High Contrast Imaging at the Photon Noise Limit with WFS-based PSF calibration

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Spirit of Lyot, June 2022, Leiden

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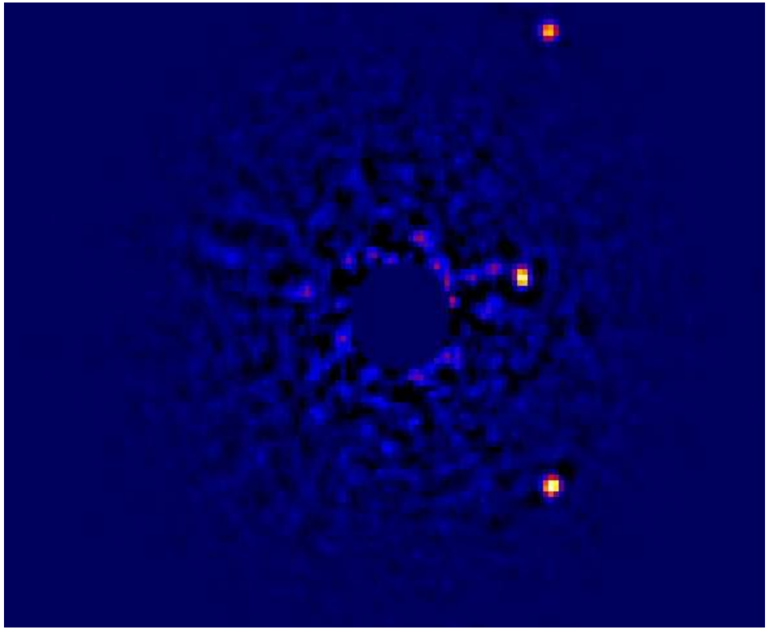
Scientific Motivation

High contrast imaging is currently limited by speckle noise at small IWA. Speckle noise typically ~100x photon noise, scales poorly with exposure time.

Poor detection confidence: is this a speckle or a planet ?

What if we knew exactly what the stellar PSF is ?
“exactly” = bias-free estimate with precision at least as good as photon noise.

Is it possible to derive PSF from WFS telemetry ?



HR8799 system (c,d,e)
Subaru Telescope/SCExAO

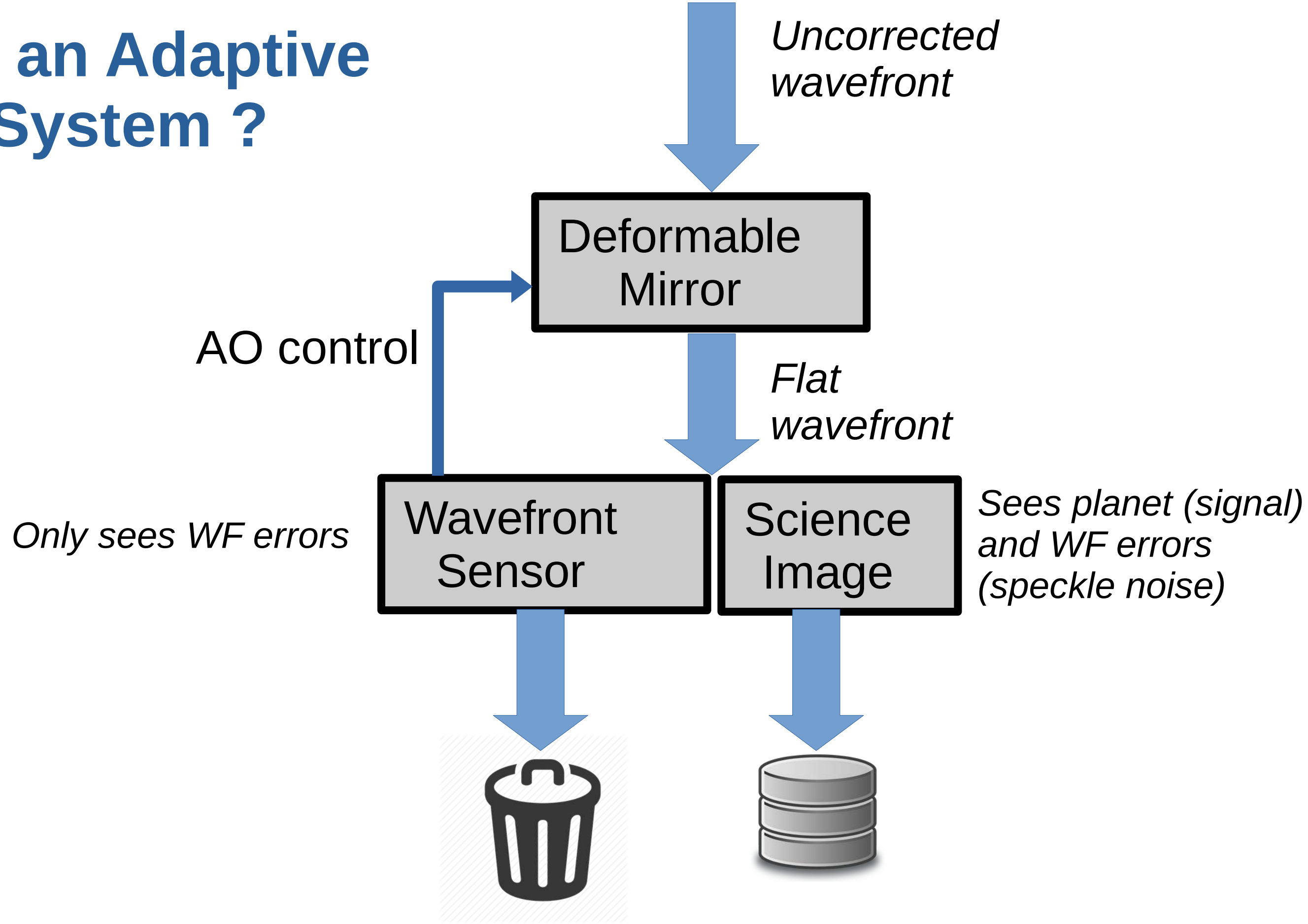
Scientific Motivation: Representative Examples

	Space-4m-Earth-G2	Ground-30m-Earth-M4
Star	G2 at 8pc	M4 at 4pc
Bolometric luminosity [L_{Sun}]	1.000	0.0072
Planet orbital radius [au]	1.0	0.085
Maximum angular separation [arcsec]	0.125	0.021
Reflected light planet/star contrast	1.5e-10	2.1e-8
Telescope diameter [m]	4	30
Science spectral bandwidth	20%	20%
Central Wavelength	797 nm (I band)	1630 nm (H band)
Maximum angular separation [λ/D]	3.0	1.9
Efficiency	20 %	20 %
Total Exposure time	10 ksec	10 ksec
Star brightness	$m_I = 3.60$	$m_H = 5.65$
Photon flux in science band (star)	7.37e8 ph/s	5.62e9 ph/s
Photon flux in science band (planet)	0.11 ph/s	118 ph/s
Background surf. brightness [contrast]	3.5e-10 (zodi+exozodi)	1e-5 (starlight)
Background flux in science band	0.26 ph/s	56200 ph/s
Photon-noise limited SNR (10 ksec)	18.1	49.7
Post-processing timescale (SNR=10 at planet flux)	50 mn	$\boxed{7 \text{ mn}}$
WFS timescale (SNR=10 at background flux)	6 mn	1.8 ms

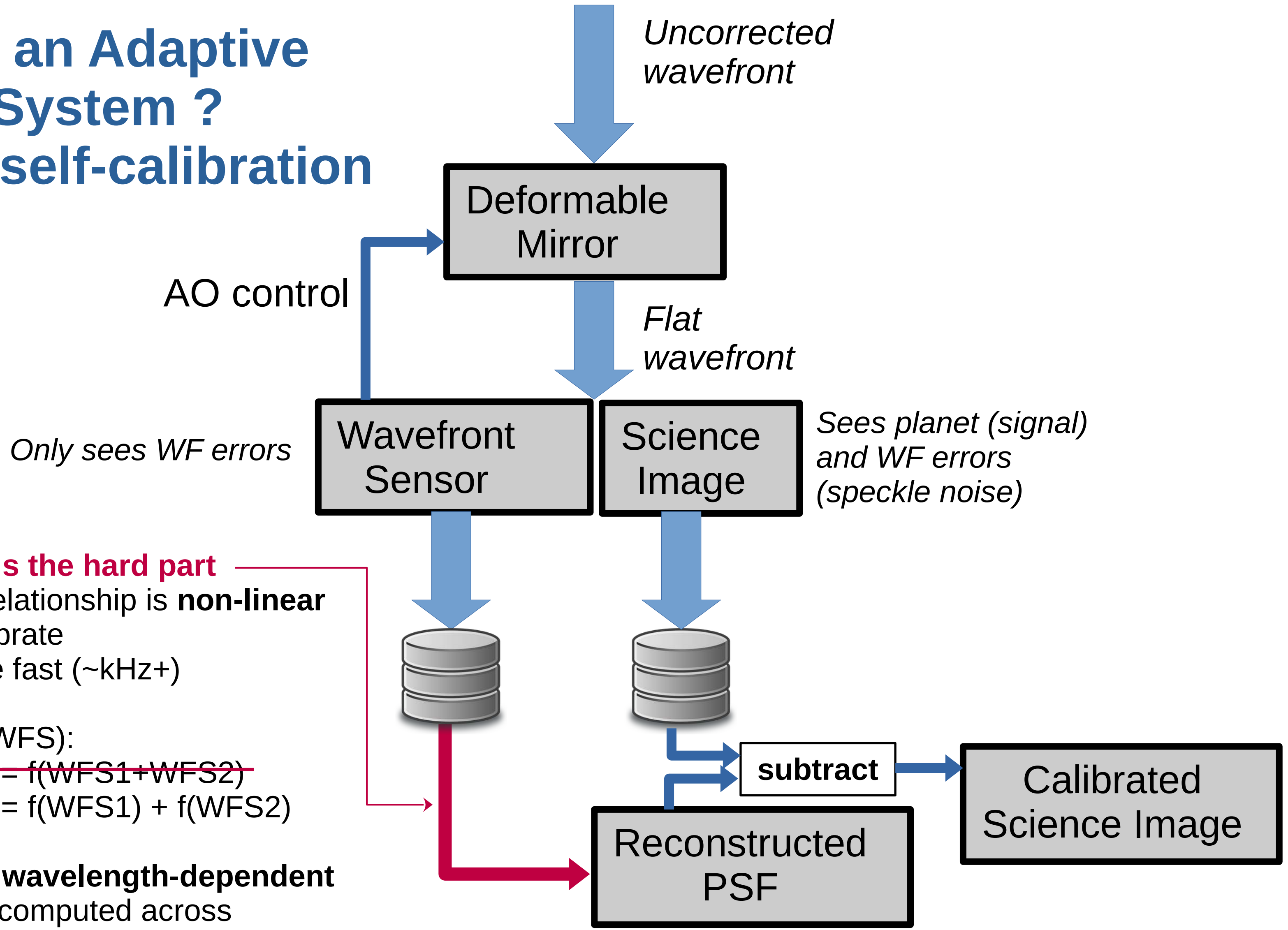
With 1e-5 raw contrast, Earth-size habitable planet imaged at SNR=10 in 7mn with 30m aperture in H band

Challenge: Planet is still 500x fainter than starlight

What is an Adaptive Optics System ?



