Adaptive Optics for High contrast imaging

"Extreme-AO"

Olivier Guyon (oliv.guyon@gmail.com)

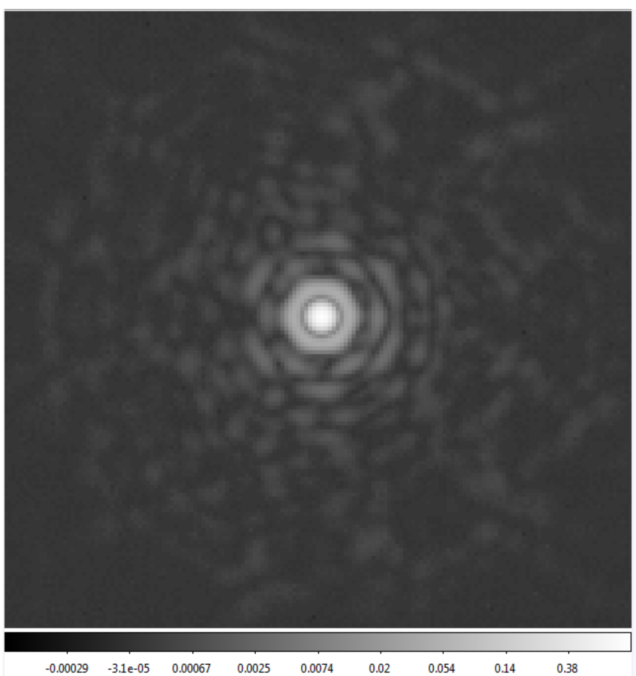
Center for Astronomical Adaptive Optics, University of Arizona (USA)
Subaru Telescope, National Astronomical Observatory of Japan, National Institute for Natural Sciences
Astrobiology Center, National Institute for Natural Sciences

High contrast AO example
Coronagraphs can now be built to deliver >1e8 contrast

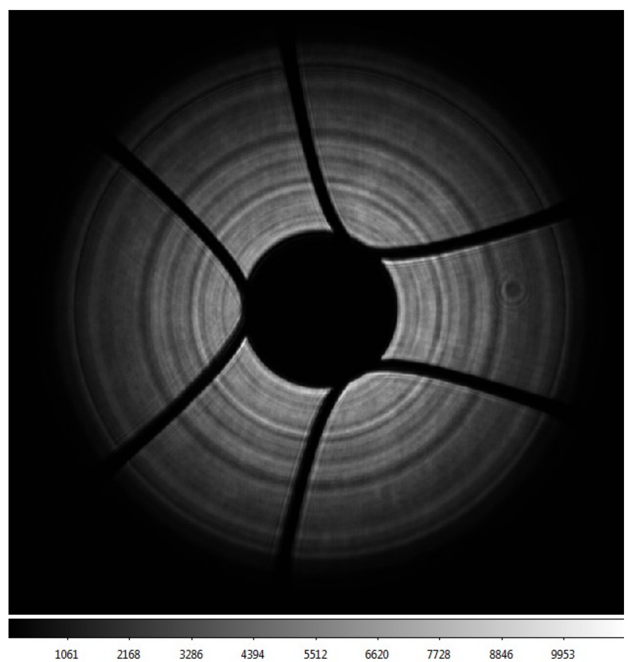
PIAACMC lab performance @ WFIRST pupil (Kern et al. 2016)

Operates at 1e-8 to 1e-7 contrast, 1.3 l/D IWA
Visible light

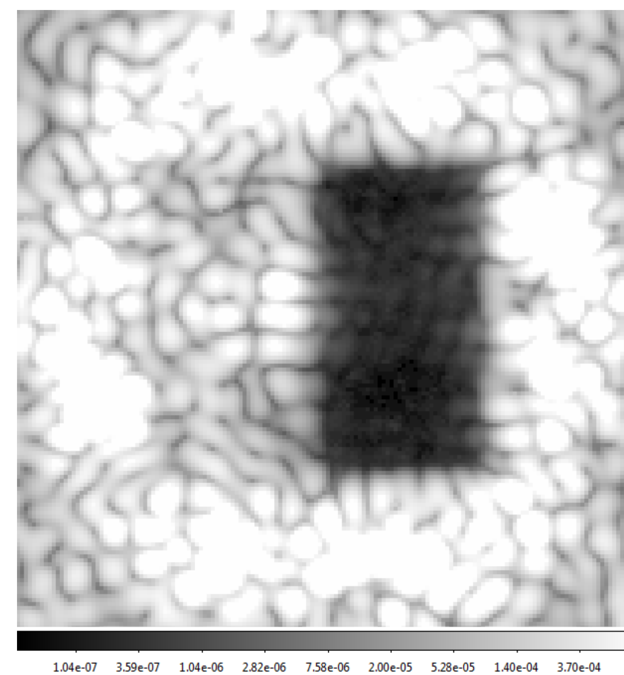
non-coronagraphic PSF



Remapped pupil

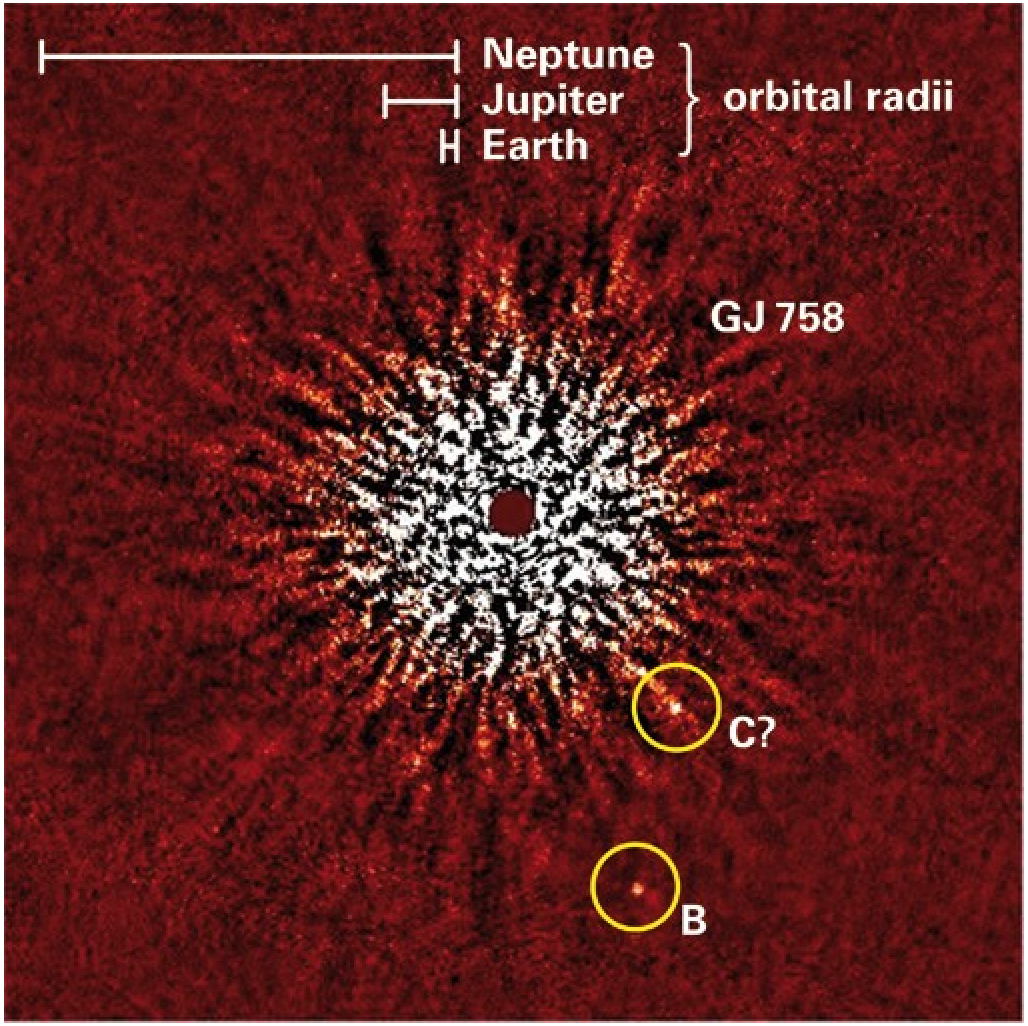


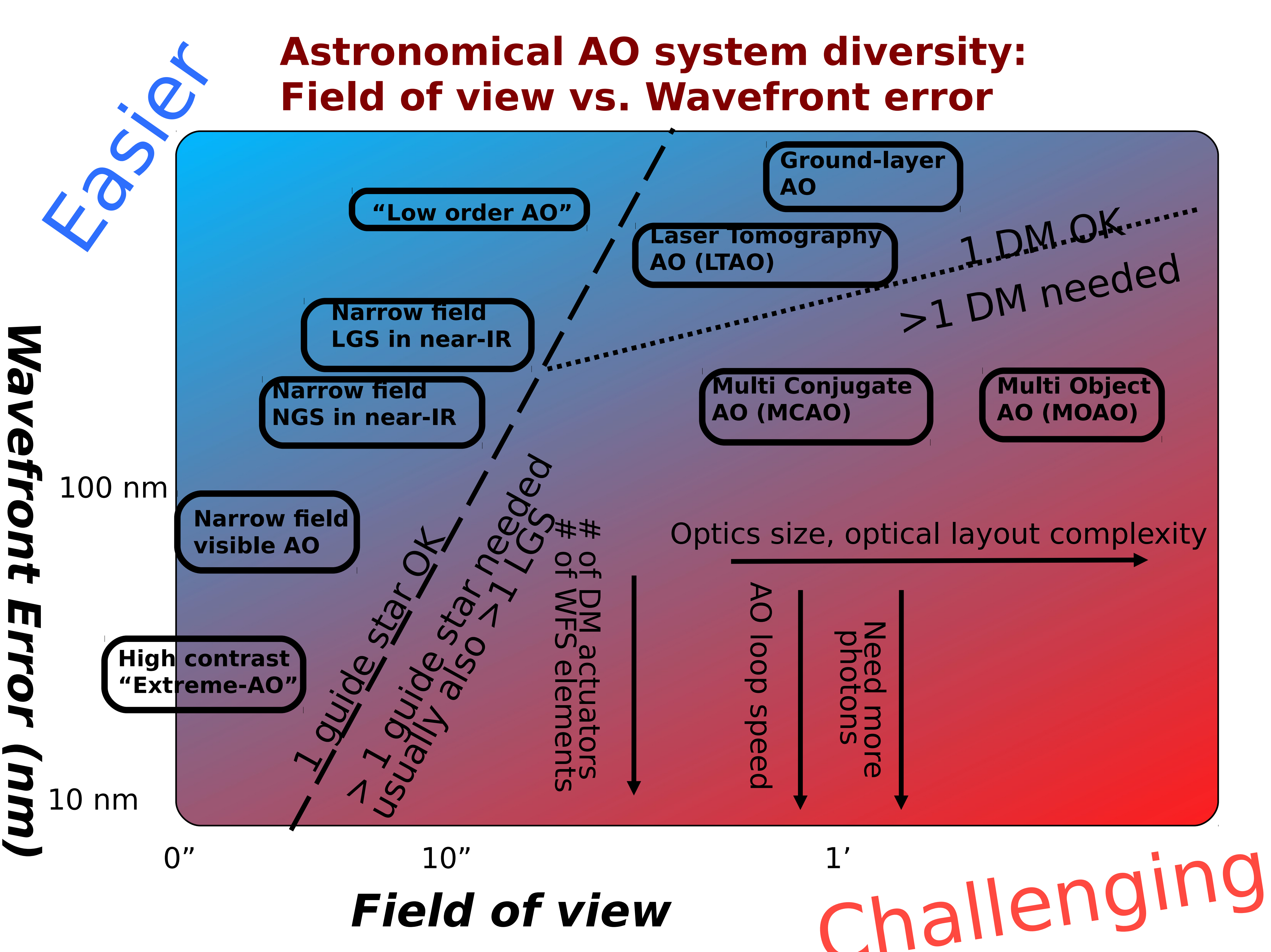
Coronagraphic image



The REAL challenge: Wavefront error (speckles)

What is a speckle ? What is a planet ?

