Coronagraph Approaches to Relax Telescope Requirements*

(*) Exploring here ***wavefront stability*** only

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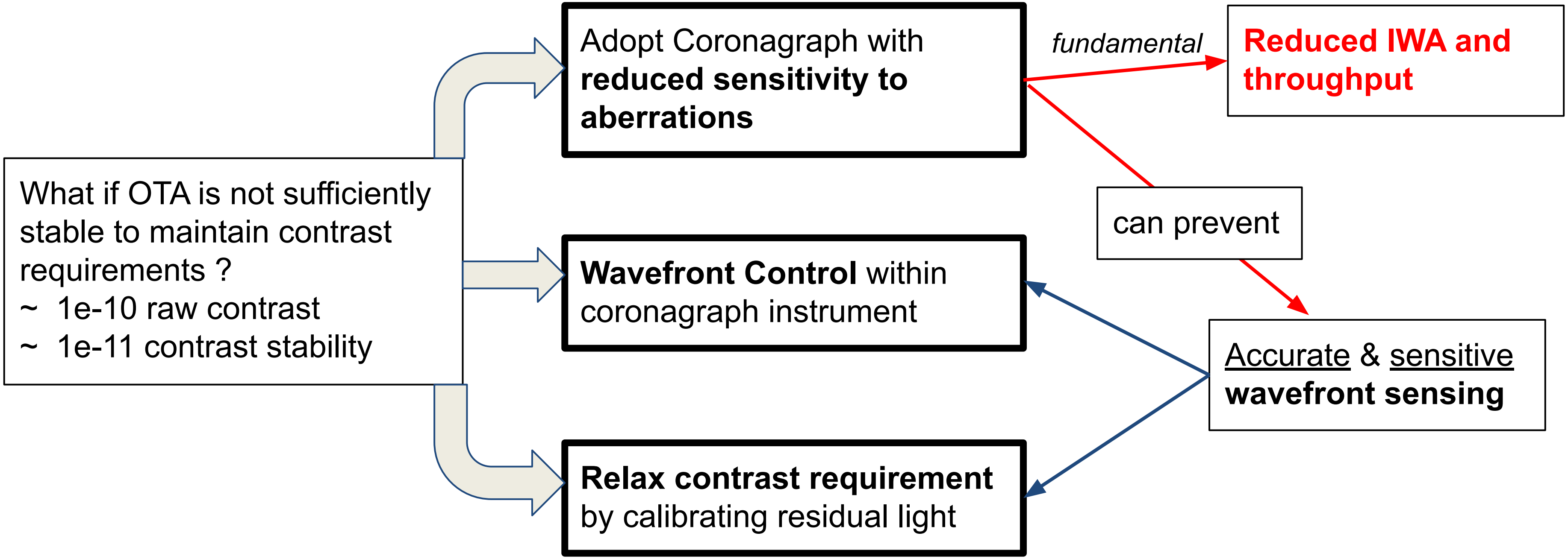
Approaches to Relax Telescope Requirements



What if OTA is not sufficiently stable to maintain contrast requirements ?
~ 1e-10 raw contrast
~ 1e-11 contrast stability

Adopt Coronagraph with **reduced sensitivity to aberrations**

Wavefront Control within coronagraph instrument

Relax contrast requirement by calibrating residual light

fundamental

Reduced IWA and throughput

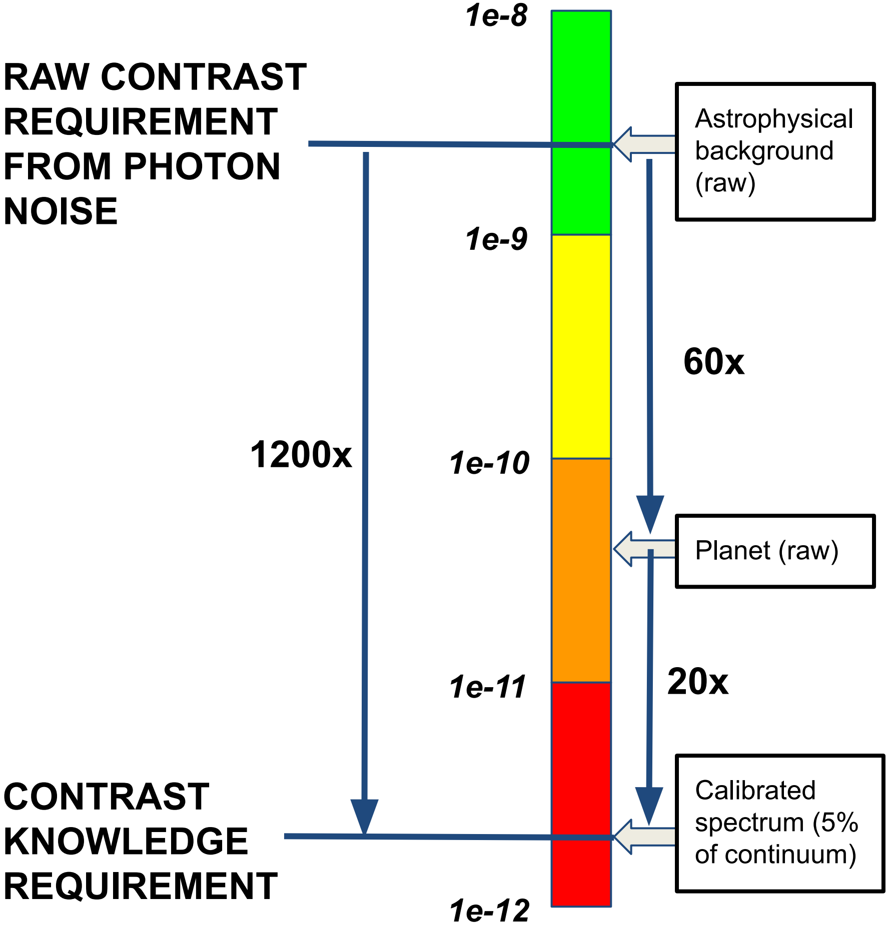
can prevent

Accurate & sensitive **wavefront sensing**

What is the Contrast Requirement ?

Sun + Earth analog @ 10pc, observed at 1.6um with 6m diameter telescope, 15% efficicency
Angular separation = 1.8 l/D
Zodi background mH=20.51 mag/arcsec2 -> background mH=19.32 (assuming achromatic albedo, 1 zodi EZ content)
Star mH = 3.32, Contrast ~4e-11
PSF area = 1.4x1.4 l/D = 0.006 arcsec^2 (diffraction limit = 55 mas)

- **Star: 3.3e8 ph/s/um**
- **Planet: 0.013 ph/s/um (C=4e-11)**
- **Astrophysical background: 0.78 ph/s/um (C=2.4e-9)**



Contrast scale

RAW CONTRAST REQUIREMENT FROM PHOTON NOISE

CONTRAST KNOWLEDGE REQUIREMENT

Coronagraph Raw Contrast

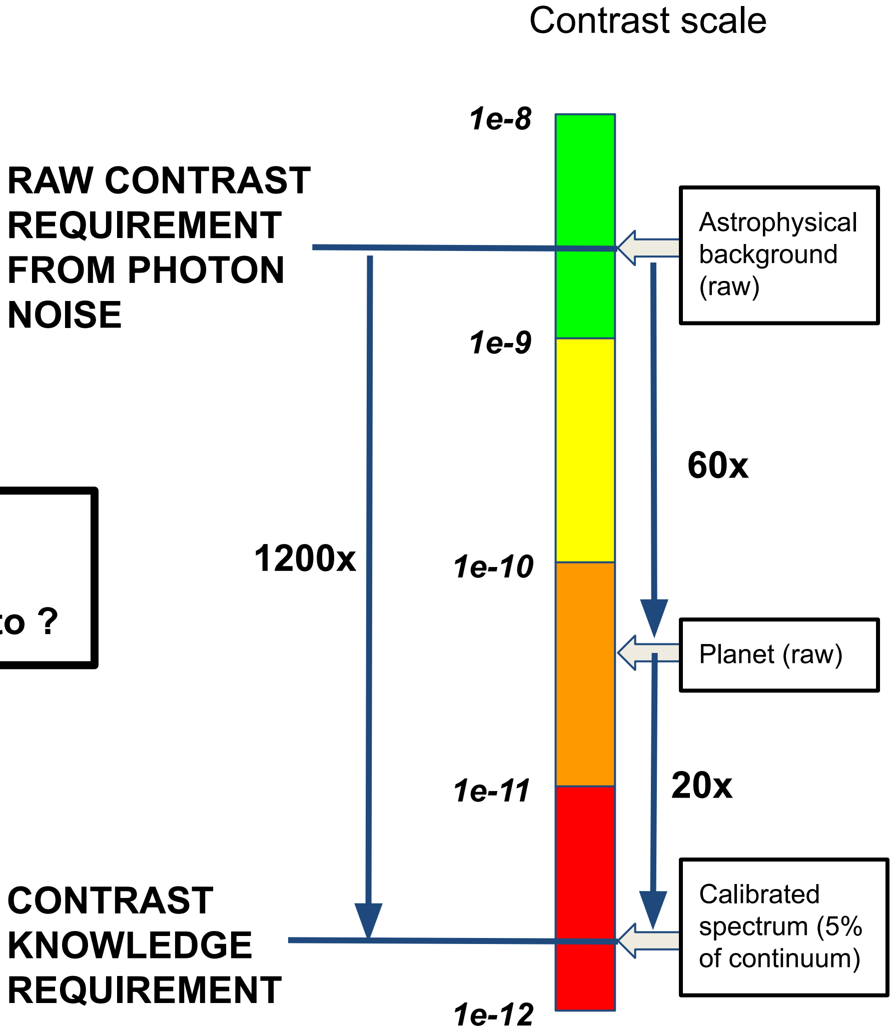
Which RAW contrast requirement should the coronagraph be designed to ?