What is an Adaptive Optics System ? … with self-calibration



This is the hard part

WFS → PSF relationship is **non-linear**
→ hard to calibrate
→ has to done fast (~kHz+)

With PSF = f(WFS):
~~PSF1 + PSF2 = f(WFS1+WFS2)~~
PSF1 + PSF2 = f(WFS1) + f(WFS2)

WFS → PSF is **wavelength-dependent**
→ need to be computed across wavelength dimension

What <u>really</u> is an Adaptive Optics System

Uncorrected wavefront

Deformable Mirror

Flatter *wavefront*

Old noisy Wavefront Sensor image

Wavefront Sensor

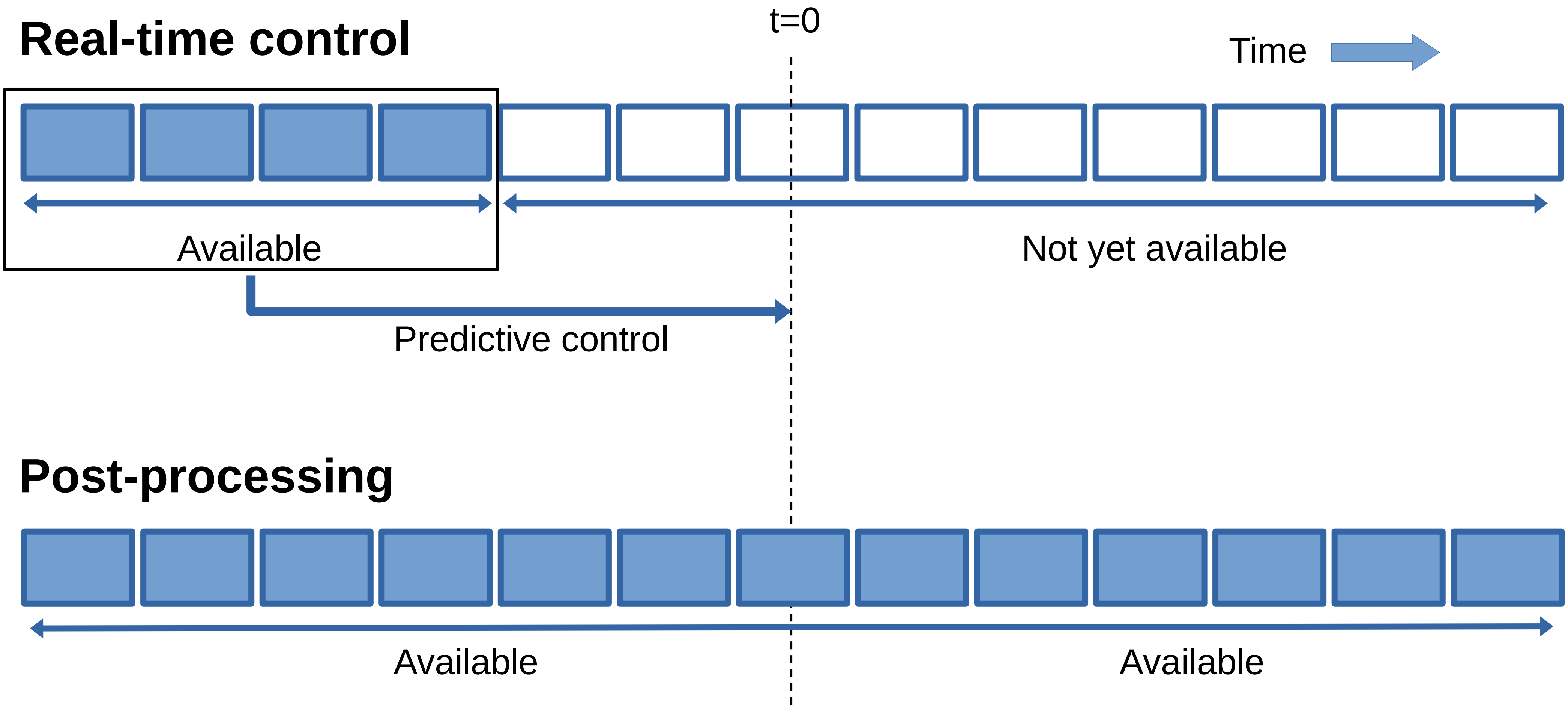
Science Image

HARDWARE

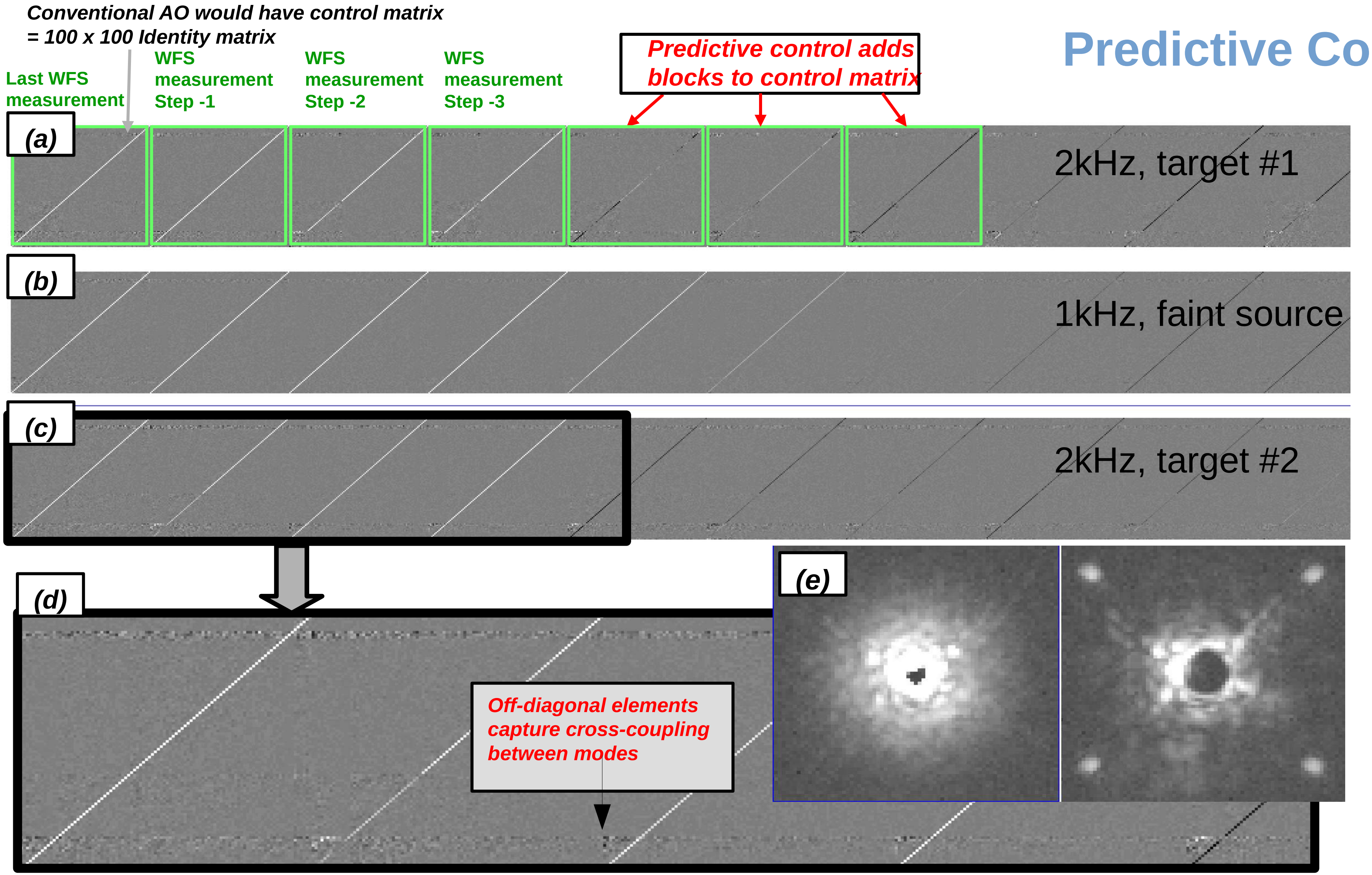
Correction null space
DM can't correct everything the WFS sees, doesn't go exactly where you tell it to

Latency & Noise
Will steal the WFS image, hang on to it for a while, add noise to it and then hand it back to you after making sure it's no longer fresh

