Starlight Suppression
(internal coronagraphs)

Emerging Technologies and their Potential

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Wish List & Science Drivers

Deeper Contrast (raw and calibrated)
Higher throughput
- → Higher exoplanet SNR images and spectra, access to lower mass planets

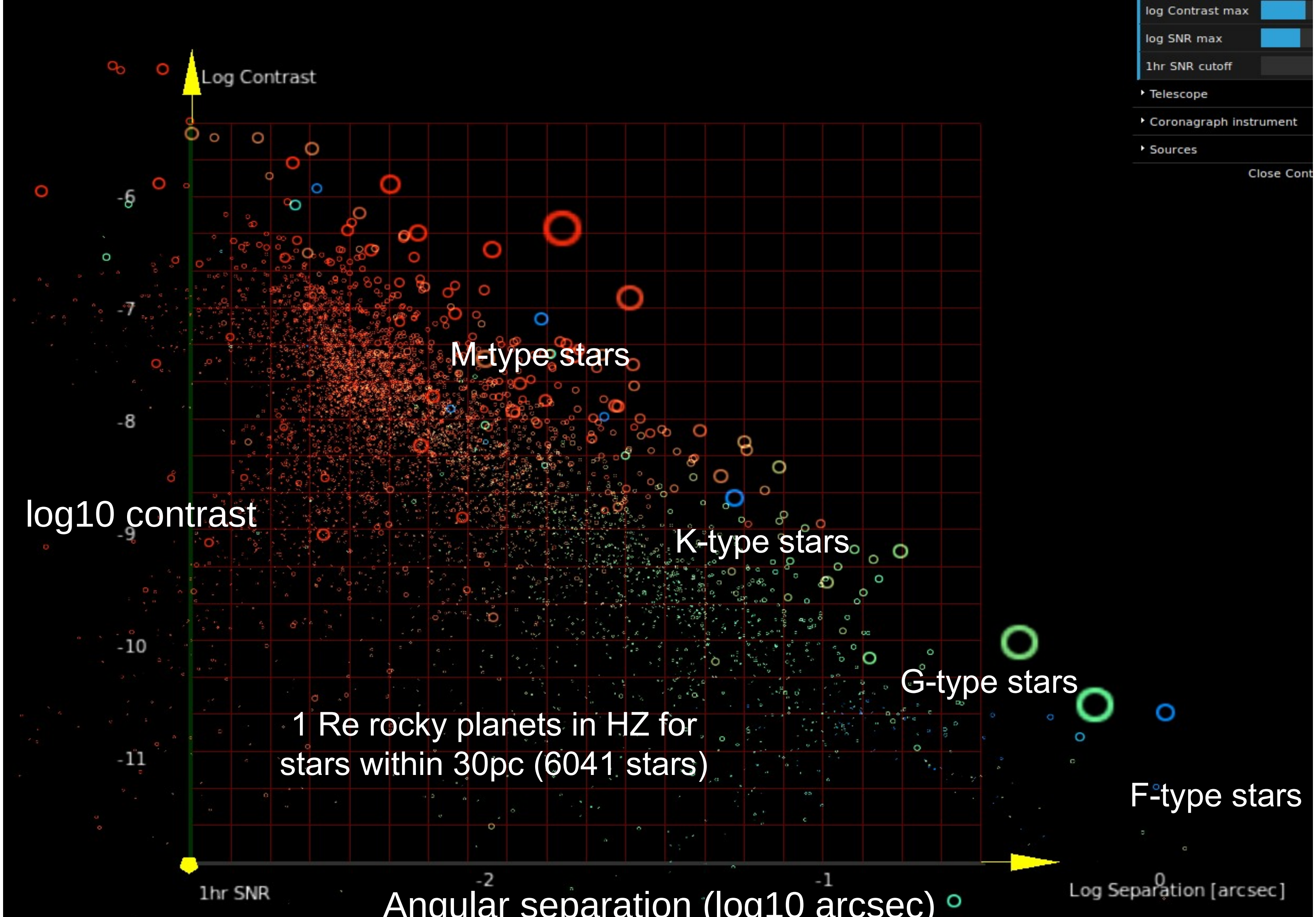
Smaller IWA
- → Larger number of planets
- → Extend spectroscopy to NIR
- → Access planet around K (&M ?) type stars

Larger OWA
- → Some of the best targets will be planets at large angular separation

Wider spectral range (ideally simultaneously)
- → NUV highly sensitive to atmospheres
- → NIR rich in molecular species

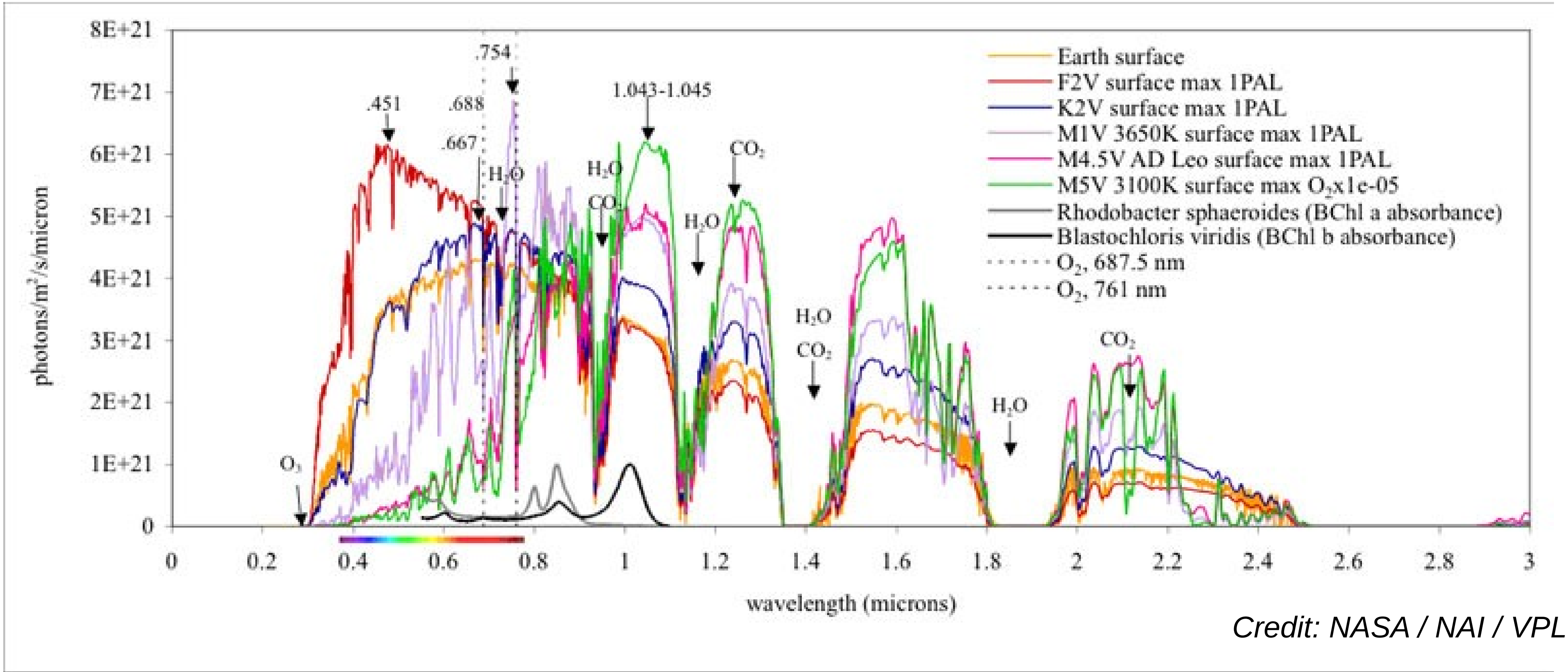
High spectral resolution spectroscopy
- → X-correlation with templates for higher detection sensitivity
- → Velocity resolution: measure instantaneous orbital speed, planet rotation

