Grand Challenges in Ground-Based Exoplanet Imaging

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Outline

1. Key scientific motivations

2. Coronagraph designs for ground-based systems

3. The wavefront control challenge

4. Areas of future development: where big gains are

Conclusions, Path Forward

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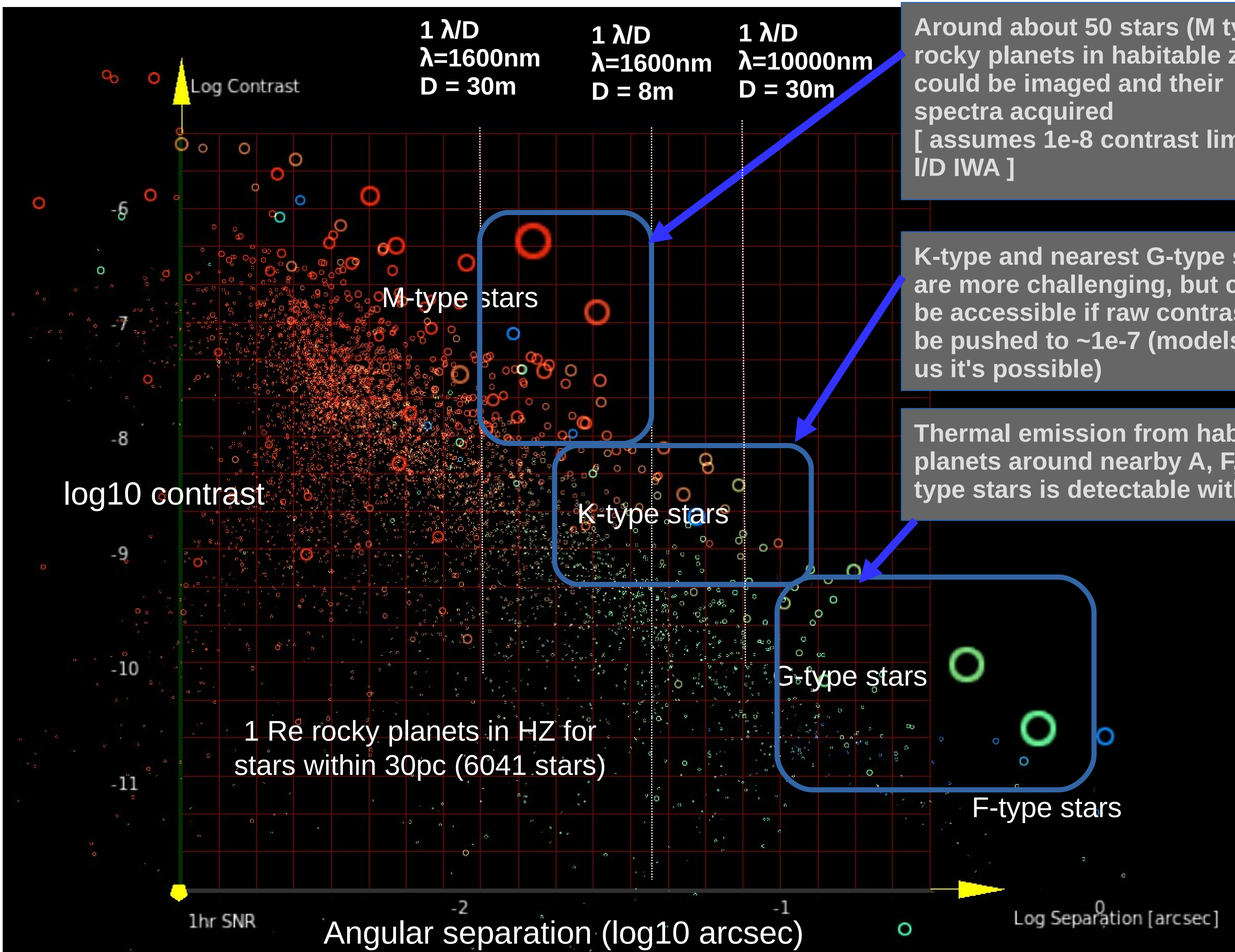
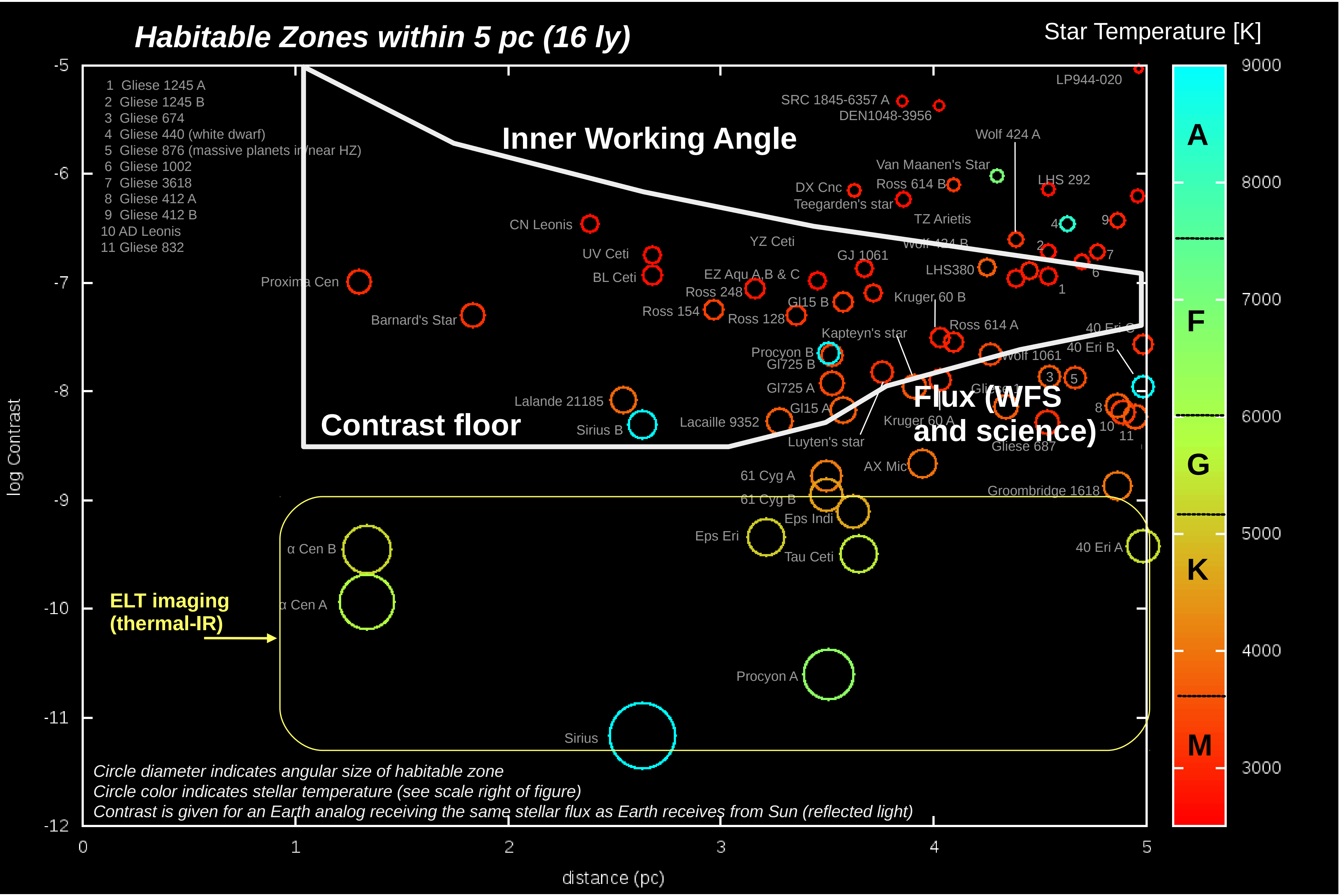
Habitable Planets: Contrast and Angular separation



Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired
[assumes 1e-8 contrast limit, 1 l/D IWA]

K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to ~1e-7 (models tell us it's possible)

Thermal emission from habitable planets around nearby A, F, G type stars is detectable with ELTs