Real-time control vs. post-processing: Latency and Noise

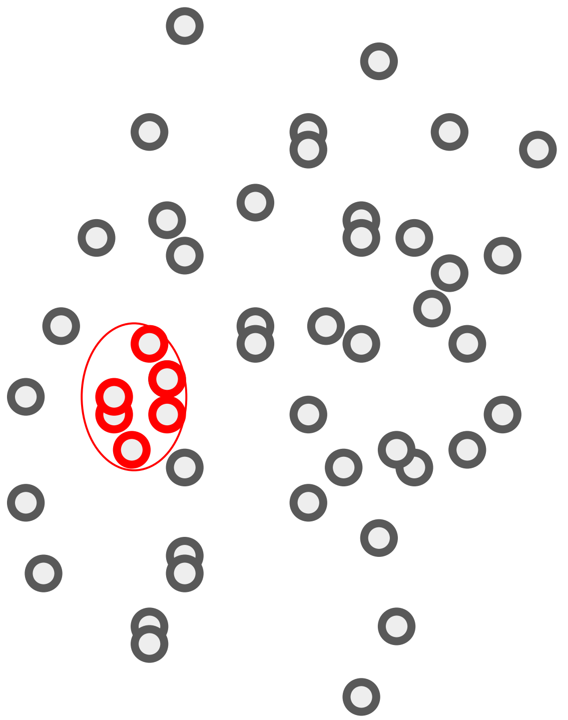


Predictive Control



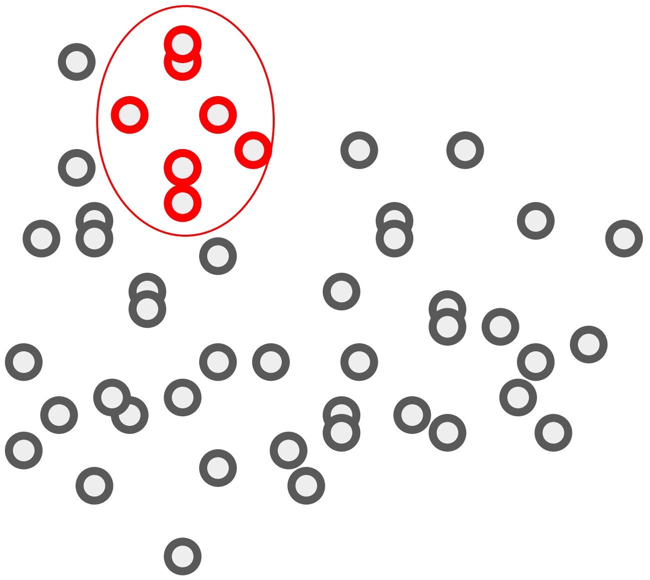
Solution Uniqueness

Input measurement space
(WFS, Bright Field, LOWFS etc...)



Input space can be mapped to output space
-> **algorithm exists**

Speckle field / Dark Hole space



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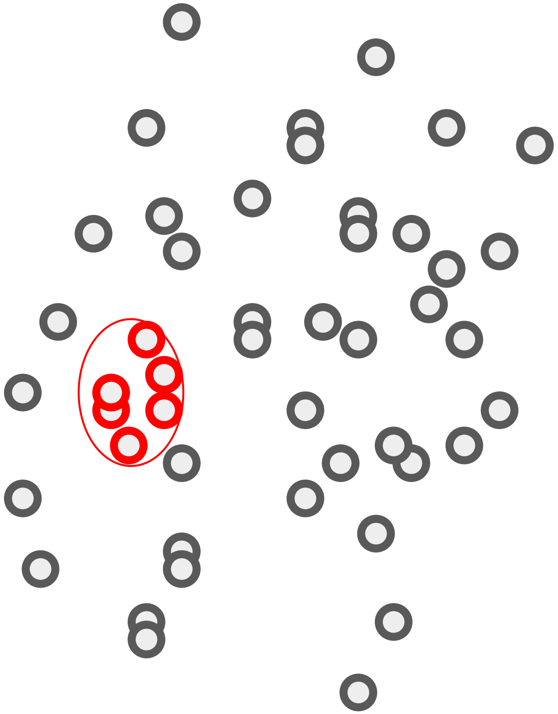
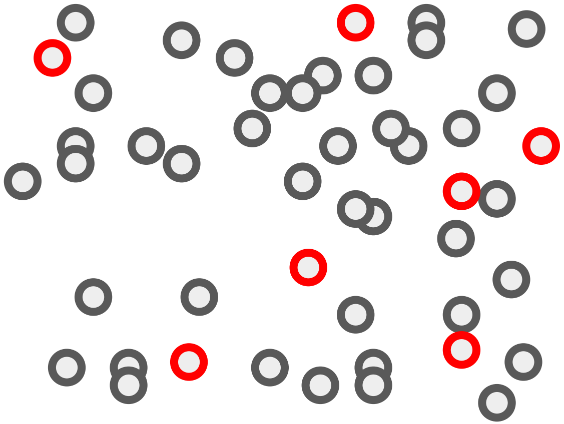


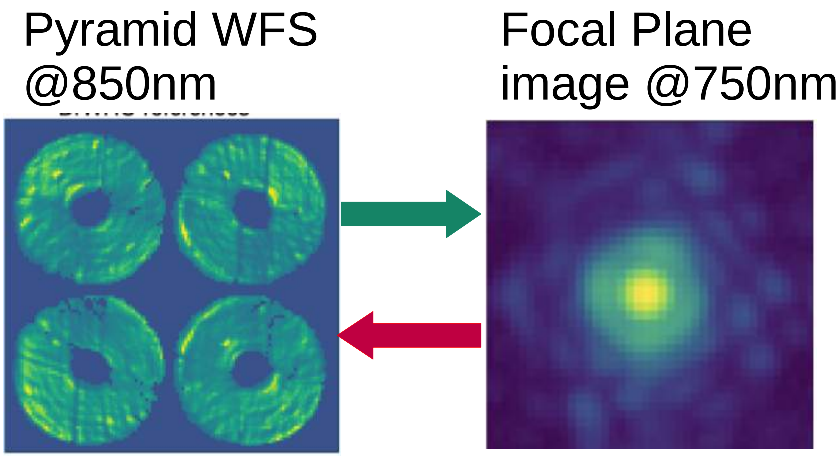
Incomplete mapping
-> **no solution**
(need more data to constrain null space)

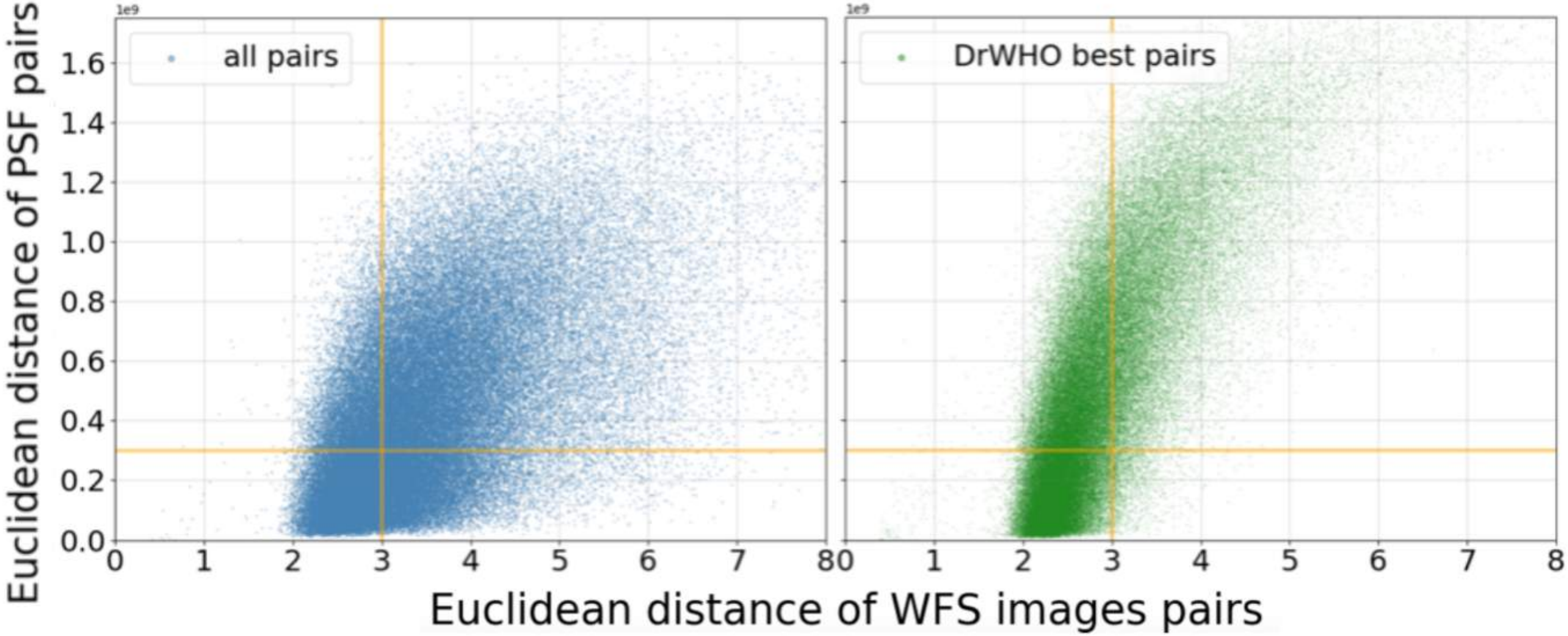
Speckle field / Dark Hole space



On-Sky Validation of Solution Uniqueness

Similar WFS → similar PSF ? **YES**
Similar PSF → similar WFS ? **NO** (except at null)