Spectro-astrometry (of planet)
- → Orbital motion, moons


log Contrast max
log SNR max
1hr SNR cutoff
Telescope
Coronagraph instrument
Sources
Close Cont
Log Contrast
-6
-7
-8
-9
-10
-11
1hr SNR
-2
-1
0
Log Separation [arcsec]
M-type stars
K-type stars
G-type stars
F-type stars
log10 contrast
1 Re rocky planets in HZ for
stars within 30pc (6041 stars)
Angular separation (log10 arcsec)

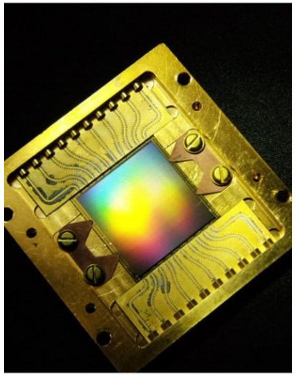
Wavefront Control

Coronagraph IWA

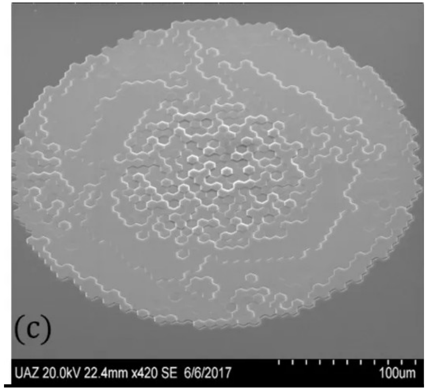


Credit: NASA / NAI / VPL

Key Enabling Technologies



Photon-counting Detectors



Optical Manufacturing

CCDs & EMCCDs

qCMOS

HgCdTe avalanche photodiode array detectors

Superconducting nanowire single-photon detector

MKIDS

Large telescope optics

Coronagraph masks

Deformable mirrors

Microlenses, optical fibers

Wavefront Control Algorithms

Predictive Control, Sensor Fusion

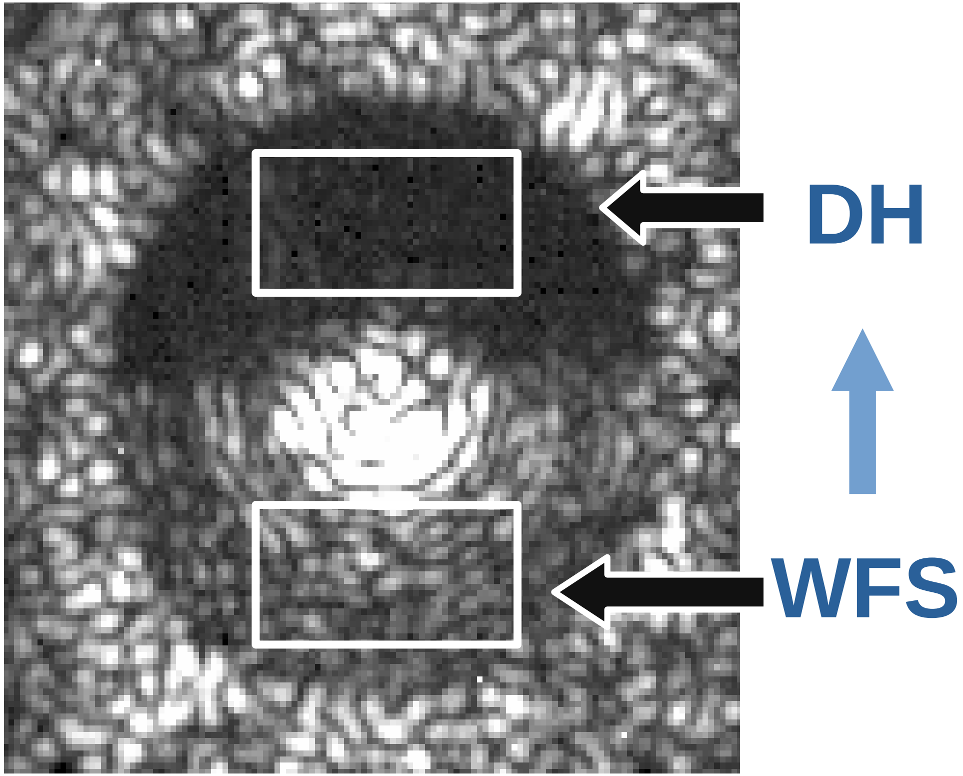