Habitable Zones within 5 pc (16 ly)
Star Temperature [K]
1 Gliese 1245 A
2 Gliese 1245 B
3 Gliese 674
4 Gliese 440 (white dwarf)
5 Gliese 876 (massive planets in/near HZ)
6 Gliese 1002
7 Gliese 3618
8 Gliese 412 A
9 Gliese 412 B
10 AD Leonis
11 Gliese 832
Inner Working Angle
Contrast floor
Flux (WFS and science)
ELT imaging (thermal-IR)
Proxima Cen
Barnard's Star
CN Leonis
UV Ceti
BL Ceti
Lalande 21185
Sirius B
Ross 154
Ross 248
EZ Aqu A,B & C
YZ Ceti
Ross 128
Gl15 B
GJ 1061
DX Cnc
Teegarden's star
Ross 614 B
Van Maanen's Star
SRC 1845-6357 A
DEN1048-3956
LP944-020
Wolf 424 A
Wolf 424 B
LHS 292
TZ Arietis
LHS380
Kruger 60 B
Ross 614 A
Kapteyn's star
Procyon B
Gl725 B
Gl725 A
Gl15 A
Lacaille 9352
Luyten's star
Kruger 60 A
Wolf 1061
40 Eri C
40 Eri B
Gliese 687
AX Mic
61 Cyg A
61 Cyg B
Eps Indi
Eps Eri
Tau Ceti
Groombridge 1618
40 Eri A
α Cen B
α Cen A
Procyon A
Sirius
A
F
G
K
M
9000
8000
7000
6000
5000
4000
3000
log Contrast
distance (pc)
Circle diameter indicates angular size of habitable zone
Circle color indicates stellar temperature (see scale right of figure)
Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)

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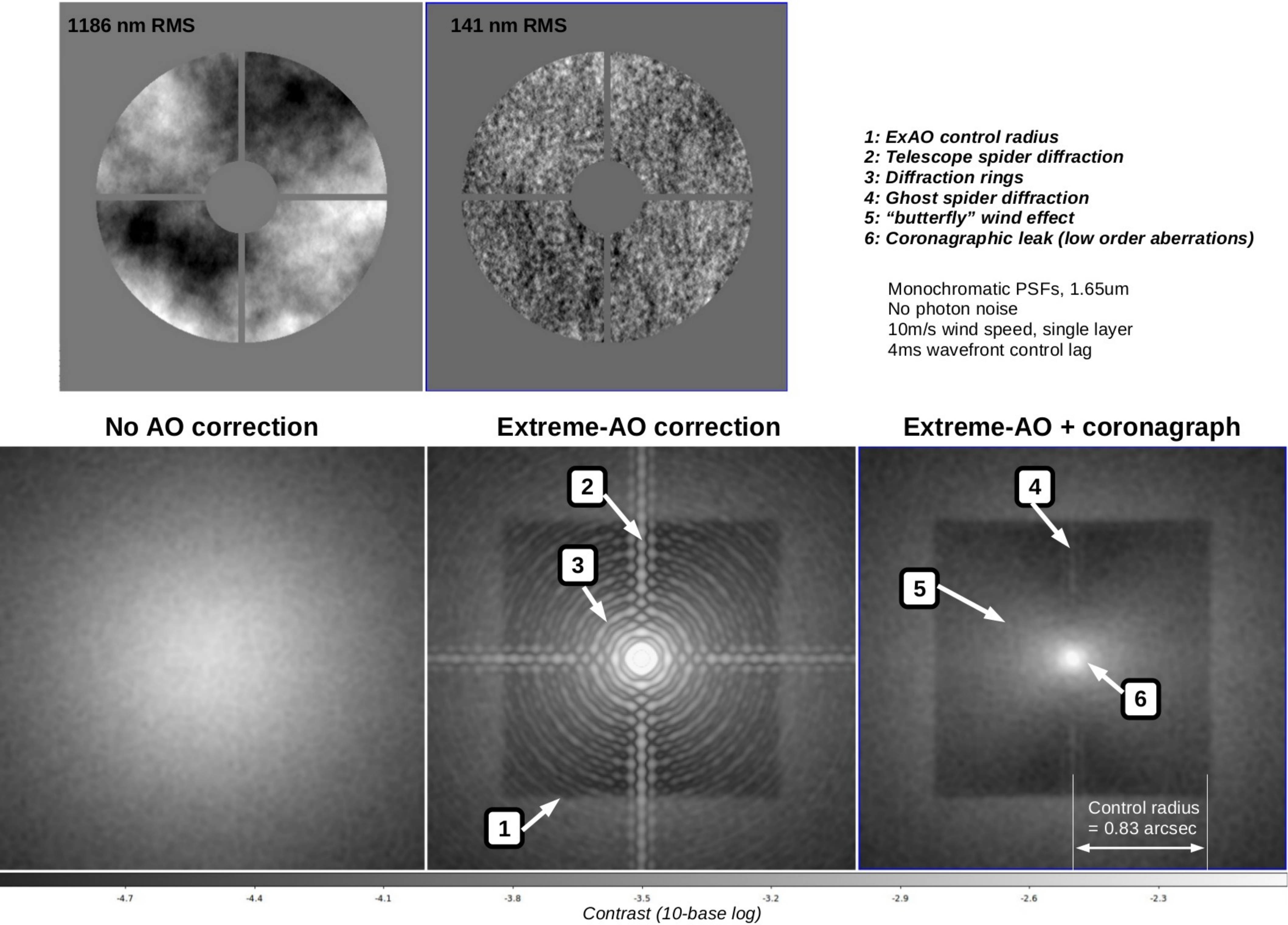
2. **Coronagraph designs for ground-based systems**

3. The wavefront control challenge

4. Areas of future development: where big gains are

Conclusions, Path Forward



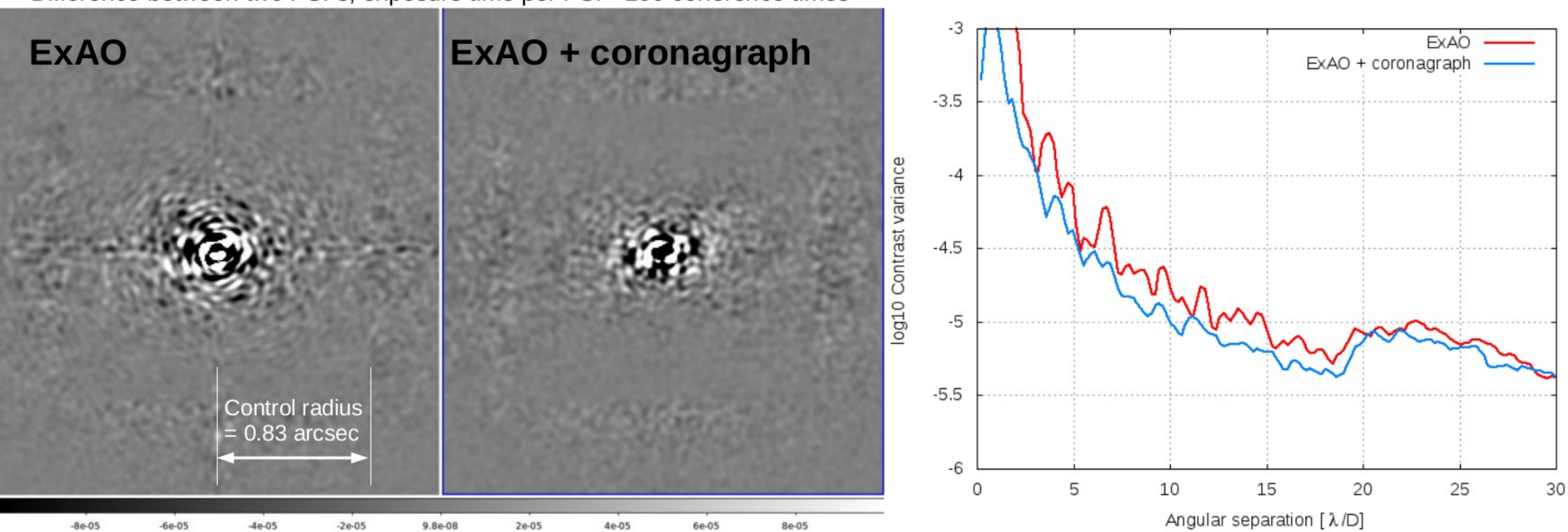
1186 nm RMS
141 nm RMS
1: ExAO control radius
2: Telescope spider diffraction
3: Diffraction rings
4: Ghost spider diffraction
5: “butterfly” wind effect
6: Coronagraphic leak (low order aberrations)
Monochromatic PSFs, 1.65um
No photon noise
10m/s wind speed, single layer
4ms wavefront control lag
No AO correction
Extreme-AO correction
Extreme-AO + coronagraph
2
3
1
4
5
6
Control radius
= 0.83 arcsec
-4.7
-4.4
-4.1
-3.8
-3.5
-3.2
-2.9
-2.6
-2.3
Contrast (10-base log)

Coronagraphs reduce speckle noise

"speckle pinning" effect
See: Bloemhof et al. 2001, Aime & Soummer 2004, Soummer et al. 2007

PSF subtraction residual (no photon noise)