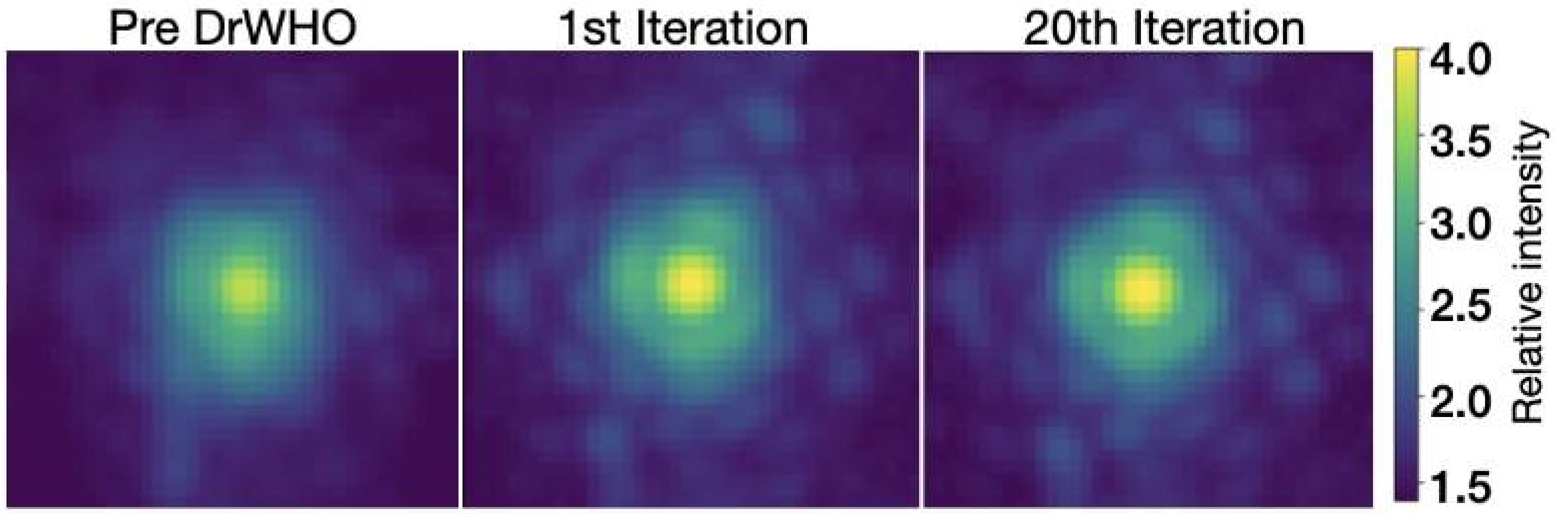




Skaf et al. 2022

WFS→ PSF relationship can be learned on-the-fly

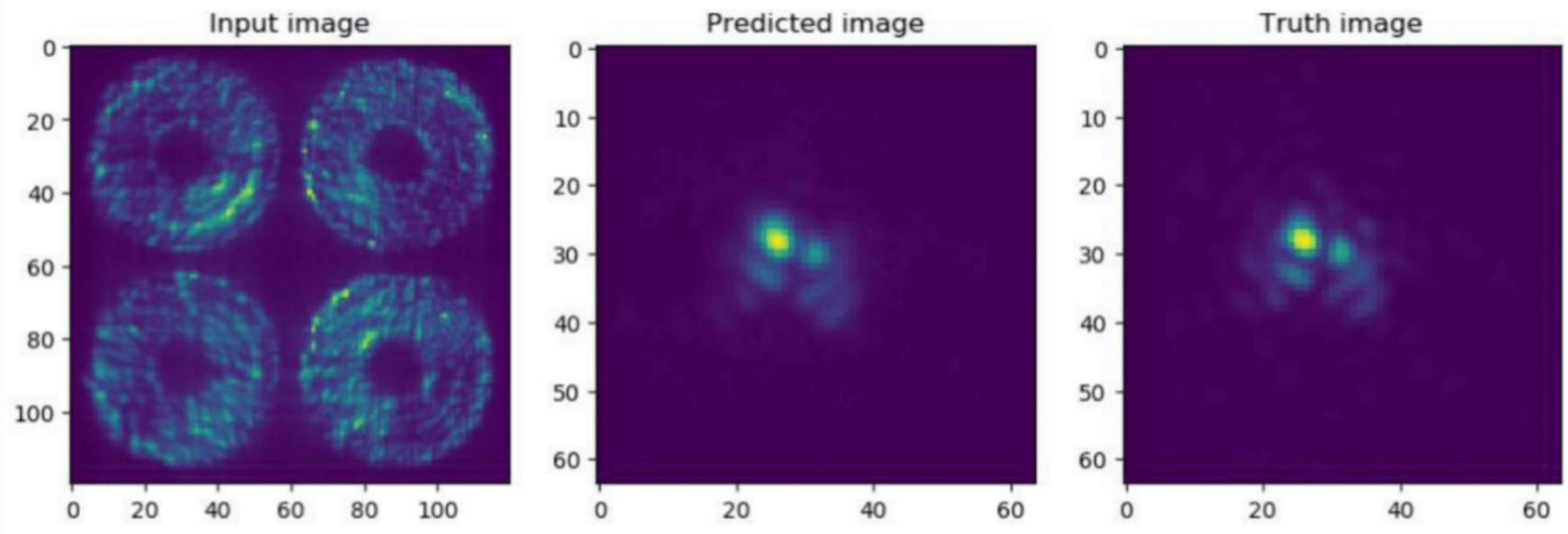
Improving WFS reference from Focal Plane Image (DrWHO)



Evolution of the on-sky PSF before running the algorithm, after the first iteration, and the after last iteration. Each image is 0.25 arcsec (40x40 pixels) across, acquired at λ = 750 nm, 30 sec exposure time (computed by co-addition of 15,000 frames acquired at 500 Hz)

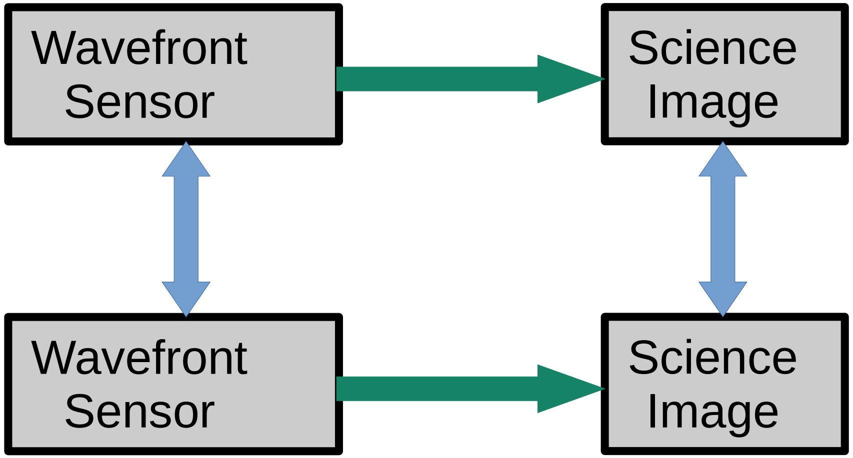
Skaf et al. 2022

On-sky WFS → PSF Derivation with Neural Net



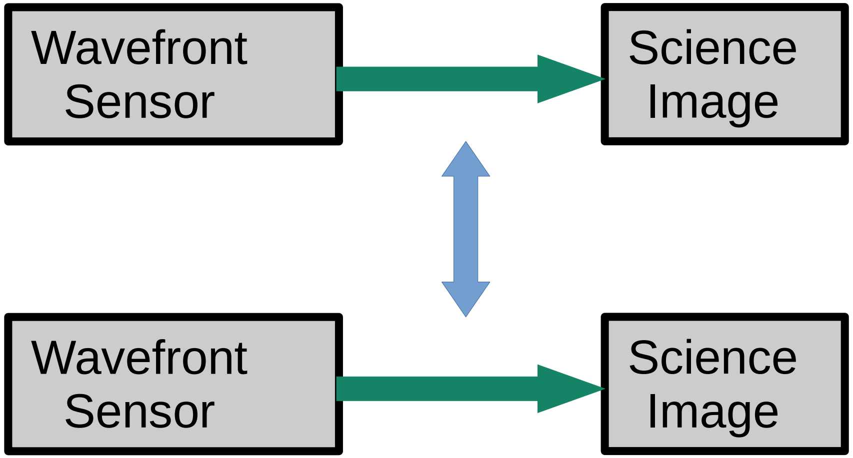
Credit: Barnaby Norris & Alison Wong

PSF Subtraction relies on WF & PSF Stability



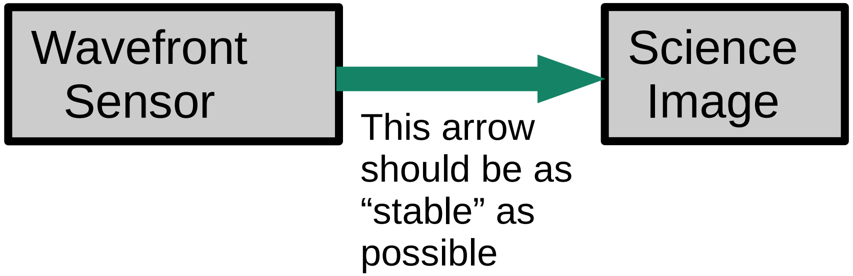
Are statistical properties of WF stable over course of observation ?

Self-Calibration relies on Stability of WFS → PSF Relationship



Are optics between WFS and science image stable over course of observation ?