Coronagraph designed to higher throughput, smaller IWA, responsive WFC
Multiple coronagraph mask options

WFC

What is the required telescope stability ?

Narrowband
Slow WFC
Low efficiency



Contrast scale

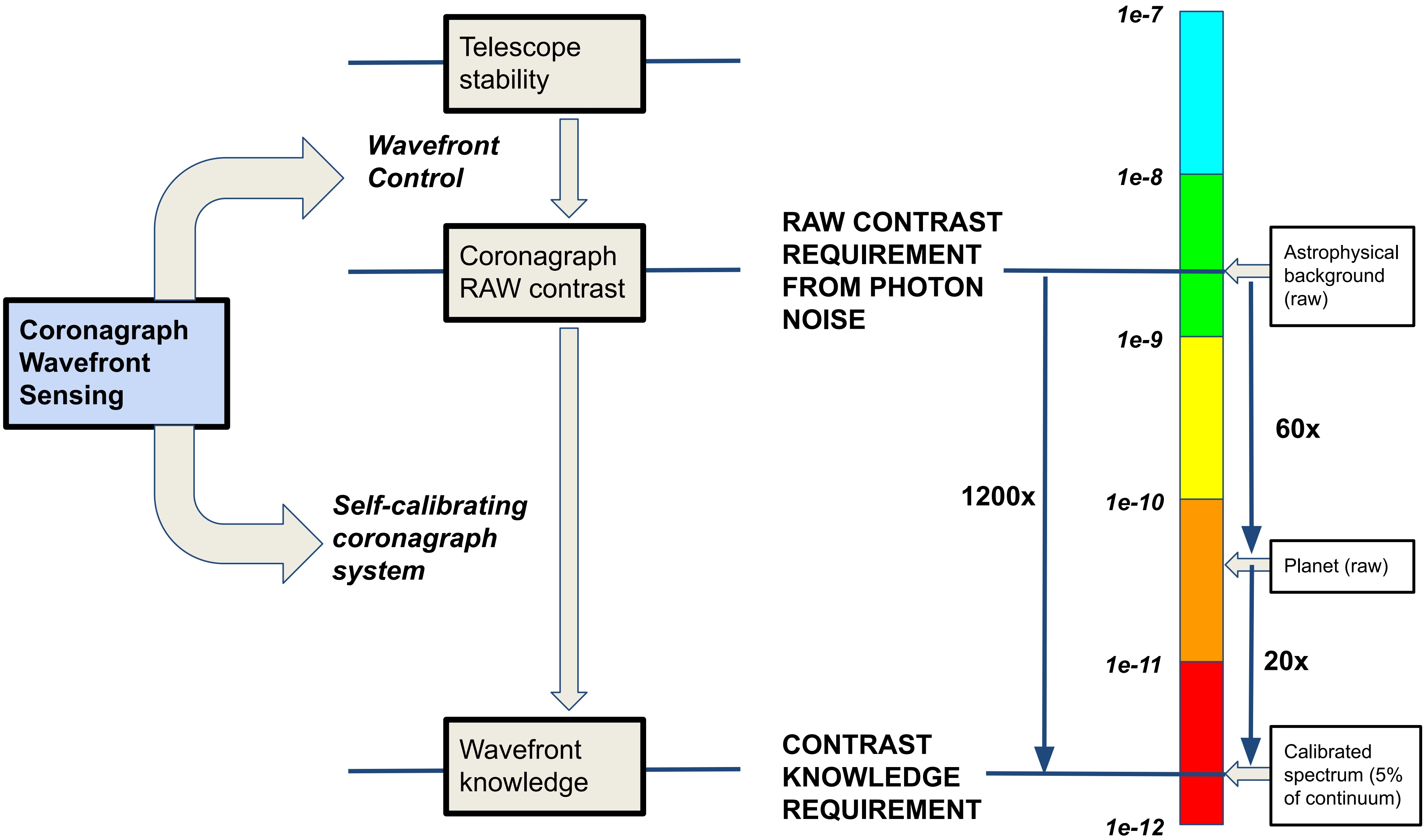
RAW CONTRAST REQUIREMENT FROM PHOTON NOISE

CONTRAST KNOWLEDGE REQUIREMENT

Astrophysical background (raw)

Planet (raw)

Calibrated spectrum (5% of continuum)



Telescope stability

Coronagraph RAW contrast

Wavefront knowledge

Coronagraph Wavefront Sensing

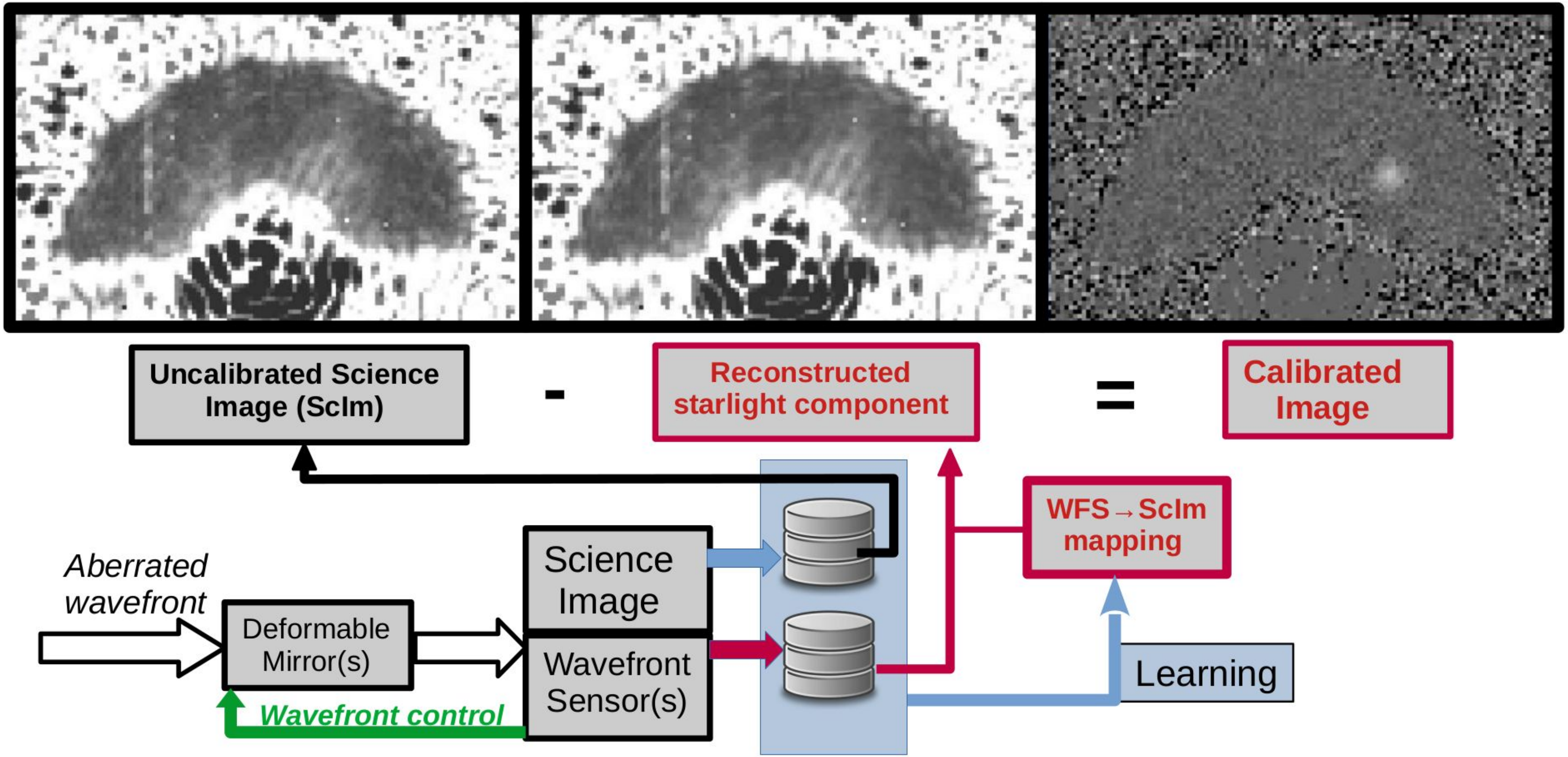
Wavefront Control

Self-calibrating coronagraph system

RAW CONTRAST REQUIREMENT FROM PHOTON NOISE

CONTRAST KNOWLEDGE REQUIREMENT

Self-Calibrating Coronagraph System



Uncalibrated Science Image (ScIm)