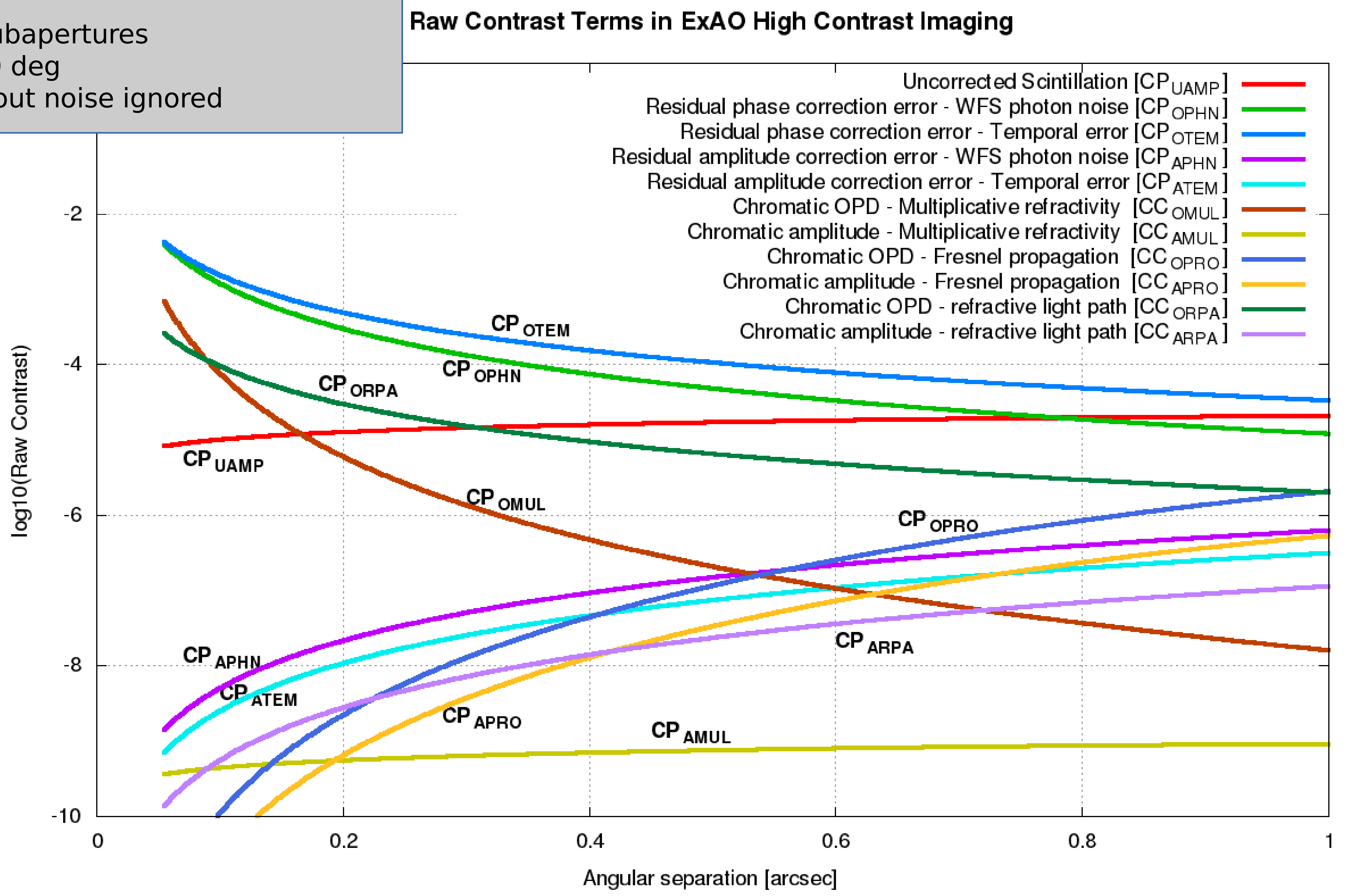




Astronomical AO system diversity:
Field of view vs. Wavefront error
Easier
Challenging
Ground-layer AO
"Low order AO"
Laser Tomography AO (LTAO)
1 DM OK
>1 DM needed
Narrow field LGS in near-IR
Narrow field NGS in near-IR
Multi Conjugate AO (MCAO)
Multi Object AO (MOAO)
100 nm
Narrow field visible AO
Optics size, optical layout complexity
1 guide star OK
> 1 guide star needed usually also >1 LGS
of DM actuators of WFS elements
AO loop speed
Need more photons
High contrast "Extreme-AO"
10 nm
Wavefront Error (nm)
0"
10"
1'
Field of view

Contrast Error Budget (Primary WFC)

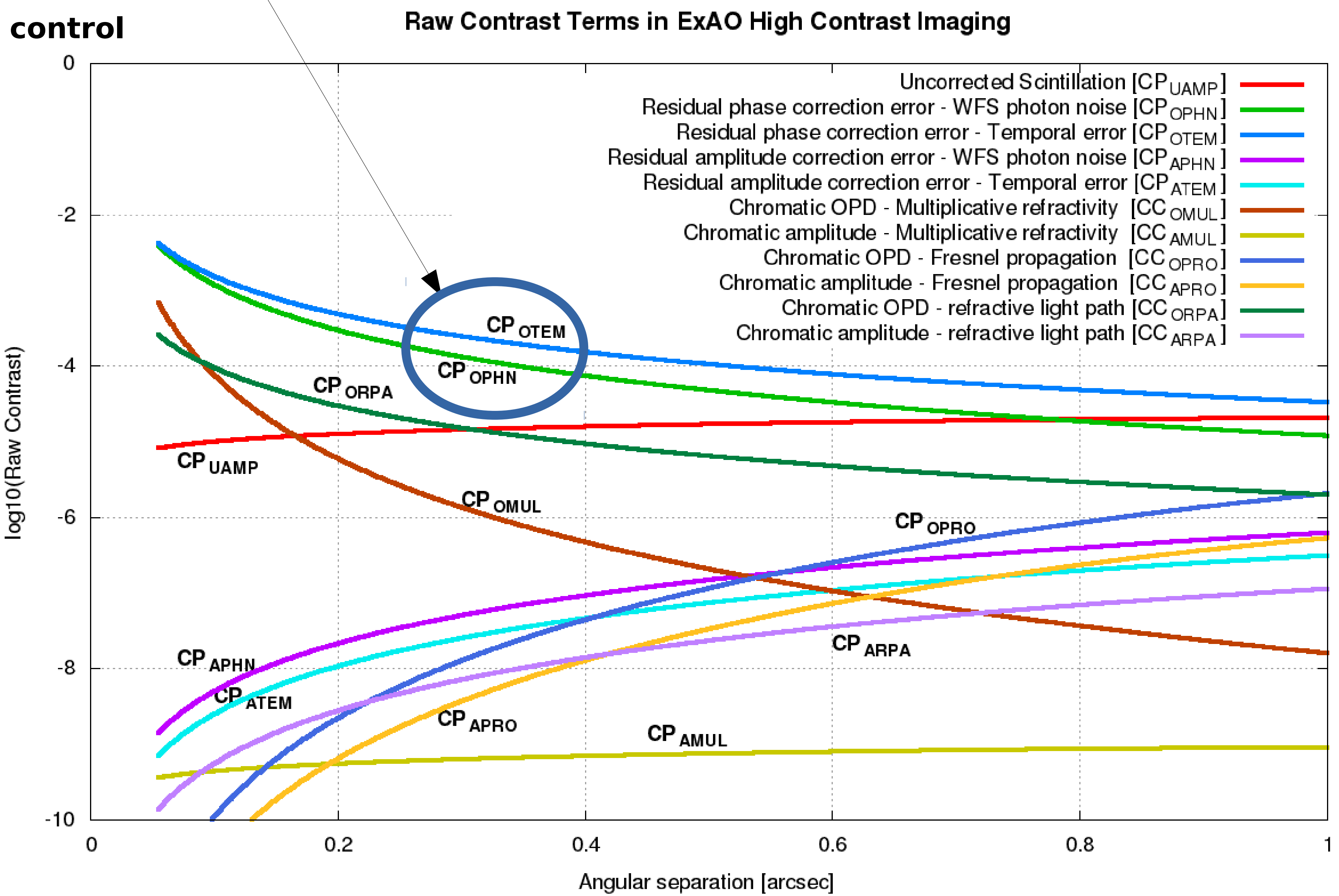
D=8m telescope
High contrast imaging at 1.6 um
Wavefront sensing at 0.8 um
30% efficiency WFS
40% wide WFS spectral band
1 kHz WFS frame rate
Integrator controller with optimal gain setting
Wind speed = 8 m/s
Fried parameter r_0 = 0.15 m at 0.5 um
m_I = 8 target
SHWFSm 15cm subapertures
Zenith angle = 40 deg
Aliasing and readout noise ignored



Contrast Error Budget (Primary WFC)

Temporal lag and WFS photon noise dominate

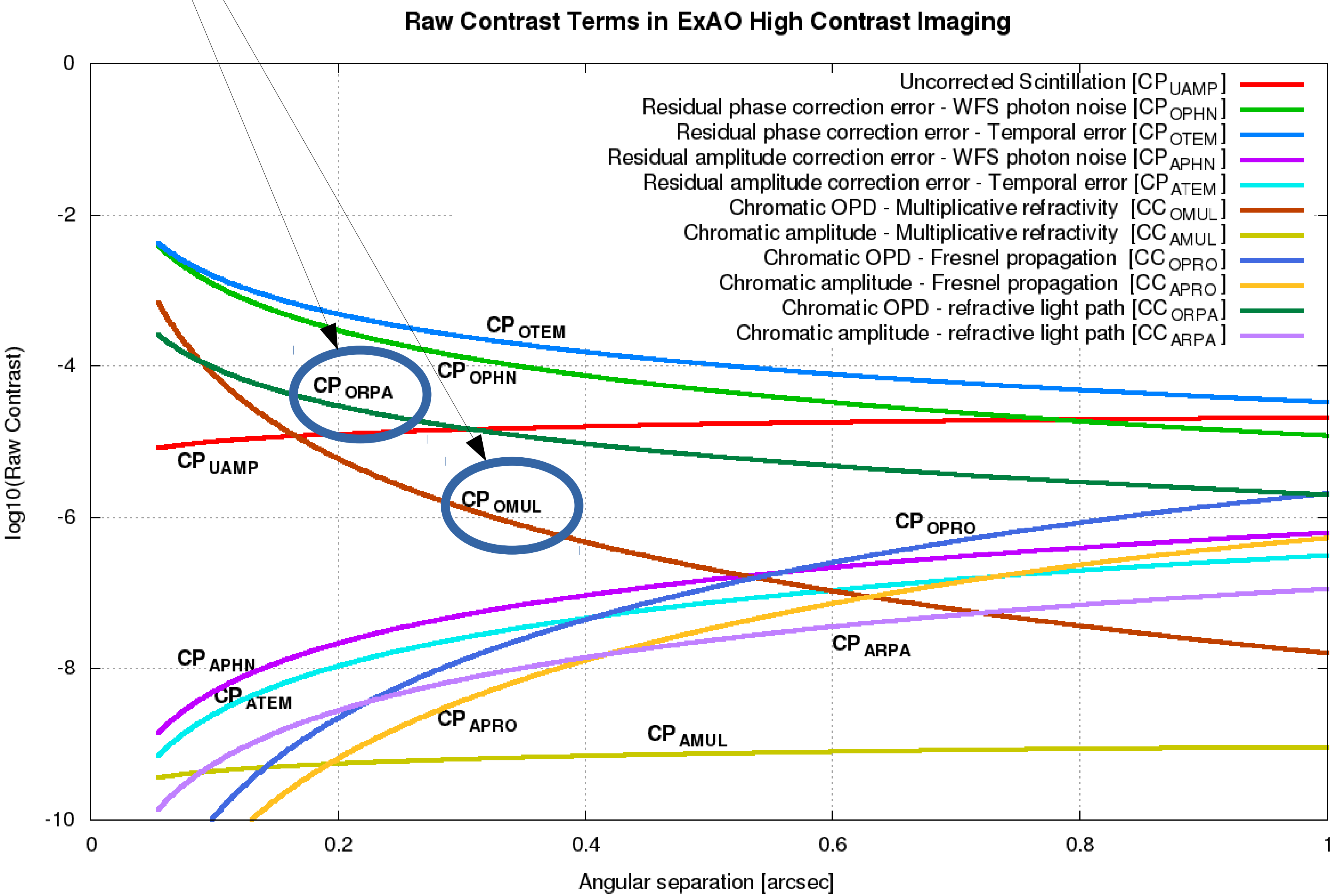
→ need fast loop
→ need efficient WFS (not a SHWFS !)
→ predictive control