Difference between two PSFs, exposure time per PSF=100 coherence times



(largely) lossless apodization

Creates a PSF with weak Airy rings

Focal plane mask: -1<t<0

Induces destructive interference inside downstream pupil

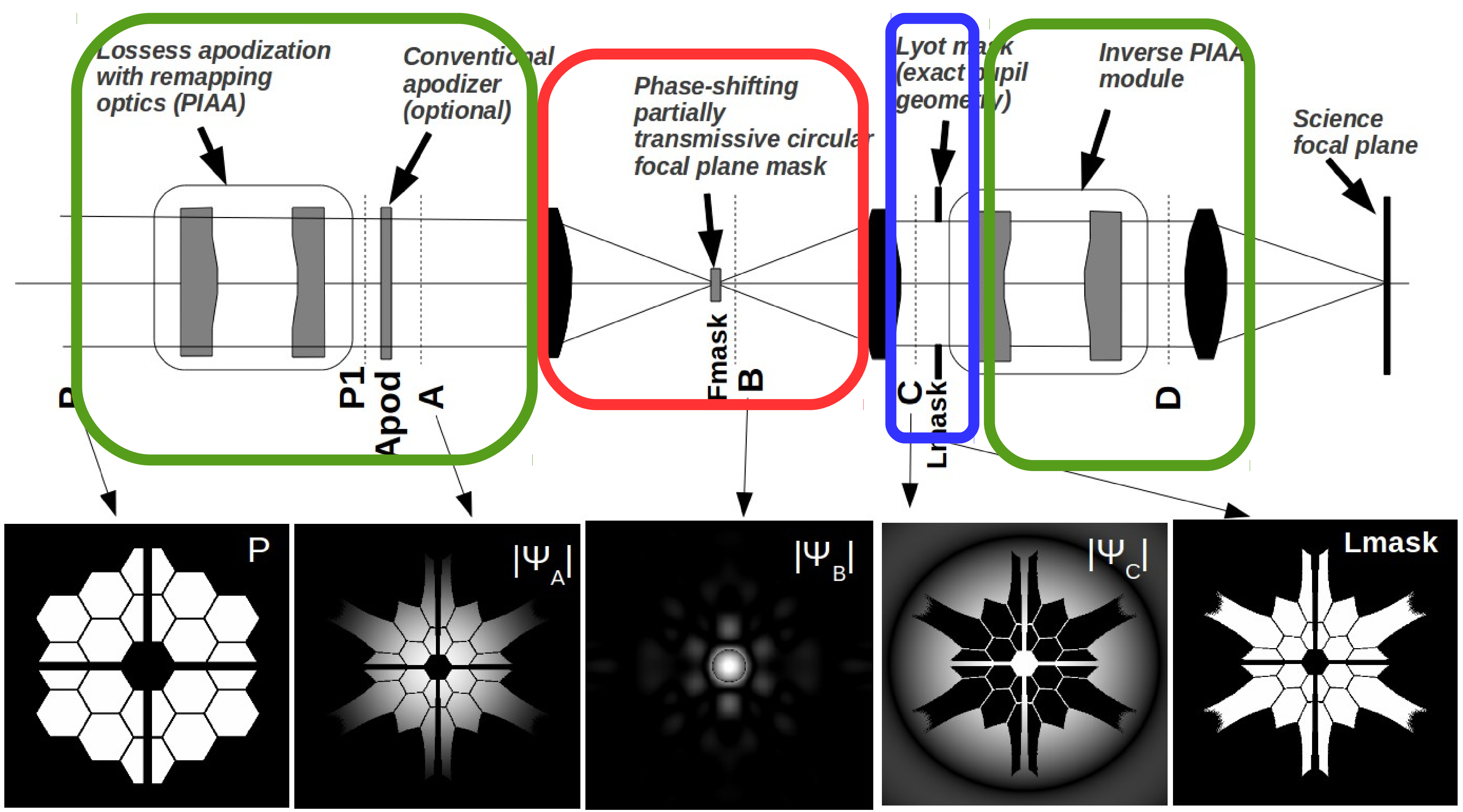
Lyot stop

Blocks starlight

Inverse PIAA (optional)

Recovers Airy PSF over wide field

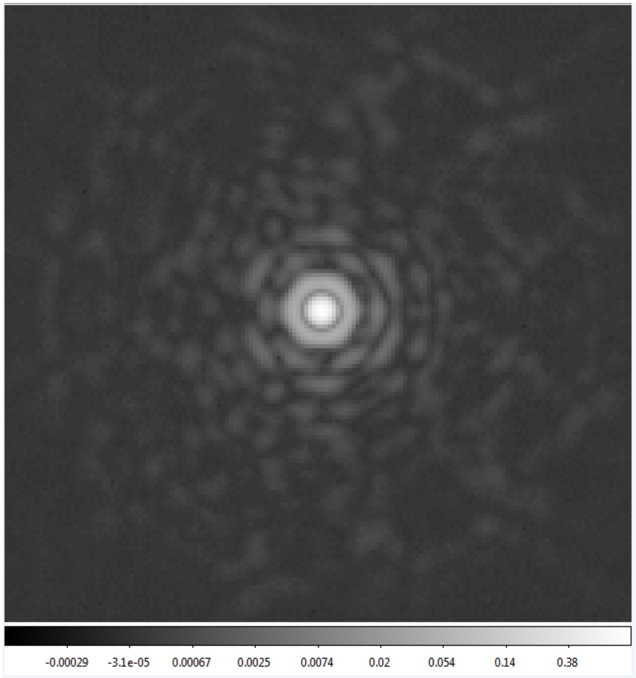
Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



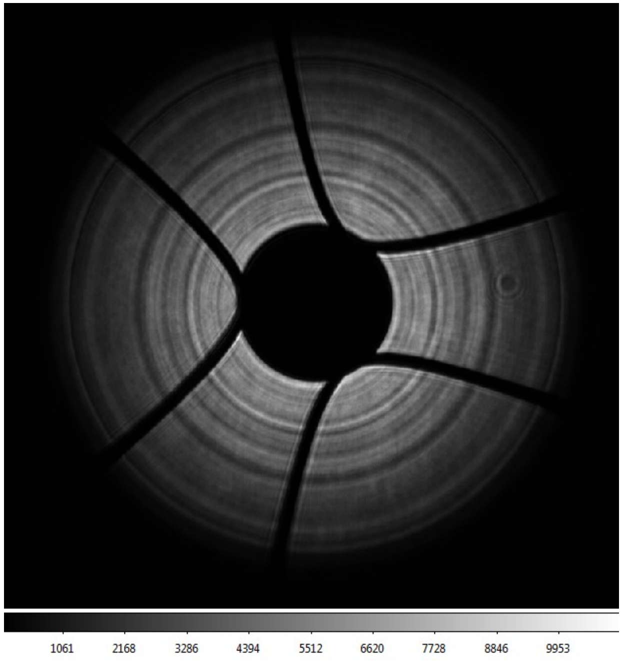
PIACMC lab performance @ WFIRST (Kern et al. 2016)