→ Improve WFS sensitivity

→ Improve WFS reliability/completeness

Continuous WFS/C without DM probing

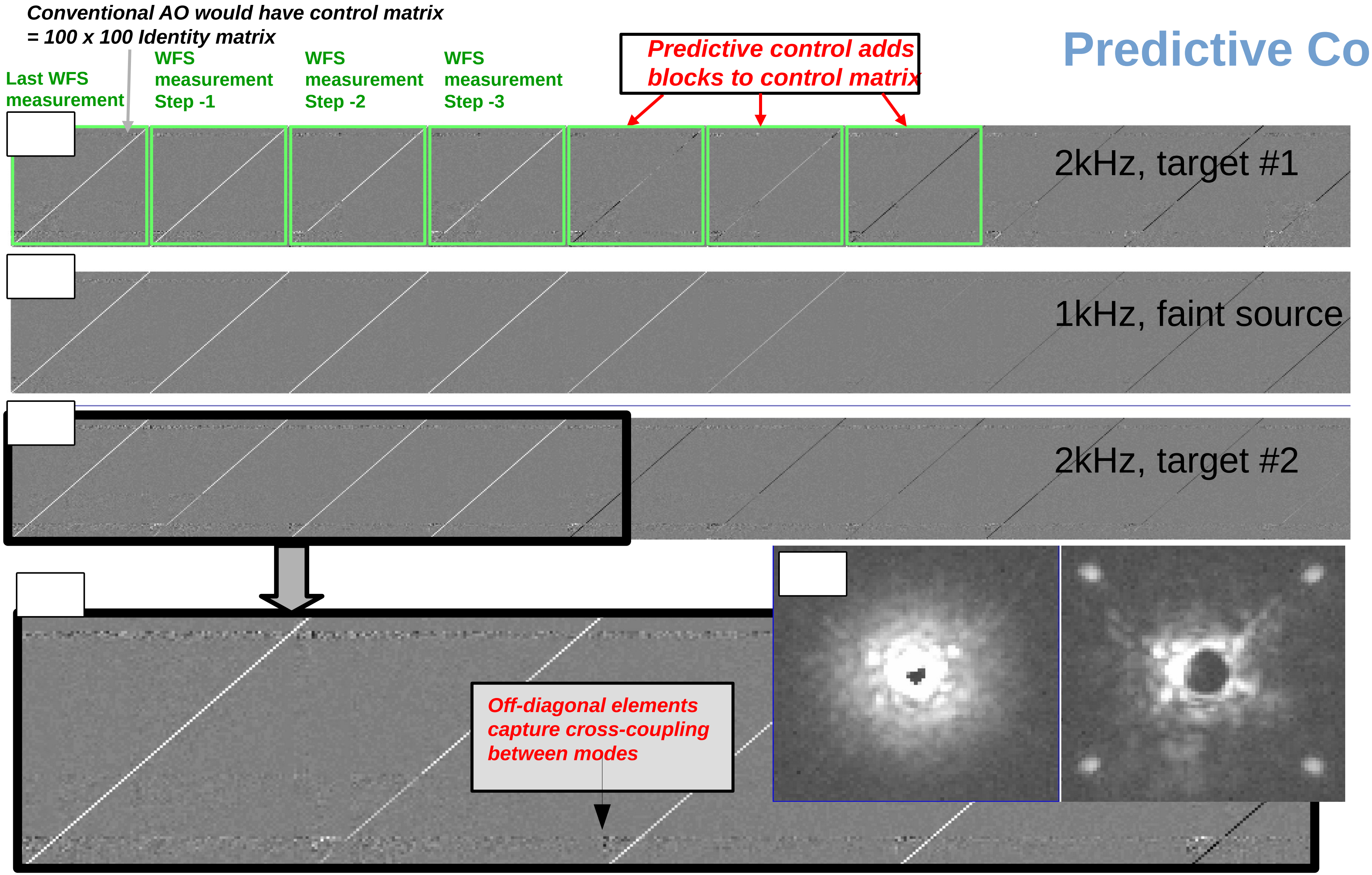
→ Full duty cycle

→ Self-calibration

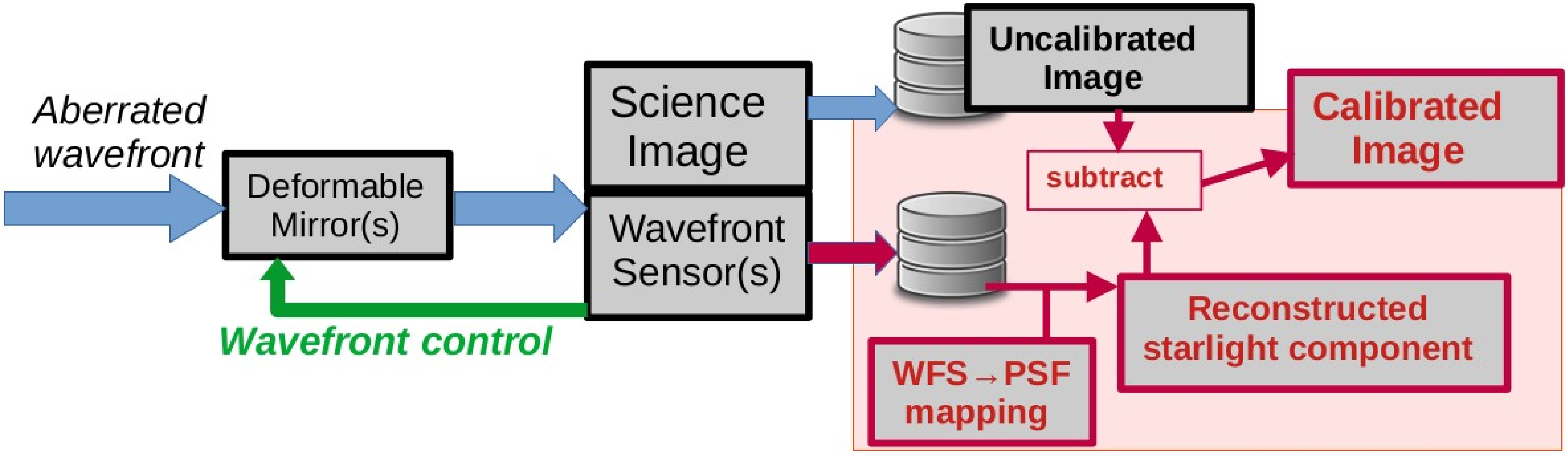


Linear Dark Field Control

Predictive Control



Self-Calibration

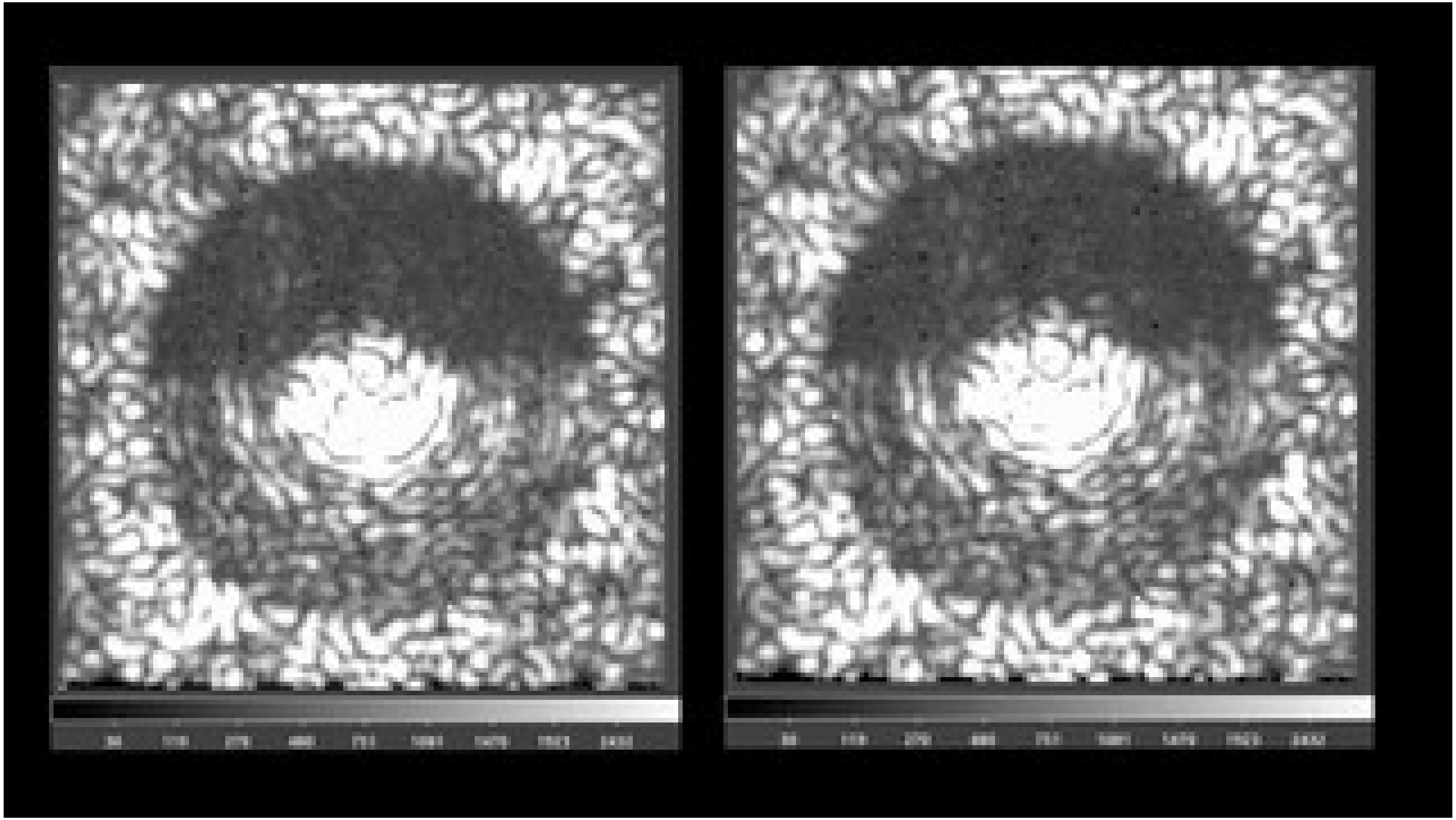


Challenges: Relationship between WFS and DH needs to be very stable.
… maybe a device realizing both functions could be built ?