Ideal Hardware Configuration keeps relationship between WFS and PSF <u>stable</u>

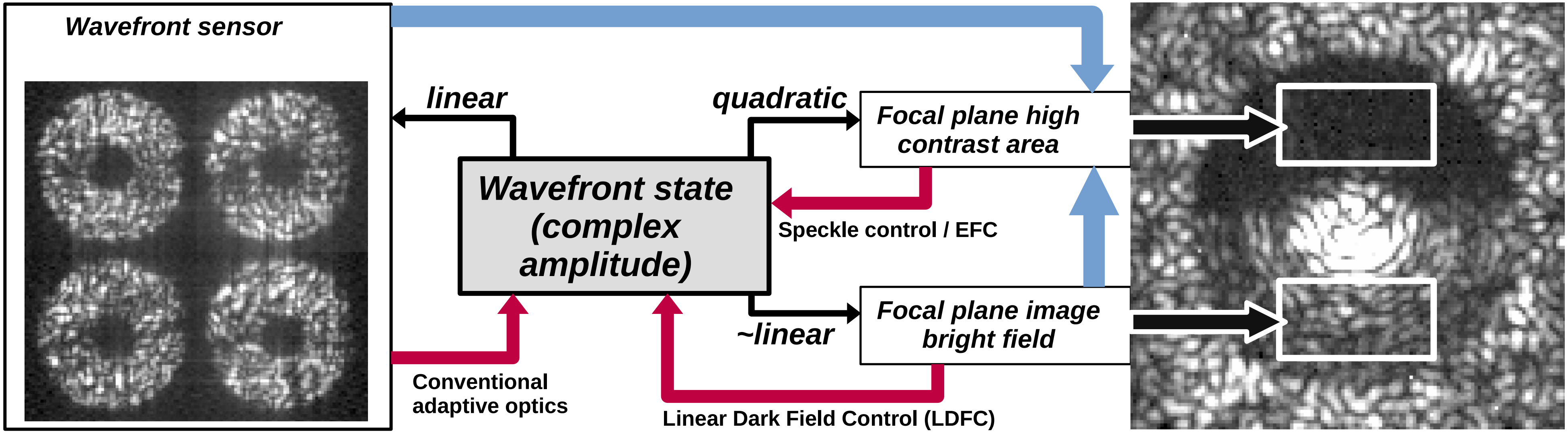


Speckle Calibration from Bright Field Starlight

WF Control **Calibration**

We focus here on CALIBRATION (blue arrows)

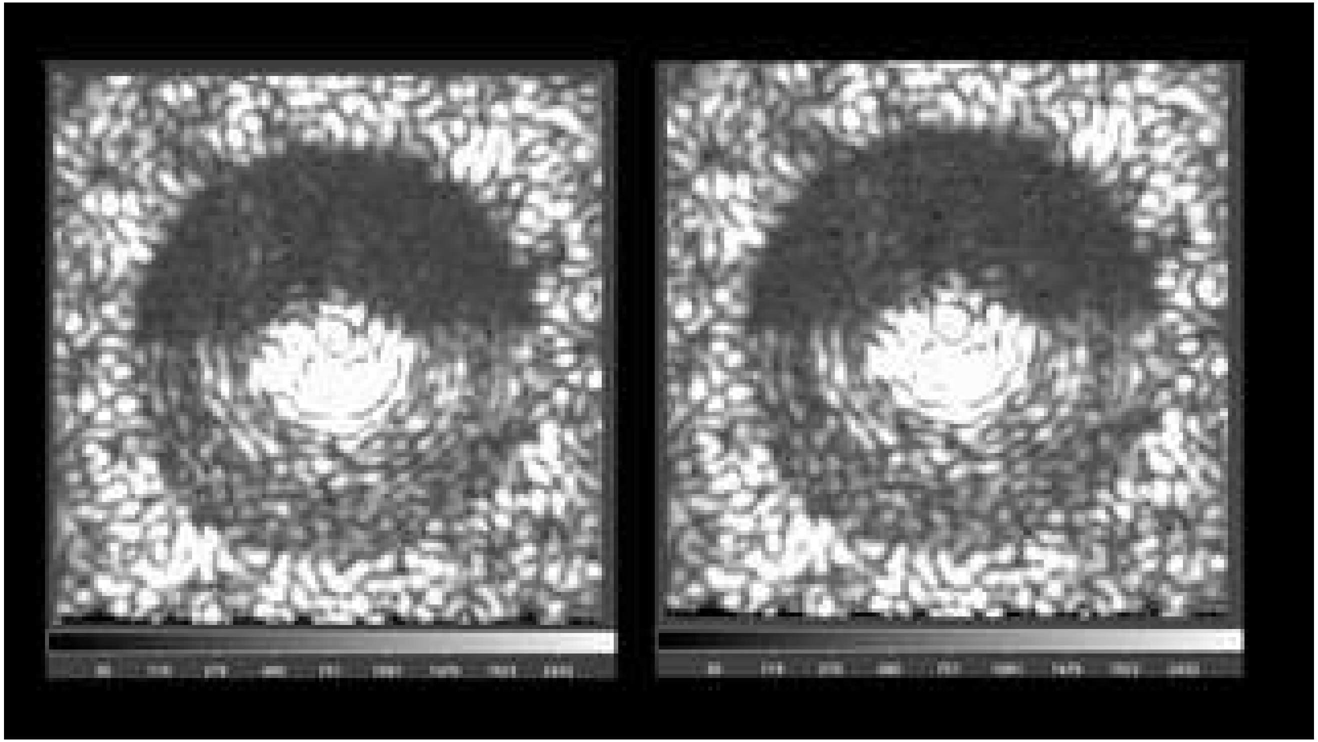
Can we reconstruct residual starlight from auxiliary wavefront sensors and cameras ?



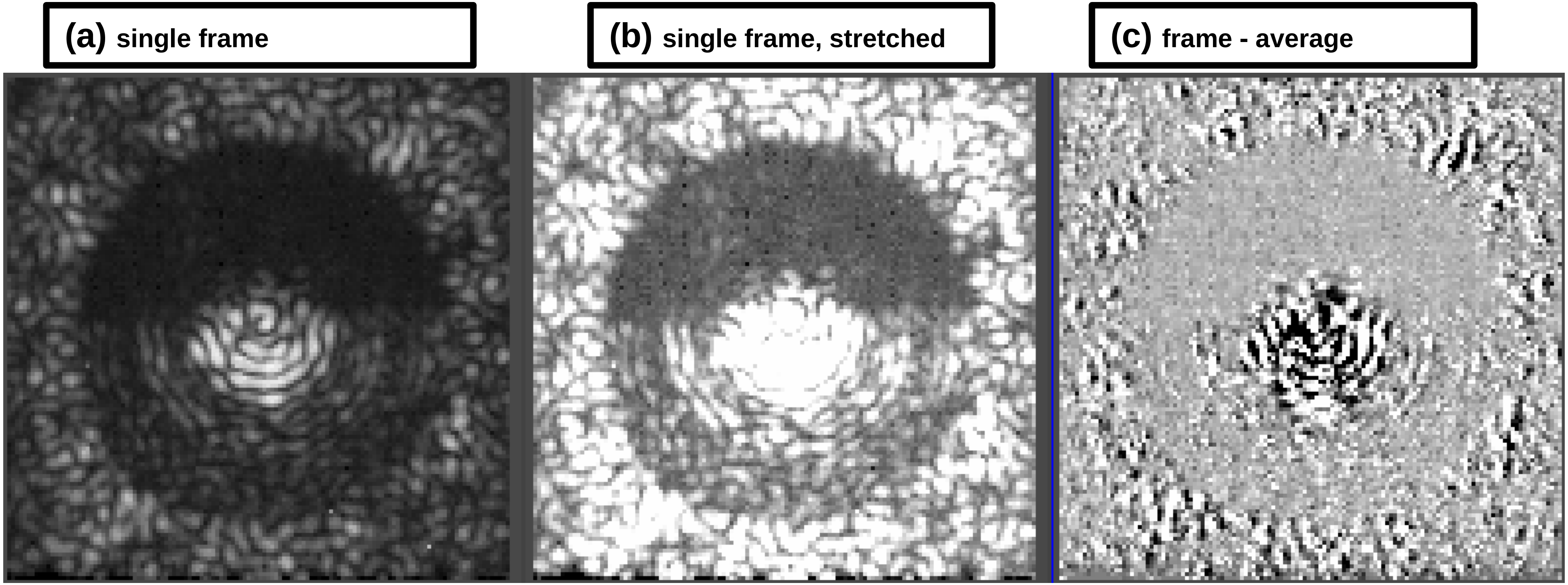
Experimental validation (lab)

