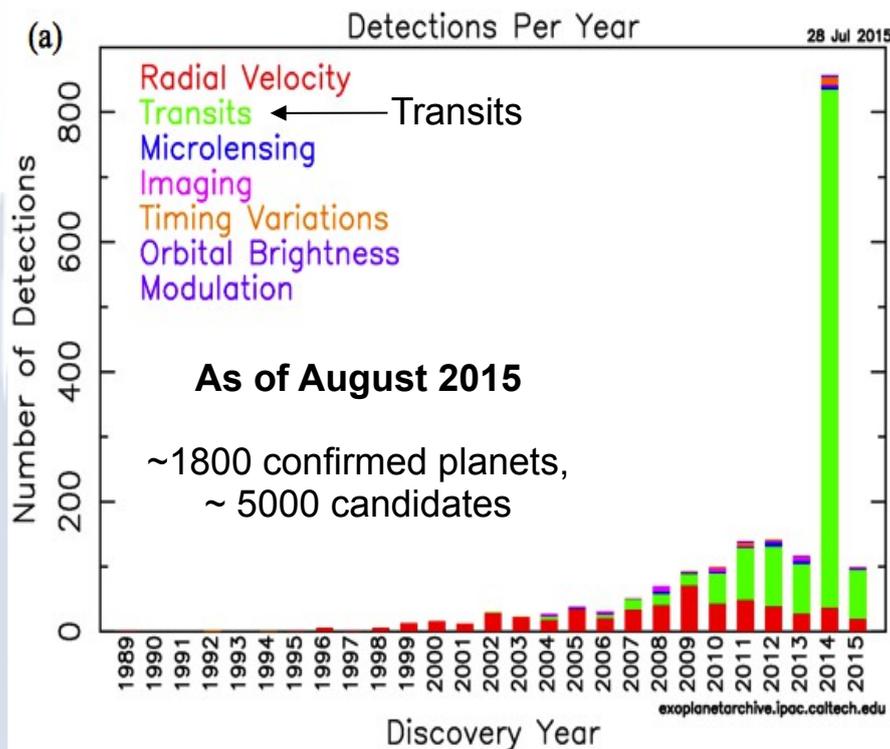


Outline

- Exoplanets and high contrast imaging
- Principle of Lyot-based Low-order Wavefront Sensor (LLOWFS)
- LLOWFS implementation on the SCExAO instrument
- Laboratory and on-sky results for different coronagraphs
- Conclusion and perspective

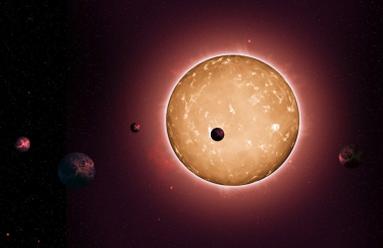


Exoplanets and scientific motivation

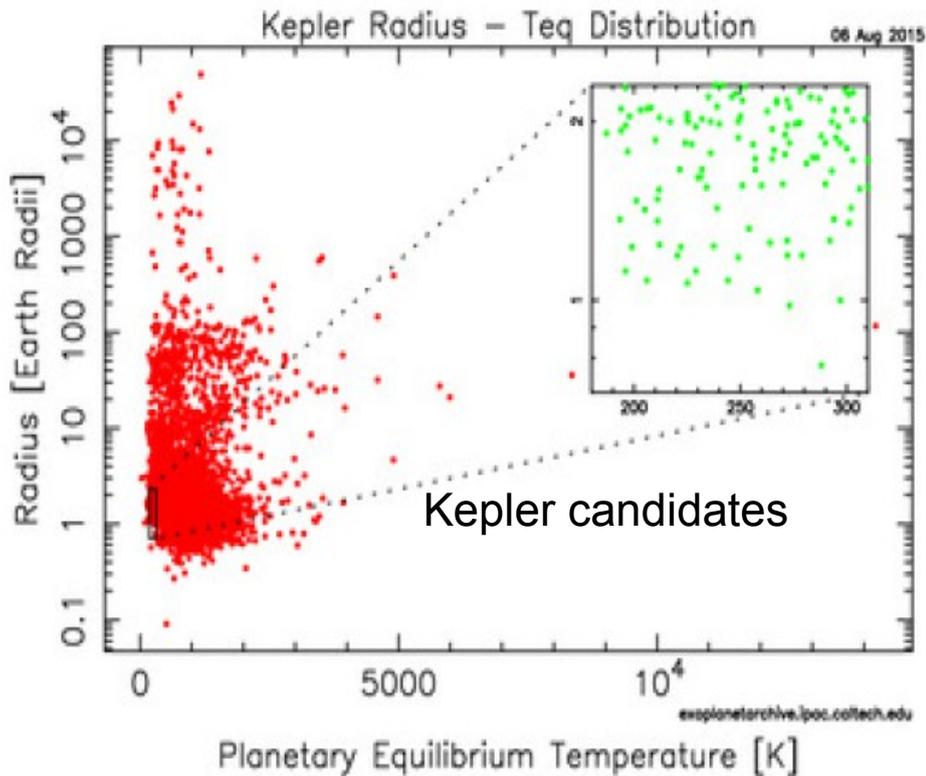


Questions to be addressed:

- Similarities with planets in our solar system
- Formation and evolution
- Atmospheric chemical composition
- Signs of biological activities



Exoplanets and scientific motivation



Goal:

Characterize atmosphere of planets in habitable zone

Direct detection via:

- Reflected light (visible)
- Thermal emission (infrared)

Challenge:

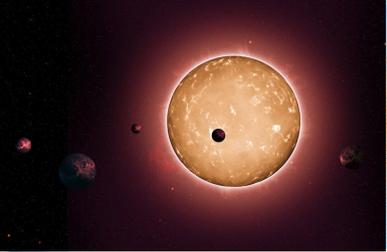
- High contrast
- Small angular separation

Earth-sun system: contrast 10^{-10} (visible)

Only a handful of massive planets at > 10 AU directly imaged from the ground

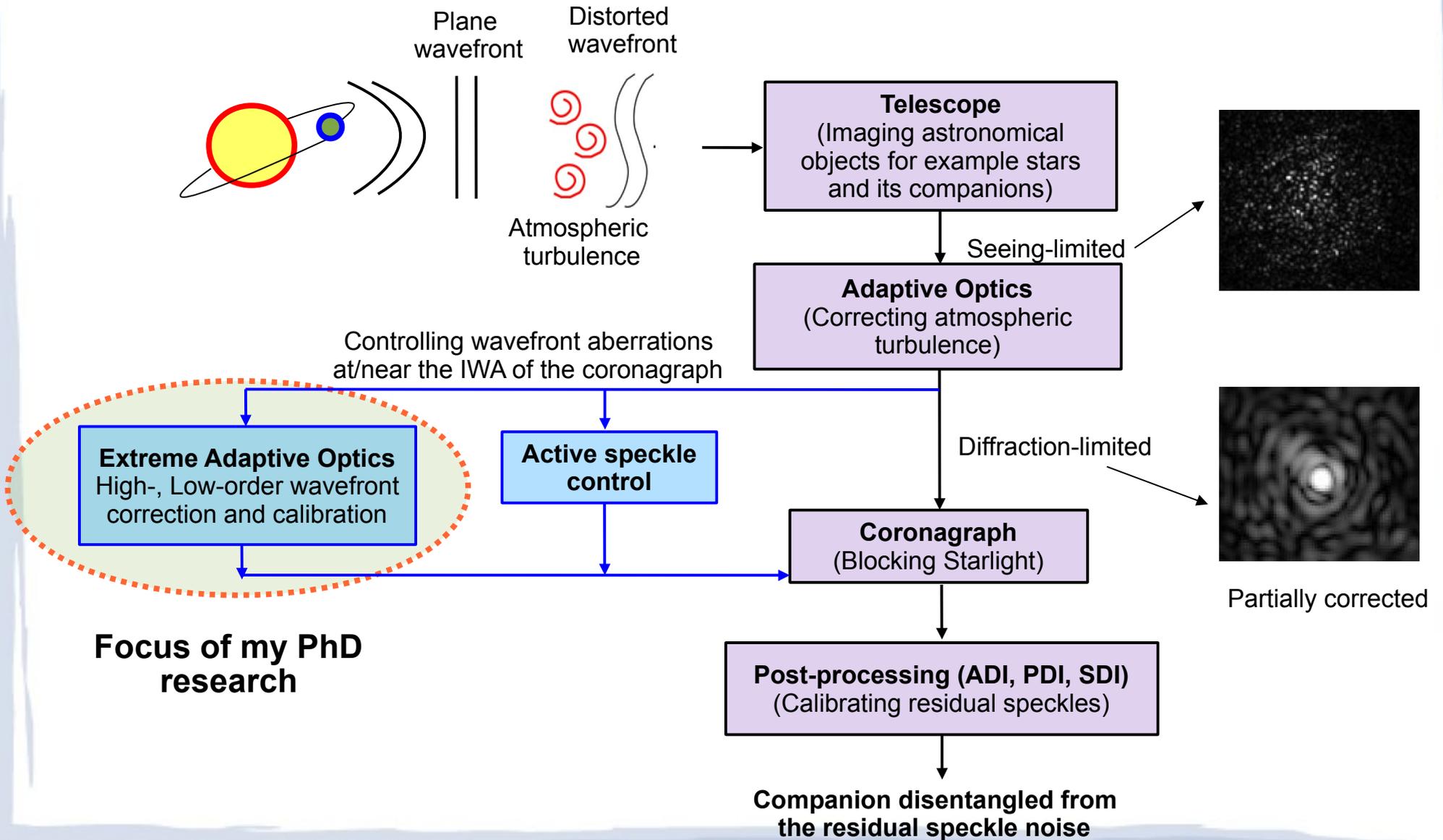
Current AO correction is insufficient to detect faint structures at < 10 AU

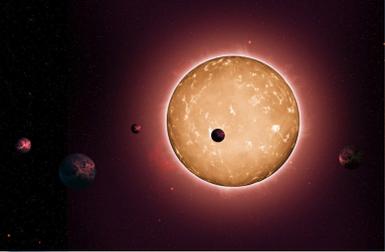
Requirement: High contrast imaging on the AO corrected PSF



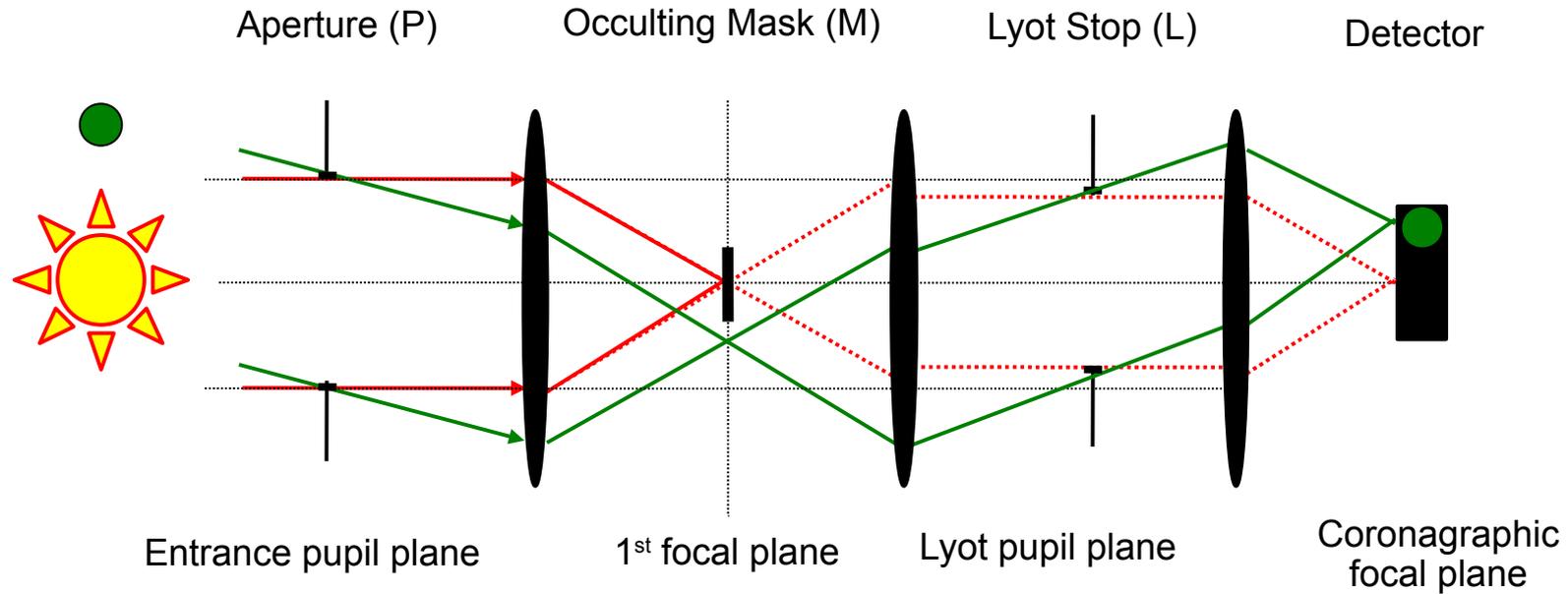
High Contrast Imaging

Wavefront correction → Starlight cancellation → Speckle calibration

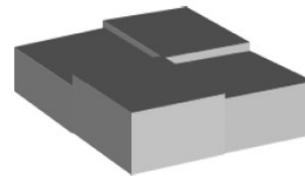




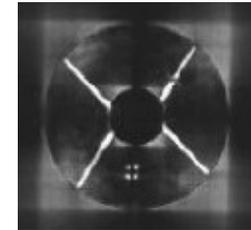
Stellar coronagraphy



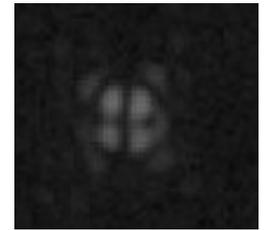
Four quadrant phase mask (FQPM)



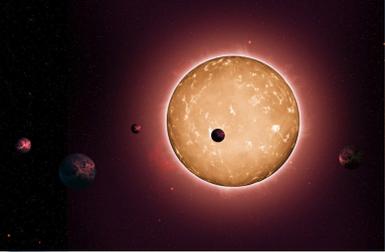
Pupil illumination downstream a FPM (with no Lyot stop)



Final Coronagraphic PSF



Phase masks are high throughput small inner working coronagraphs.