-

Reconstructed starlight component

=

Calibrated Image

Aberrated wavefront

Deformable Mirror(s)

Science Image

Wavefront Sensor(s)

Wavefront control

WFS → ScIm mapping

Learning

Fundamental Advantages of a Self-Calibrating Coronagraph System

… why can't a WFC loop achieve the same raw contrast as the post-processed PSF ?
(separately from coronagraphy being extremely difficult at high contrast)

Correction null space > measurement null space

- Some errors can be seen by WFS but not corrected
- It is much easier to add/upgrade WFS to capture wide range of errors than to add/upgrade DMs to correct them

Sensitivity

- Speckle control WFC loop can only use light inside dark hole
- PSF calibration can use any starlight (out of band, outside dark hole)

Coherent mixing

- Speckle control WFS loop can be background-limited on zodi+exozodi, or needs to use large probes (not useful as science data)
- PSF calibration does not need probing, can use bright starlight with coherent mixing with WF errors (LDFC)

Time

- Speckle control WFC loop can only use past measurements (poor time response)
- PSF calibration can combine past, current and future measurements
- WFS can capture high speed errors (PSD) that cannot be corrected

Optimizing Wavelength for Sensitivity

Short wavelength : better optical gain from intensity to OPD

Red target: higher photon count at longer wavelength

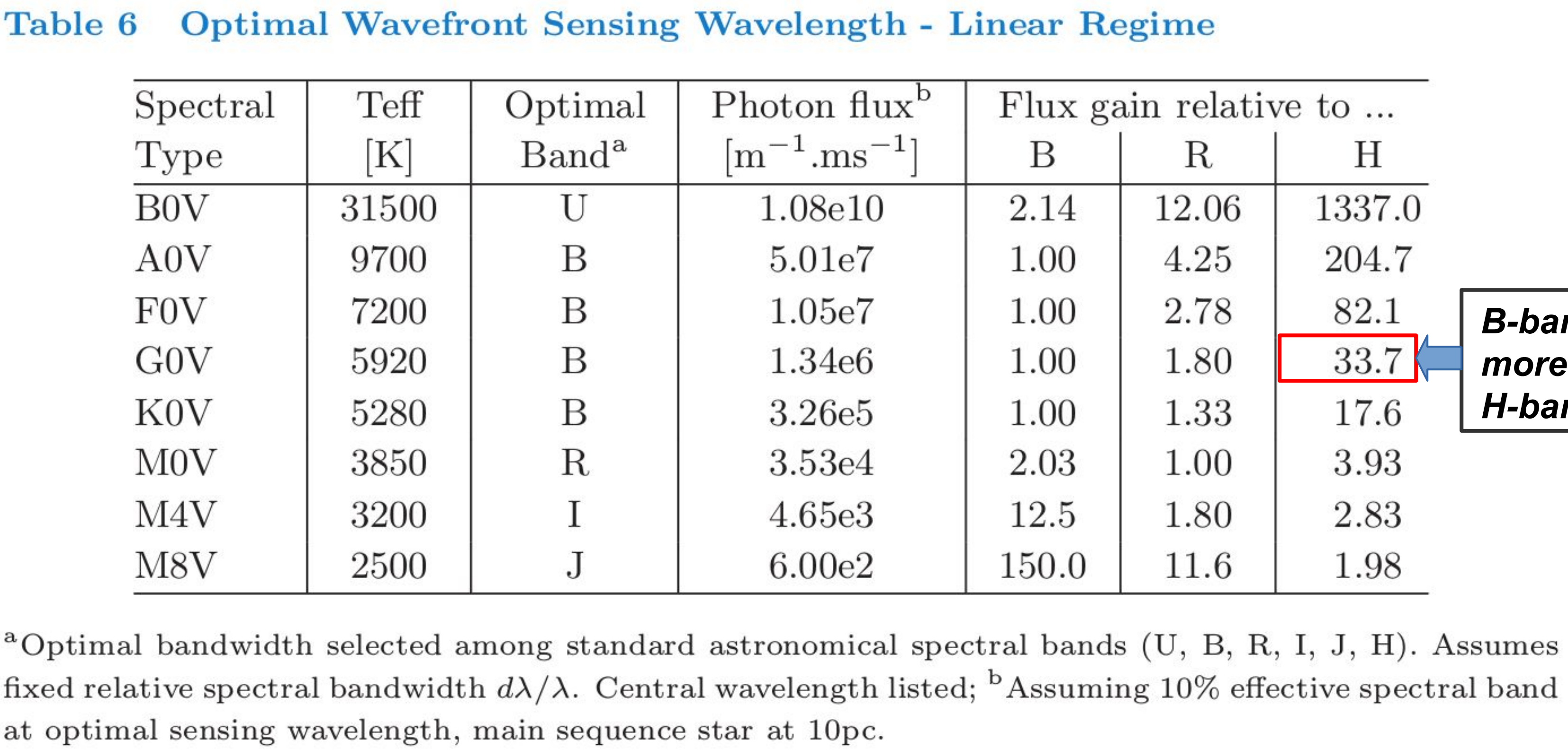


Table 6 Optimal Wavefront Sensing Wavelength - Linear Regime

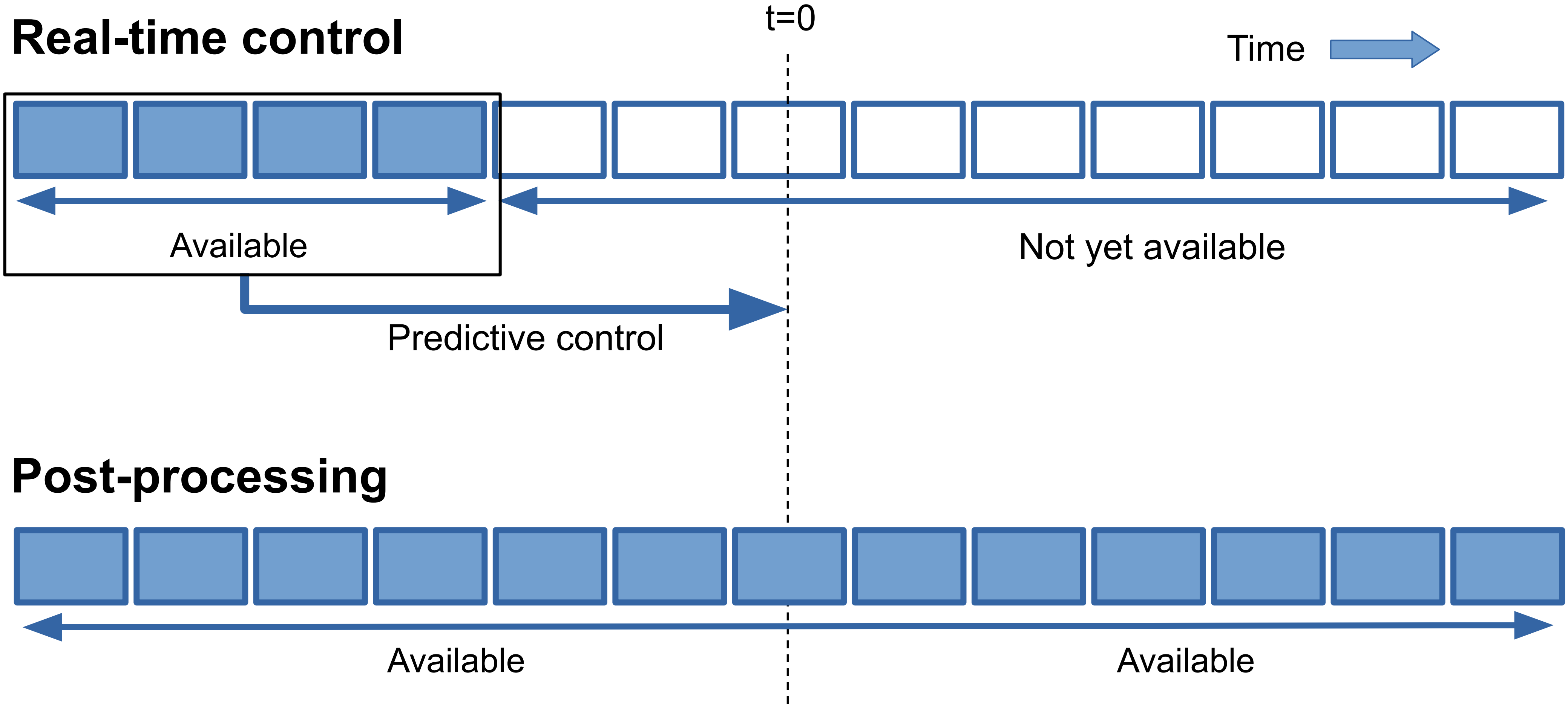
Spectral Type	Teff [K]	Optimal Band[a]	Photon flux[b] $[m^{-1}.ms^{-1}]$	Flux gain relative to ... B	R	H
B0V	31500	U	1.08e10	2.14	12.06	1337.0
A0V	9700	B	5.01e7	1.00	4.25	204.7
F0V	7200	B	1.05e7	1.00	2.78	82.1
G0V	5920	B	1.34e6	1.00	1.80	33.7
K0V	5280	B	3.26e5	1.00	1.33	17.6
M0V	3850	R	3.53e4	2.03	1.00	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