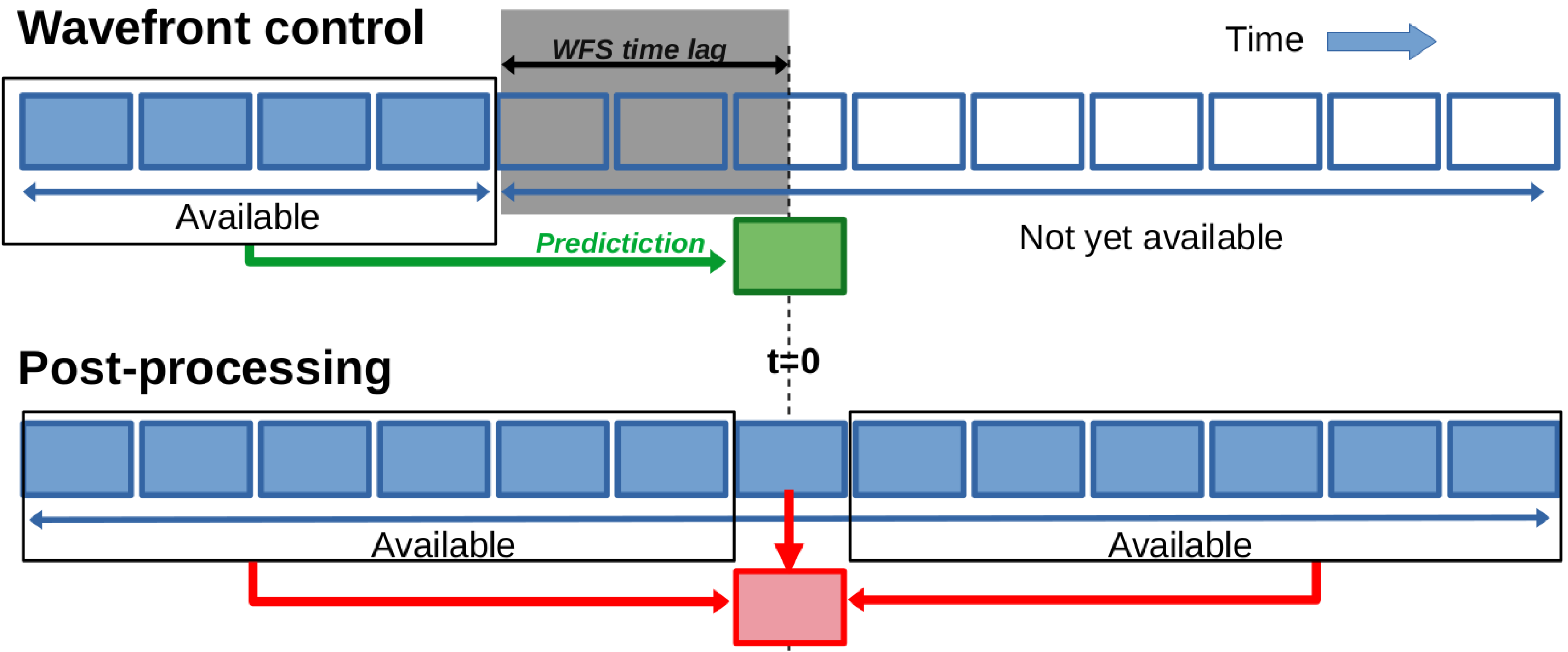
Early demonstration: 5.5x contrast gain

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

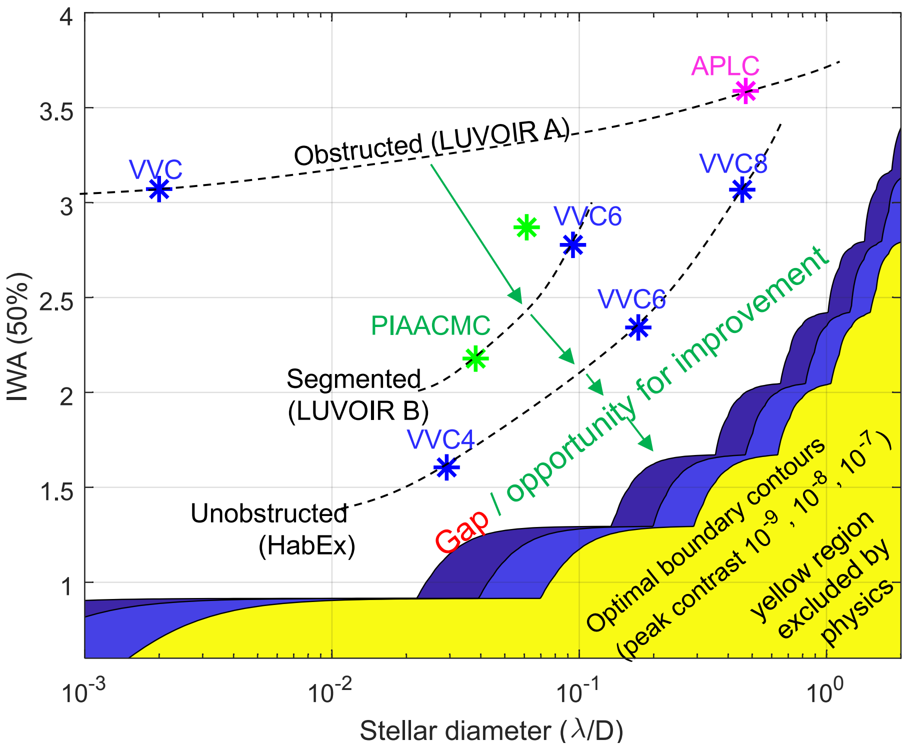
UNCALIBRATED **CALIBRATED**



Why is Post-processing calibration <u>fundamentally</u> superior to active control ?