A major challenge in high contrast imaging

Goal of current ground-based instruments. Directly image young planets at angular separation $< 10 \lambda/D$.

What we need.

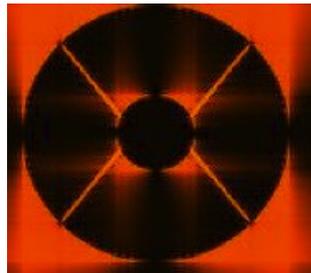
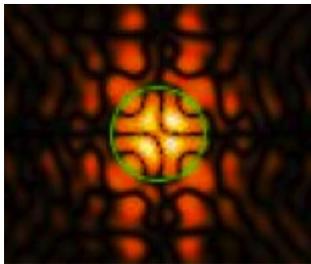
- (1) SR $> 90\%$,
- (2) Residual of $< 50 \text{ nm}$,
- (3) Raw contrast of $\sim 1e-4$ in IR and
- (4) wavefront calibration to $\sim 1e-6$ contrast at $\sim 1 \lambda/D$.

Technical challenge.

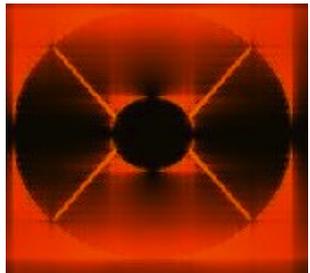
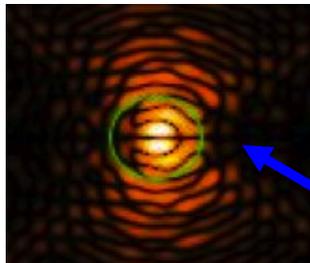
How well the low-order wavefront aberrations upstream of a coronagraph are controlled and calibrated.

Simulation with a FQPM coronagraph

Coronagraphic PSF
(no aberration)

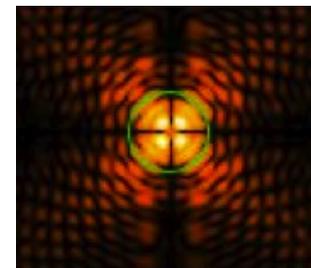


Tip aberration

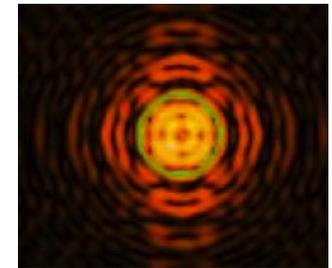


PSF is de-centered, can easily mimic a companion

Focus aberration

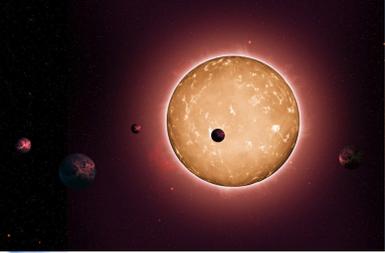


Astigmatism aberration



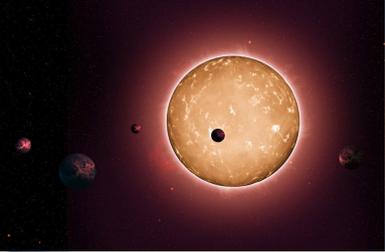
PSF is broadened, can be misinterpreted as a circumstellar feature

Coronagraphs optimized for small inner working angle (IWA) are extremely sensitive to low-order errors!



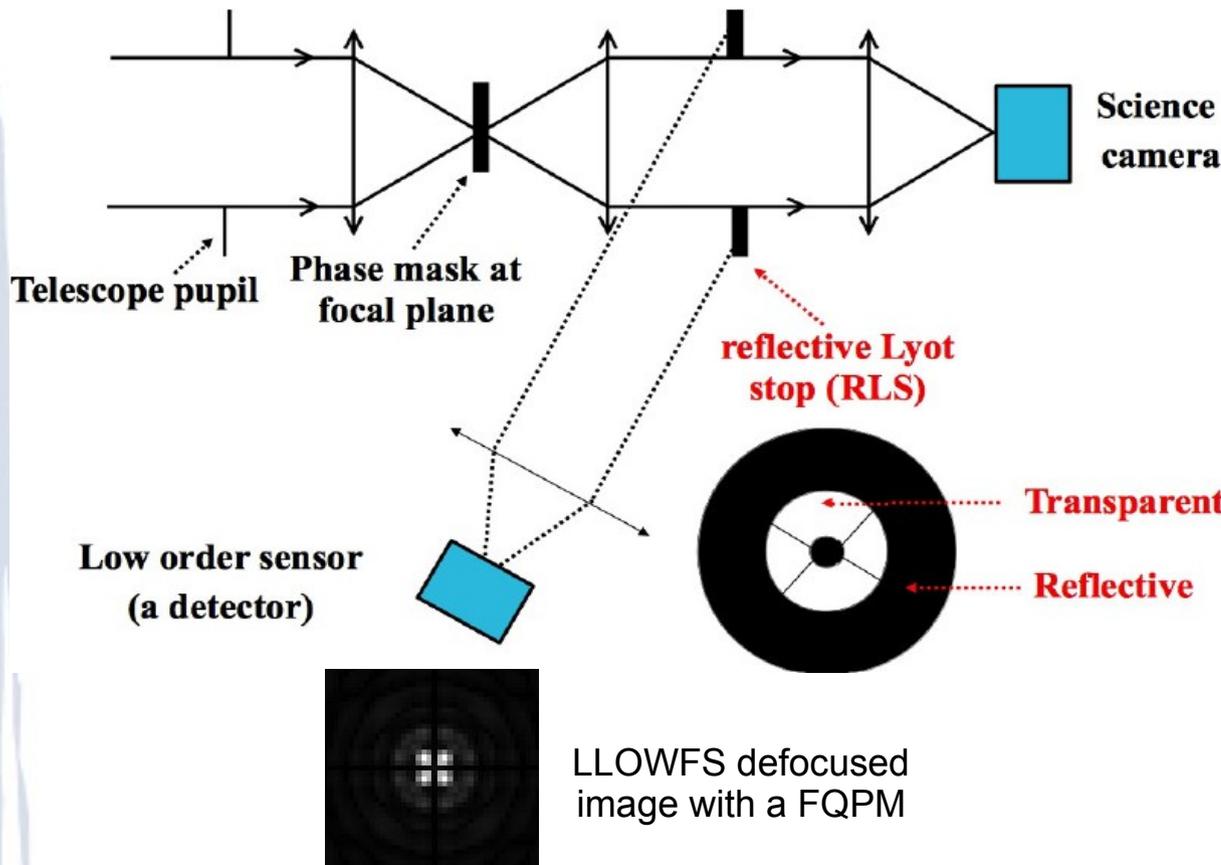
Outline

- ✓ Exoplanets and high contrast imaging.
- Principle of Lyot-based low-order wavefront sensor (LLOWFS)
 - Concept
 - Simulation
 - First laboratory result



Lyot-based low-order wavefront sensor (LLOWFS): Concept

No solution existed to address low-order aberrations more than just tip-tilt for PMCs!



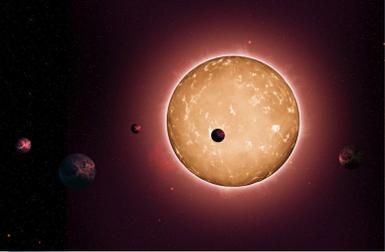
Linearity Approximation

If post-AO wavefront residuals $\ll 1$ radian RMS, then

$$I_{R(\alpha)} - I_0 = \sum_{i=1}^n \alpha_i S_i + v_n$$

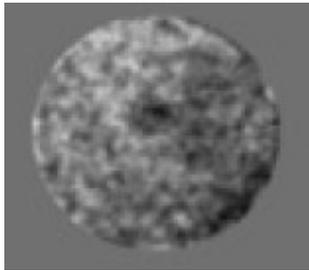
- I_0 = Reference image,
- I_R = Reflected image with aberration,
- i = low-order modes,
- n = total number of modes,
- α = amplitude of the modes,
- S = calibrated response of the sensor to the low-order modes (Orthonormal images)
- v = residual of high-order modes

Valid only if I_0 stays constant for the duration of the experiment



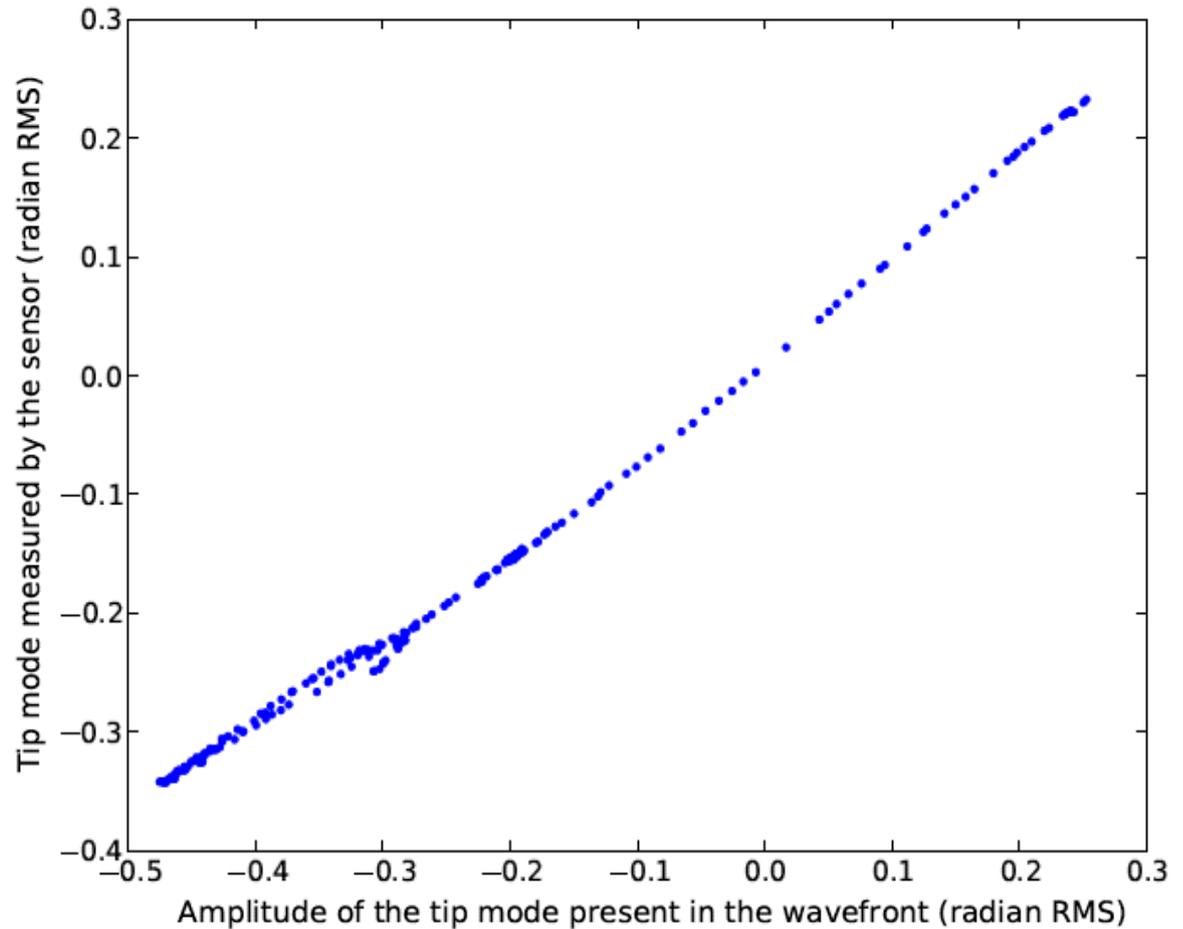
LOWFS: Simulation example

Simulation with a FQPM: Under post-AO wavefront residuals

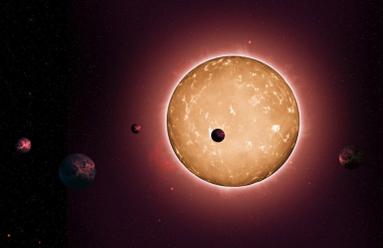


Simulated series of 200 post-AO phasemaps with random high- and low-order modes.