Contrast Error Budget (Primary WFC)

Chromatic terms in atmospheric OPD

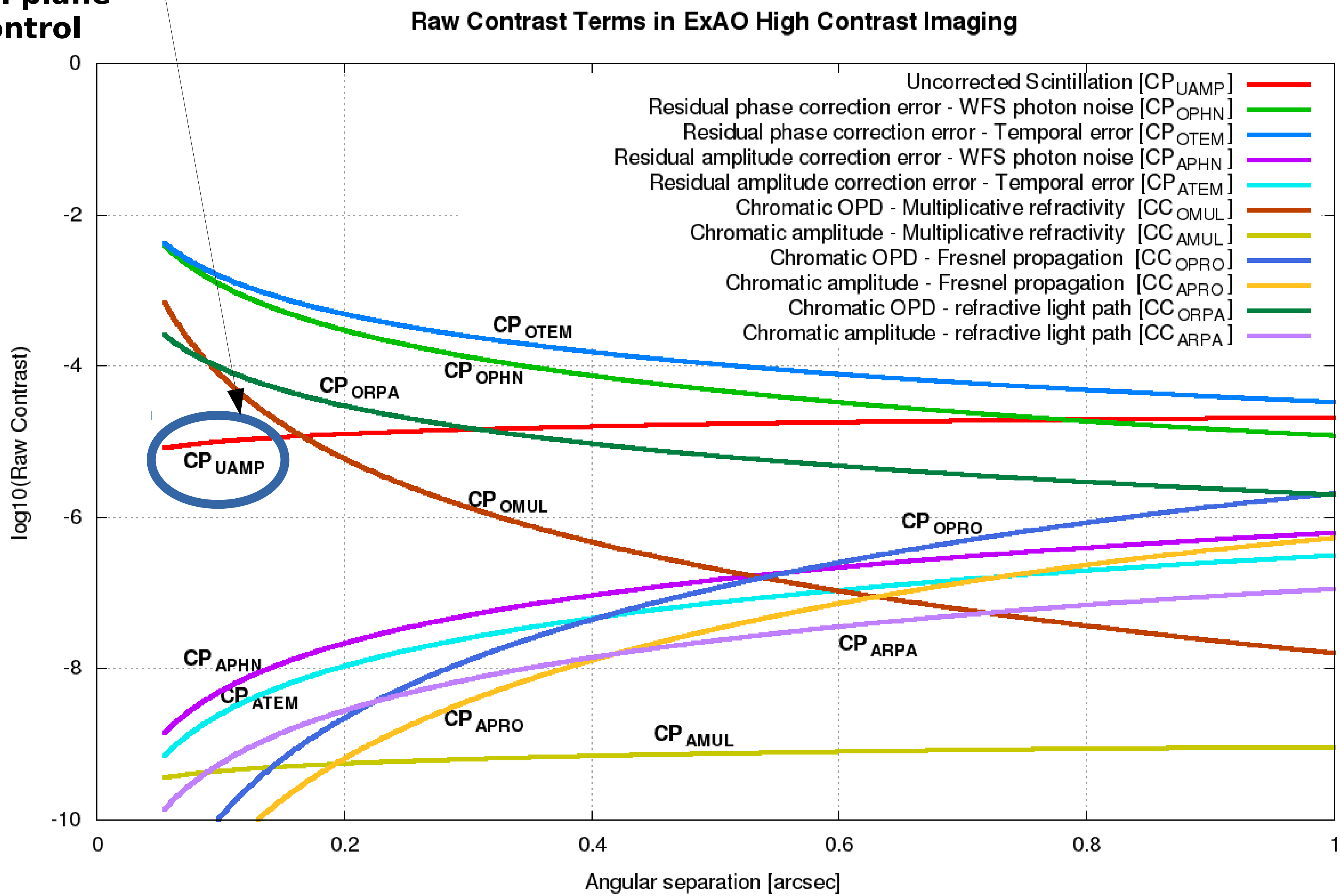
→ need WFS at/near science band



Contrast Error Budget (Primary WFC)

Scintillation

→ need amplitude measurement
.. or
→ need focal plane (speckle) control



Wavefront Control: challenges & solutions

WFS efficiency
M stars are not very bright for ExAO → need high efficiency WFS
For low-order modes (TT), seeing-limited (SHWFS) requires (D/r0)^2 times more light than diffraction-limited WFS
This is a **40,000x gain for 30m telescope**
(assuming r0=15cm) → 11.5 mag gain

Low latency WFC
System lag is extremely problematic → creates "ghost" slow speckles that last crossing time
Need ~200us latency (10 kHz system, or slower system + lag compensation), or multiple loops

WF chromaticity
Wavefront chromaticity is a serious concern when working at ~1e-8 contrast
Visible light (~0.6 – 0.8 um) photon carry most of the WF information, but science is in near-IR

Non-common path errors
It doesn't take much to create a 1e-8 speckle !

PSF calibration
What is a speckle, what is a planet ?

Diffraction-limited pupil-plane WFS
Low or no modulation PyWFS is diffraction-limited
This is a **40,000x gain for 30m telescope**
(assuming r0=15cm) → 11.5 mag gain

Fast WFC loop
Fast hardware (Cameras, GPUs) can now run loop at ~5 kHz on ELT
Example: SCExAO runs 2000 actuators, 14,400 sensors at 3.5kHz using ~10% of available RTS computing power

Predictive Control
Eliminates time lag, improves sensitivity

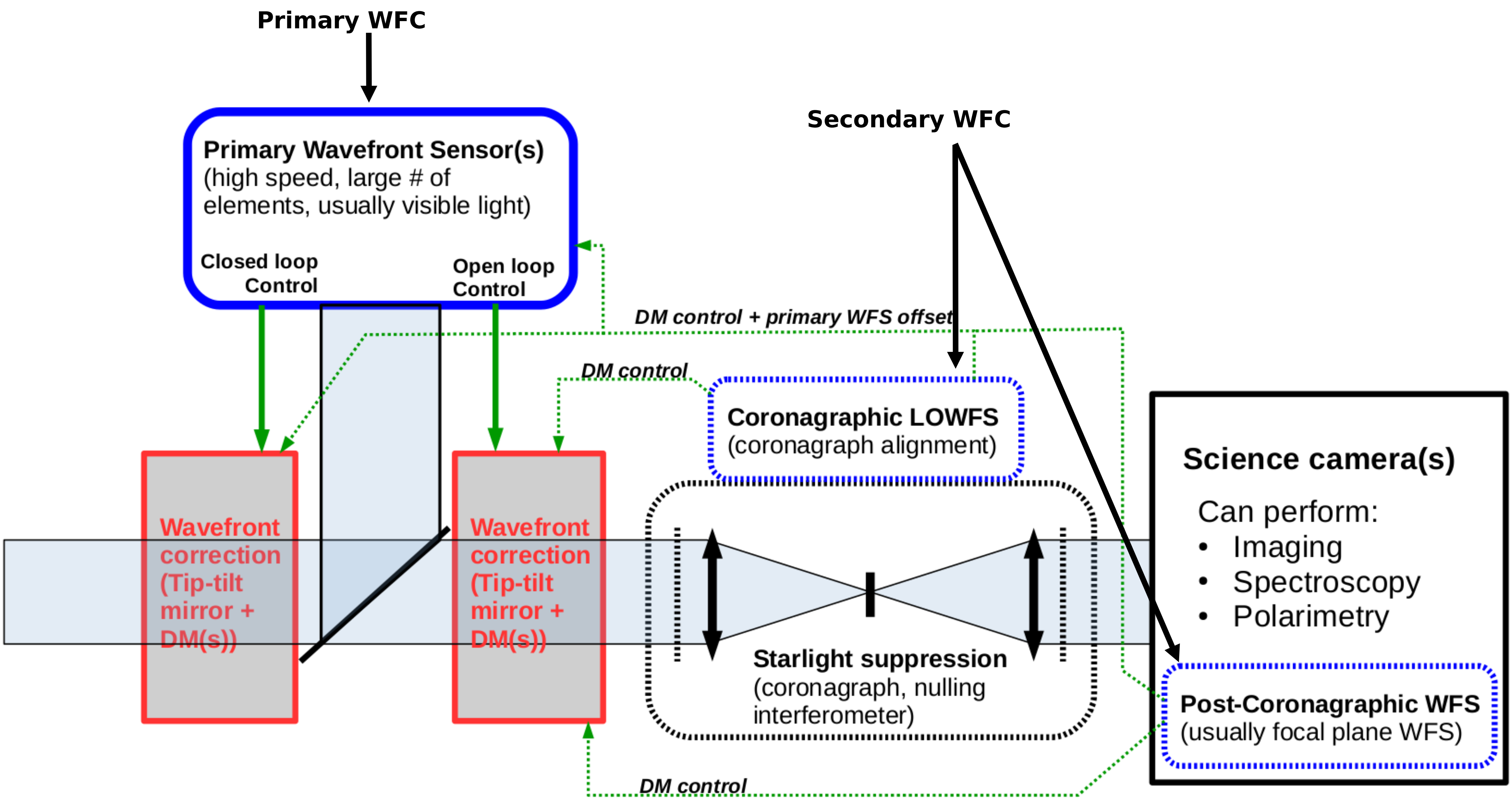
Fast speckle control, enabled by new detector technologies
Addresses simultaneously non-common path errors, (most of) lag error, chromaticity, and calibration

Real-time telemetry → PSF calibration
WFS telemetry tells us where speckles are → significant gain using telemetry into post-processing