Coronagraphy at its fundamental limits



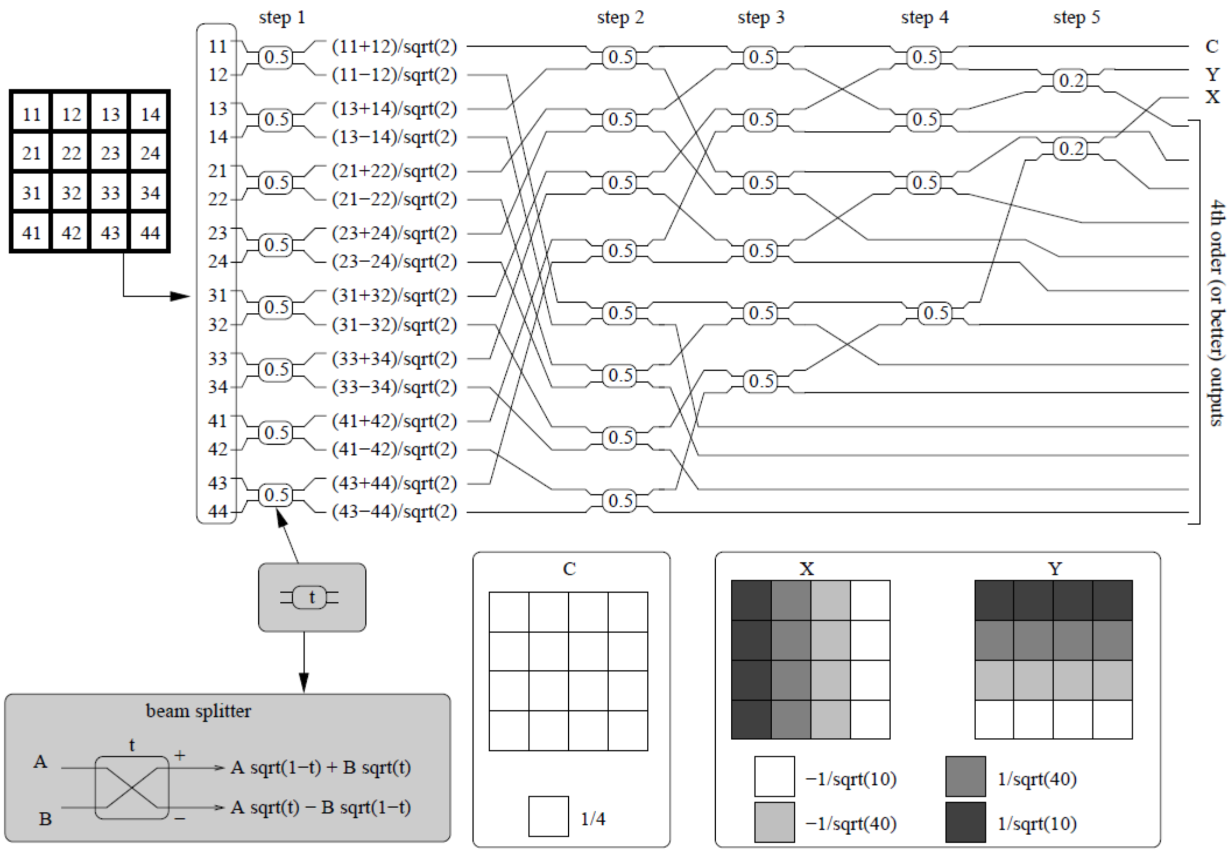
Belikov et al. 2021

Current coronagraph options deliver IWA that is ~ 2x to 3x larger than the fundamental limit.

Gap is largest for centrally obscured apertures.

2.5x factor in IWA means ...
~16x in volume (accessible targets)
2.5x in red-edge wavelength limit
Access to planets around cooler stars

Can this be built ?



Guyon et al. 2006

Photonic Nulling

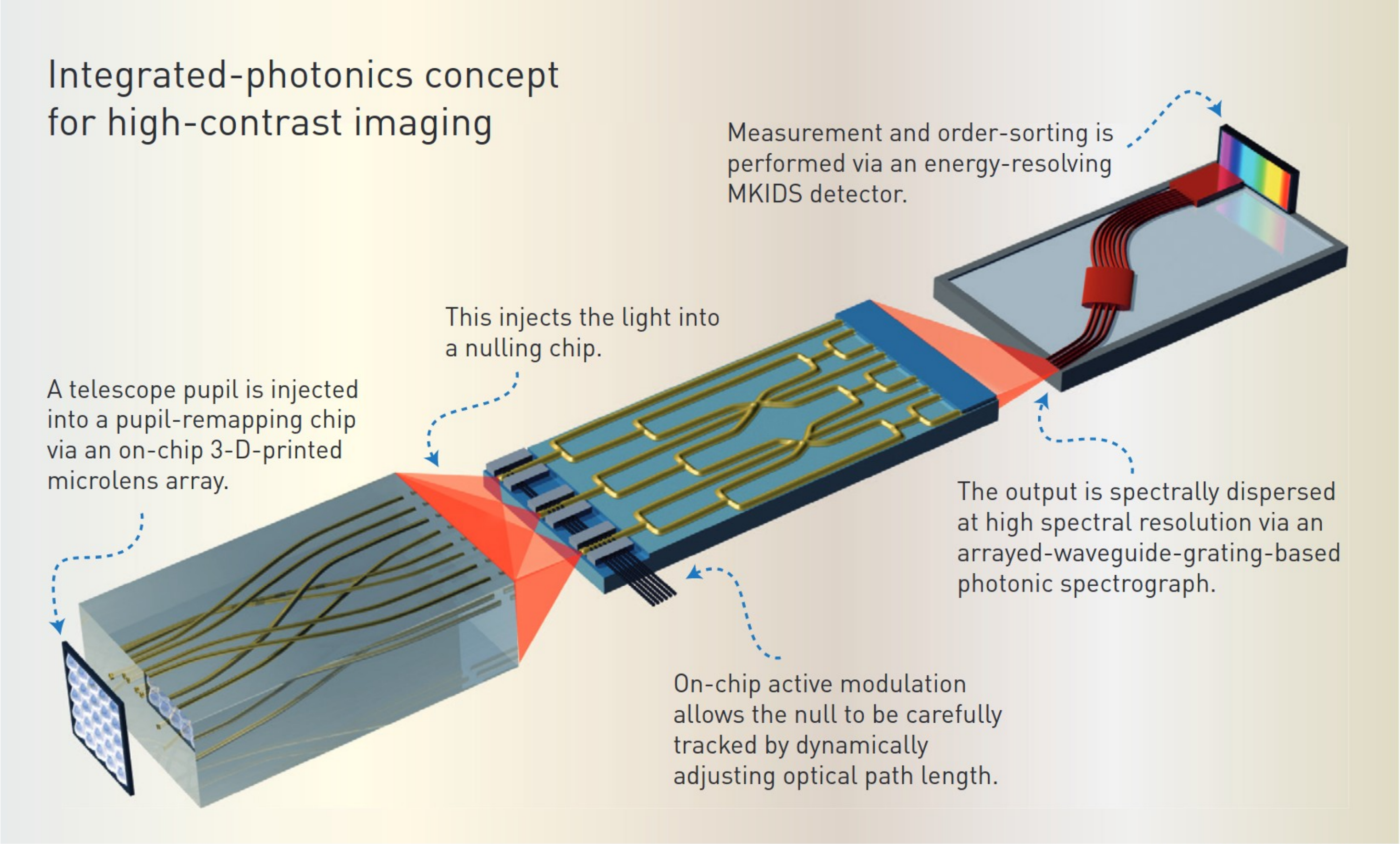


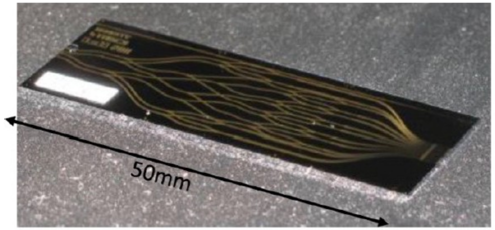
Illustration by Phil Saunders

Key advantages:

Access to very small separation (better than coronagraphy)