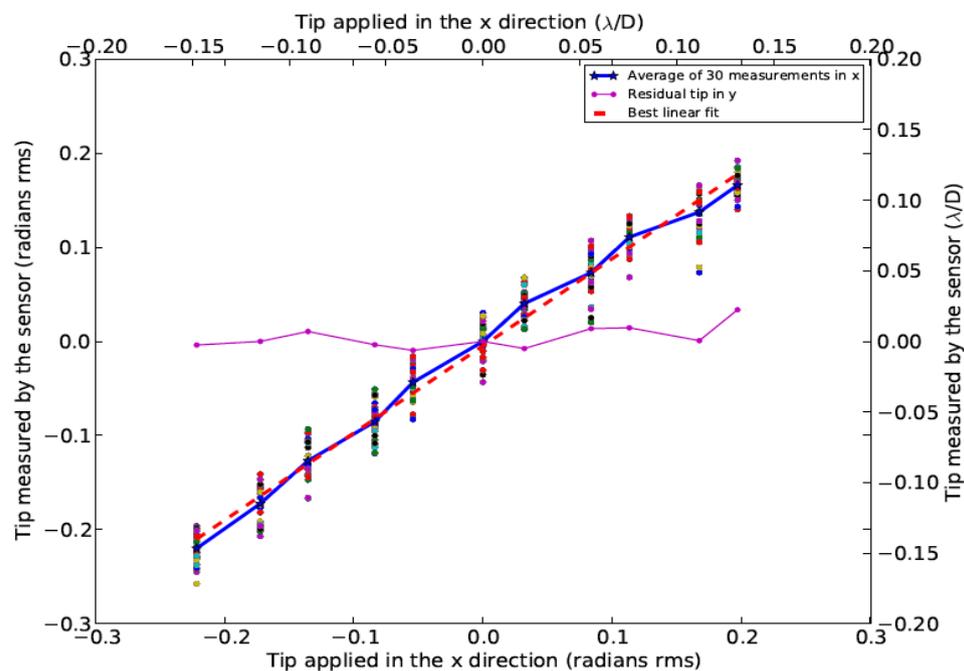
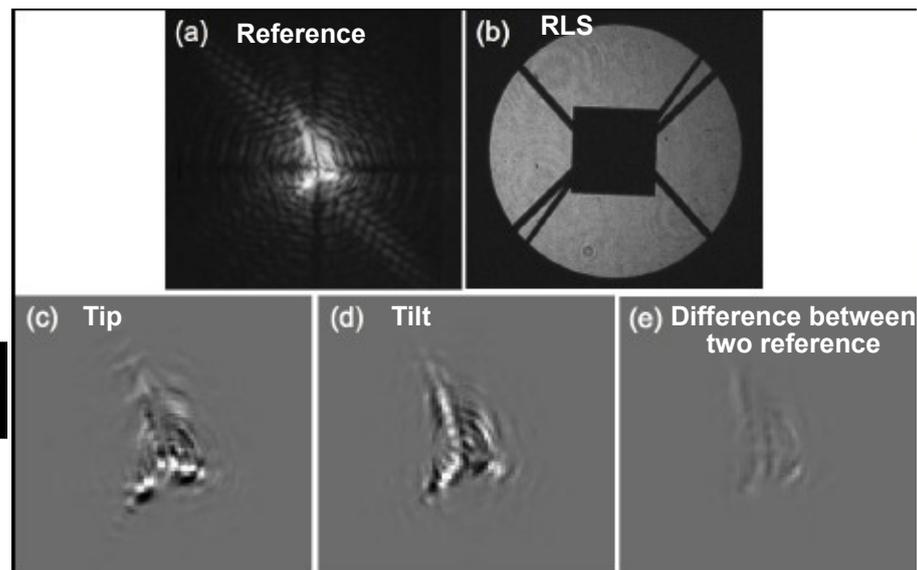
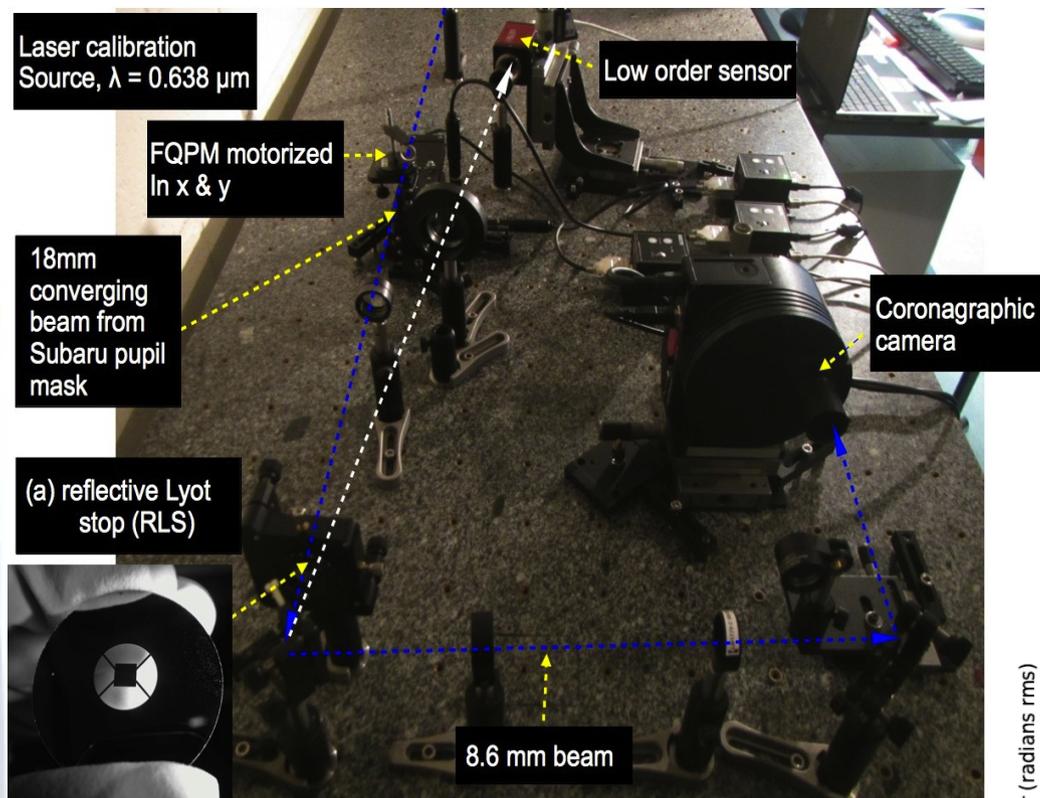
Total amplitude of ~ 180 nm phase RMS average over all the phasemaps.



Linearity range for tip-tilt mode: ± 0.2 radian RMS ($\pm 0.12 \lambda/D$)



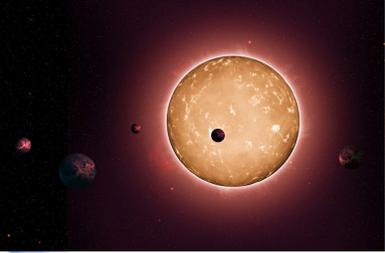
LLWF¹: First laboratory experiment at LESIA



Linearity range for tip-tilt mode:

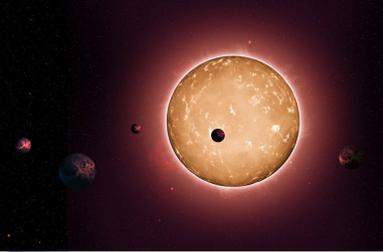
± 0.19 radian RMS (± 0.12 I/D)

Singh et al., 2014, PASP, 126, 586

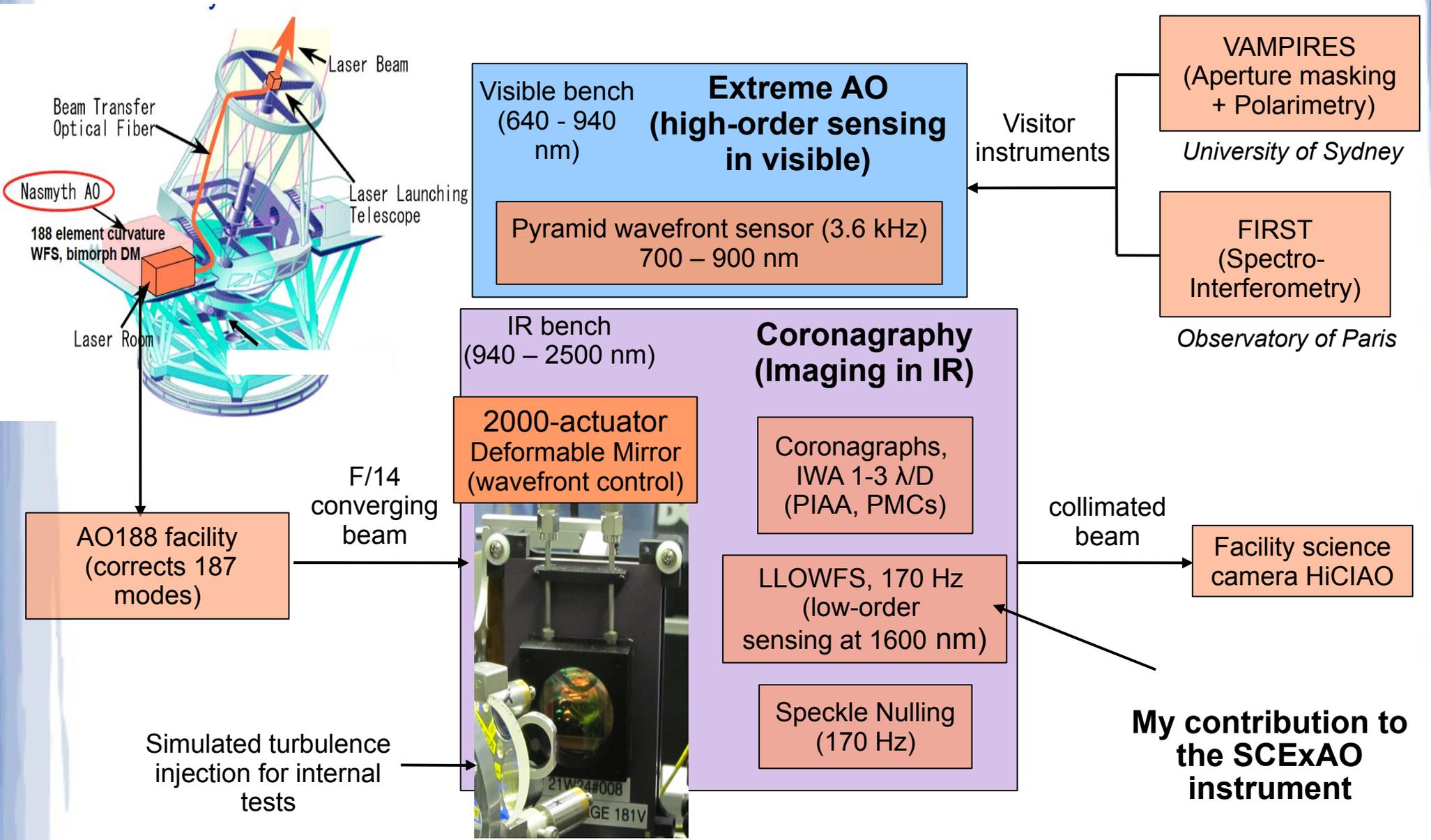


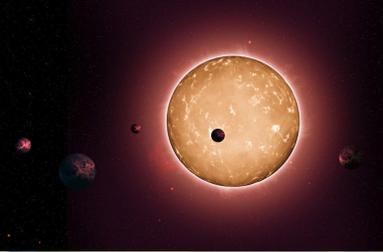
Outline

- ✓ Exoplanets and high contrast imaging
- ✓ Principle of Lyot-based low-order wavefront sensor (LLOWFS)
- LLOWFS implementation on the SCExAO instrument
 - Subaru coronagraphic extreme adaptive optics instrument
 - Mode of operation
 - Control scheme