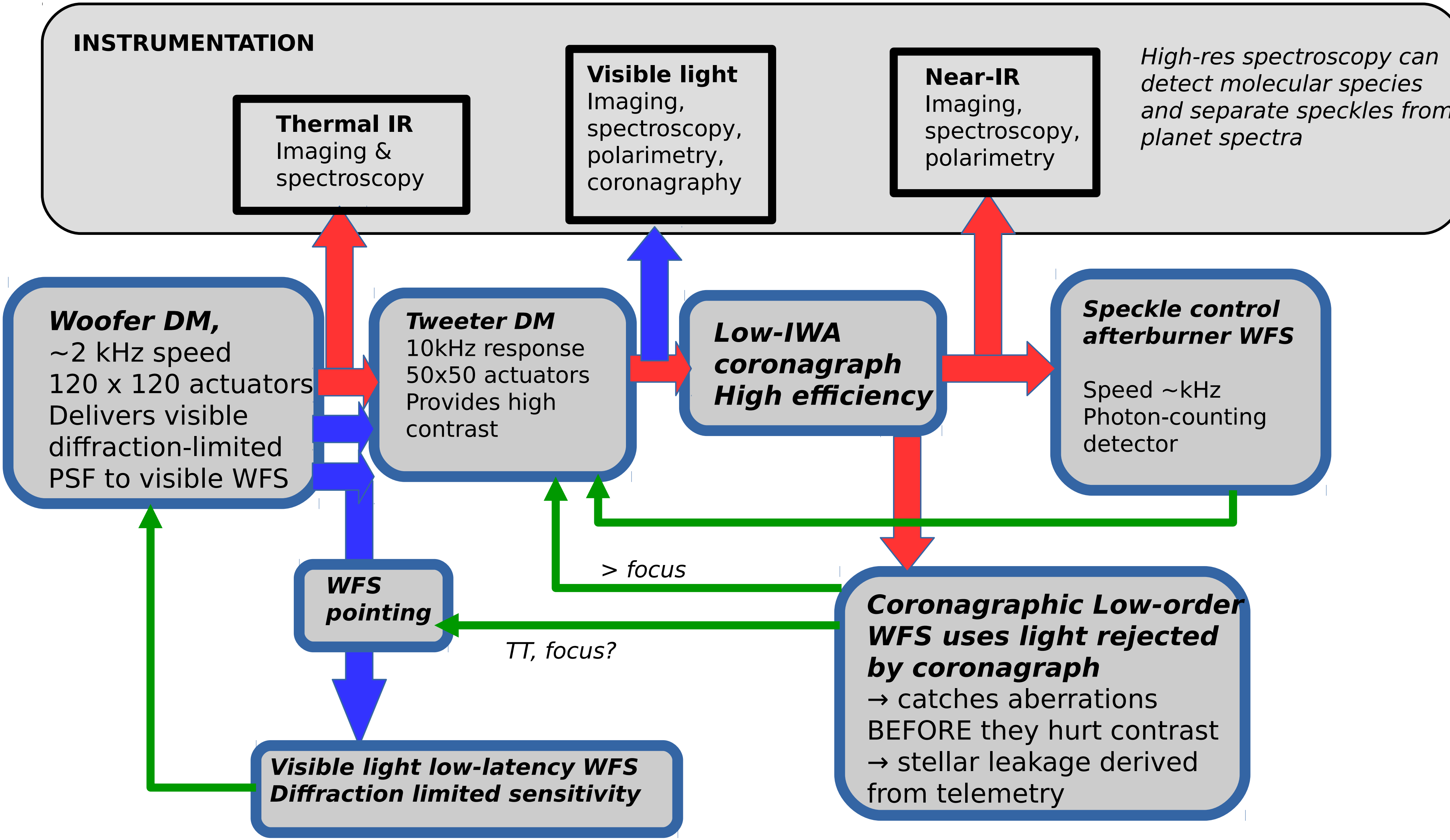
Spectral discrimination (HR)
Especially powerful at high spectral resolution

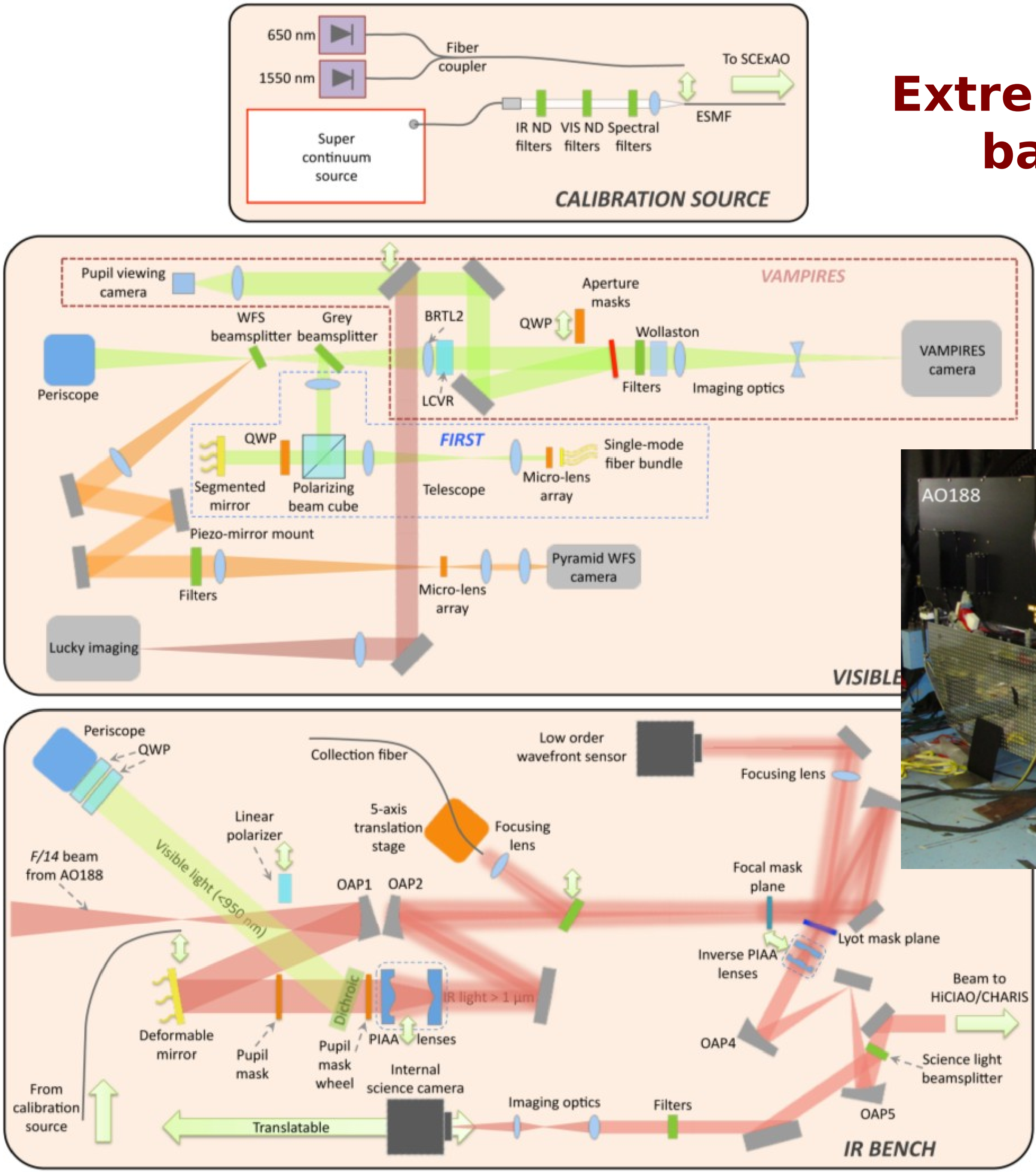
ExAO system architecture

New systems include secondary WFC loop (WFS performed within and after coronagraph)



Example system architecture with instrumentation





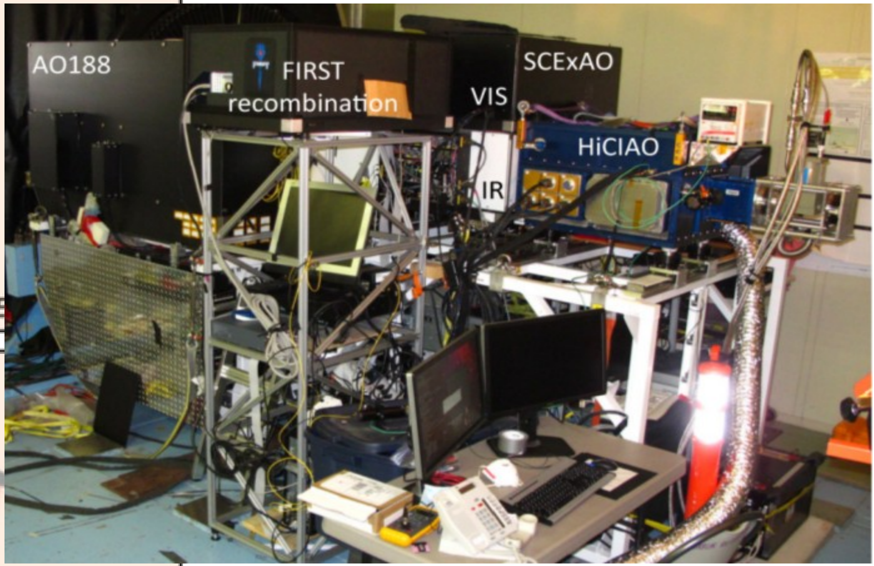
Extreme-AO ground-based system

4 wavefront sensors:

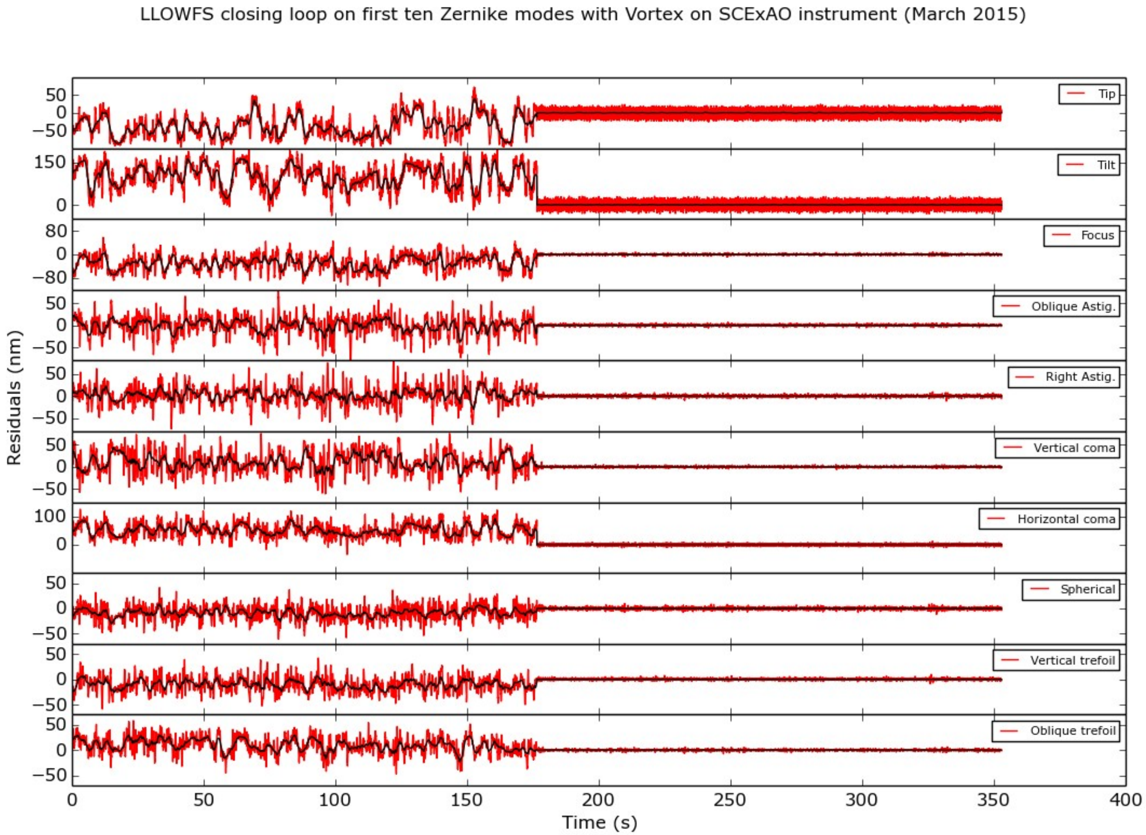
- Coarse correction (visible WFS)
- Extreme-AO (visible pyramid)
- Low-order (near-IR)
- Speckles (near-IR)