1550nm, 25nm BW, Lyot Coronagraph
7 kHz frame rate

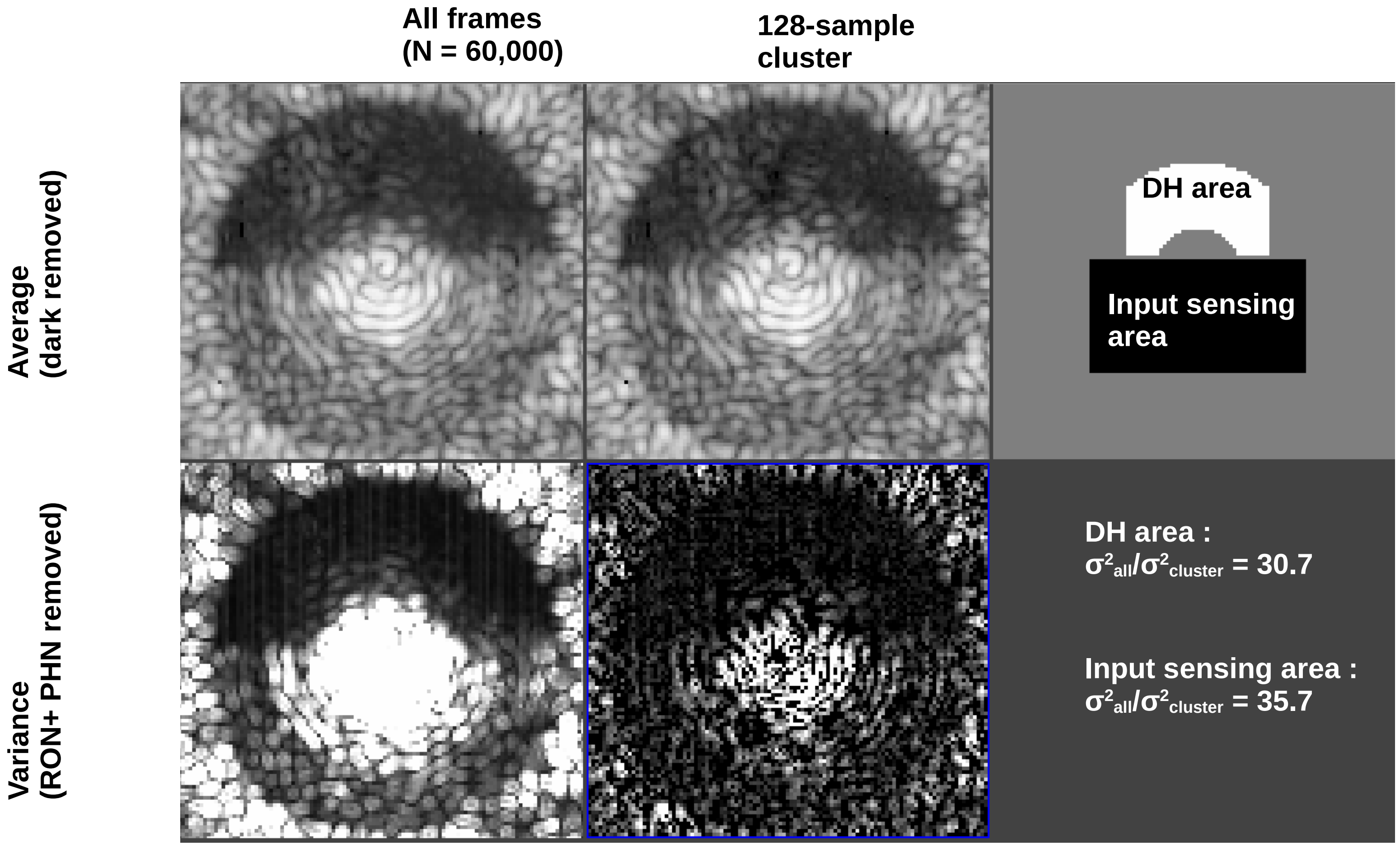
UNCALIBRATED **CALIBRATED**



Single Frame Residual is at RON+PHN Level



30x Gain in Speckle Variance Demonstrated



Optimizing Wavelength for Sensitivity

Short wavelength : better optical gain from intensity to OPD
Red target: higher photon count at longer wavelength

Table 6 Optimal Wavefront Sensing Wavelength - Linear Regime

Spectral Type	Teff [K]	Optimal Band[a]	Photon flux[b] $[m^{-1}.ms^{-1}]$	Flux gain relative to ... B	R	H
B0V	31500	U	1.08e10	2.14	12.06	1337.0
A0V	9700	B	5.01e7	1.00	4.25	204.7
F0V	7200	B	1.05e7	1.00	2.78	82.1
G0V	5920	B	1.34e6	1.00	1.80	$\boxed{33.7}$
K0V	5280	B	3.26e5	1.00	1.33	17.6
M0V	3850	R	3.53e4	2.03	1.00	3.93
M4V	3200	I	4.65e3	12.5	1.80	2.83
M8V	2500	J	6.00e2	150.0	11.6	1.98

[a]Optimal bandwidth selected among standard astronomical spectral bands (U, B, R, I, J, H). Assumes fixed relative spectral bandwidth $d\lambda/\lambda$. Central wavelength listed; [b]Assuming 10% effective spectral band at optimal sensing wavelength, main sequence star at 10pc.

B-band WFS is 33.7x more efficient than H-band WFS

Integating WFS and "PSF" within the same optical chip

*"***Astrophotonics: The Rise of Integrated Photonics in Astronomy***"*
Norris & Bland-Hawthorn.
Optics and Photonics News (2019)
https://www.osa-opn.org/home/articles/volume_30/may_2019/features/astrophotonics_the_rise_of_integrated_photonics_in/

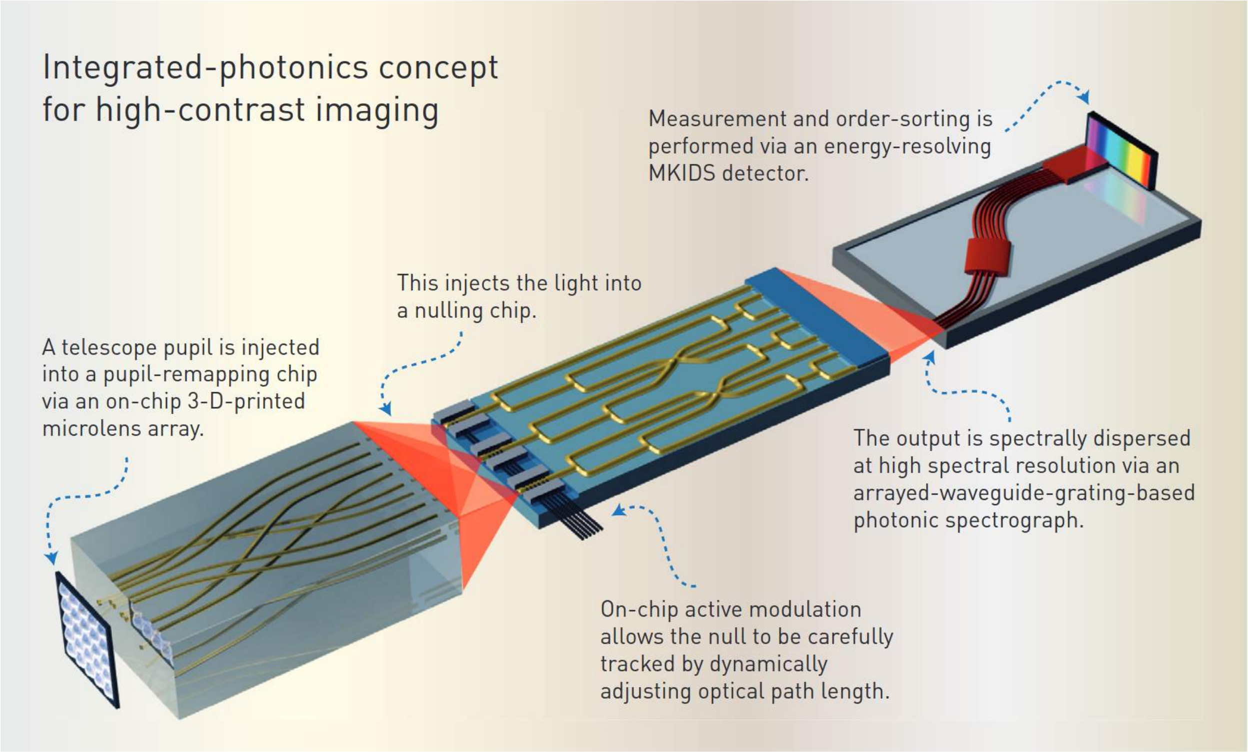
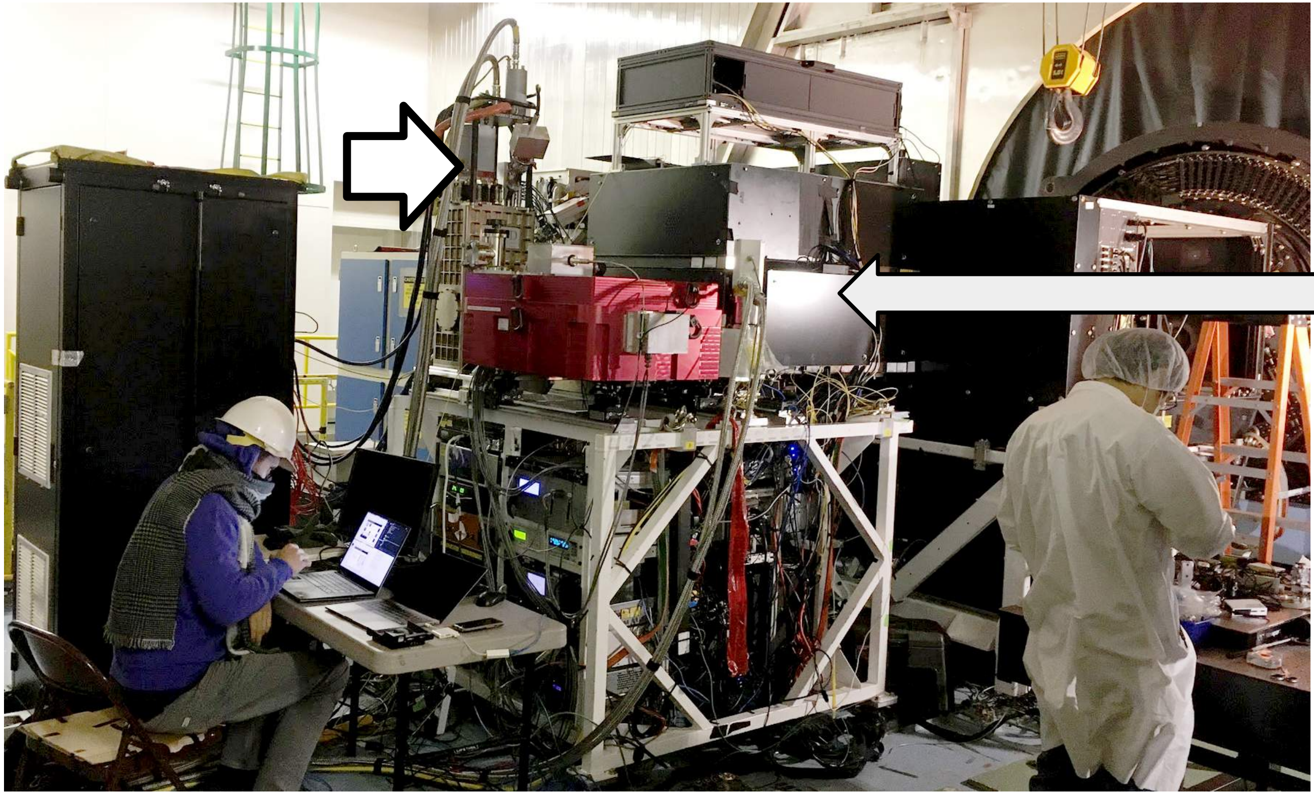