SCEXAO instrument block diagram

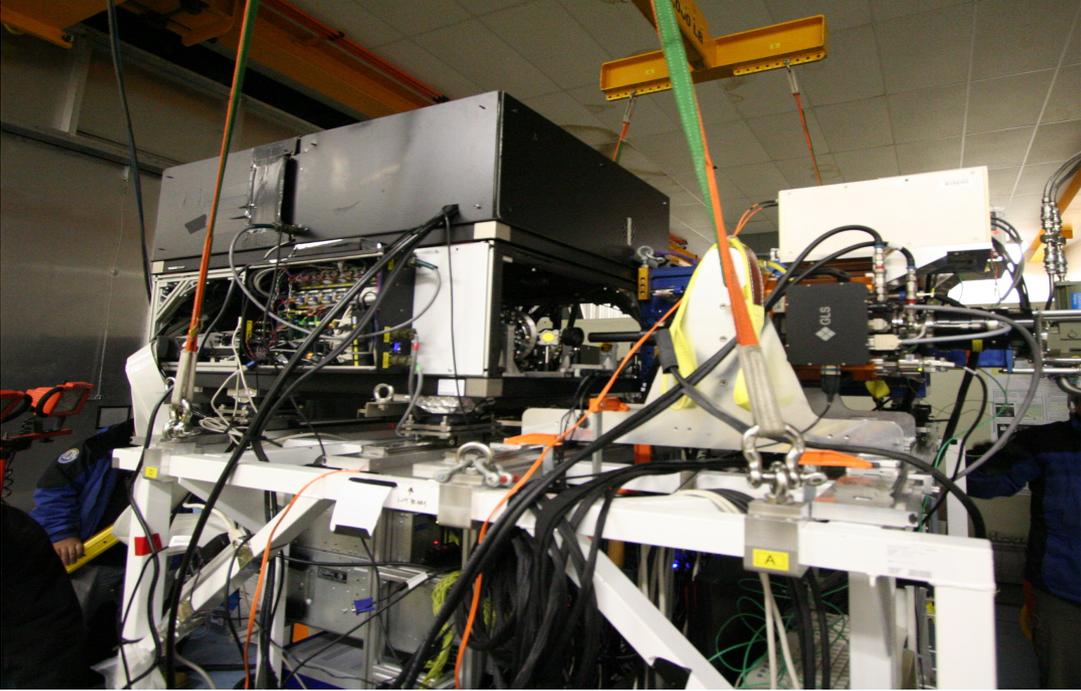




SCEXAO instrument

SCEXAO instrument at the summit of Mauna Kea

Visible bench



Nasmyth IR focus

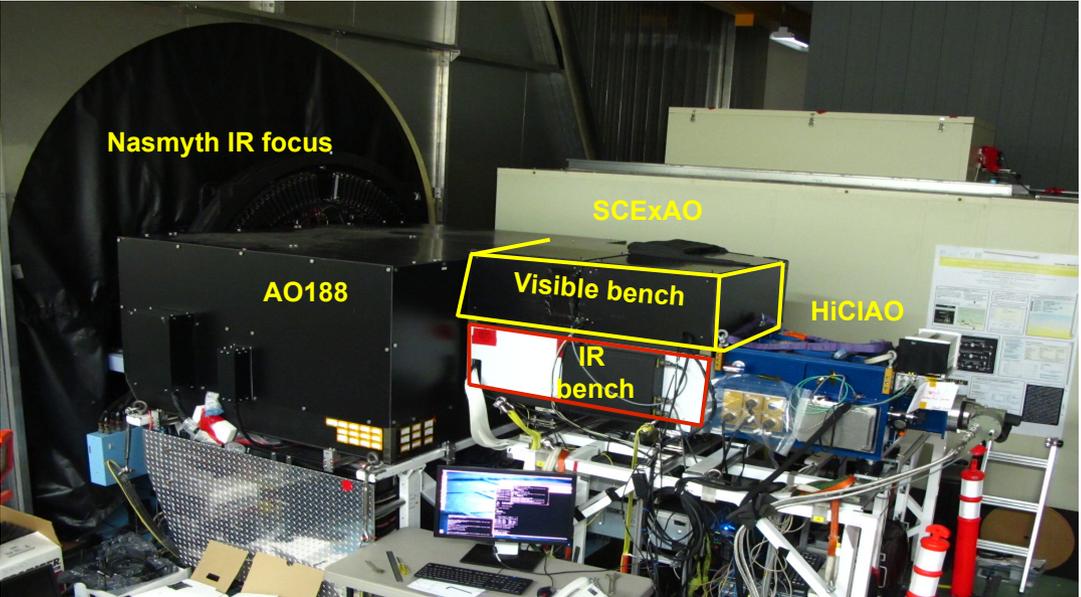
AO188

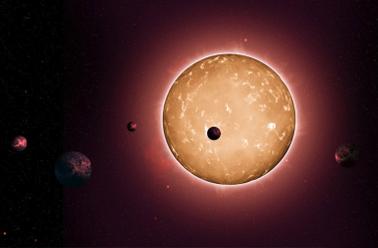
Visible bench

IR bench

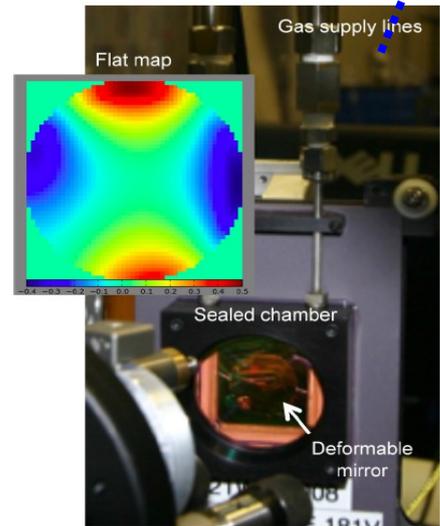
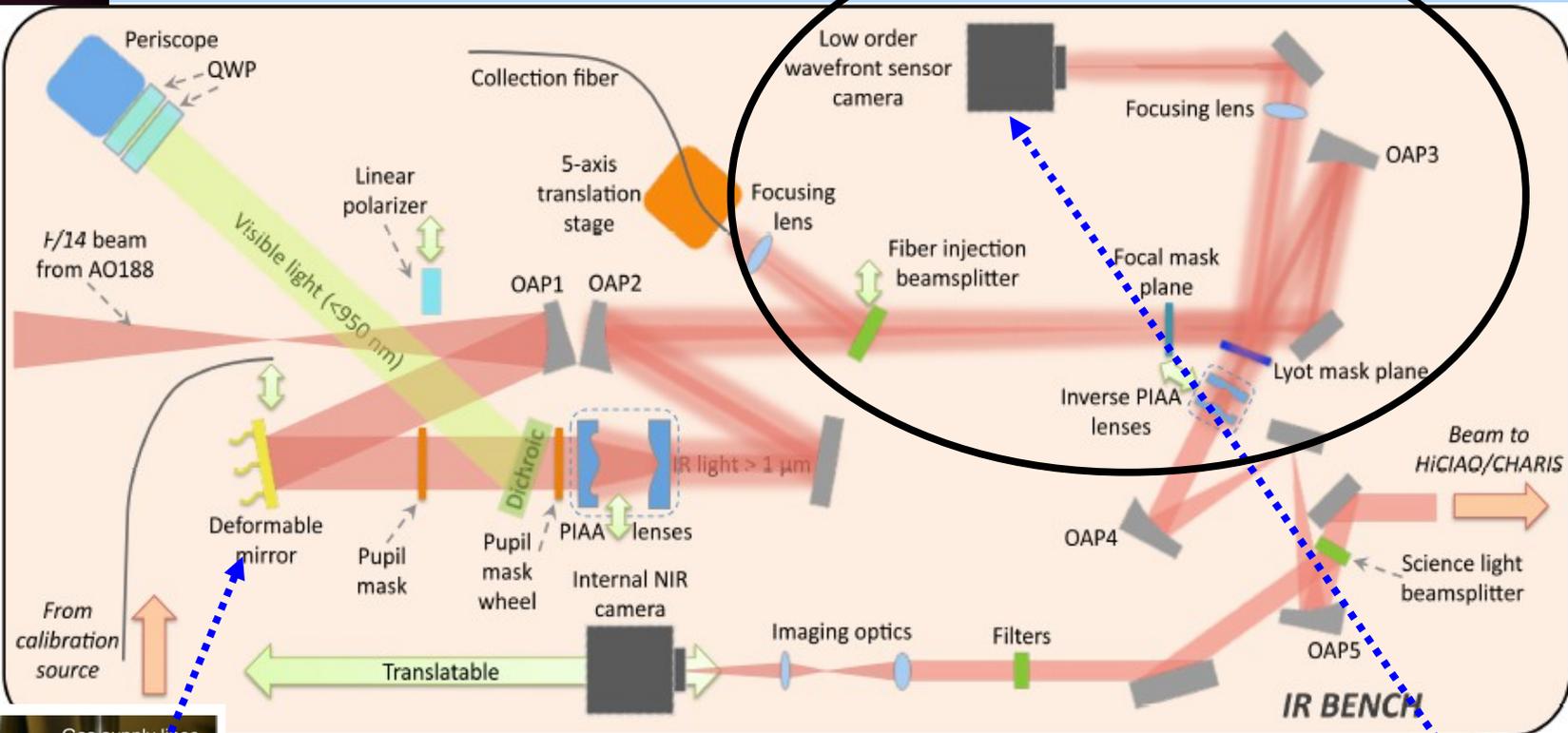
SCEXAO

HICIAO





LLOWFS implementation on SCExAO

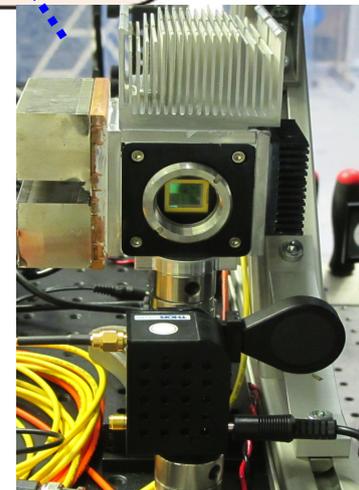


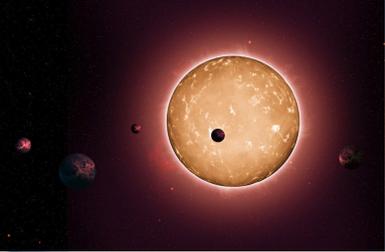
Correction

2000-actuator Deformable Mirror (DM)
 1.5 μm stroke
 5 dead actuators (1.5 actuators in the pupil)

Sensing

InGaAs CMOS camera
 Detector size: 320 x 256
 Read-out noise (e⁻): 140
 Frame rate: 170 Hz

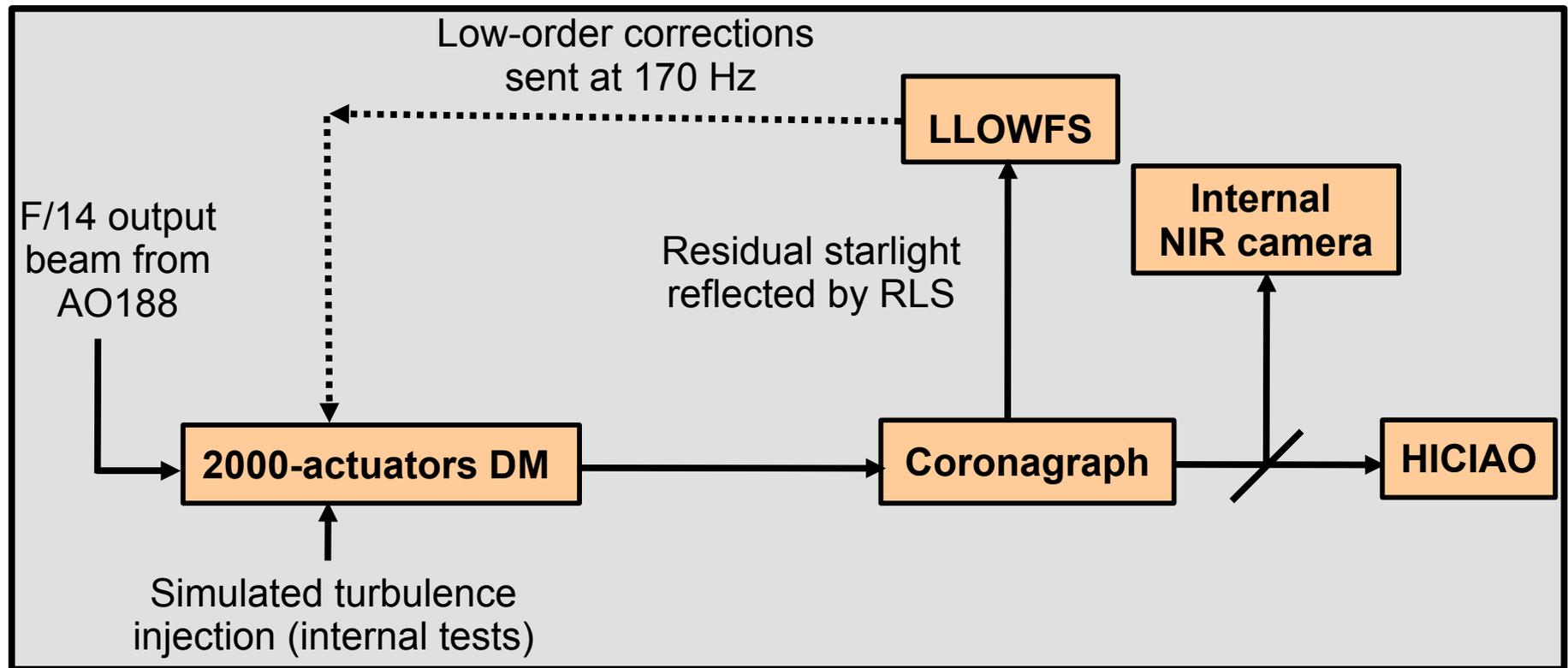




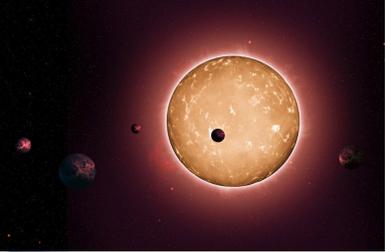
LLOWFS operation on SCExAO

LLOWFS mode of operation in non ExAO regime (~ 30 – 40 % SR in H) during my thesis

Direct interaction with DM: Correction of **35 Zernike modes** in the laboratory and **10 modes** on-sky



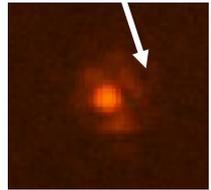
SCExAO IR bench



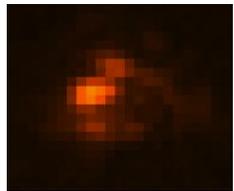
LOWFS: Control scheme

Aberrated coronagraphic PSF

Vortex mask



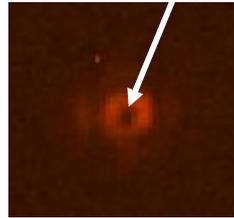
Aberrated LLOWFS PSF



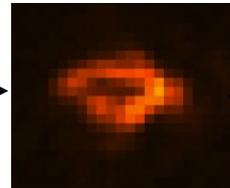
Input

Corrected coronagraphic PSF

Output
Vortex mask

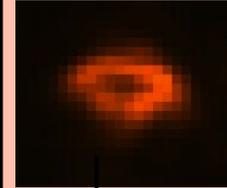


Corrected LLOWFS PSF

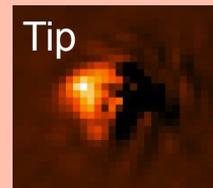


Calibration

Reference



Response Matrix



Singular Value Decomposition method

Reference

Sensor

Corrections

Measurements, α_i

Control

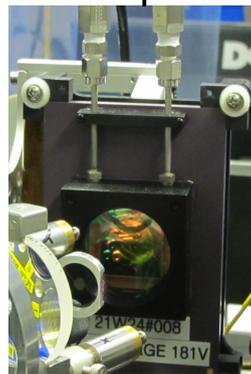
Integrator controller

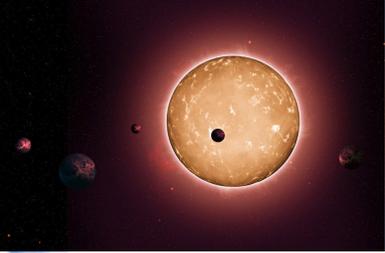
$$\sum_{i=0}^n [(gain \times \alpha_i) \times Z_i]$$