3 deformable mirrors:

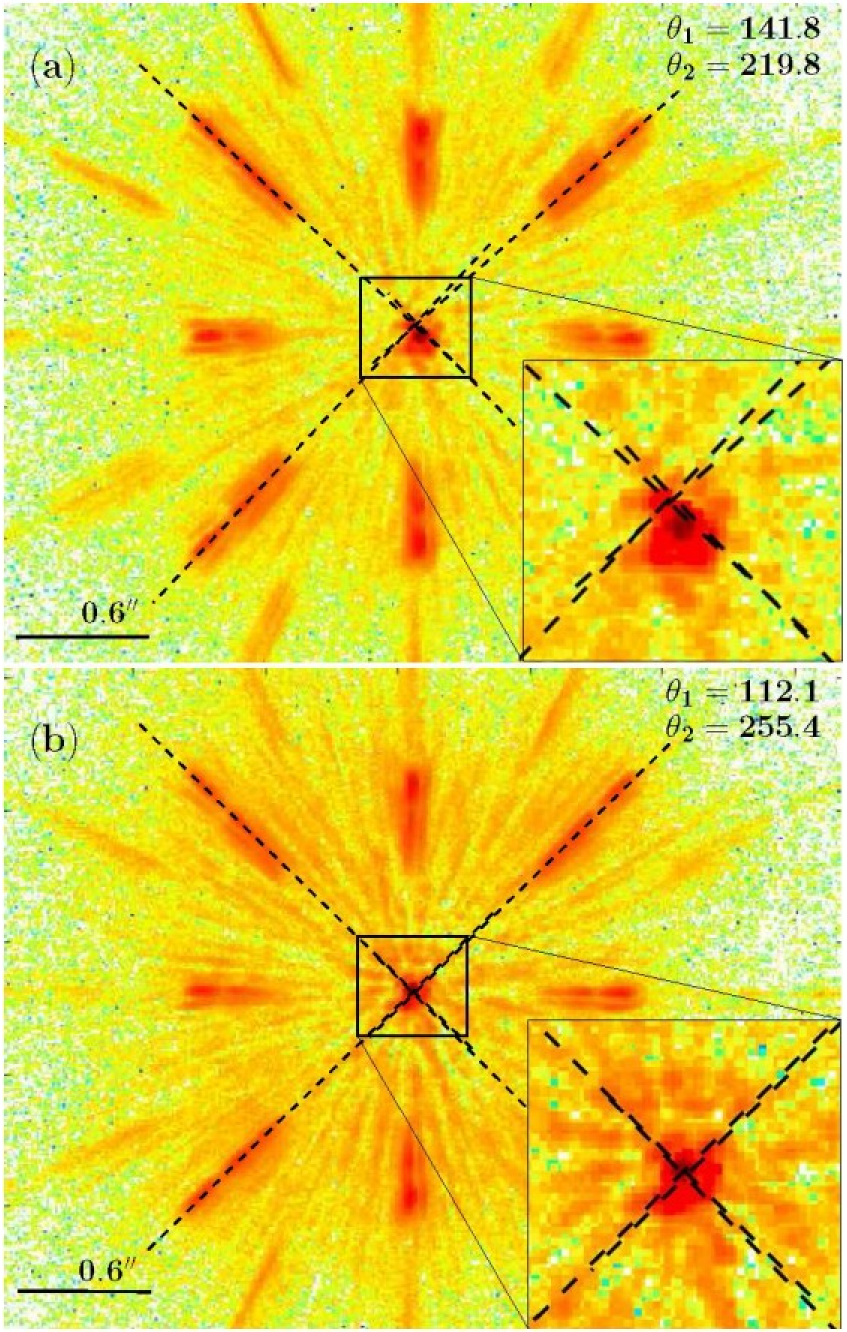
- 188 element bimorph
- 2000 element MEMs
- 37 segments MEMs



Managing Chromaticity: TipTilt and Low Orders

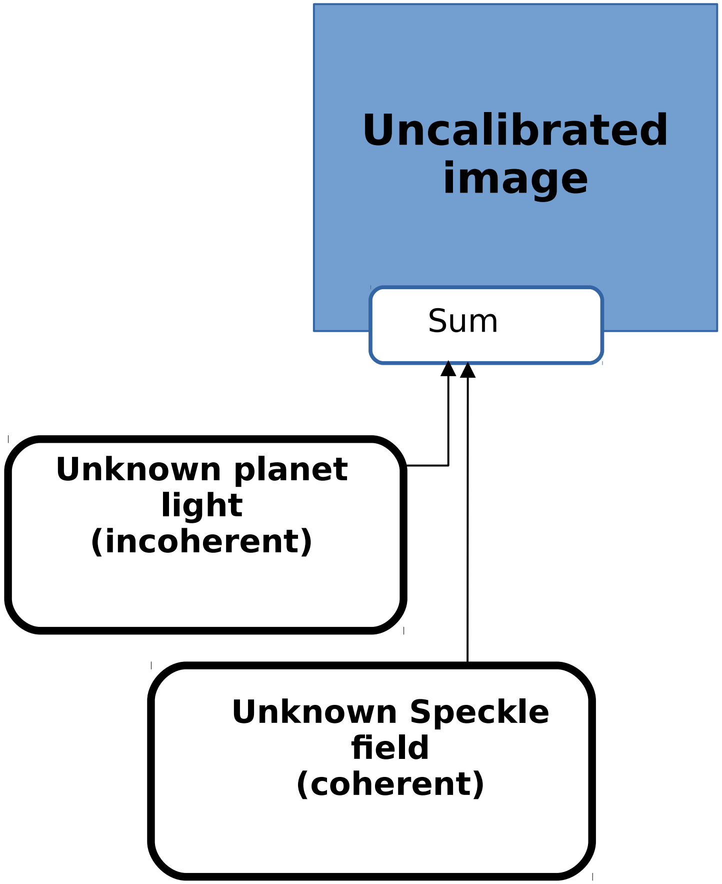


Near-IR low-order coronagraphic WFC
(Singh et al. 2015+)

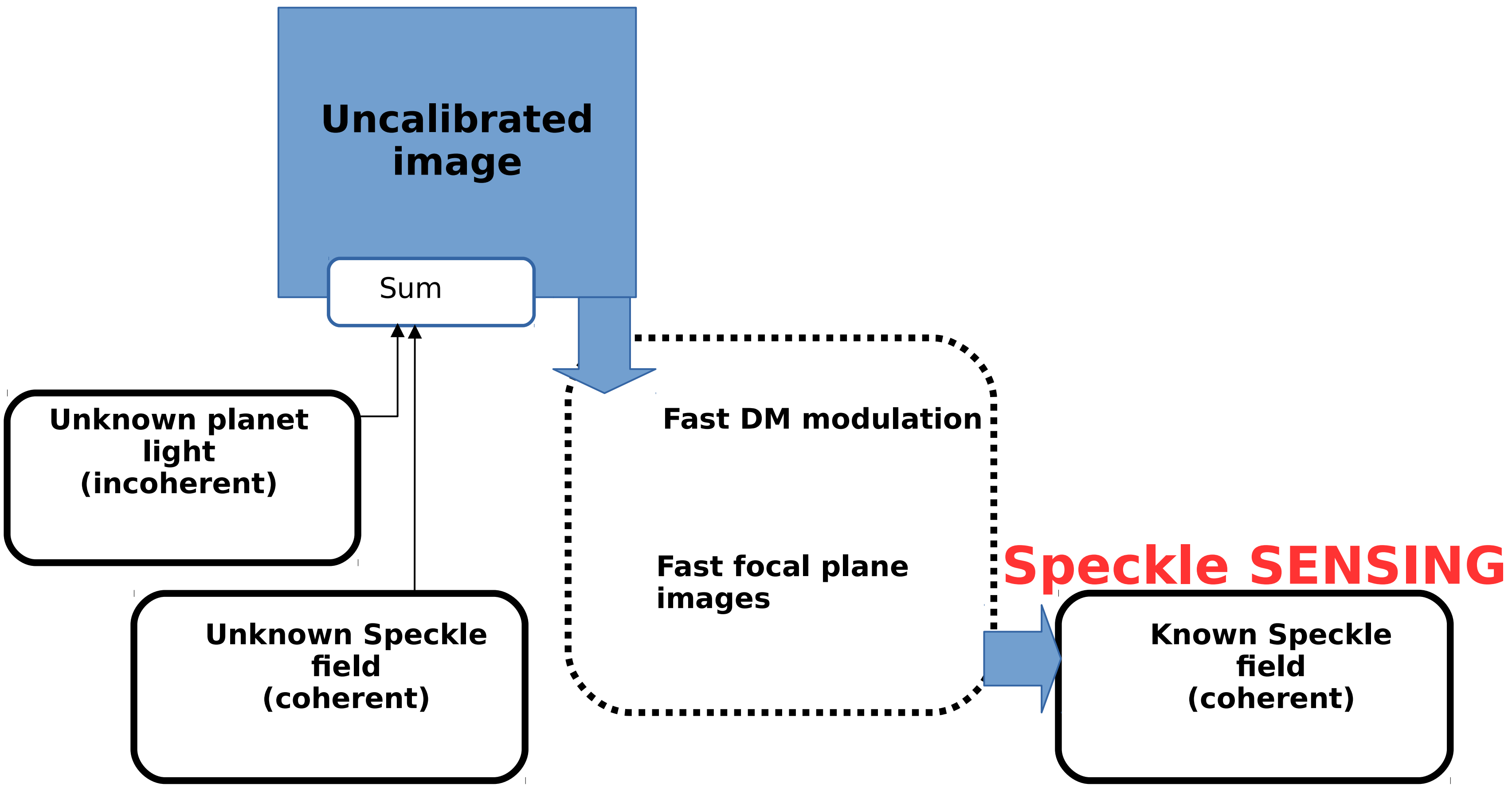


Closed loop atmospheric dispersion compensation
(Pathak et al. 2016, 2017)