Operates at 1e-7 contrast, 1.3 l/D IWA, 70% throughput
Visible light

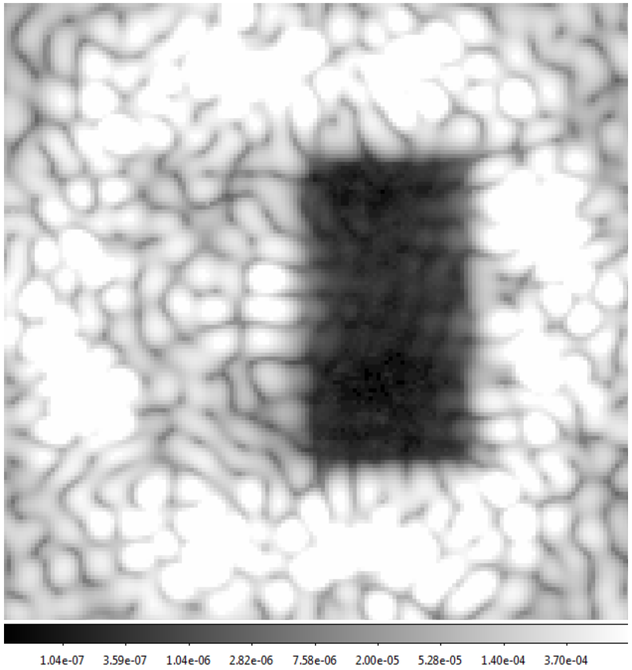
non-coronagraphic PSF



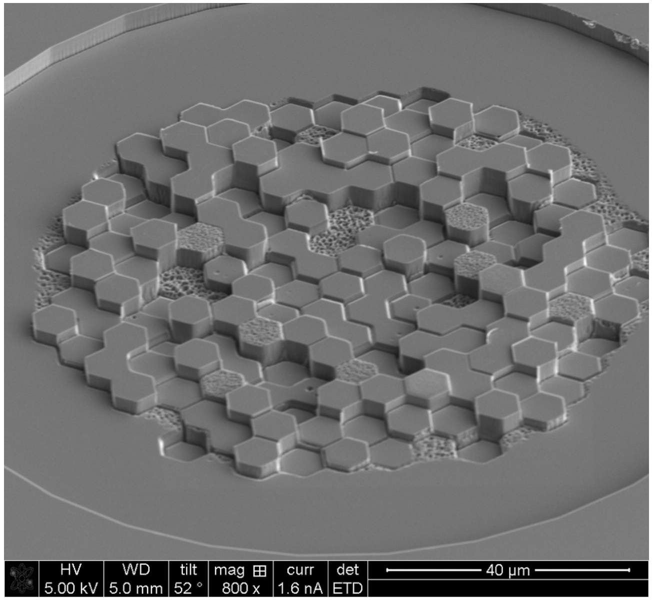
Remapped pupil



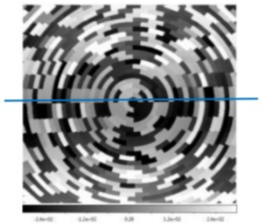
Coronagraphic image

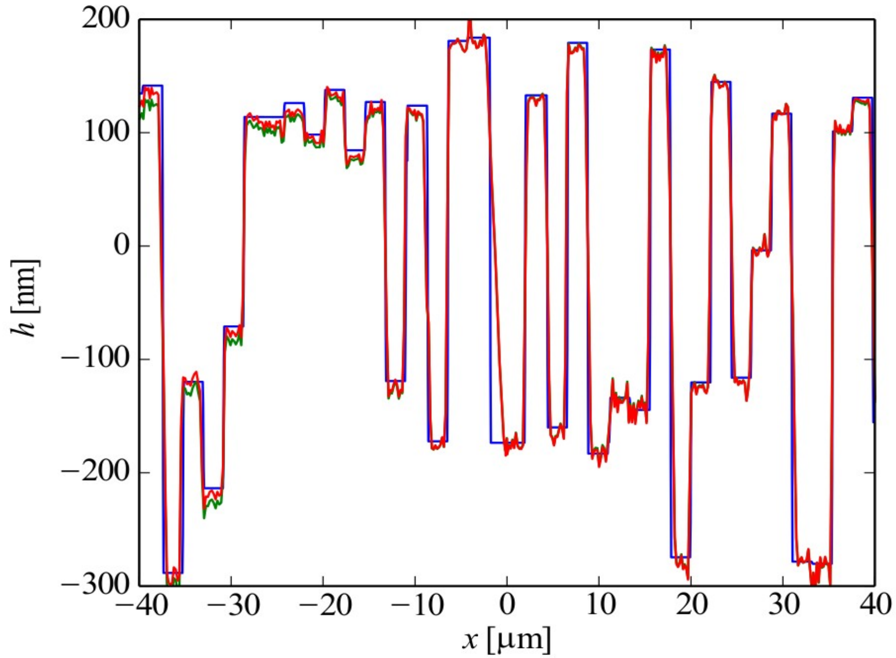


Multi-zone PIAACMC focal plane mask

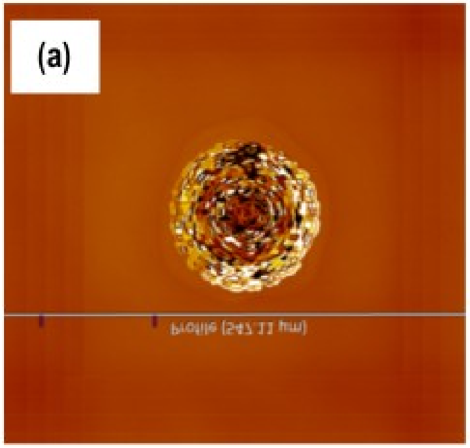


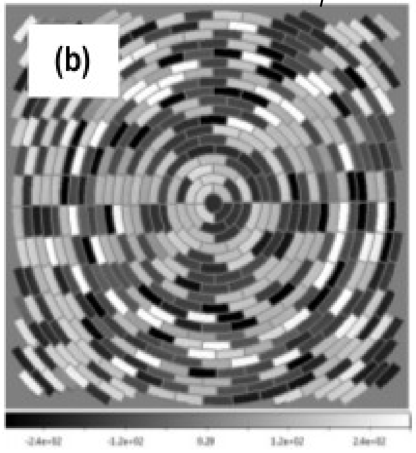
← SCExAO focal plane mask (2017)

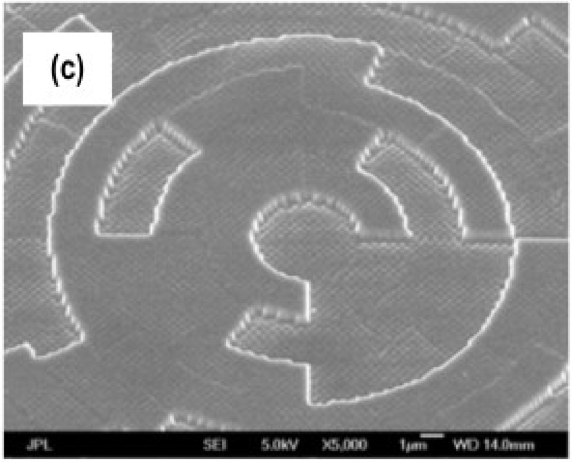


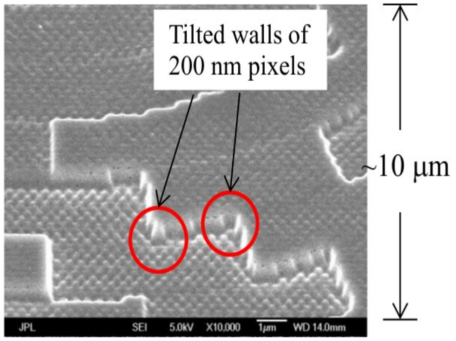


Focal plane mask manufactured at JPL's MDL
Meets performance requirements
(WFIRST PIAACMC Milestone report)