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

Real-time control



t=0

Time

Available

Not yet available

Predictive control

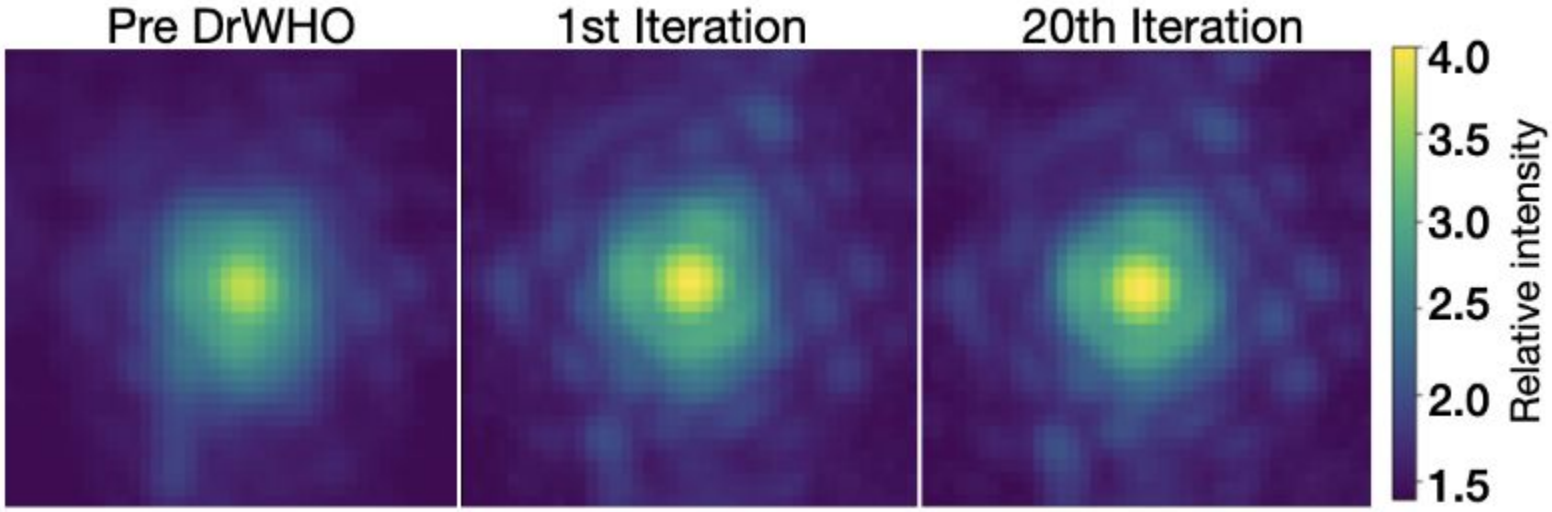
Post-processing

Available

Available

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

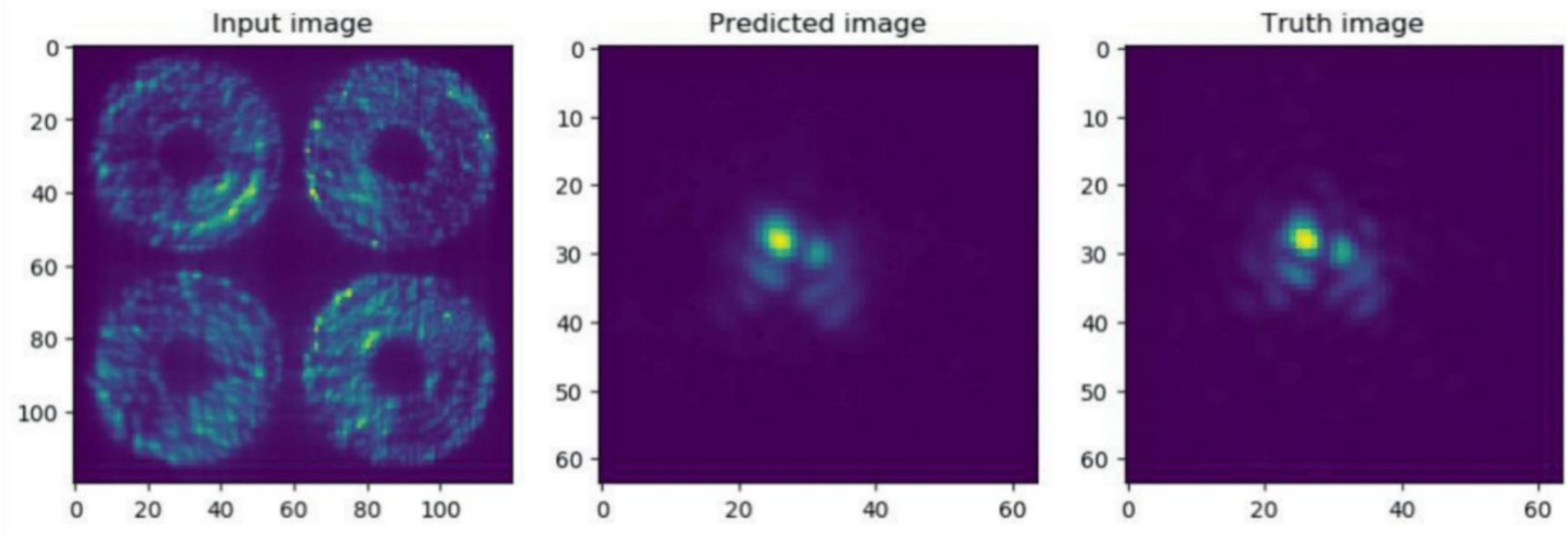
Improving WFS reference from Focal Plane Image (DrWHO)



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)

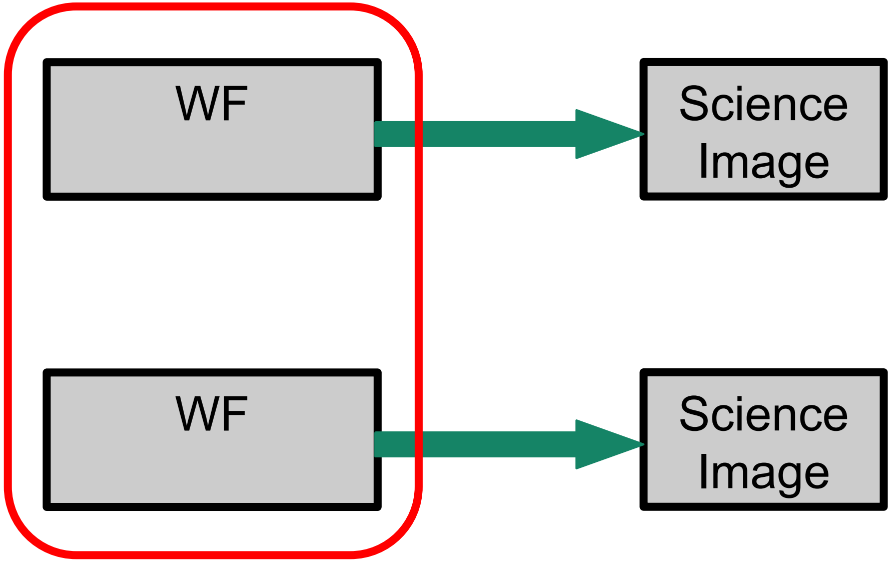
Skaf et al. 2022

On-sky WFS→PSF Derivation with Neural Net



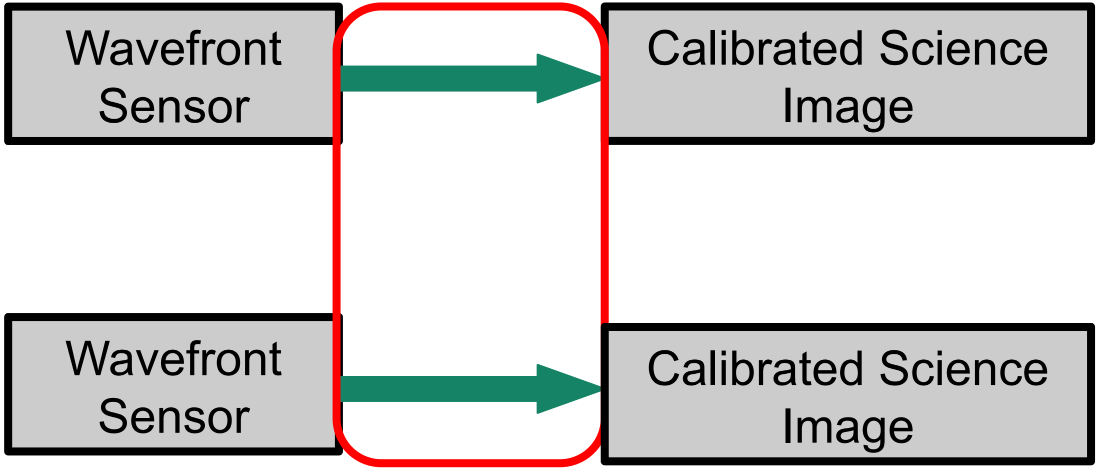
Credit: Barnaby Norris & Alison Wong

PSF Subtraction (RDI / ADI) relies on WF Stability -> TELESCOPE stability requirement



Are statistical properties of WF stable between observations ?