Zernike phasemaps (Z_i)

Commands

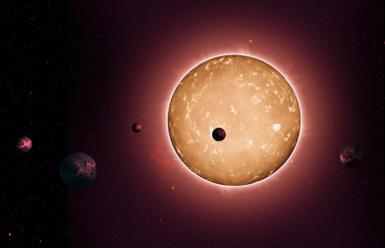
Actuator (DM)





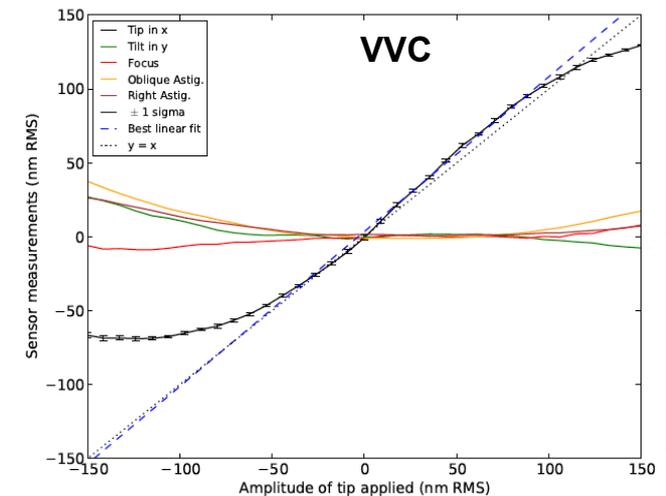
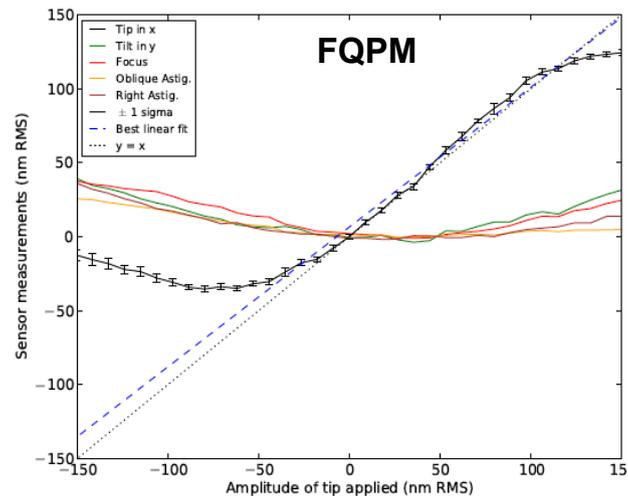
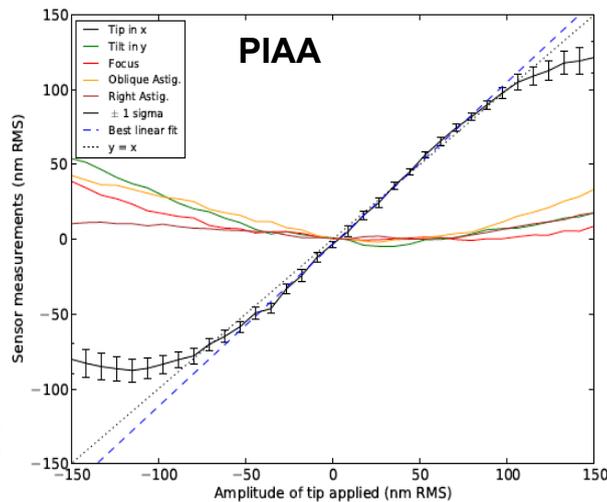
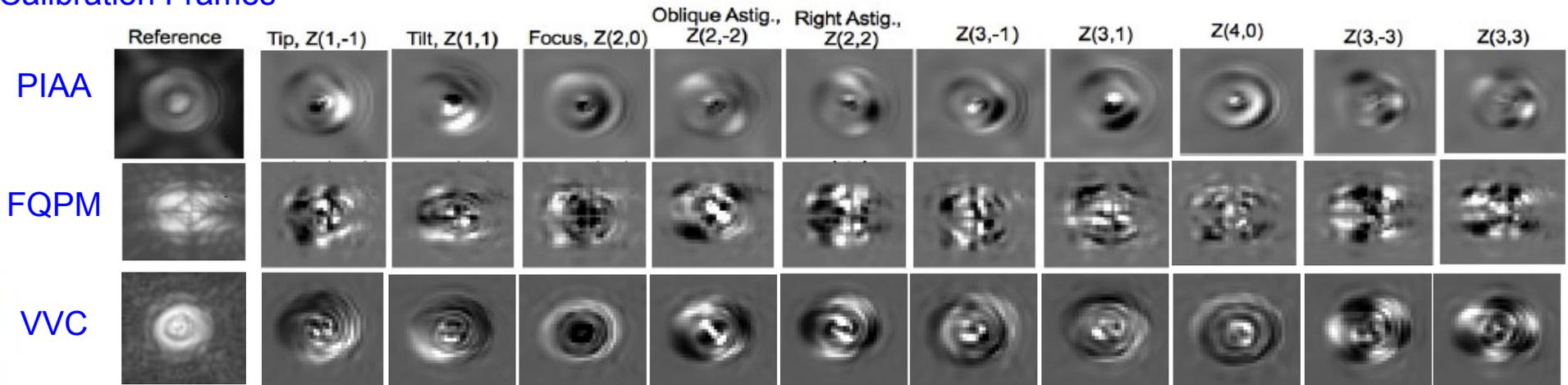
Outline

- ✓ Exoplanets and high contrast imaging
- ✓ Principle of Lyot-based low-order wavefront sensor (LLOWFS)
- ✓ LLOWFS implementation on the SCExAO instrument
- Laboratory and on-sky results for different coronagraphs (non ExAO regime)
 - Sensor linearity
 - Spectral analysis
 - Coronagraphic image stability



Laboratory results: Sensor Linearity

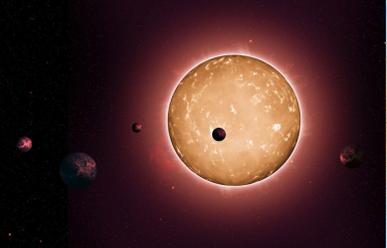
Calibration Frames



Sensor linearity: Roughly **150 nm RMS** (from -50 to $+100$ nm RMS, non-linearity of $< 10\%$ at 100 nm)

Measurement accuracy for the sensor response to:

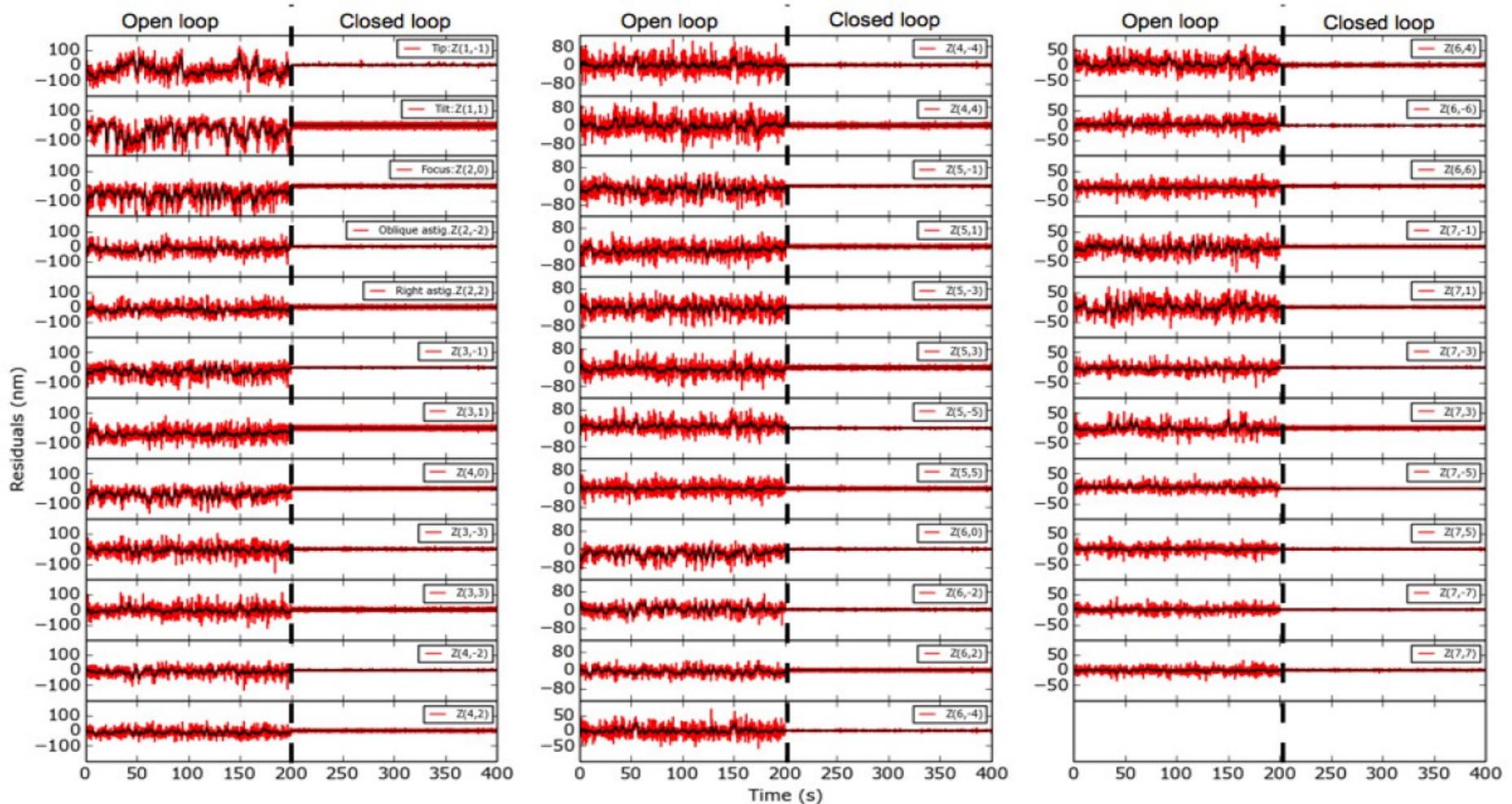
- Tip aberration: **< 6 nm RMS**
- Residuals in other modes within the linearity range: **~ 45 nm RMS** for all the coronagraphs.

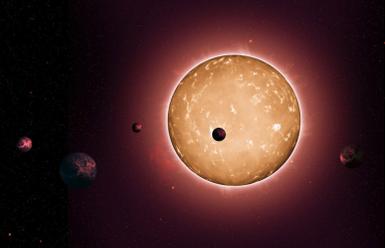


Laboratory results: Temporal measurement

Laboratory Turbulence: infinite sequence of phase screens with Kolmogorov profile,
100 nm RMS amplitude, 10 m/s wind speed.

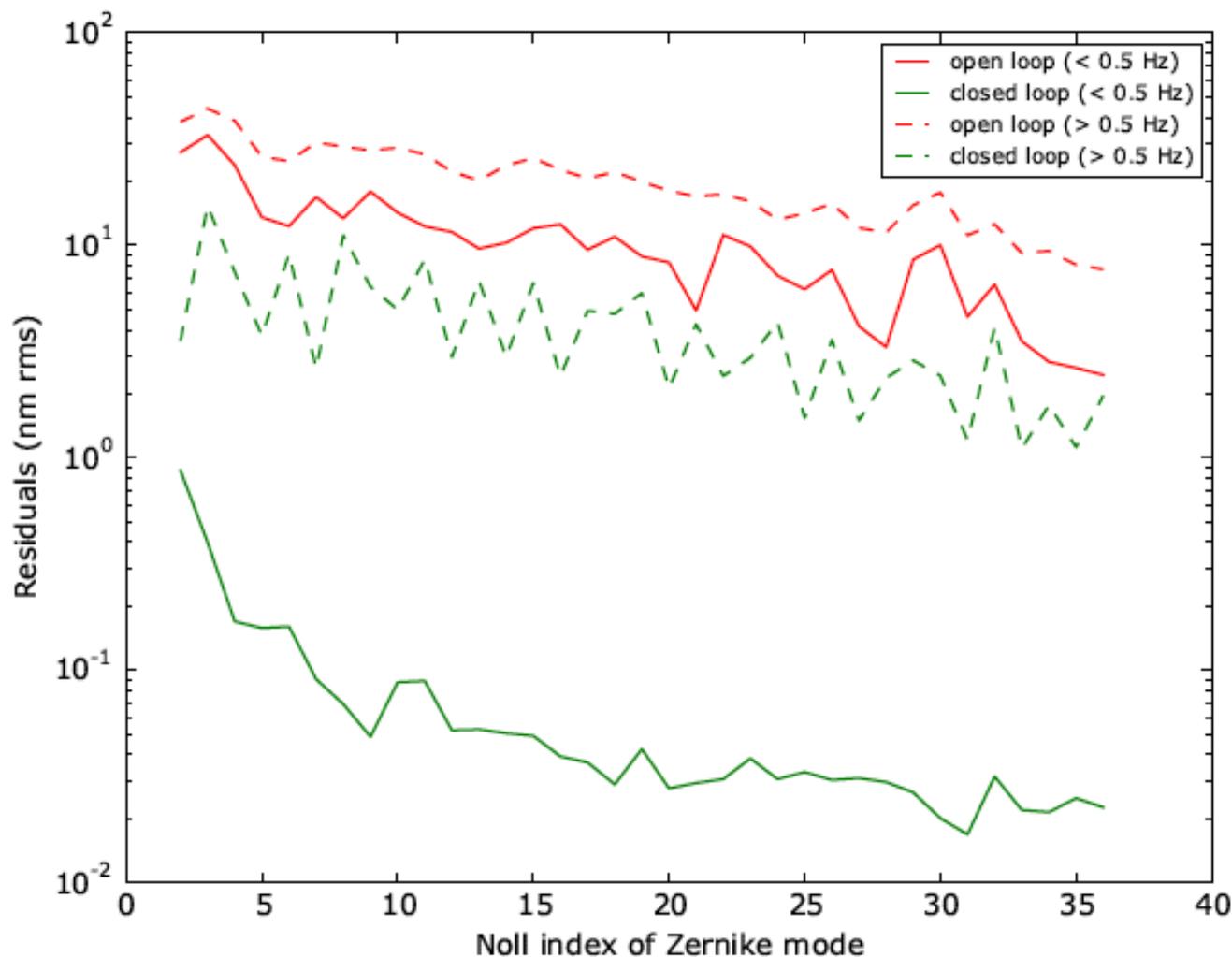
Closed-loop on 35 Zernike modes with a VVC





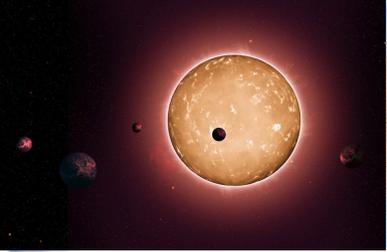
Laboratory results: Temporal measurement

The correction at frequencies < 0.5 Hz is about 2 orders of magnitude, leaving sub nanometer residuals for all the modes.