High sensitivity wavefront sensing integrated within chip

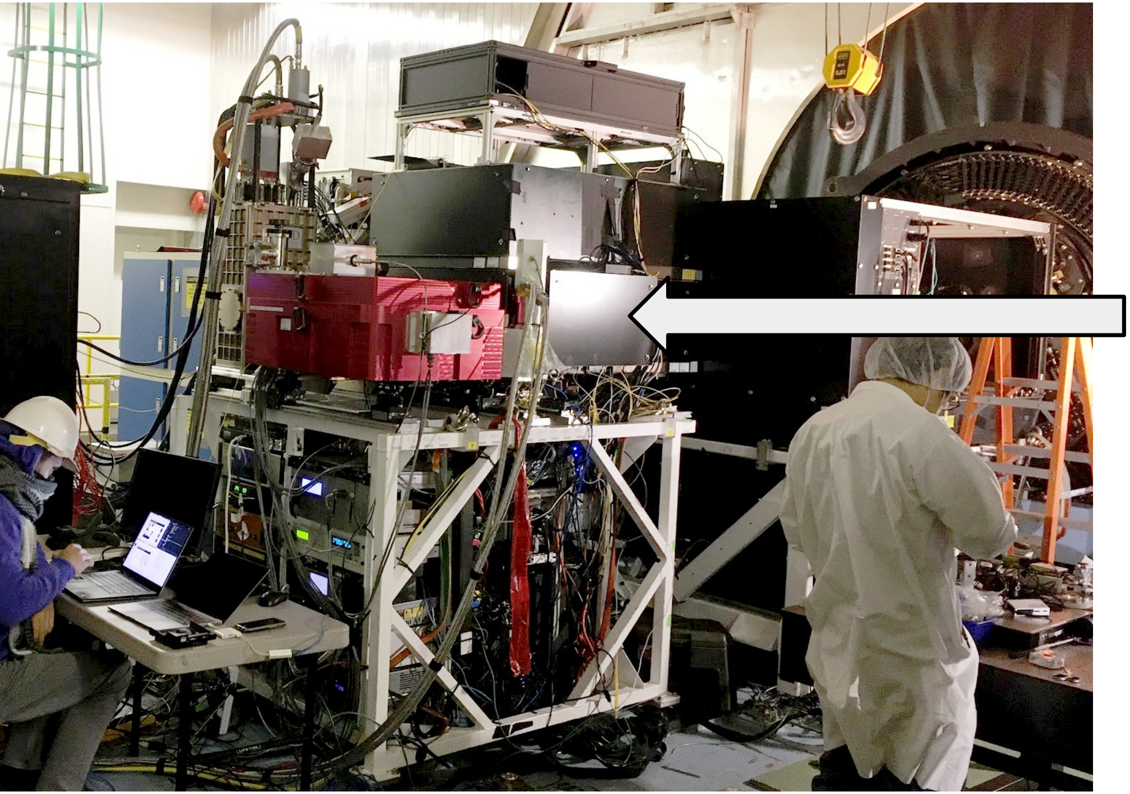
Spectroscopy at output

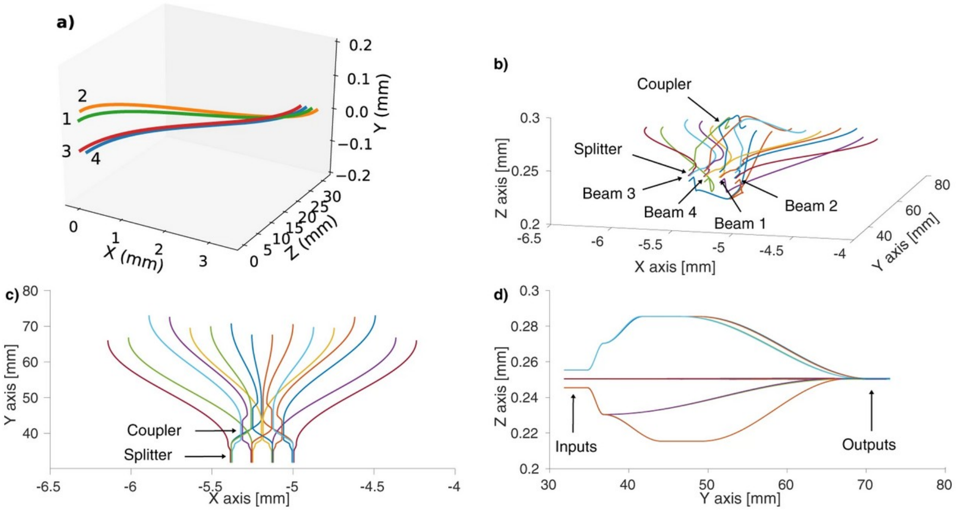


GRAVITY photonic beam combiner (Perraut et al. 2018)