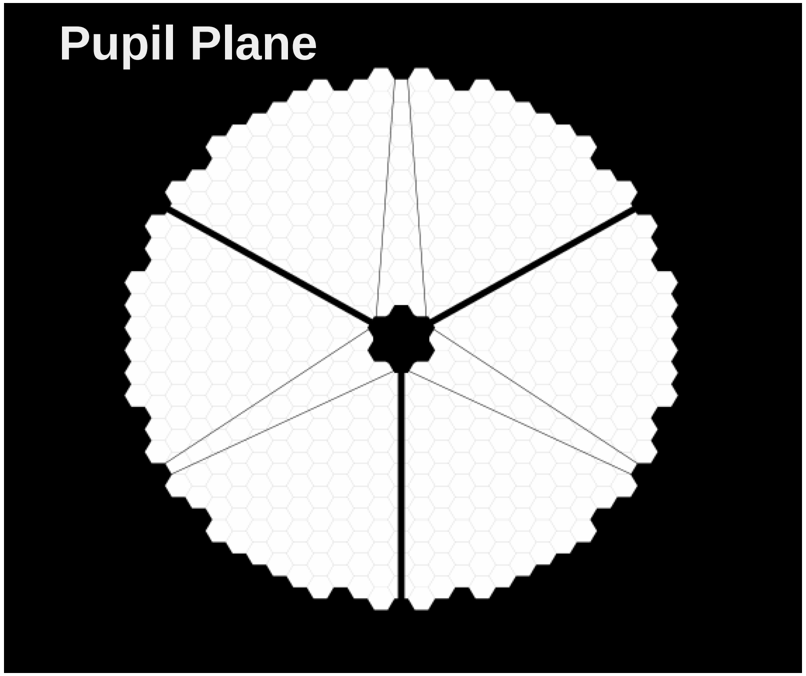


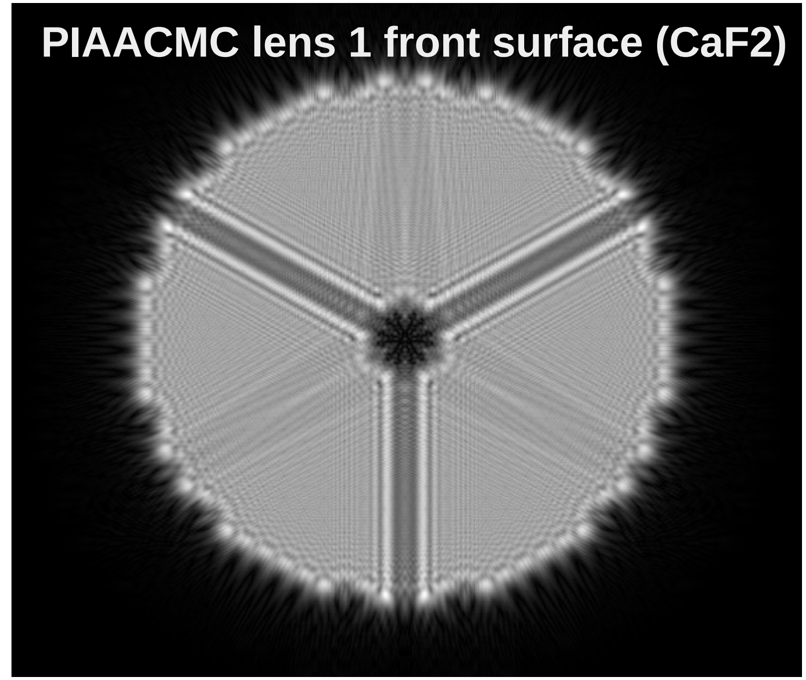


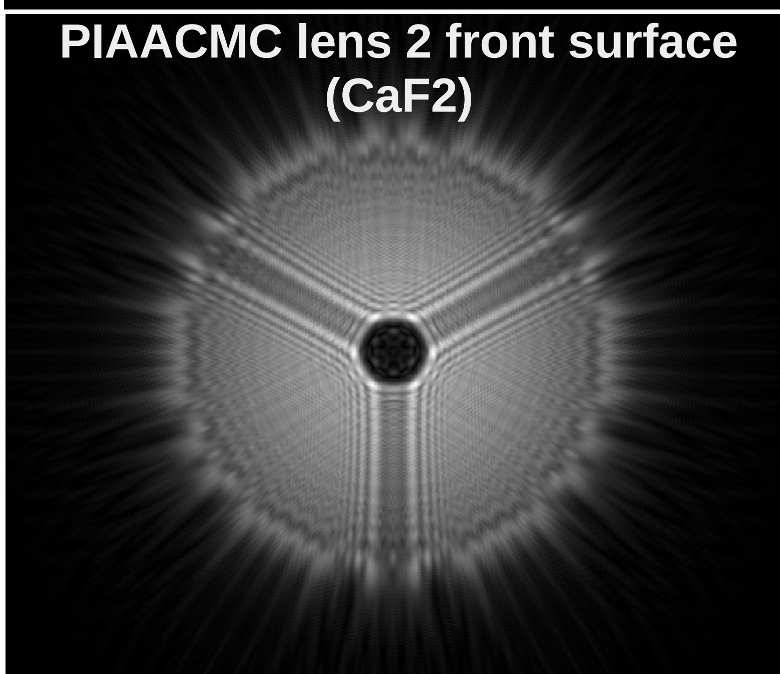


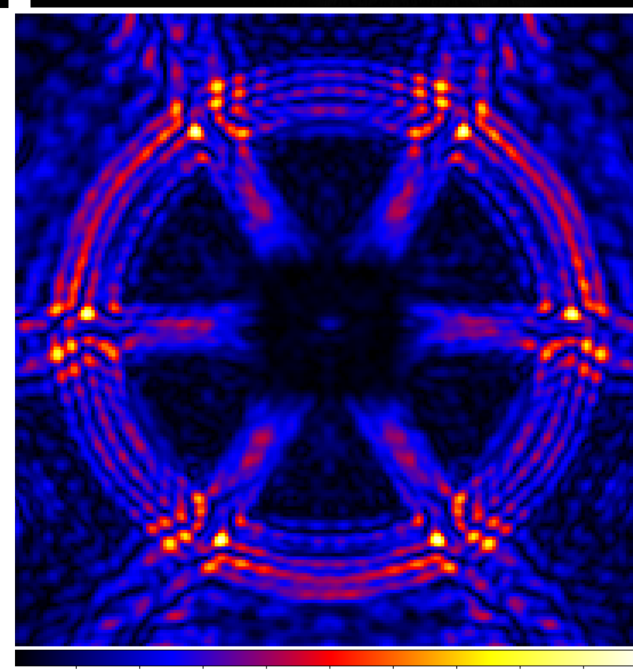


TMT coronagraph design for 1 l/D IWA









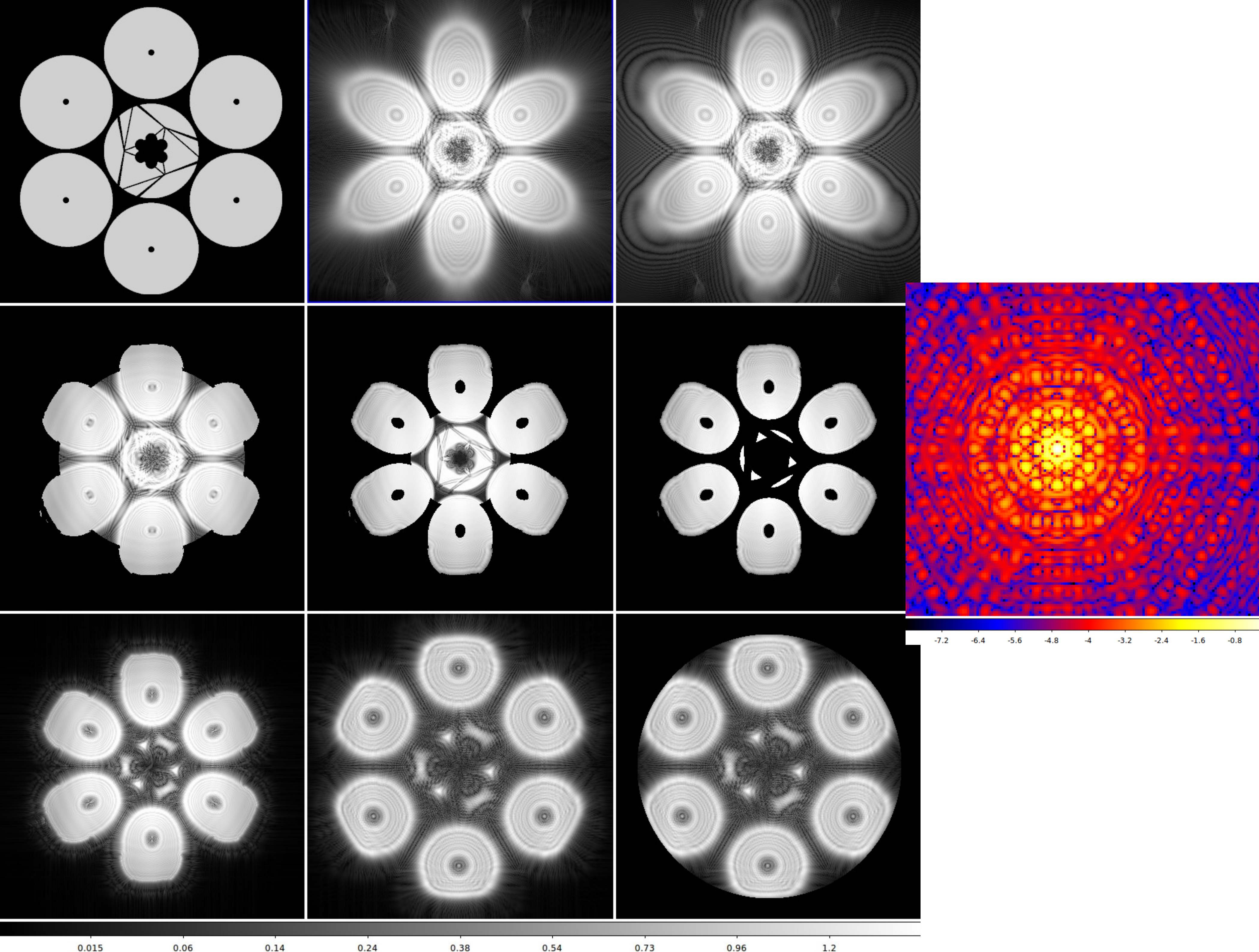
PSF at 1600nm