Pointing residuals for open- and closed-loop sampled at 0.5 Hz are about $10^{-2} \lambda/D$ (0.8 mas) and a few $10^{-4} \lambda/D$ (0.02 mas)

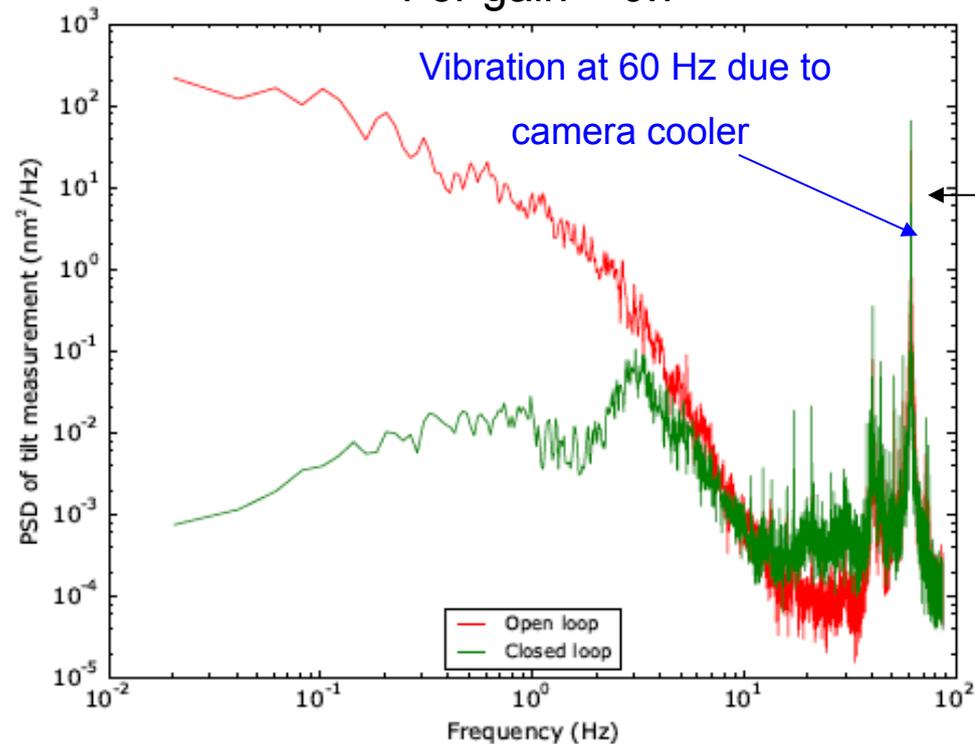
Similar results for the other coronagraphs.



Laboratory results: Spectral analysis

Smoothed open- and closed-loop PSD of **tip aberration** for a VVC. Loop closed at 170 Hz.

For gain = 0.7



Vibration issue
solved

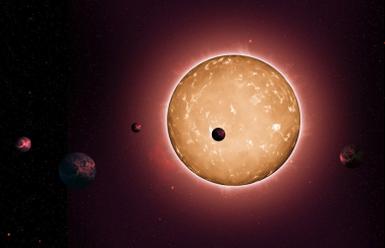
*Singh et al., 2015,
PASP, accepted*

For frequencies < 0.5 Hz: Reduction in residual by a factor of 30 to 500 on all the modes.

At 0.5 Hz, improvement by 2 orders of magnitude.

For frequencies > 0.5 Hz, improvement is only between 3 and 12, due to vibrations.

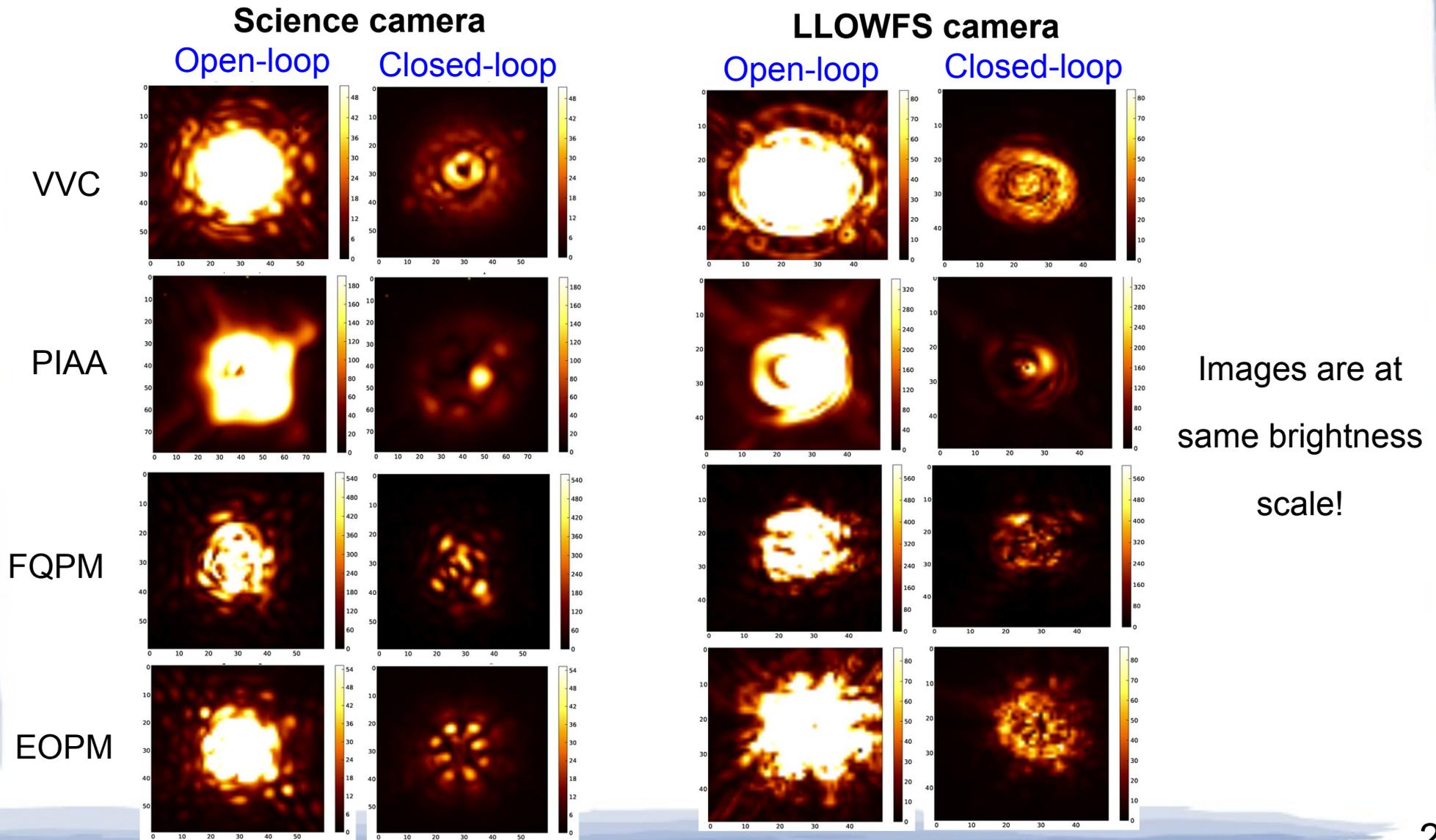
For long exposures, the correction is limited by the vibration while for short exposures, it is limited by the photon noise.

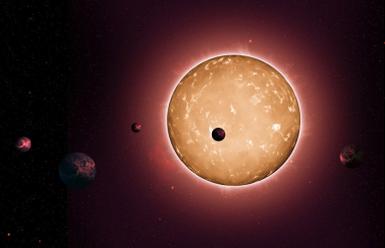


Laboratory results: Improved stability

Standard deviation of the processed frames.

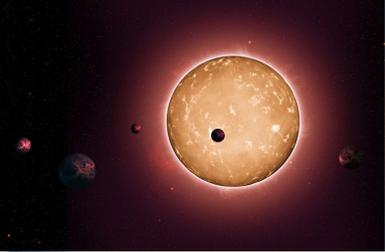
Standard deviation is more stable in closed-loop!





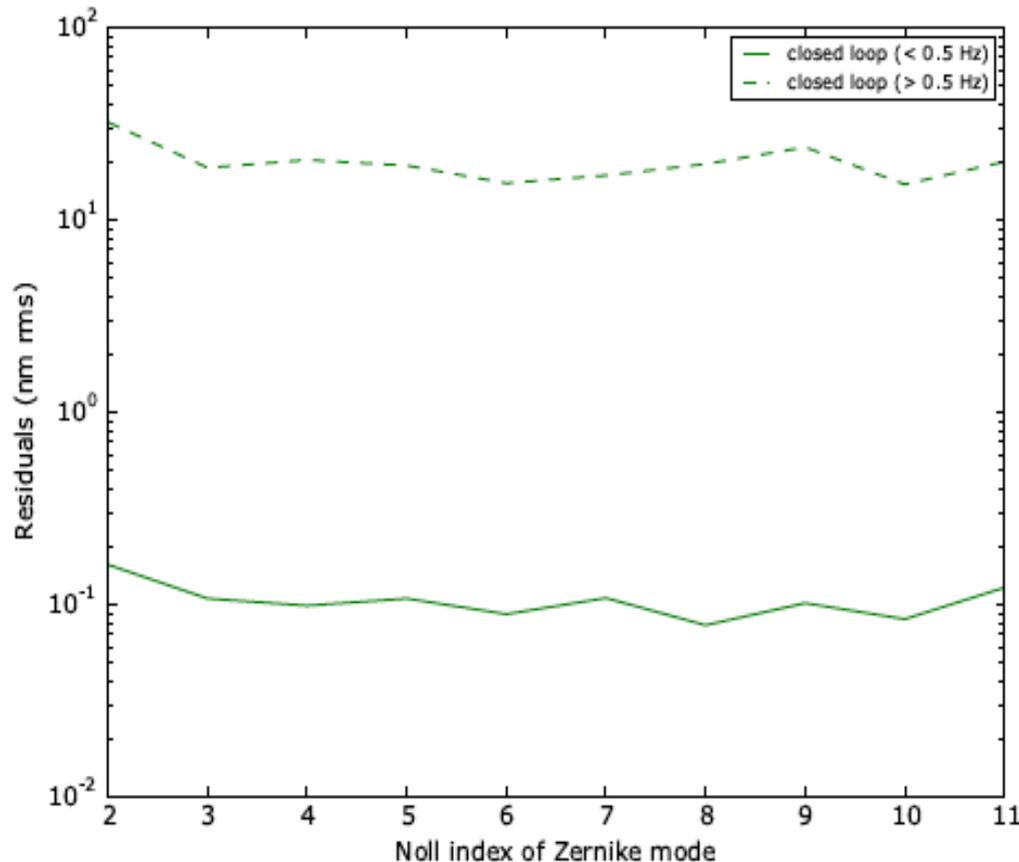
LLWFWS in action





On-sky results in non ExAO regime: Temporal measurement

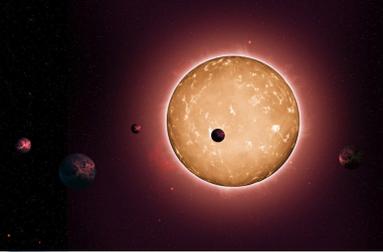
Observation of a star with $mH = 1.92$ with a VVC (seeing 0.35" in H band)
AO188: 30 – 40 % SR in H-band with a ~ 200 nm RMS wavefront error.



LLOWFS loop closed on 10 modes
with a gain of 0.5 at 170 Hz.

Best on-sky pointing residual
obtained with the LLOWFS in non
ExAO regime.