"**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/

GLINT photonic nuller testbed

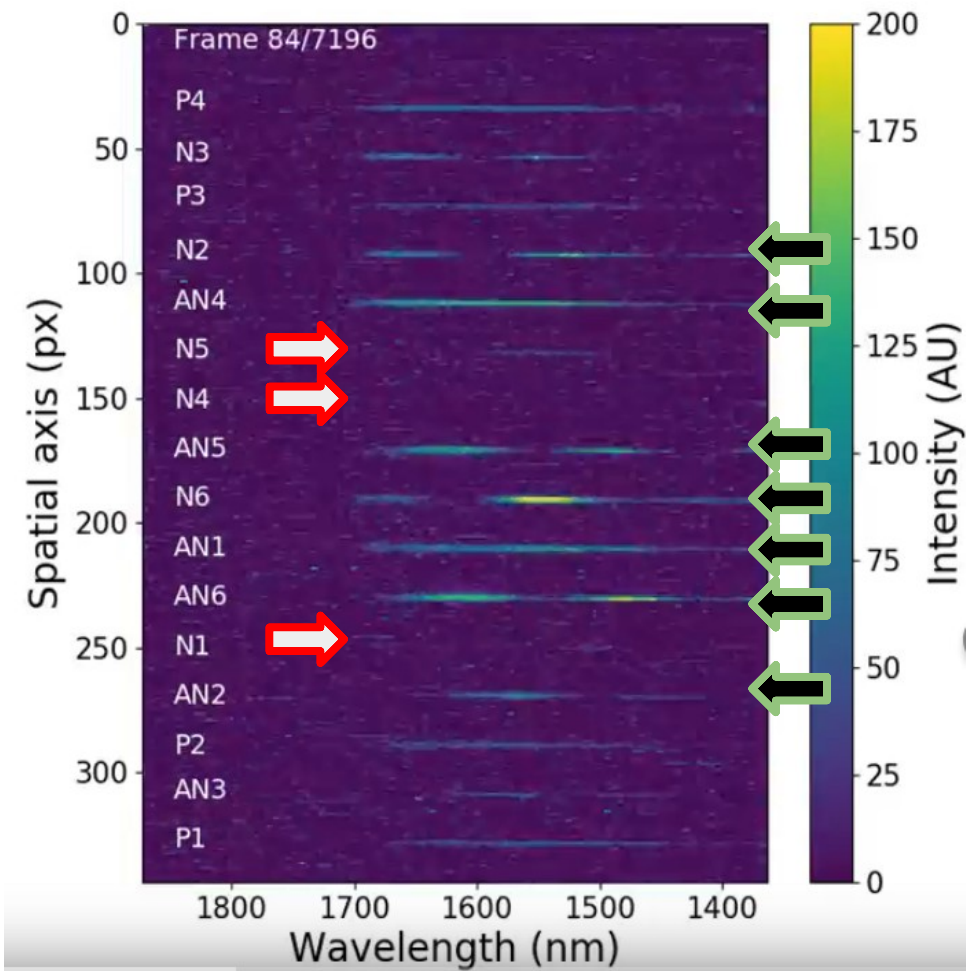




a Schematics of the pupil remapper of the chip, coherently transforming the 2D configuration of the inputs (on the left) matching the desired pupil sampling pattern into a 1D configuration (on the right). The waveguide paths have been optimised to match their optical path lengths despite their different routes. The green waveguide is associated with beam 1, orange with beam 2, red with beam 3 and blue with beam 4. **b** Perspective view of the beam combiner of the chip. **c** Plan view in which light propagates from the 4 inputs at the bottom towards the top, encountering 4-way splitters and codirectional couplers. **d** Right-side view of the chip showing the locations of the inputs and the outputs. The inputs, outputs, splitters and couplers are indicated on the (**b**–**d**) diagrams. The axis scale proportions in all the schematics differ for clarity in the drawing.

"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

Photonic nuller raw data



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

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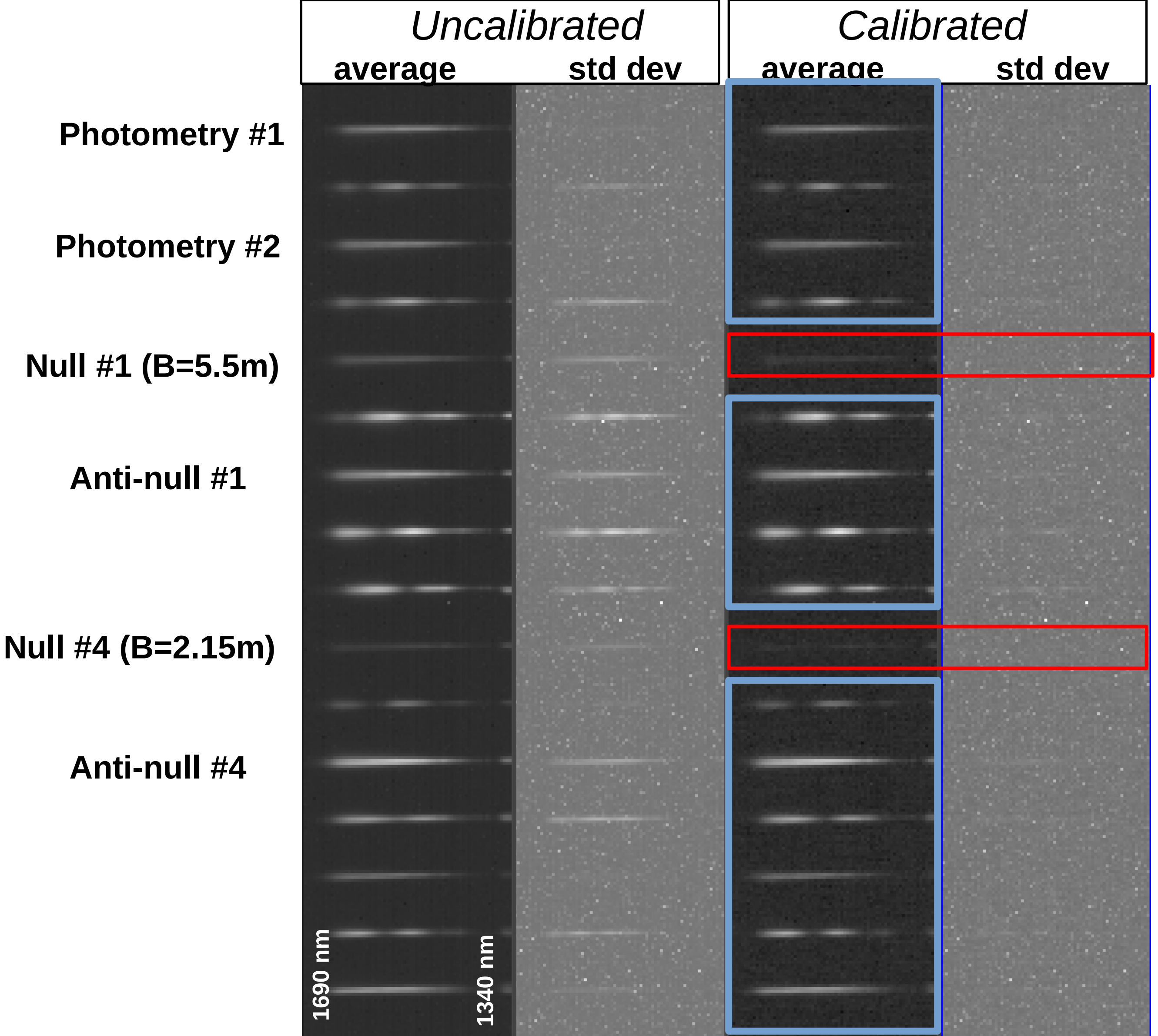
Photonic nuller self-calibration



GLINT – on-sky
Alpha Boo

1.4 kHz frame rate

CONCLUSIONS

- **~2x gain in IWA may be possible by coronagraph design**
- **Advances in WFS/C can increase contrast, efficiency, and sensitivity to WF aberrations**
- **Self-calibration of science data from WFS telemetry can remove speckle noise**

An integrated-on-a-chip photonic nulling instrument could simultaneously provide these benefits.

Photonic nulling approach is well-suited for small angular separations, but does not scale well with fied of view.

→ Optimal coronagraph approach is target-dependent