Self-Calibration relies on Stability of WFS→PSF Relationship -> INSTRUMENT internal optics stability requirement



Are optics between WFS and science image stable between observation ?

Ideal Hardware Configuration keeps relationship between WFS and PSF stable

relationship should be as stable as possible

This stability is key to achieving ~1000x gain by PSF calibration

Can we build integrated coronagraph + WFS systems such that WFS-PSF relationship is stable over time ? ... at the ~1e-12 contrast level

Options for WFS Integrated with Starlight Suppression

Low-Order Coronagraphic Wavefront Sensor / Zernike WFS

Bright starlight reflected/diffracted by focal plane occulter

Photonic Nulling Circuit

Optimized for simultaneous starlight suppression and wavefront sensing

Linear Dark Field Control (LDFC)

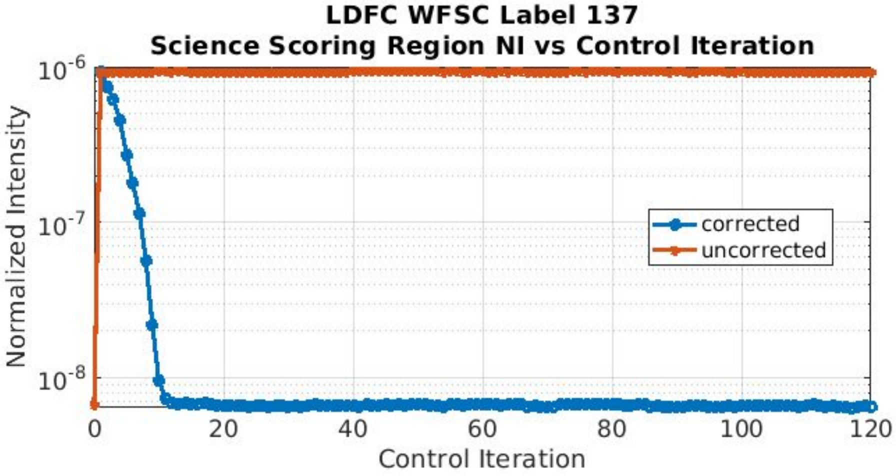
Post-coronagraph out-of-band (spatial or spectral) light used for WFS/C.

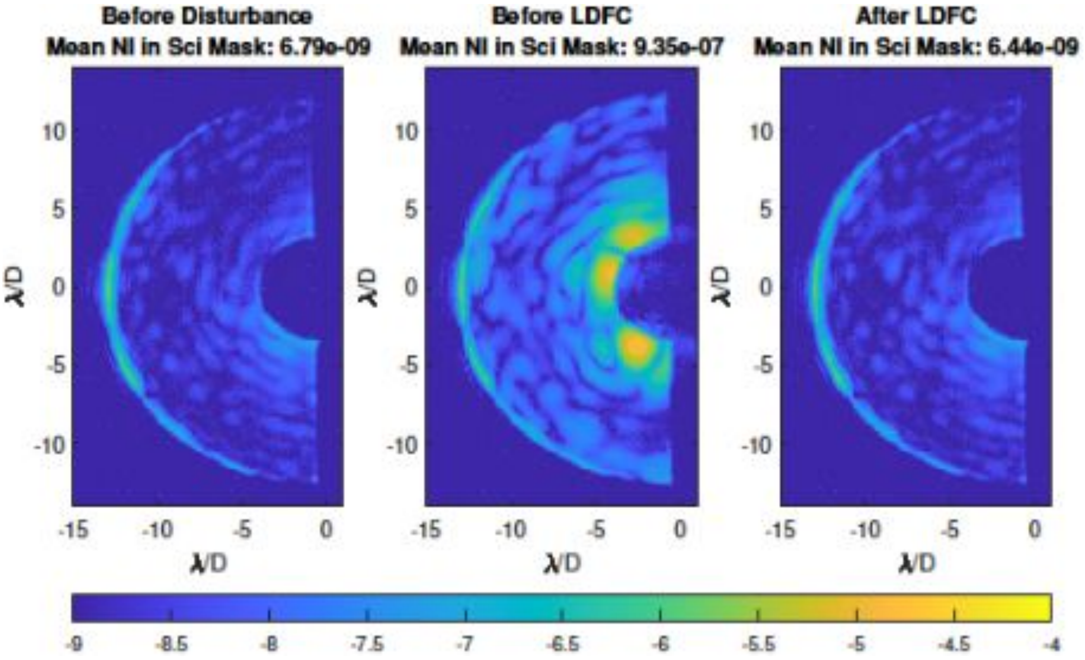
Wavefront control with spectral LDFC

(preliminary results from LDFC team)