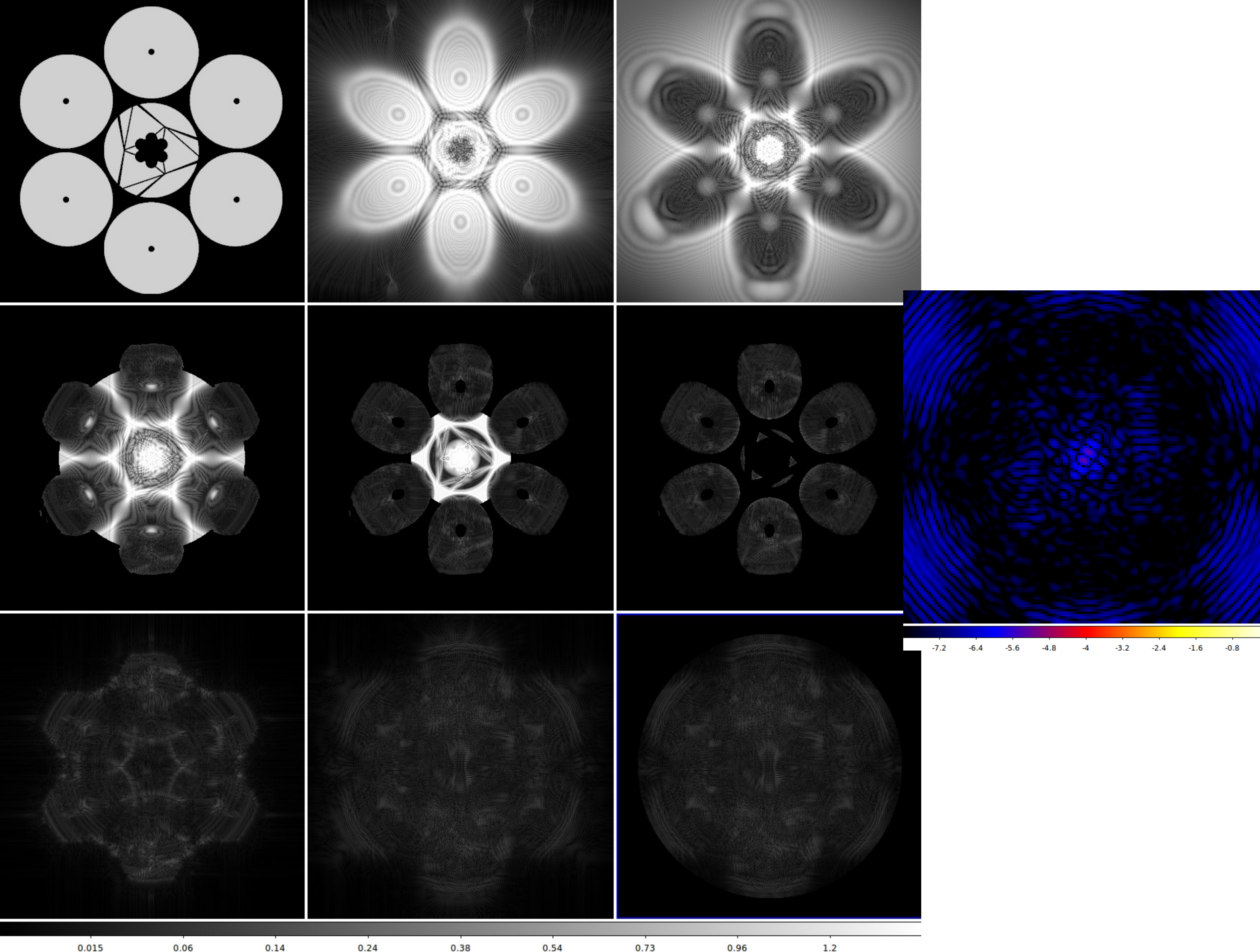
3e-9 contrast in 1.2 to 8 l/D

80% off-axis throughput

1.2 l/D IWA

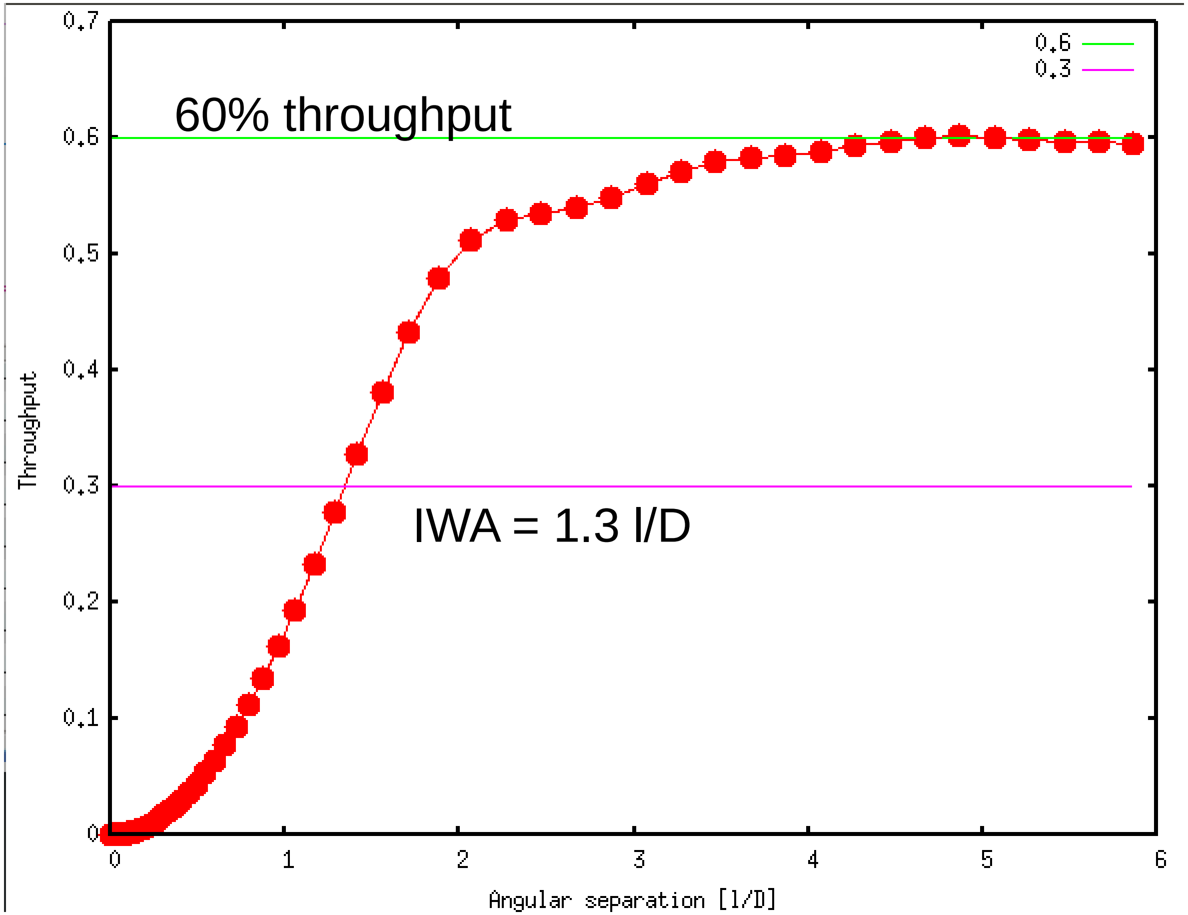
CaF2 lenses
SiO2 mask


-7.2 -6.4 -5.6 -4.8 -4 -3.2 -2.4 -1.6 -0.8
0.015 0.06 0.14 0.24 0.38 0.54 0.73 0.96 1.2