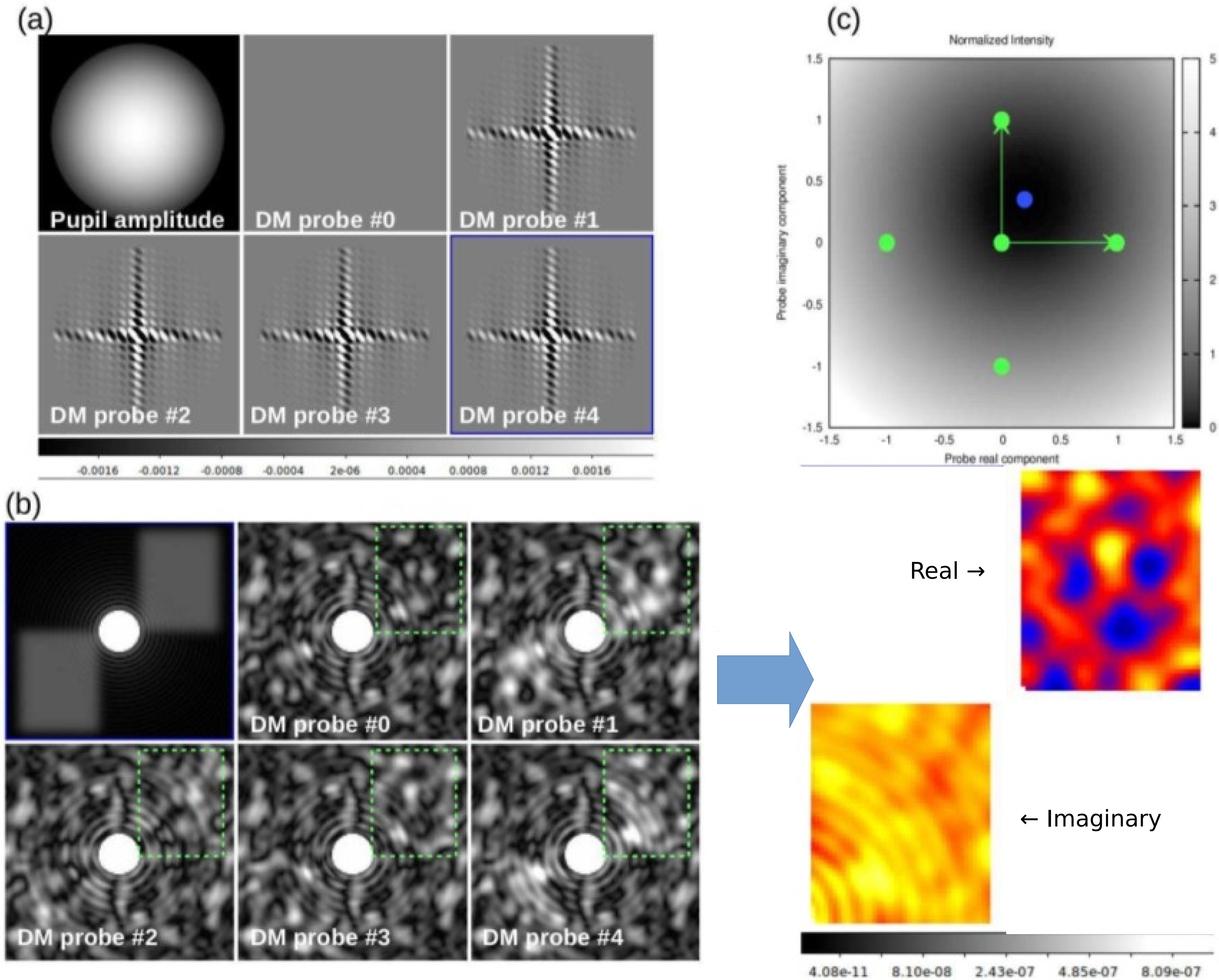
High Speed Speckle Control & Calibration



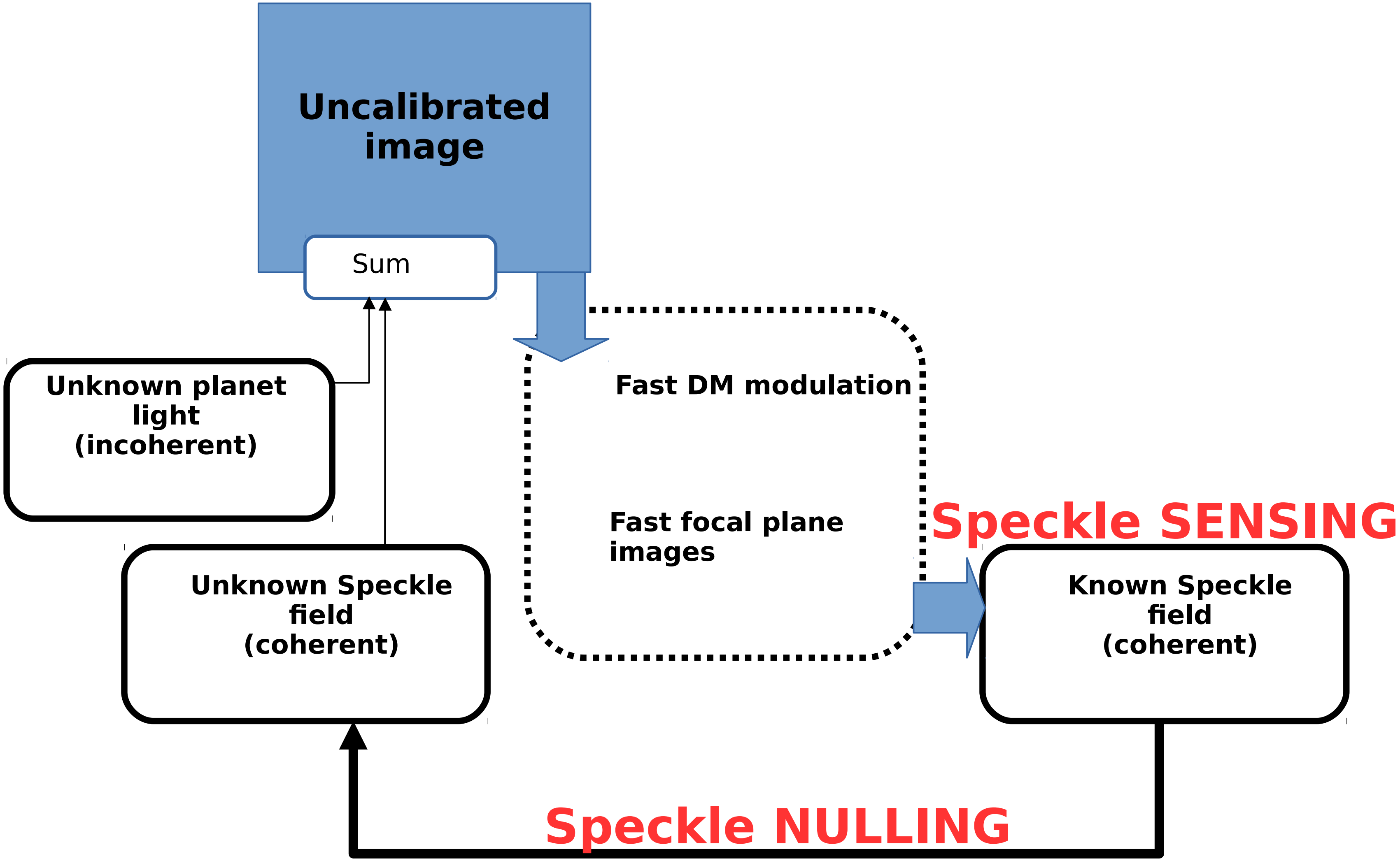
High Speed Speckle Control & Calibration



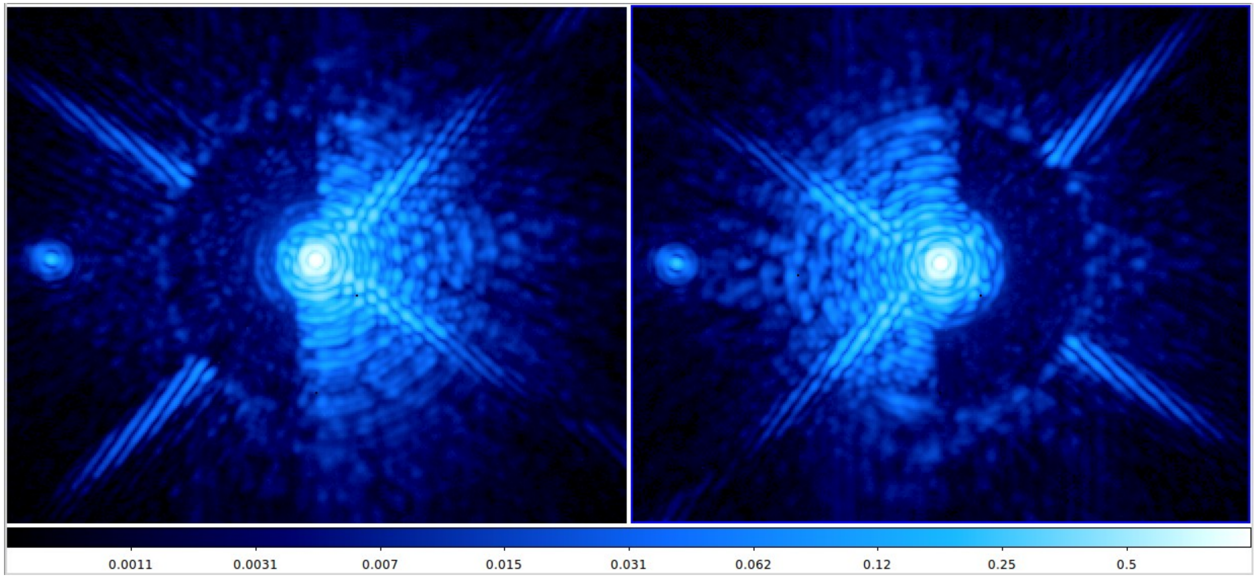
Coherent Speckle Differential Imaging

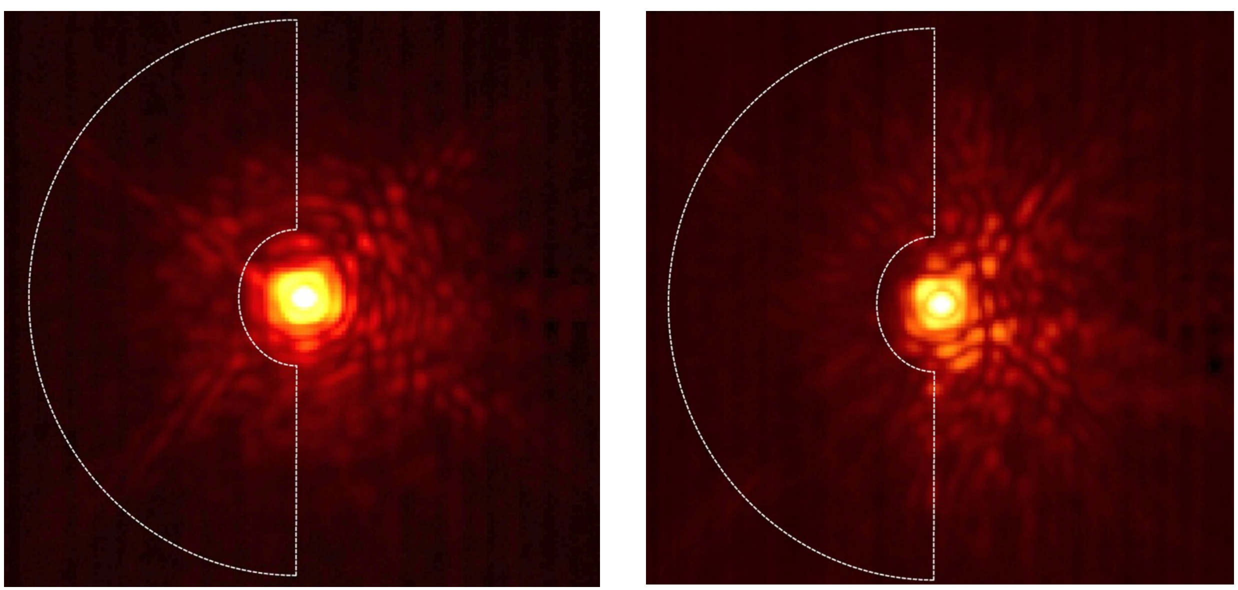


High Speed Speckle Control & Calibration



Speckle Control





Speckle nulling, in the lab and on-sky (no XAO).