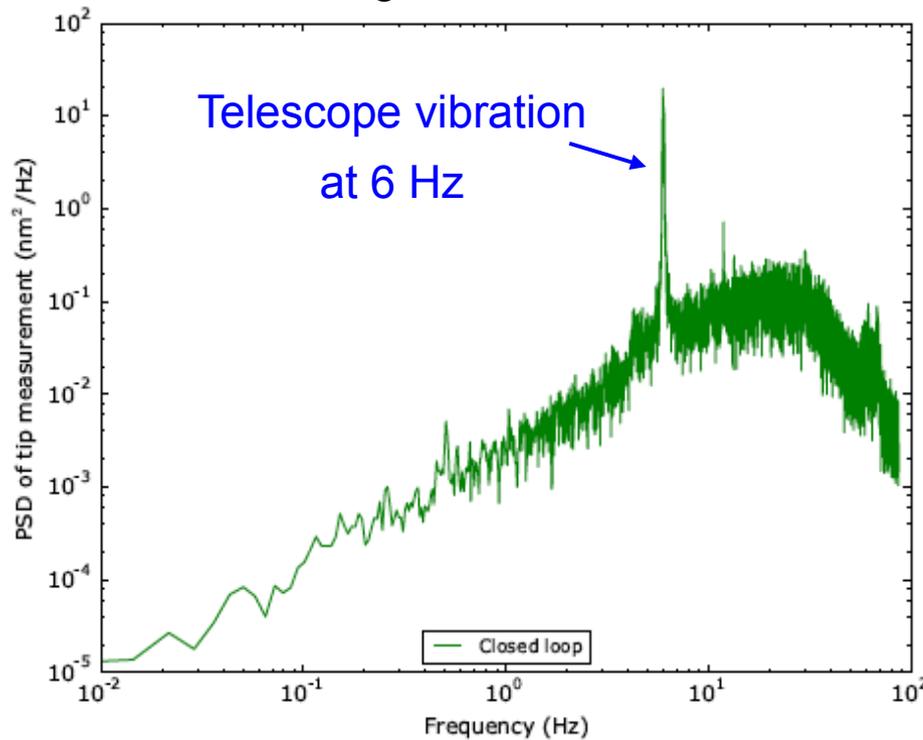
For frequencies < 0.5 Hz, Correction is ~ 2 orders of magnitude better than at higher frequencies.
Closed-loop pointing residual of $10^{-4} \lambda/D$ (0.02 mas) is obtained for slow varying errors.



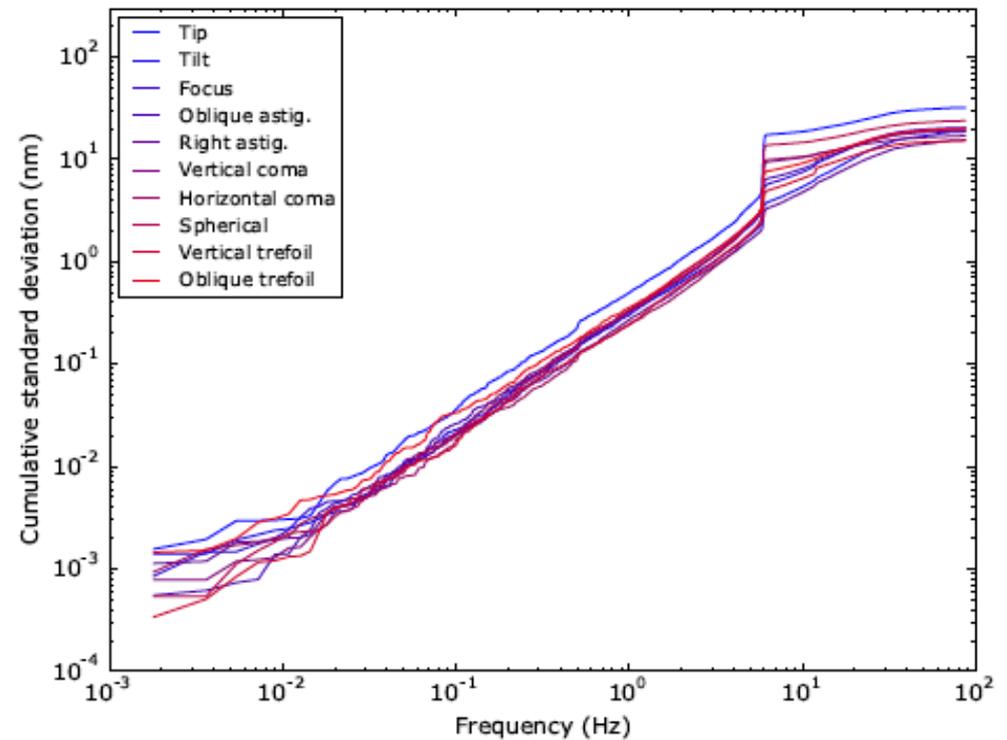
On-sky results in non ExAO regime: Spectral analysis

Closed-loop PSD and the cumulative standard deviation of the 10 modes.

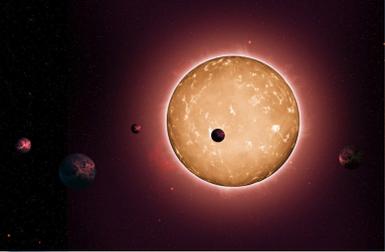
gain = 0.5



Closed-loop PSD of the tip aberration



Vibration at 6 Hz is visible as a step in the cumulative standard deviation plot

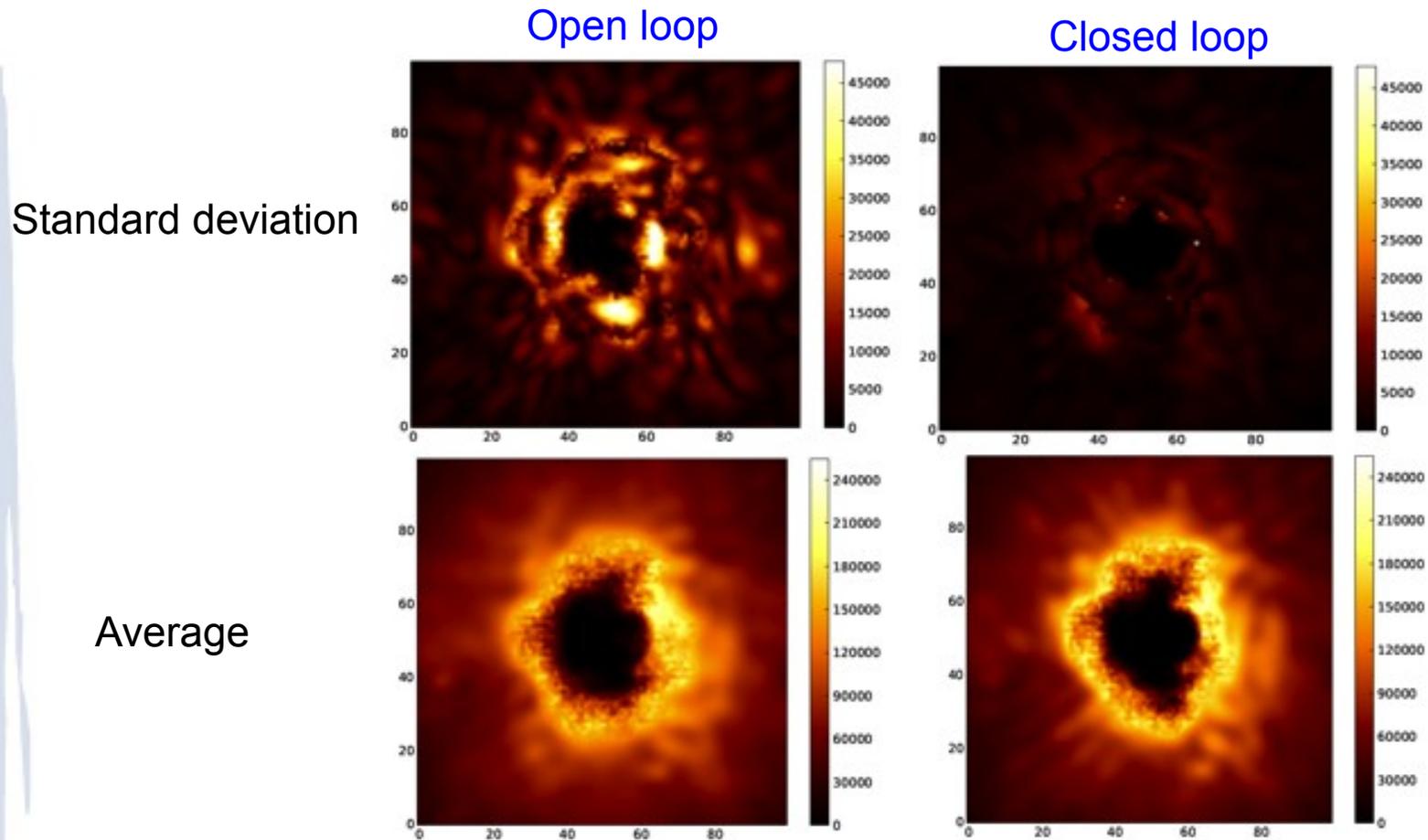


On-sky results in non ExAO regime: Improved stability

Observation of a star with $mH = 1.92$ with a VVC (seeing 0.35" in H band)

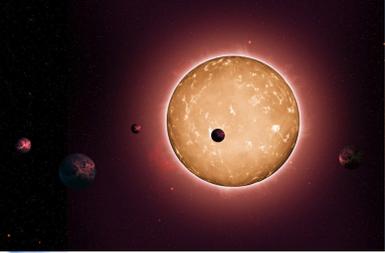
HiCIAO frames are de-stripped, Flat-fielded and bad pixels removed.

Standard deviation and average per pixel of 4 frames only (few seconds of exposure time).



Variance is improved by an order of magnitude.

*Singh et al., 2015b,
Under preparation*



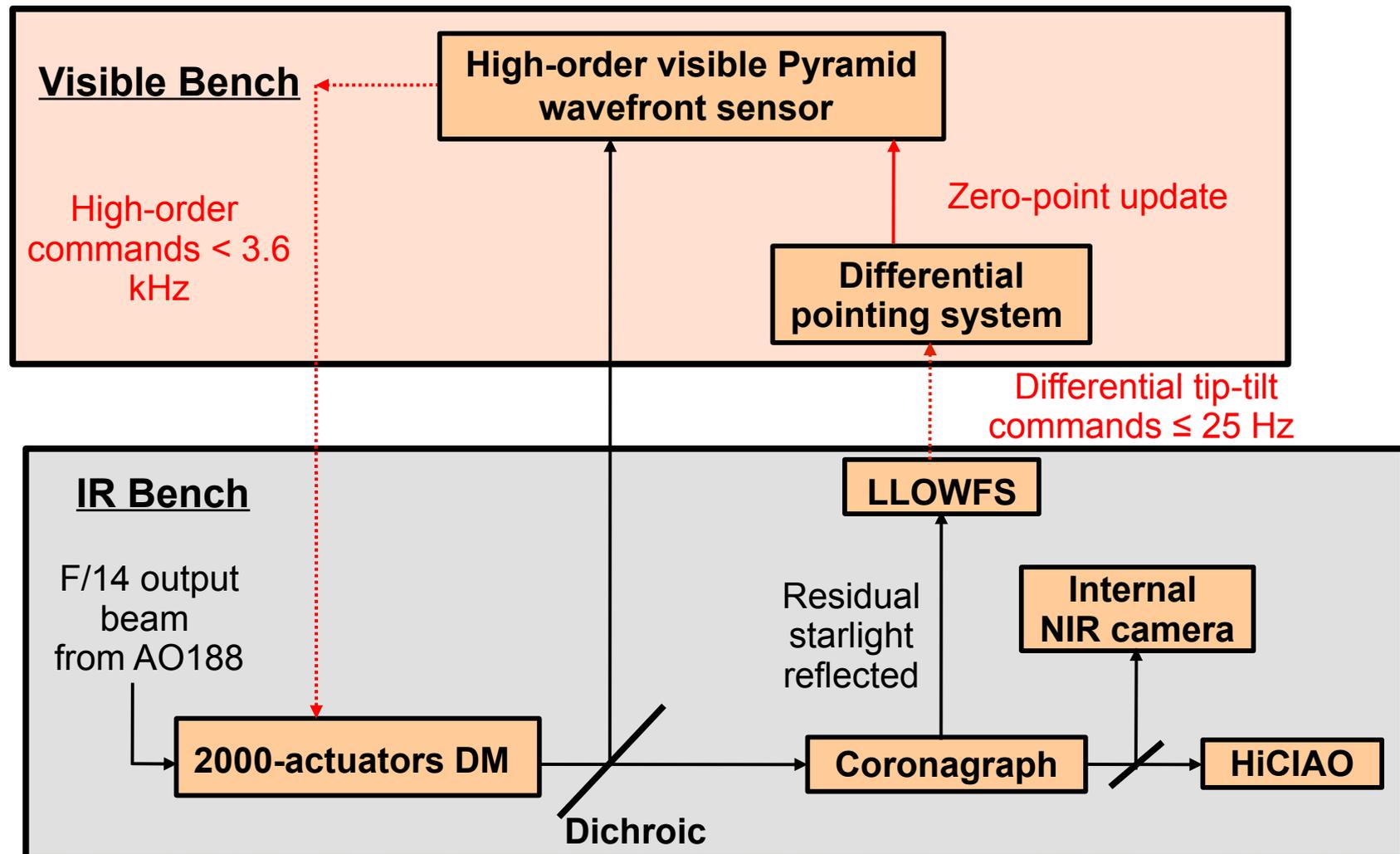
Outline

- ✓ Exoplanets and high contrast imaging
- ✓ Principle of Lyot-based low-order wavefront sensor (LLOWFS)
- ✓ LLOWFS implementation on the SCEXAO instrument
- ✓ Laboratory and on-sky results for different coronagraphs (Non-ExAO regime)
- **LLOWFS operation in ExAO regime**
 - Integration of LLOWFS inside SCEXAO's high-order Pyramid wavefront sensor
 - On-sky results

LLOWFS operation in ExAO regime

LLOWFS integrated with high-order Pyramid wavefront sensor to deal with the differential chromatic low-order aberrations in the IR science channel.