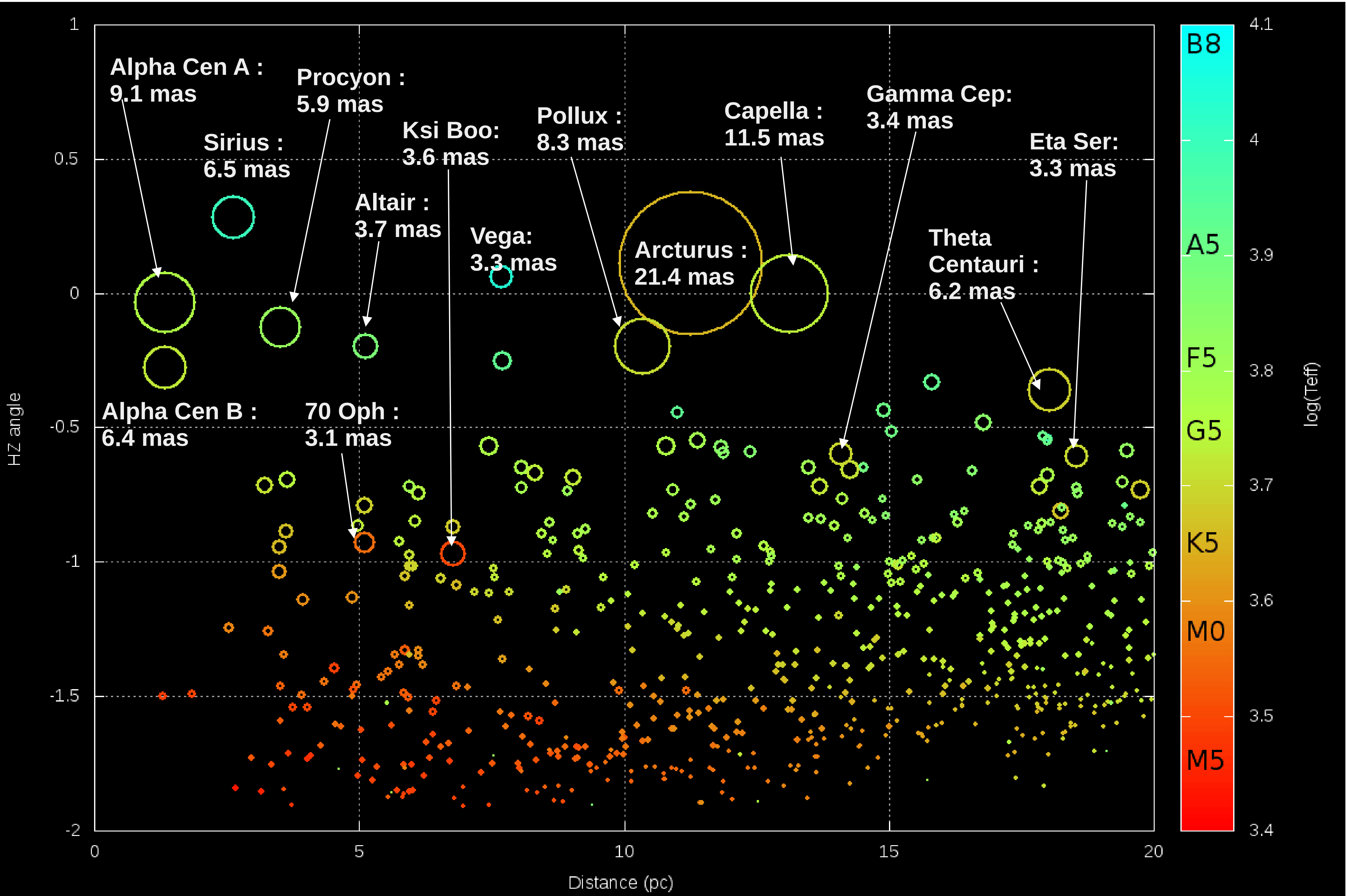

-7.2 -6.4 -5.6 -4.8 -4 -3.2 -2.4 -1.6 -0.8
0.015 0.06 0.14 0.24 0.38 0.54 0.73 0.96 1.2

Performance (GMT pupil)

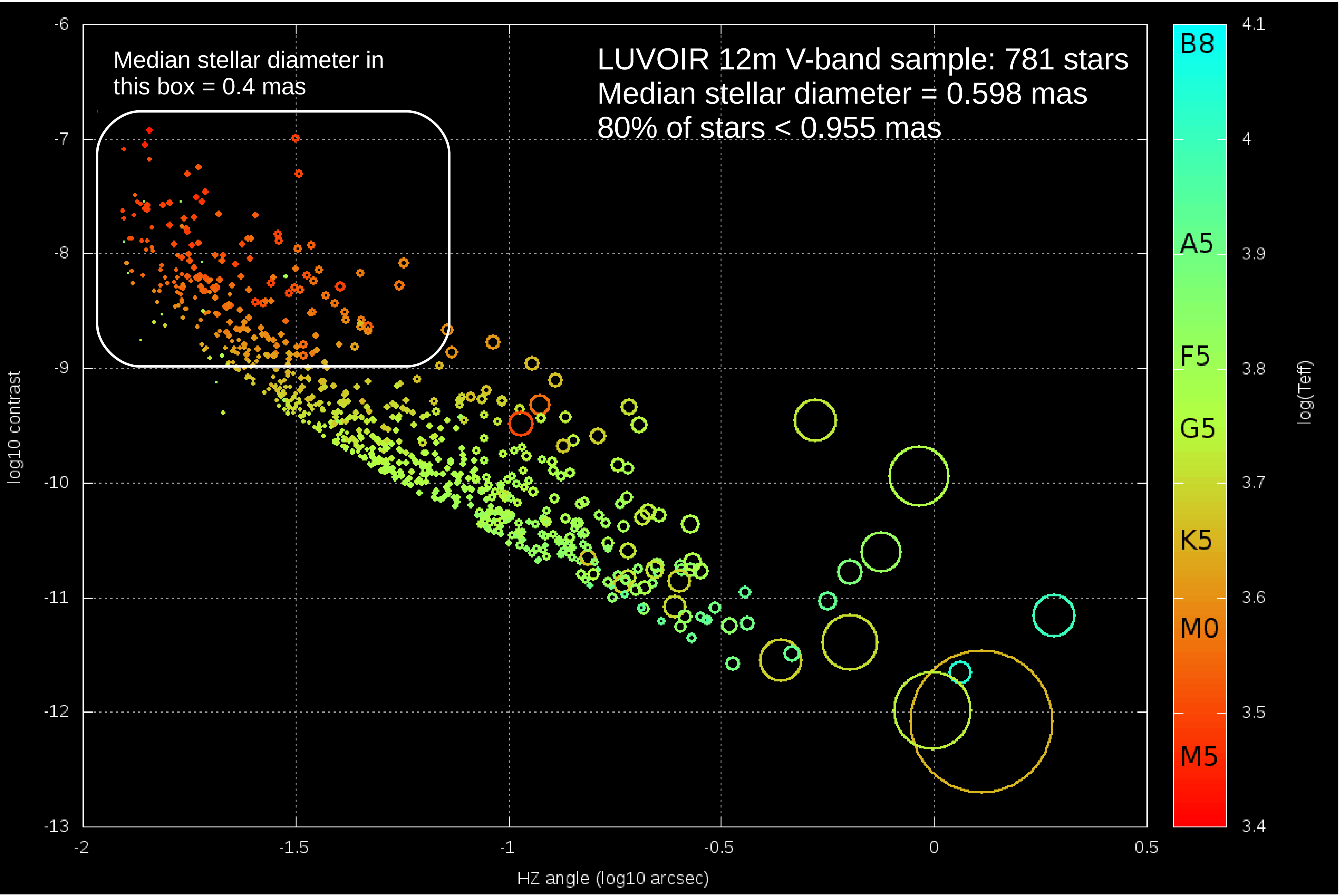
1e-7 contrast
3e-6 contrast @ 3 l/D for 6% l/D disk



Stellar angular sizes strongly correlate with HZ angle



… and contrast

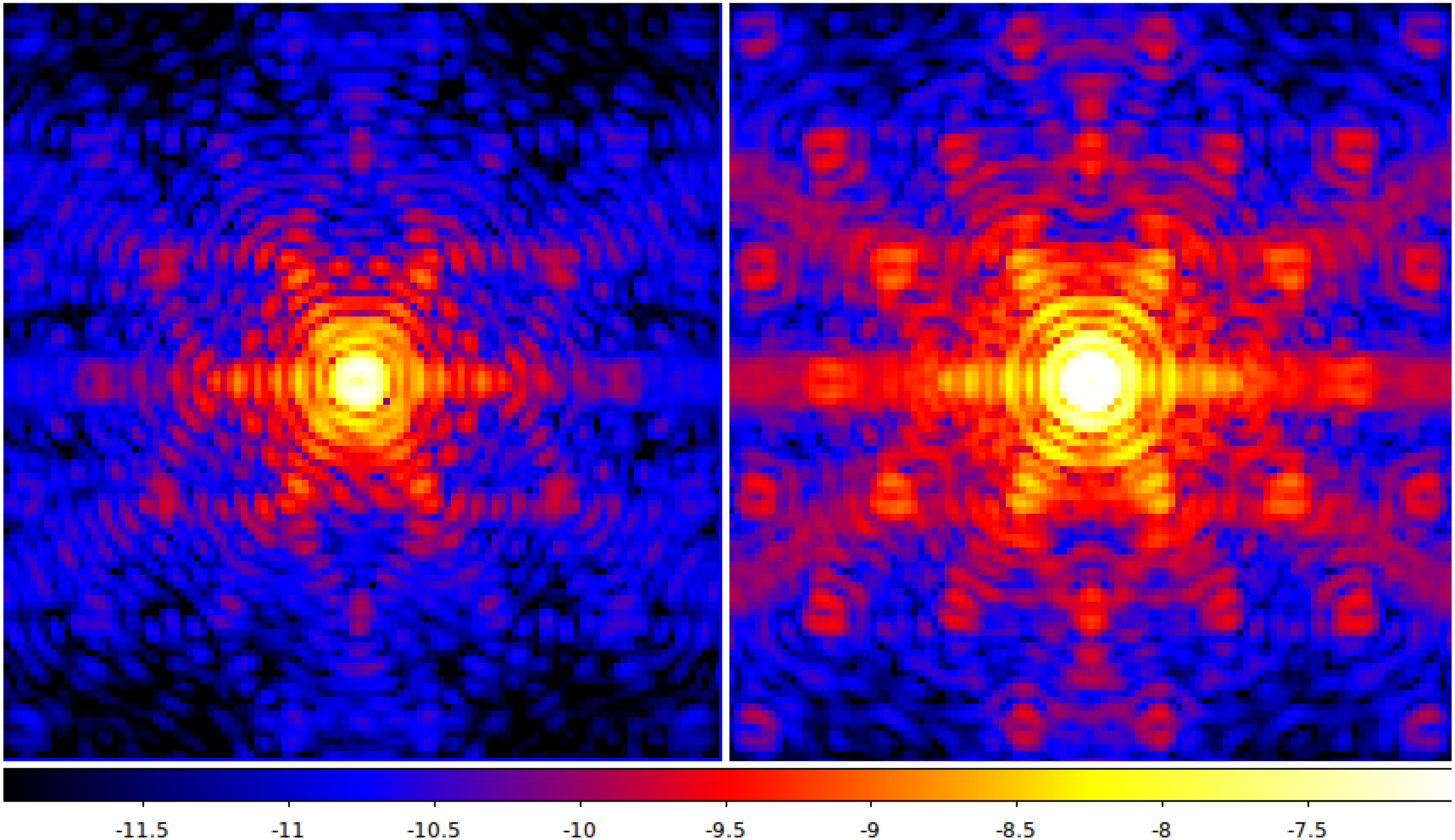


PSF is dominated by stellar angular size

PSF dominated by incoherent spots due to stellar angular size →contributes to photon noise, but does not interfere coherently with wavefront errors → can be removed in post-processing