Experience limited by detector readout noise and speed.

KERNEL project: C-RED-ONE camera.

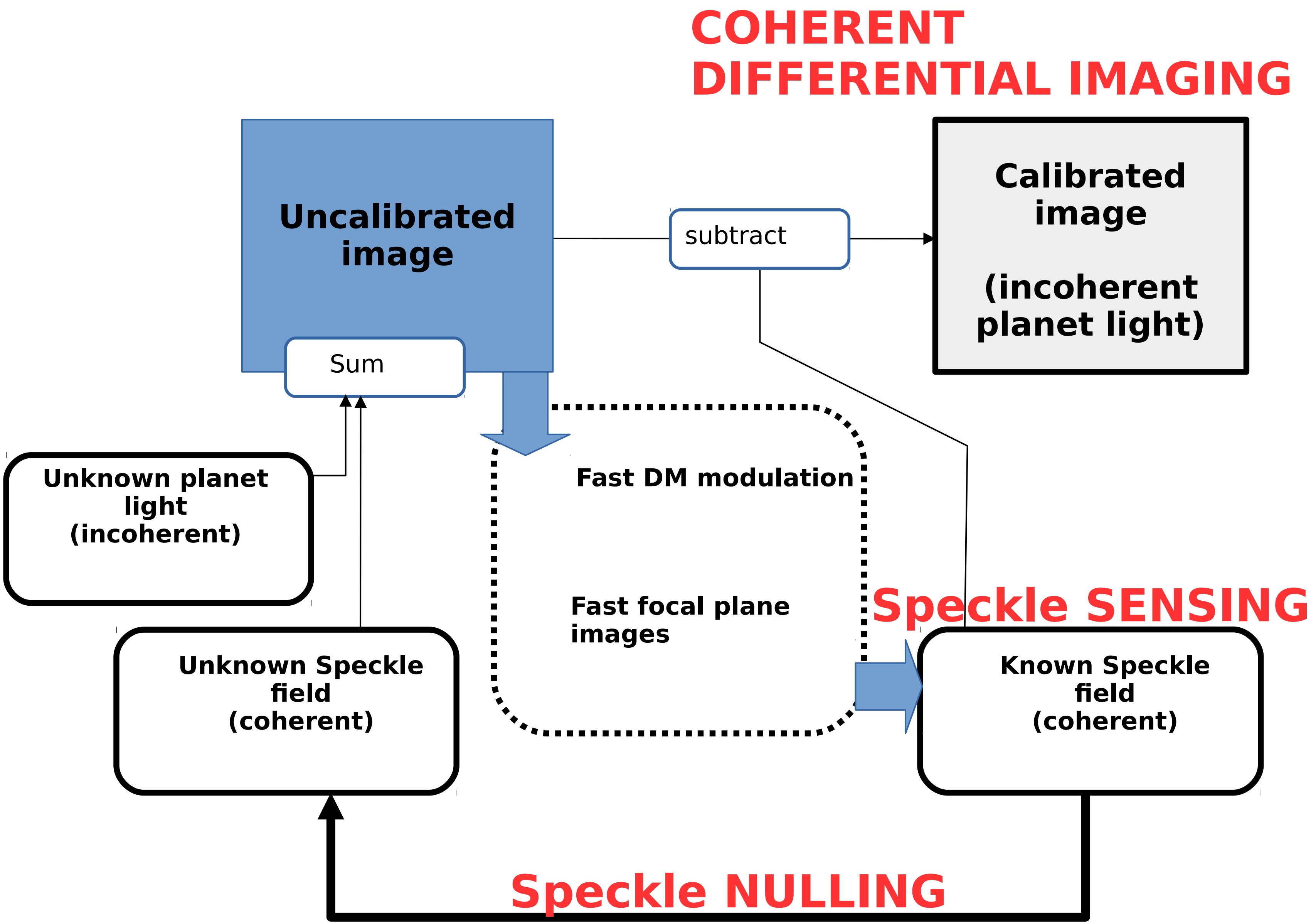
From:
- 114 e- RON
- 170 Hz frame rate

To:
- 0.8 e- RON
- 3500 Hz frame rate

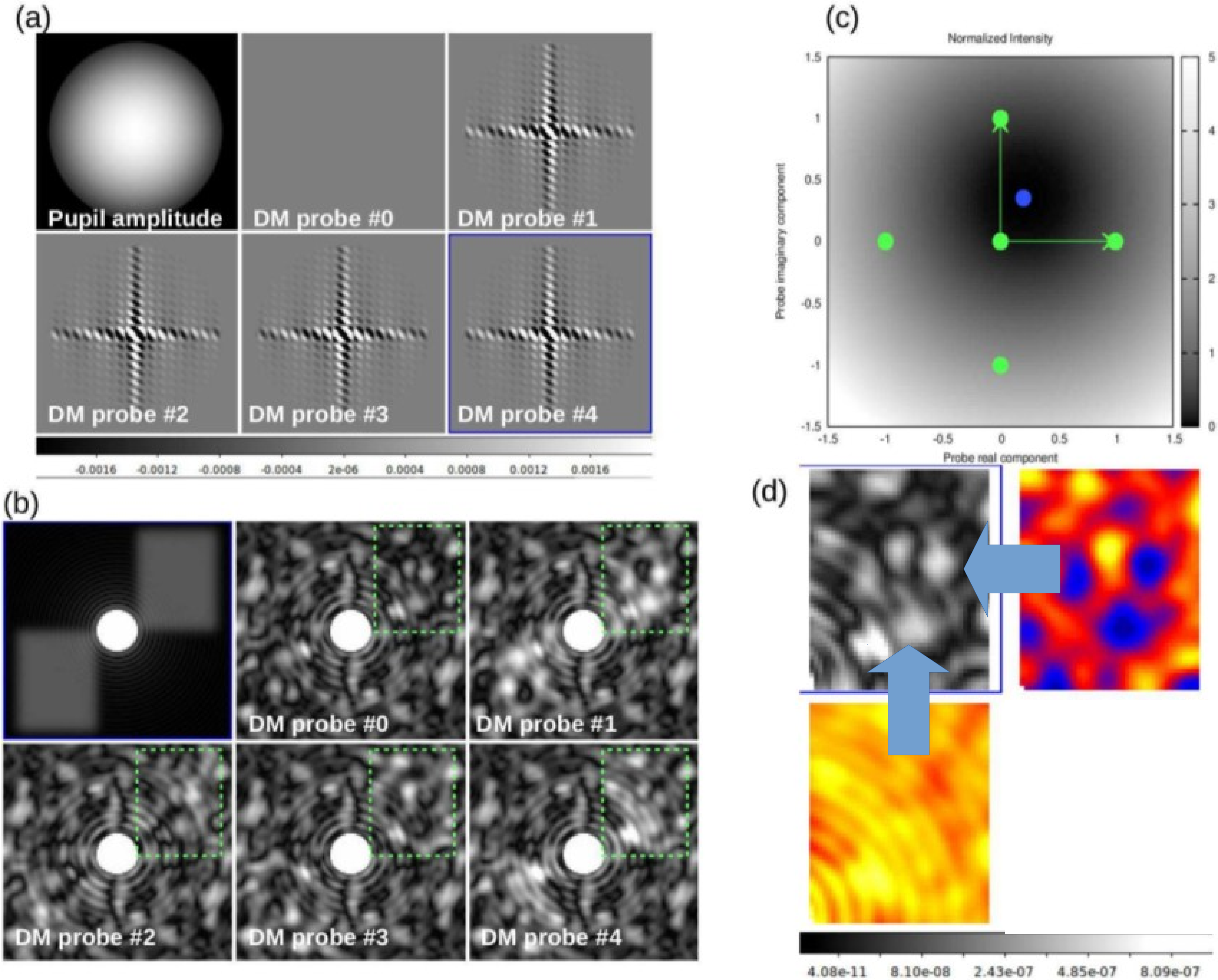
Expect some updates

Observatoire de la CÔTE d'AZUR

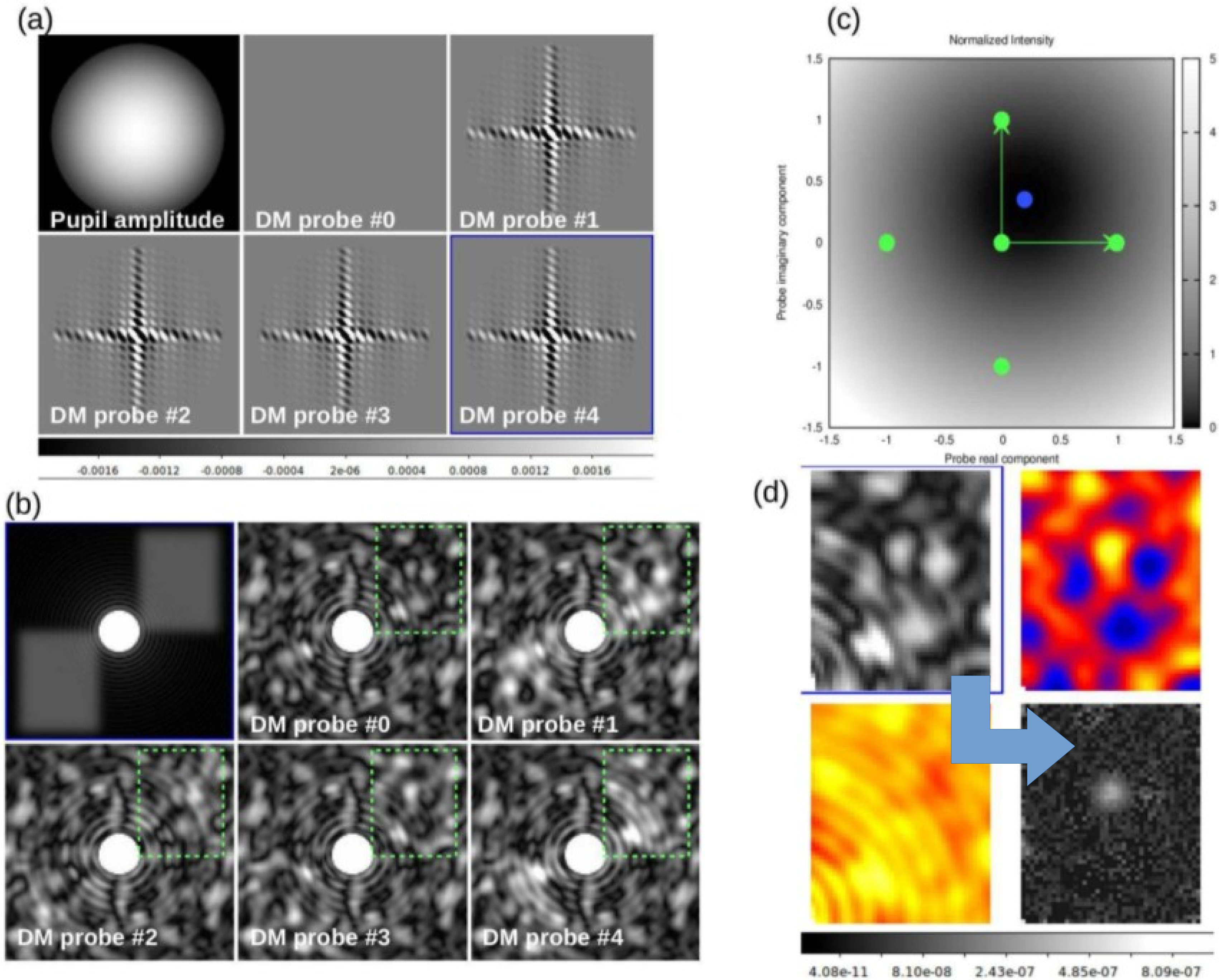
High Speed Speckle Control & Calibration