Only tip-tilt are addressed in the laboratory and on-sky in ExAO regime during my thesis

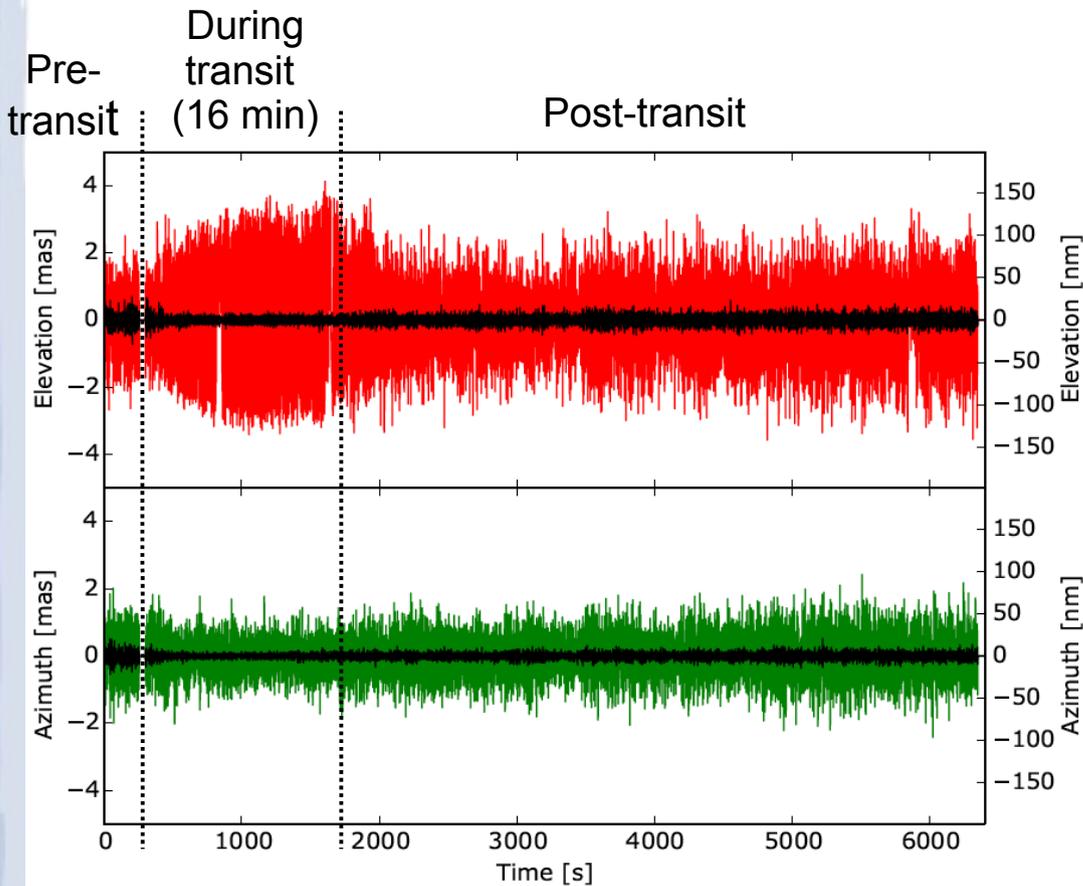




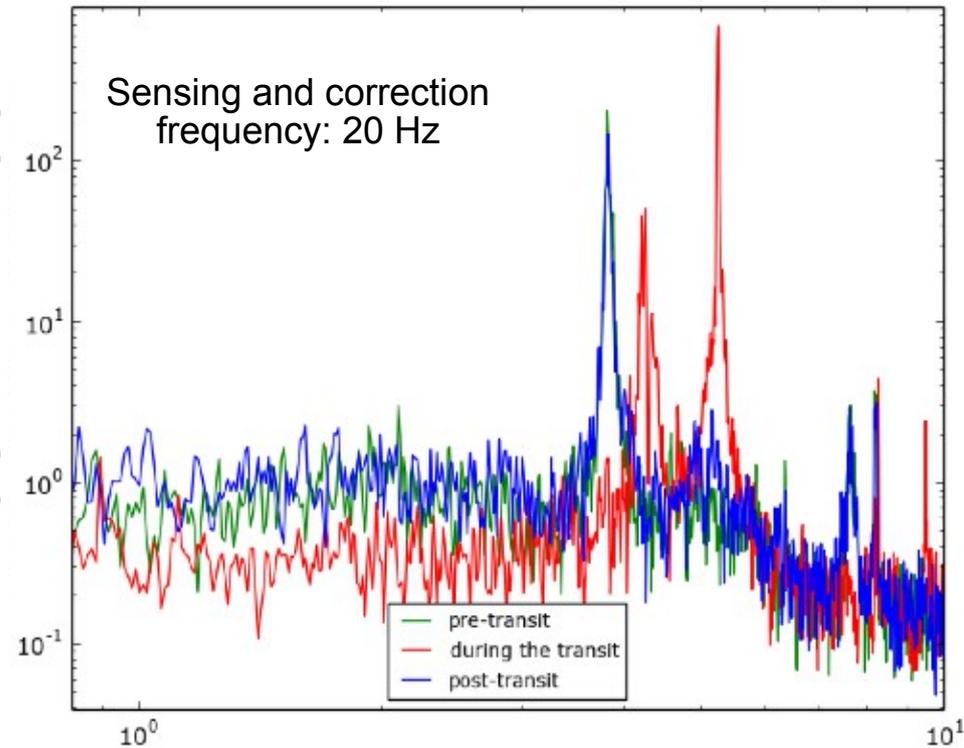
On-sky results in ExAO regime

A G8V C Spectral type variable star ($m_H = 5.098$), 800 modes corrected (60-70% SR in H).

1h 45m long LLOWFS + PyWFS closed-loop temporal measurements.



Closed-loop PSD of the residuals in the Elevation direction



The strength of the vibration at 3.8 Hz is amplified by a factor of ~ 2 at 5.2 Hz during the transit of the target (target at maximum elevation).



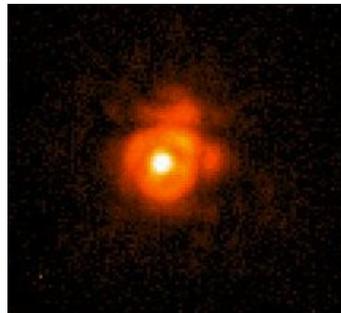
On-sky results in ExAO regime

Vibrations excited during transit of the target (target at maximum elevation)

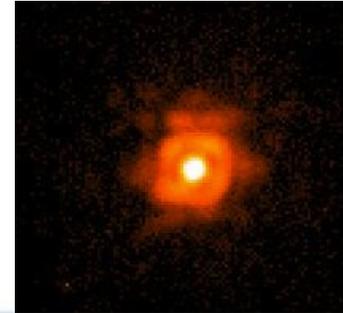


A G8V C Spectral type variable star (mH = 5.098)

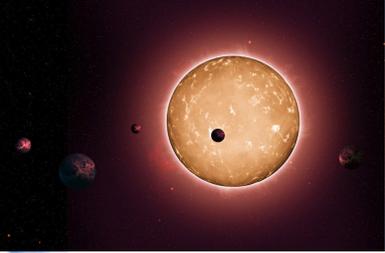
PyWFS closed +
LLOWFS open



PyWFS closed +
LLOWFS closed

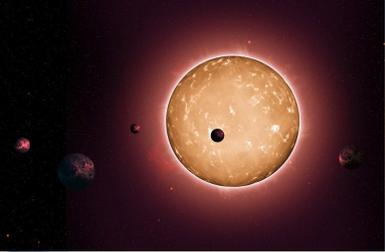


No Vortex, only Lyot stop in
Single HiCIAO frame, 1.5s



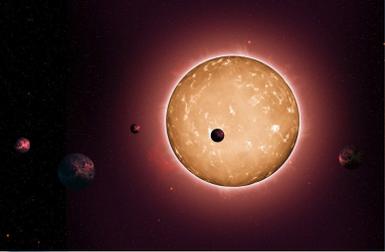
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- ✓ Integration of LLOWFS inside SCExAO's high-order Pyramid wavefront sensor and on-sky results (ExAO regime)
- **Conclusion and Perspective**



Factors affecting LLOWFS performance

- LLOWFS stability depends on the correction provided by the AO188 and the PyWFS. Uncorrected high frequency variations will break LLOWFS loop.
- LLOWFS correction is a trade off between the defocus of the sensor, speed of the loop and number of modes corrected.
 - Bright targets: more defocus, faster correction, correction of > 10 modes
 - Faint targets: closer to focus, slower correction, correction of only 2-3 modes
- Excitation of the vibrations.
- Noisy on-sky reference and response matrix due to bad seeing.
 - Asymmetries in the response matrix can introduce non-linearities in the calibrated response of the sensor.
- Tuning of the loop by setting the gain manually.
 - Not knowing whether the gain applied is optimal. Can make the loop unstable!



Upgrades to improve LLOWFS performance

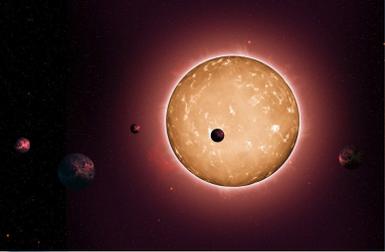
Upgrades already done

- To correct high number of modes and to improve the speed in ExAO regime, LLOWFS simultaneously send the correction to the DM and update the zero point of the PyWFS. Correcting 16 modes now!
- To deal with the telescope vibrations, accelerometers are installed to measure the vibrations.
- To increase the SNR, LLOWFS camera is cooled and the reflectivity of the RLS is improved.
- Integrate both LLOWFS and speckle nulling loop inside the PyWFS control loop.

Near-future upgrades

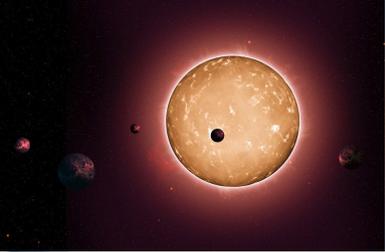
- Implement a LQG controller for the low-order loop to provide an optimal control of the vibrations.
- Use low-order telemetry to calibrate the uncorrected low-order aberrations in real-time.
- A10kHz frame rate LLOWFS camera project has already been funded.

Should allow SCEAO to detect young Jupiters (a few Mj) by a factor of ~ 3 closer to their host stars than is currently possible.



Conclusion

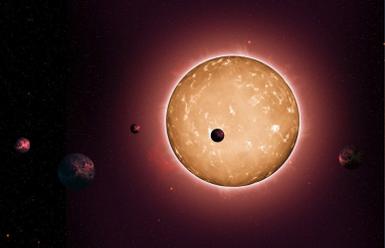
- LLOWFS only solution for the PMCs to address pointing and other low-order aberrations. *Singh et al 2014, PASP*
- Operational on the SCExAO instrument. Open to use for the science observations.
- Successful loop closure in the laboratory with the PIAA, the VVC and the FQPM/ EOPM coronagraphs. Closed-loop pointing residual between $10^{-3} \lambda/D$ and $10^{-4} \lambda/D$ in non ExAO regime.
- On-sky correction of 10 Zernike modes with the VVC and the PIAA. Obtained a closed-loop tip-tilt residuals of a few $10^{-3} \lambda/D$ for slow varying errors. *Singh et al 2015, PASP, accepted*
- Improved the variance of the coronagraphic images by an order of magnitude. Detection sensitivity should improve by same factor.
- Successfully integrated LLOWFS with PyWFS and addressed the NCP errors between the visible wavefront sensing channel and the infrared science channel.
- Obtained most durable and stable pointing with LLOWFS on faint targets with a VVC in ExAO regime. Loop remain closed for 1 hour 45 minutes! *Singh et al 2015b, under preparation*
- LLOWFS measurements addressed unknown vibration issues during transit of the target that are crucial for the ADI.
- Under high Strehl ratio, LLOWFS is envisioned to provide pointing residuals of $10^{-3} \lambda/D$ in ExAO regime on a regular basis.



Perspective

Both LLOWFS approaches can easily be implemented on any ExAO instrument that has:

- either a dedicated low-order DM or
 - has the possibility to feed the low-order correction to their existing DM or to a tip/tilt mirror.
-
- The **PICTURE-C** mission, a high-altitude balloon carrying a VVC has selected LLOWFS to deal with the pointing errors over SHWFS and Curvature WFS.
 - LLOWFS is under study for the **Keck Planet Imager**, an upcoming upgrade of the Keck AO system.
 - LLOWFS can help the direct imagers of the **ELTs** to probe the habitable region around the M-type main sequence stars.
 - SCEXAO including LLOWFS is envisioned to be a first light instrument for TMT.
 - Equally relevant for the next generation HCI instruments aboard space telescopes such as **WFIRST-AFTA, Exo-C and ACESat** to deal with the low-order aberrations induced by the thermal drifts and the telescope pointing.
 - Linearity study on SCEXAO can give the requirement on the pointing of the spacecraft,
 - The level of correction demonstrated on SCEXAO can be scaled to space conditions to give specifications on the acceptable level of vibrations.



Questions?