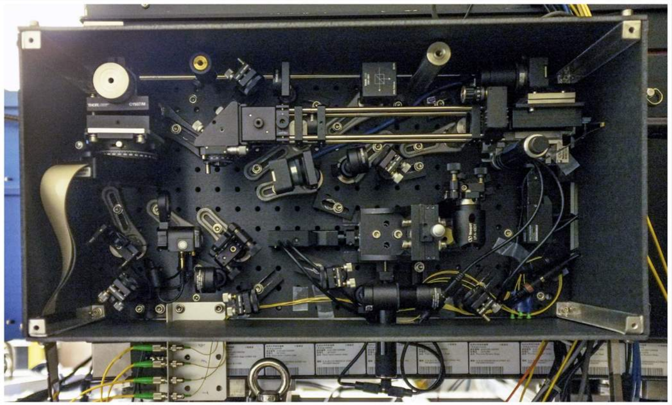
Illustration by Phil Saunders

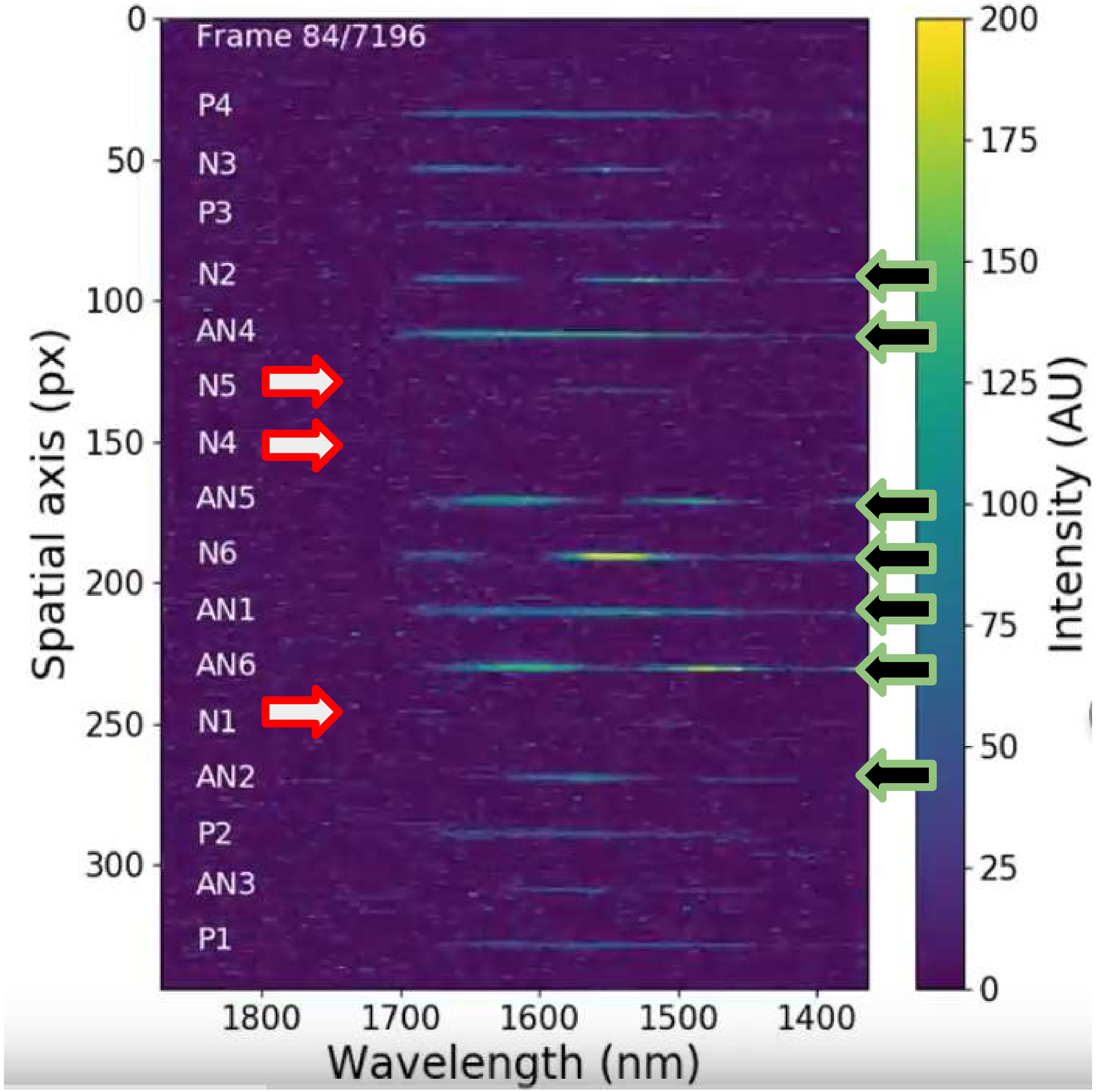
GLINT module @ Subaru/SCExAO



GLINT module

PNC prototype





Null output: starlight is almost completely removed by destructive interference, providing deep contrast.
➔This is where planet light and spectra are extracted

Fringe tracking output: Bright starlight interference efficiently encode residual small (nm-level) optical aberration
➔Feed this information in real-time to upstream deformable mirror for correction
➔Use this information to calibrate how much starlight is left in null outputs

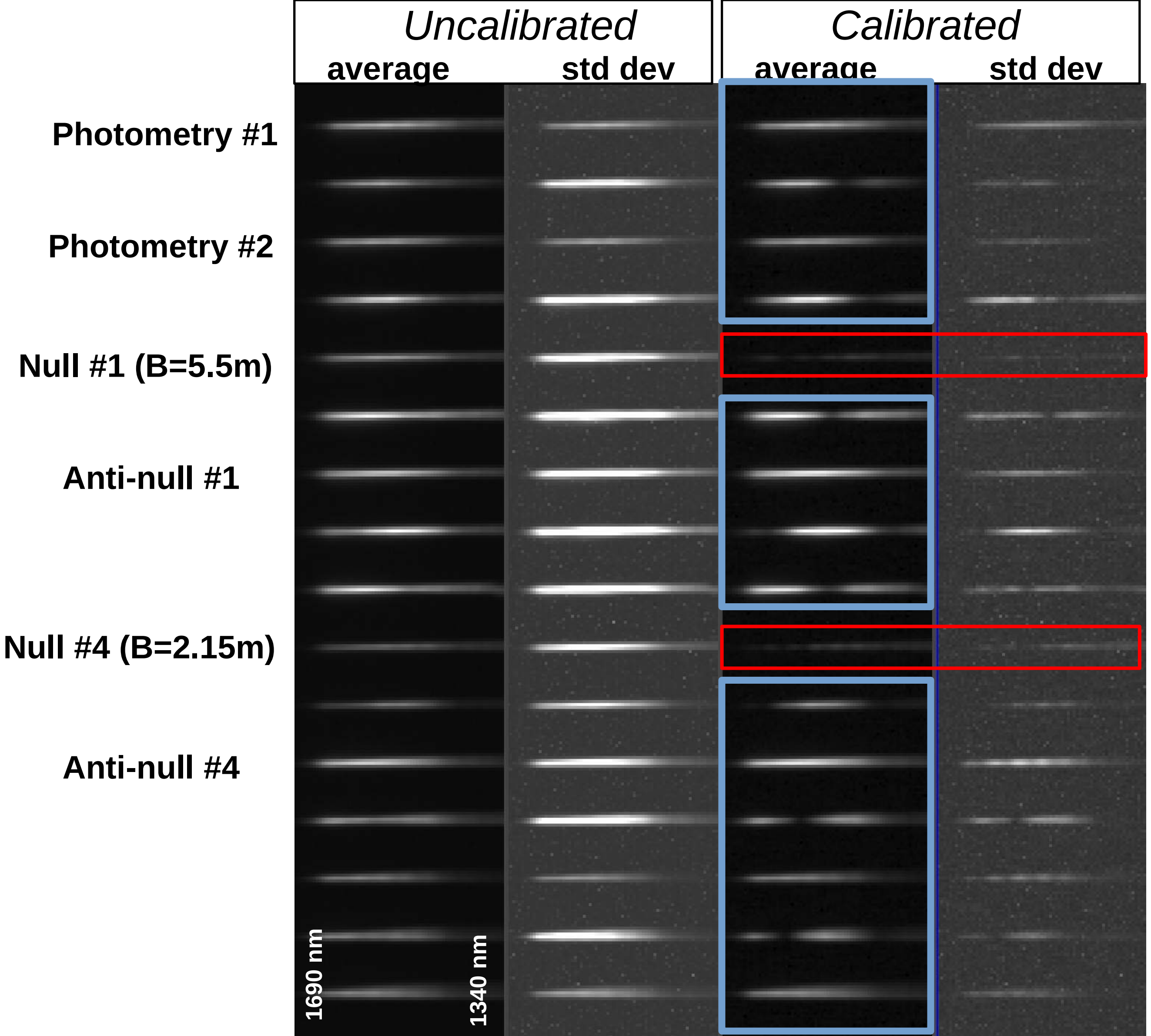
"Scalable photonic-based nulling interferometry with the dispersed multi-baseline GLINT instrument"
Martinod, Norris, Tuthill...Guyon et al.
Nature Communications (2021)
link: https://www.nature.com/articles/s41467-021-22769-x