Maintains <7e-9 contrast in the presence of 1e-6 dynamical WF aberrations

Raw contrast gain >100x demonstrated

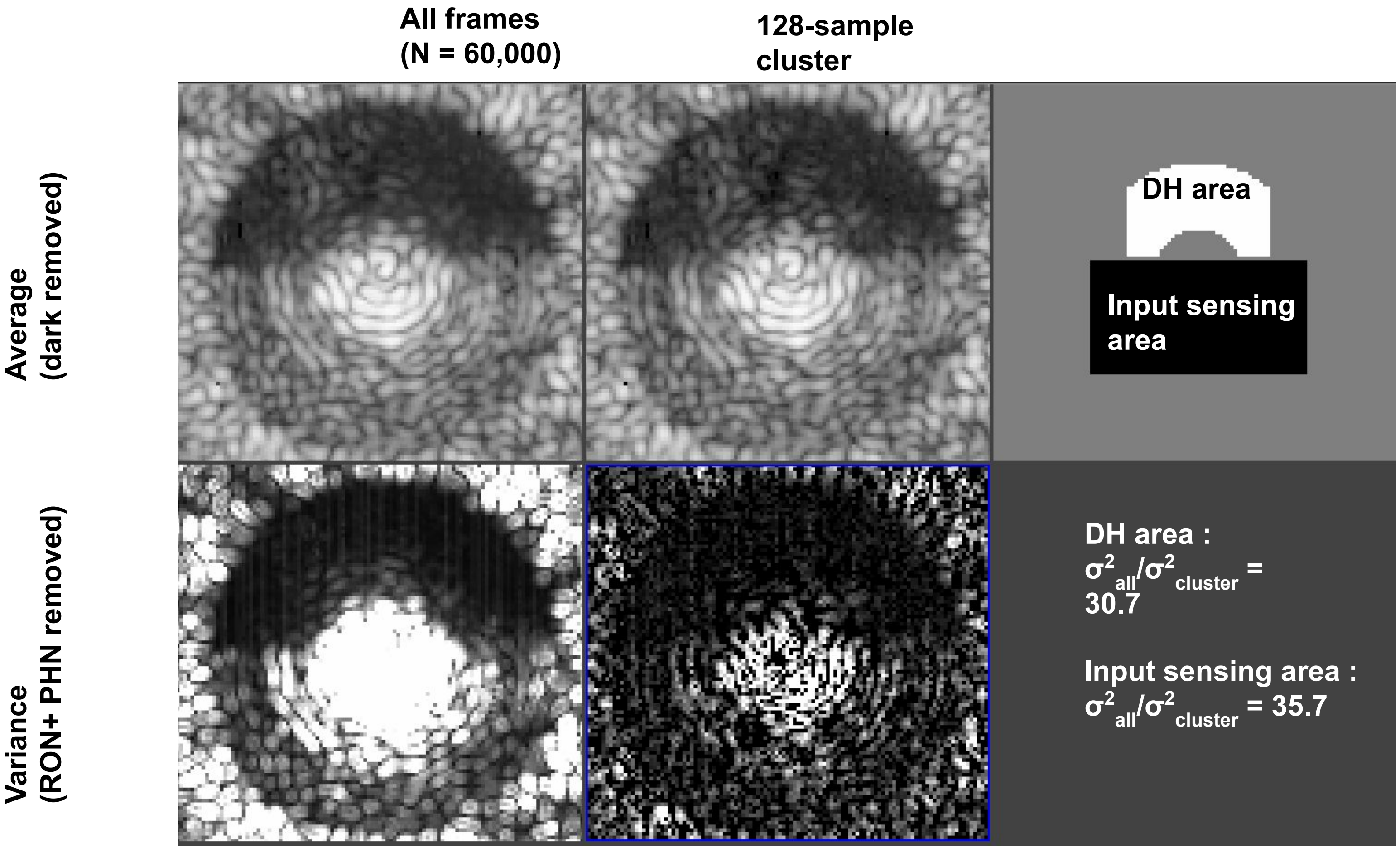

LDFC WFSC Label 137
Science Scoring Region NI vs Control Iteration


Before Disturbance
Mean NI in Sci Mask: 6.79e-09

Before LDFC
Mean NI in Sci Mask: 9.35e-07

After LDFC
Mean NI in Sci Mask: 6.44e-09

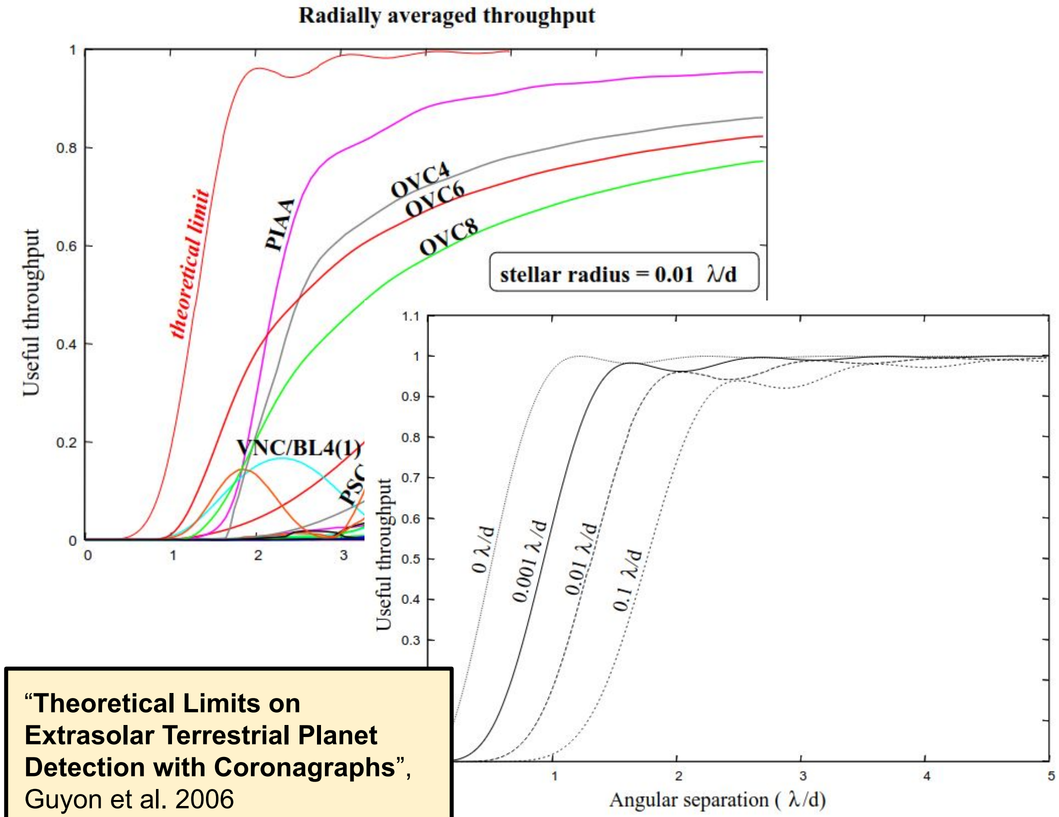
PSF calibration with spatial LDFC



DH area :
$\sigma^2_{all}/\sigma^2_{cluster}$ = 30.7

Input sensing area :
$\sigma^2_{all}/\sigma^2_{cluster}$ = 35.7

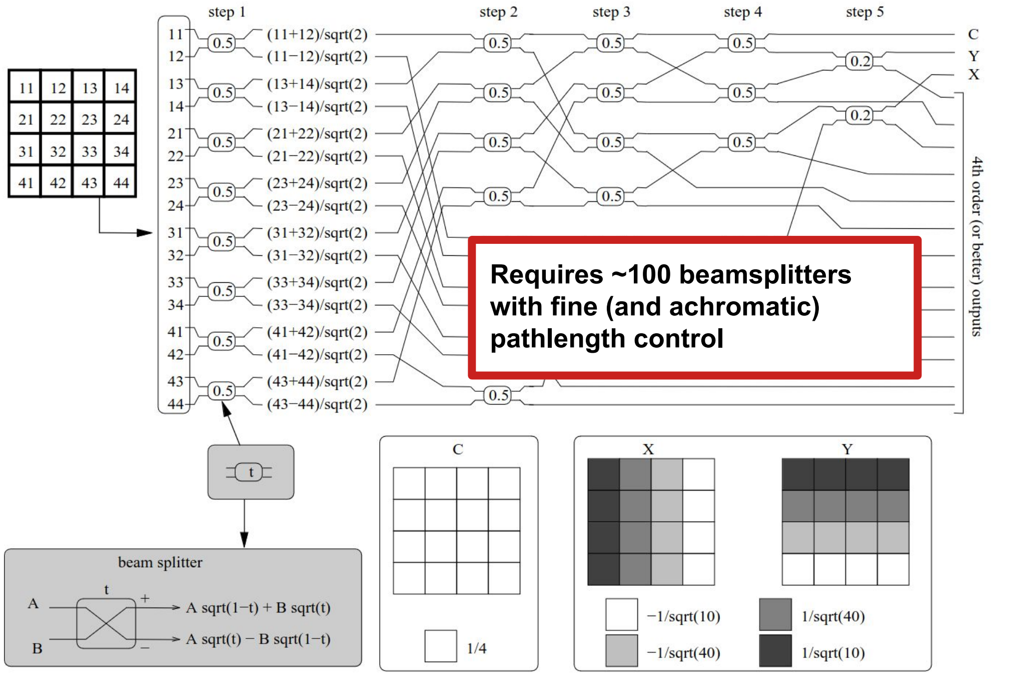
Optimal coronagraph conceptualized but then (2006) deemed impossible to realize



.— Upper limit on the off-axis throughput
oronagraph for different stellar radii.

“Theoretical Limits on Extrasolar Terrestrial Planet Detection with Coronagraphs”, Guyon et al. 2006

See also recent Belikov et. al work

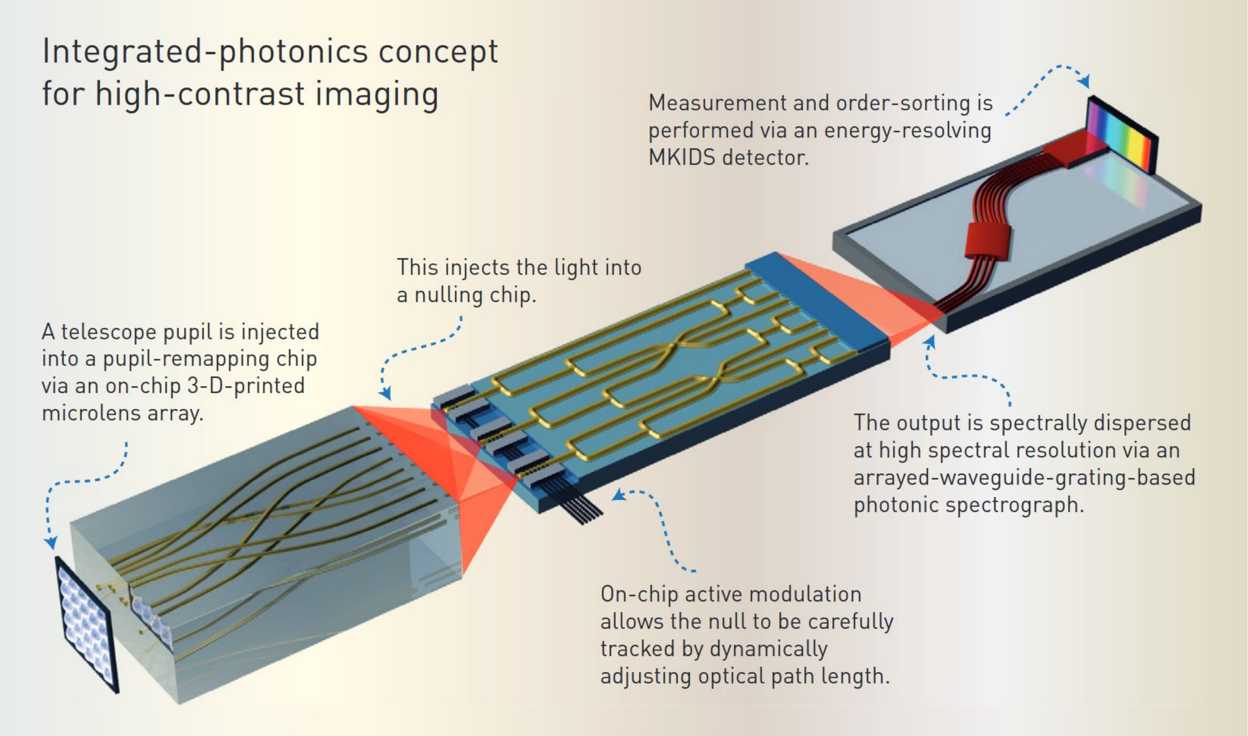


Requires ~100 beamsplitters with fine (and achromatic) pathlength control

Fig. 10.— Example of a beam splitter-based coronagraphs with $c_0 = c_1 = c_2 = 0$ (perfect rejection of the first 3 vectors M_i) designed for a square aperture. The telescope pupil (top left) is decomposed in a series of individual subpupils (shown in the input vector on the right of the pupil) which undergo interferometric combinations through beam splitters. The coronagraph outputs isolates the first 3 modes found in an extended source, as shown in the bottom right: C $(= M_0)$, X $(= M_1)$ and Y $(= M_2)$. This coronagraph produces a 4^{th} order null and therefore provides some immunity to stellar angular size. The same technique can be generalized to circular pupil and better sensitivity to stellar angular size (more vectors M_i isolated).