Coherent Speckle Differential Imaging



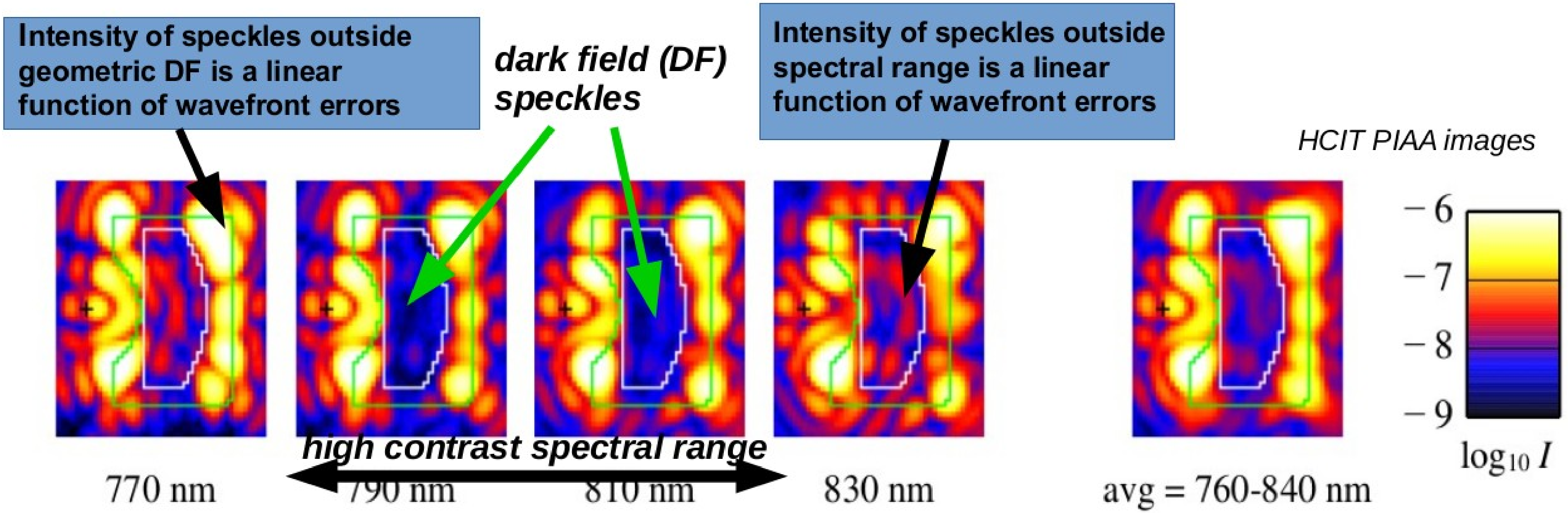
Coherent Speckle Differential Imaging



Linear Dark Field Control (LDFC)

Speckle intensity in the DF are a non-linear function of wavefront errors → current wavefront control technique uses several images (each obtained with a different DM shape) and a non-linear reconstruction algorithm (for example, Electric Field Conjugation – EFC)

Speckle intensity in the BF are linearly coupled to wavefront errors → we have developed a new control scheme using BF light to freeze the wavefront and therefore prevent light from appearing inside the DF



Predictive control & sensor fusion→ 100x contrast gain ?

See also: Males & Guyon 2017 (astro-ph)

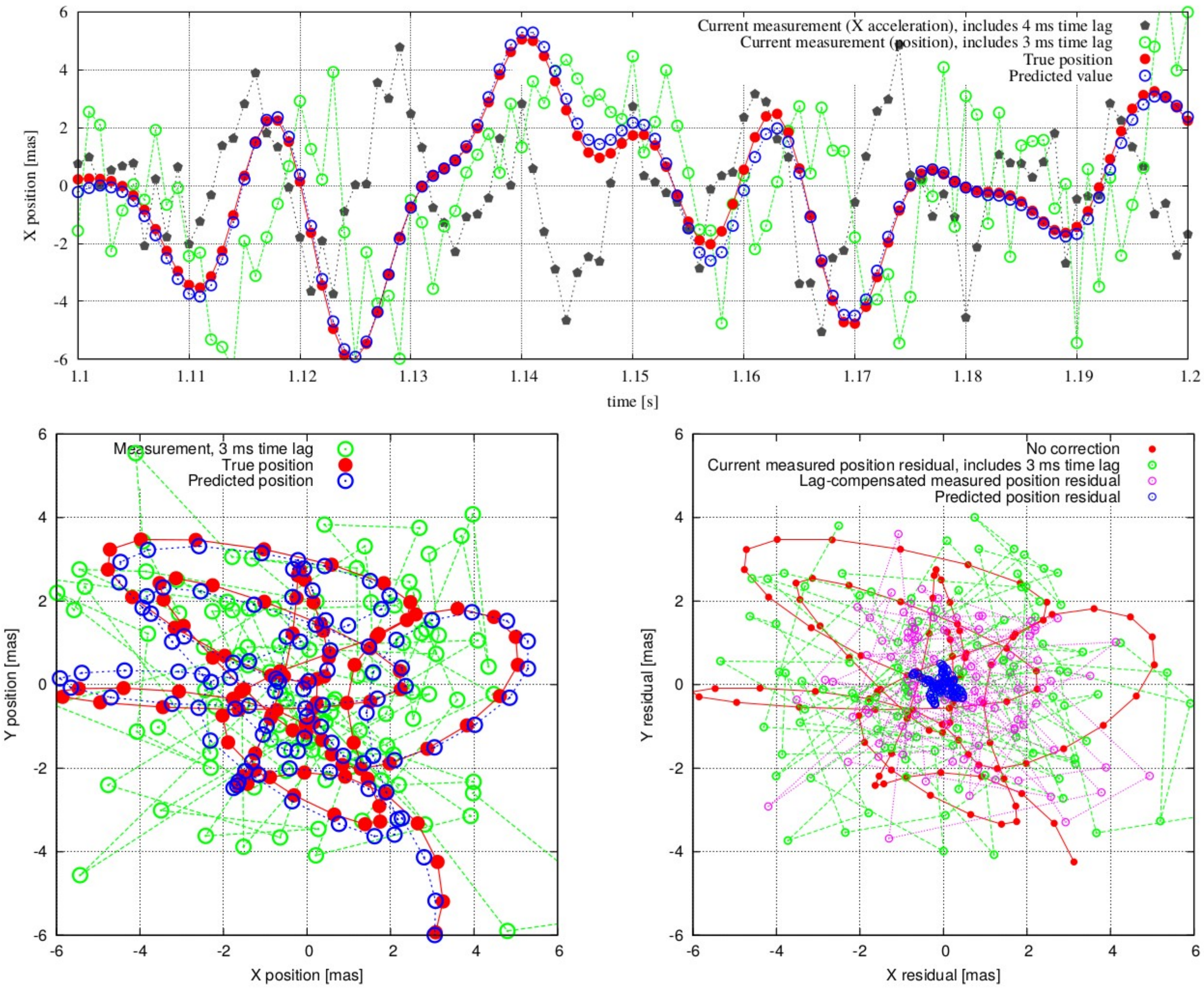
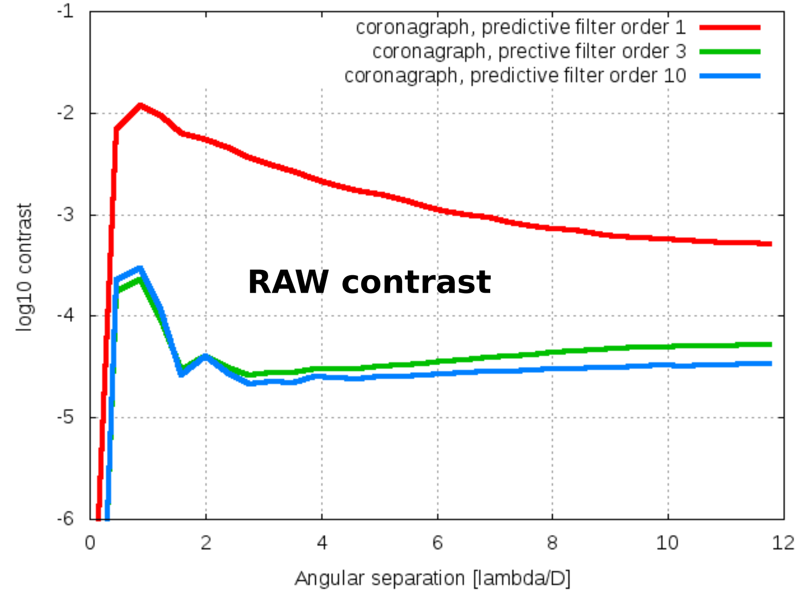
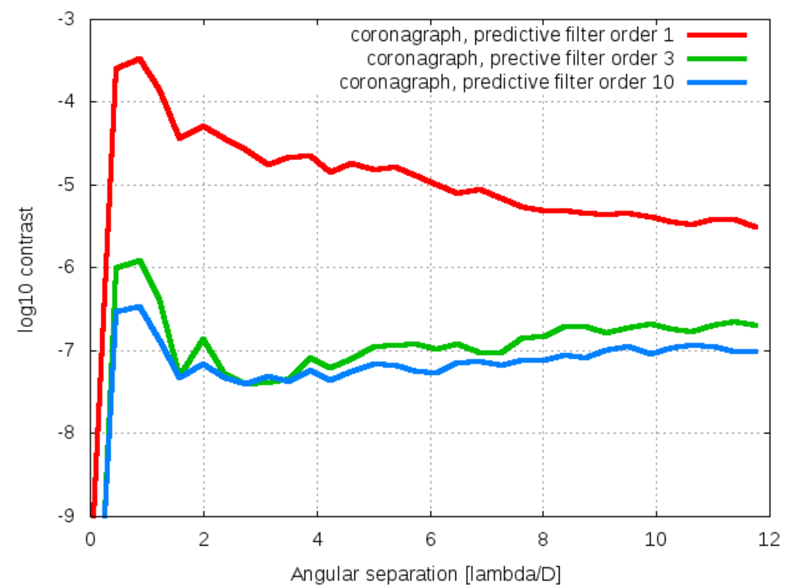


FIG. 3.— Top left: 2D-tracks for true pointing (red), predicted pointing (blue) and last measured position (green). Top right: Residual pointing error. Bottom: Single axis (x) values.



1hr detection limit (PSF subtraction residual)



Differential Detection Techniques

Angular Differential Imaging (ADI)
Does not address noise limit from slow speckles

Spectral Differential Imaging (SDI) (low spectral resolution)
Limited by chromaticity in speckles

High Resolution Spectroscopy (Snellen et al., Mawet et al.)
Very clean signal (narrow lines) not present in starlight
But few % of planet light used → photon noise (from starlight) limits use
Great for giant planets. Challenging for Habitable planets.
(See Wang et al. 2017)

Polarization Differential Imaging
Polarized light fraction is small (<10% ?)
→ photon noise (from starlight) limits use

Coherent Differential Imaging
Can use 100% of light
Challenging to implement, calibration issues