GLINT – lab+turbulence

1.4 kHz frame rate

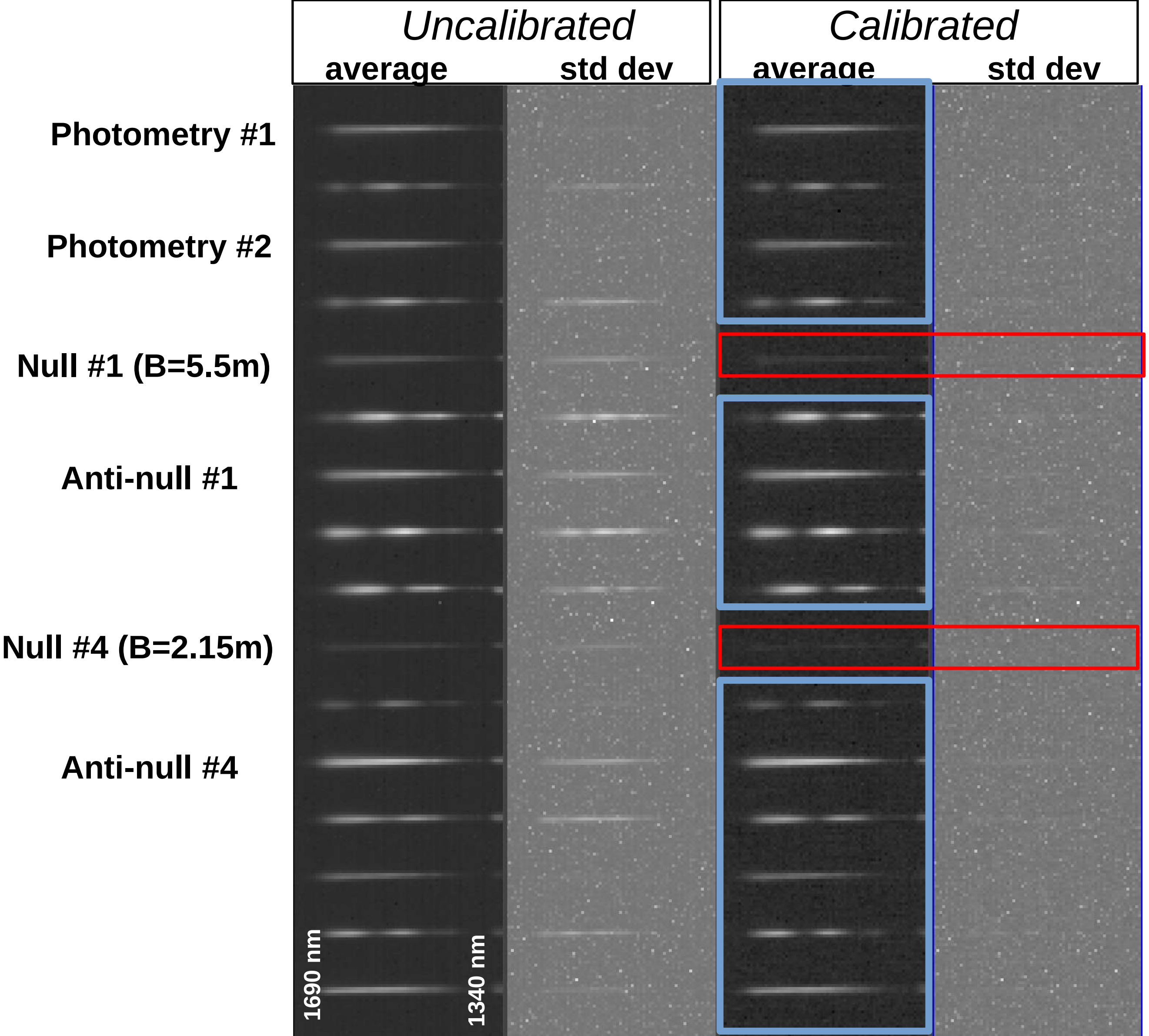
Uncalibrated: 12796 samples

Calibrated: 20 samples



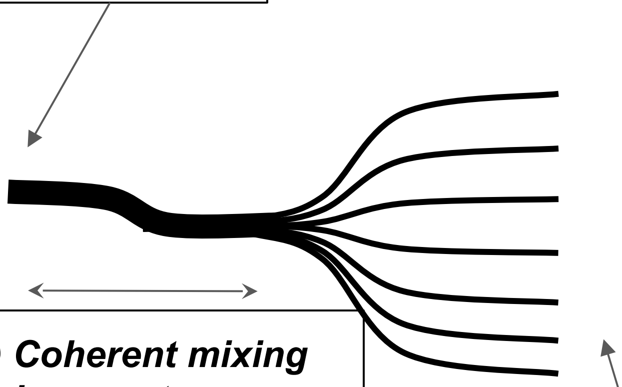
GLINT – on-sky Alpha Boo

1.4 kHz frame rate



Photonic Lantern

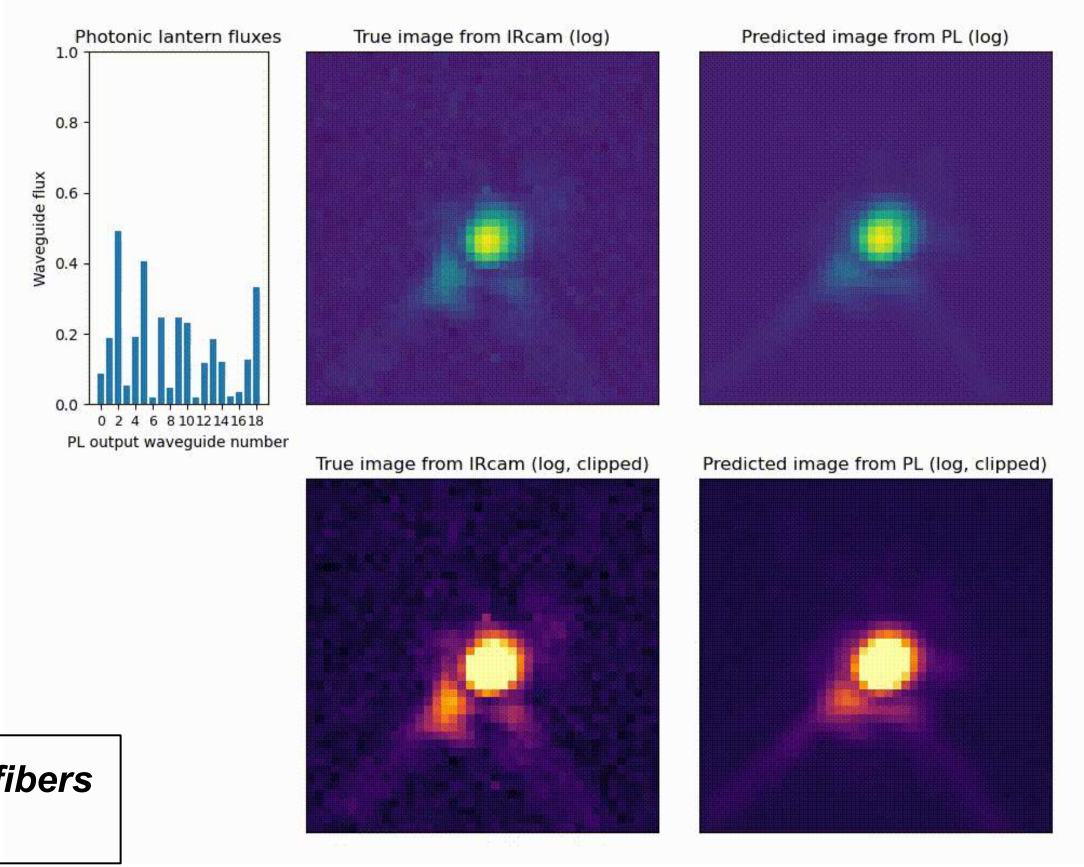
(a) Multimode fiber efficiently captures light



(b) Coherent mixing region creates interference signals

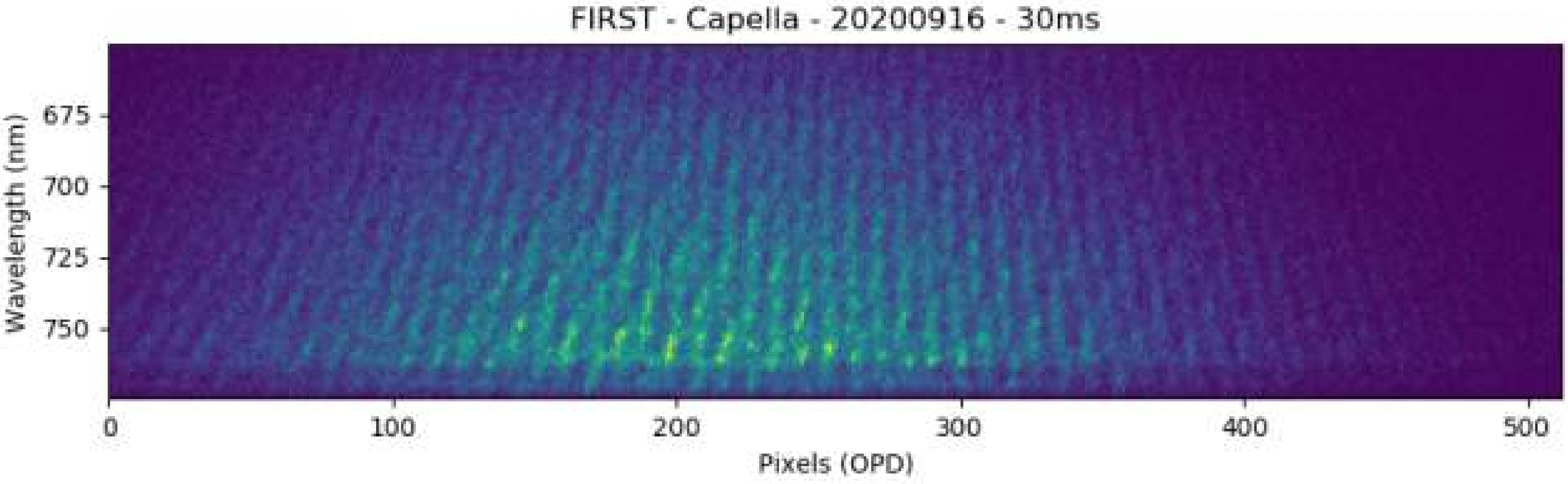
(c) Single mode fibers (SMFs) output

Vega, March 24 2022
PIAA optics → 19-element PL



Credit: Barnaby Norris, Univ. Sydney

Interferometric WFS with FIRST instrument



Credit: S. Vievard and V. Deo

On-sky demonstration of interferometric WFS
→ provides path to high sensitivity chromatic WF measurement

Conclusions

Self-calibrating high contrast imaging systems could eliminate speckle noise
→ Deeper detection limits, limited by photon noise in science images
→ Reliable science data

Early on-sky experiments are encouraging, but there are tough challenges :
- Computation algorithms and speed in high-dimension space
- Hardware implementation: wavelength diversity, data acquisition speed, internal stability

Photonic solutions (Photonic Nulling chip, Lantern, Integrated Optics) seem well-suited for achieving self-calibration:
- Small number of degrees of freedom
- Can be spectrally dispersed with high readout speed