Can now be realized with high-throughput photonic device integrating WFS and Starlight Suppression

"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/



Integrated-photonics concept for high-contrast imaging

Measurement and order-sorting is performed via an energy-resolving MKIDS detector.

This injects the light into a nulling chip.

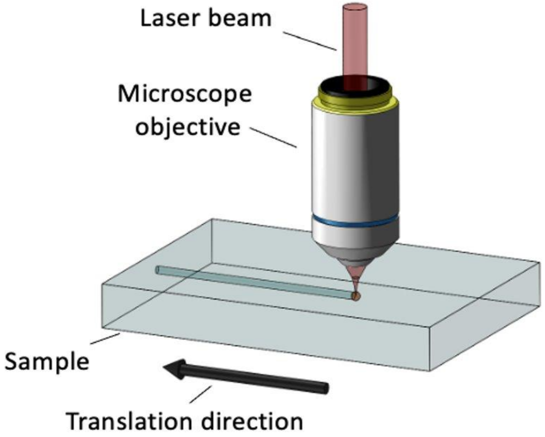
A telescope pupil is injected into a pupil-remapping chip via an on-chip 3-D-printed microlens array.

The output is spectrally dispersed at high spectral resolution via an arrayed-waveguide-grating-based photonic spectrograph.

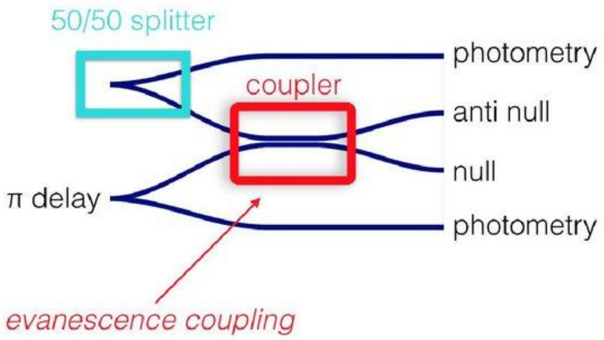
On-chip active modulation allows the null to be carefully tracked by dynamically adjusting optical path length.

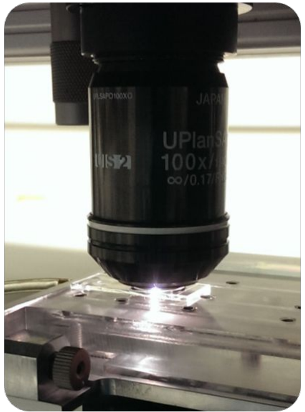
Illustration by Phil Saunders

Ultrafast Laser Inscription (ULI) allows for 3D photonic devices with high broadband throughout in borosilicate glass

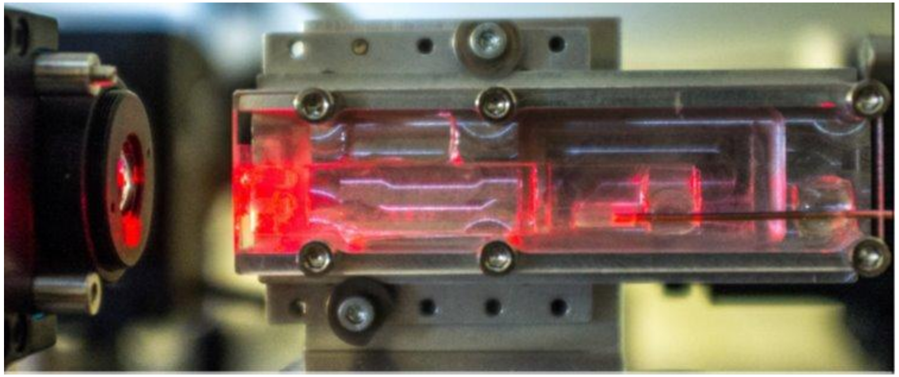


Simon Gross, Glen Douglass, Teresa Klinner-Teo, Elizabeth Arcadi, Michael J. Withford, Barnaby Norris, Peter Tuthill, Marc-Antoine Martinod, Eckhart Spalding

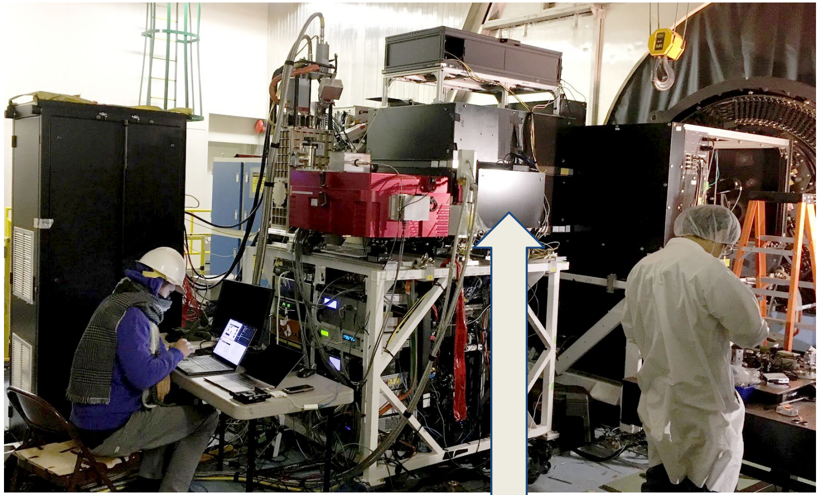


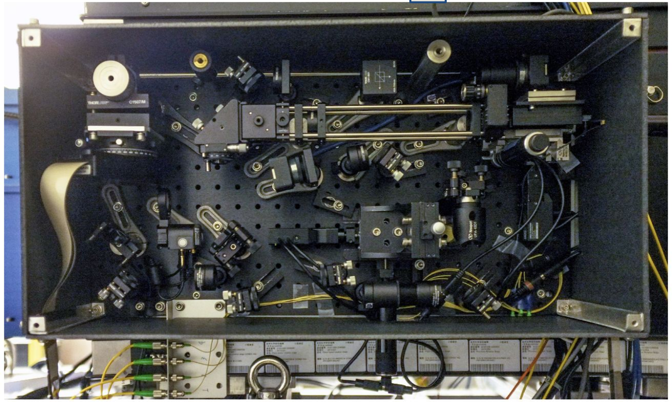


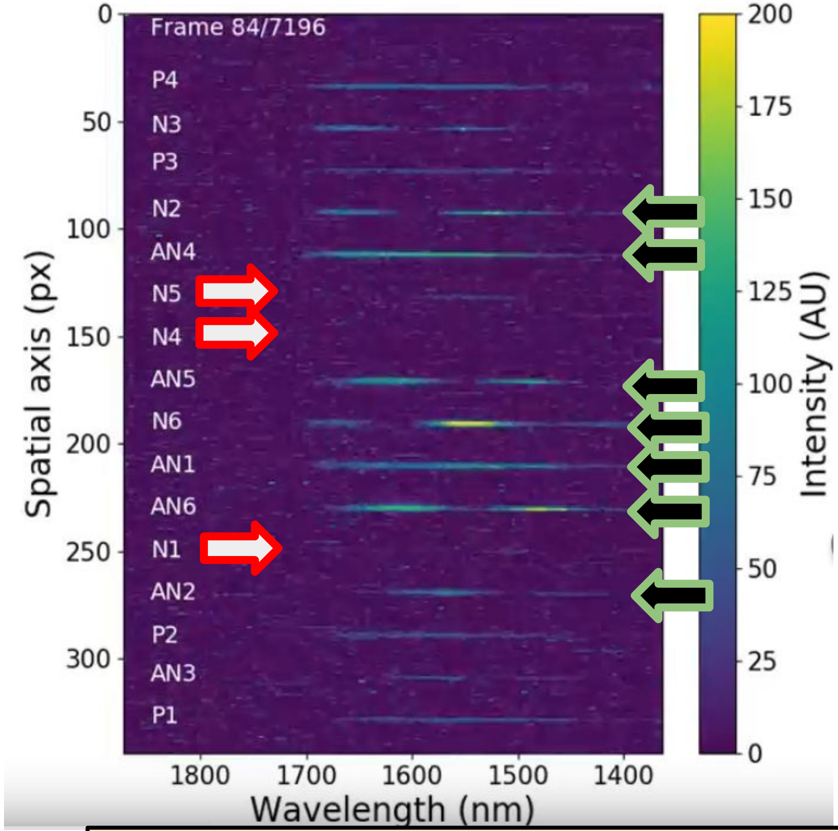
Partnership with ULI group at Macquarie University to realize high-contrast photonic devices



Guided Light Interferometric Nulling Technology (GLINT) instrument @ Subaru/SCExAO







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

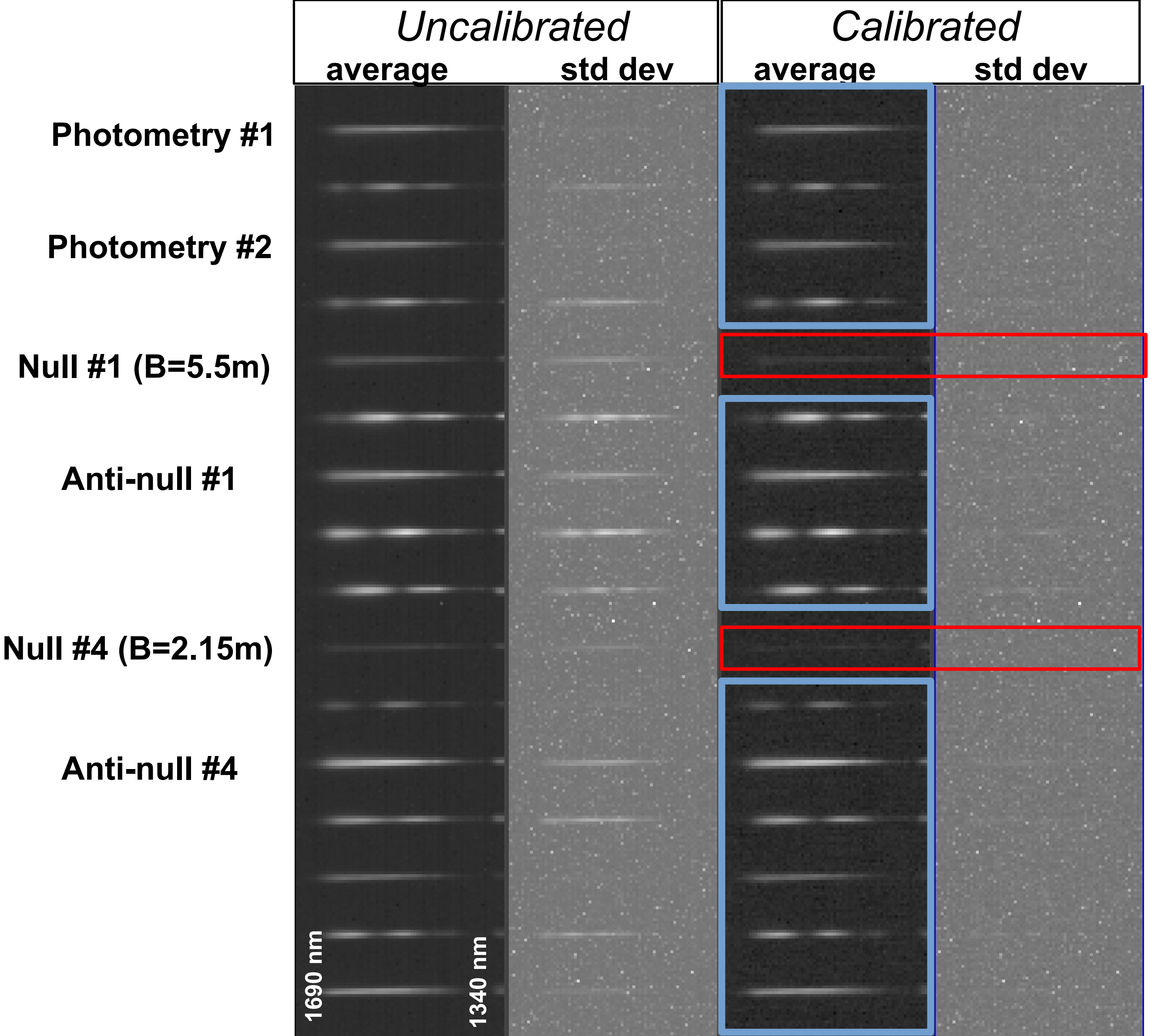
"Scalable photonic-based nulling interferometry with the dispersed multi-baseline GLINT instrument"

Martinod, Norris, Tuthill...Guyon et al.

Nature Communications (2021)

link: https://www.nature.com/articles/s41467-021-22769-x

On-sky demonstration of self-calibrating photonic chip reaches photon + readout noise limit



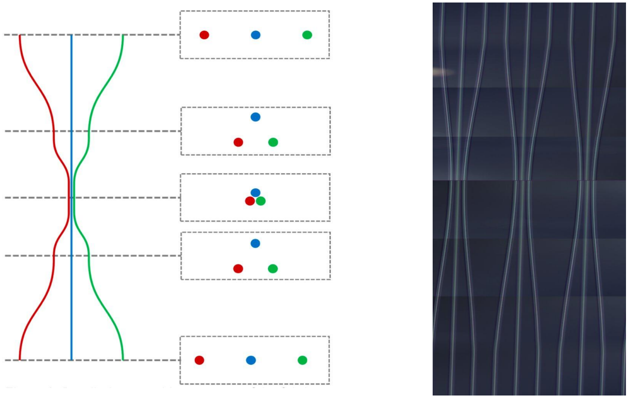
GLINT – on-sky
Alpha Boo

1.4 kHz frame rate

Deeper Broadband Contrast and WFS-optimized Chips: Tricouplers and Phase Shifters

Tricoupler

3D beam combiner with perfect 120deg symmetry
2 input illuminated -> 3 output
PI-phase shift between 2 input beams yields one output null + 2 balanced WFS output

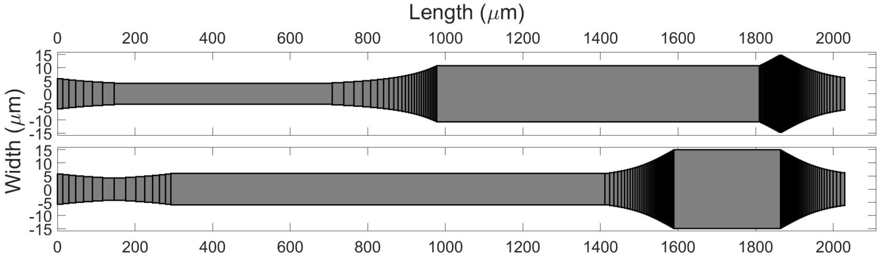


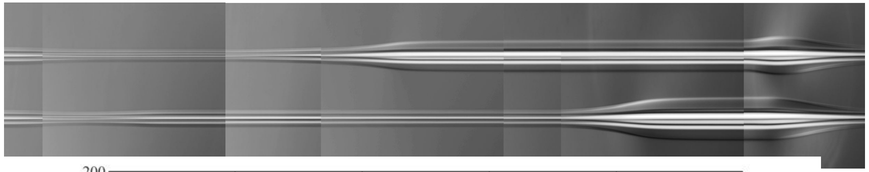
Tricoupler Device	Null Depth
Gen1	2.2×10^{-4}
Gen2	1.0×10^{-5}
Gen3 Block 1	1.7×10^{-6}
Gen3 Block 3	1.0×10^{-4}

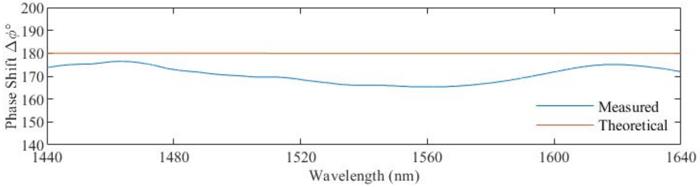
Current tricoupler performance at 1550nm, expressed in null depth
Credit: Elizabeth Arcadi, Macquarie Univ.

Phase Shifter

Fine control of chromatic phase for broadband null







Current nearIR phase shifter achieves 1e-3 broadband null. Improvement to 1e-4 underway. This is *before WFC.*
Credit: Glenn Douglas, Macquarie Univ.

Conclusions

Self-calibrating high contrast imaging systems could eliminate speckle noise
→ Deeper detection limits, limited by photon noise in science images
→ Coronagraph and telescope designed to relaxed contrast requirements, smaller IWA
→ 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 well-suited for achieving self-calibration for high-performance coronagraphy :
- Small number of degrees of freedom
- Can be spectrally dispersed