Instead of radial average contrast, we use 50-percentile (search) and 20-percentile (spectroscopy) radial contrasts for performance evaluation: we avoid the bright spots

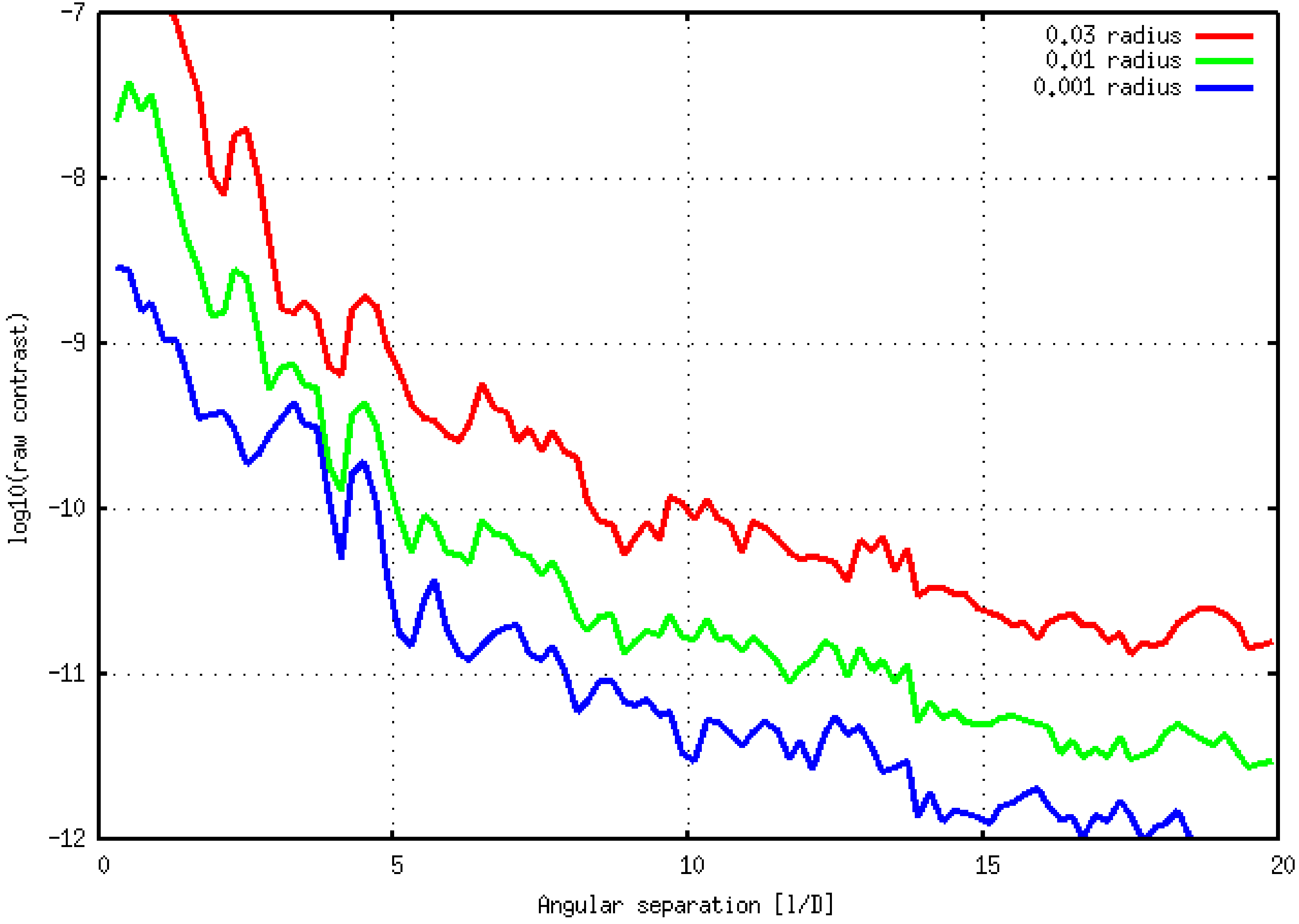
Source radius = 0.01 l/D **Source radius = 0.03 l/D**



10% bandwidth optimized

APLCMC design – Raw Contrast

(20 percentile along each radius)



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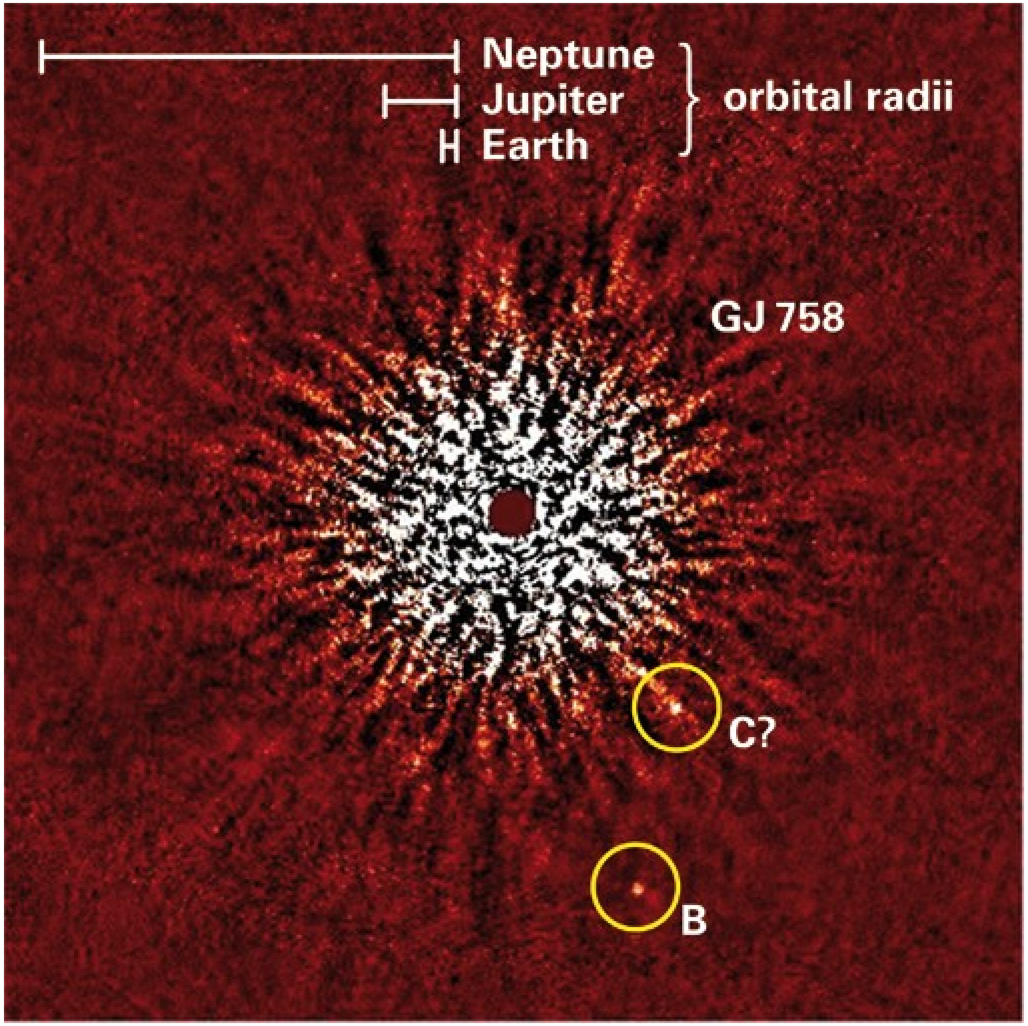
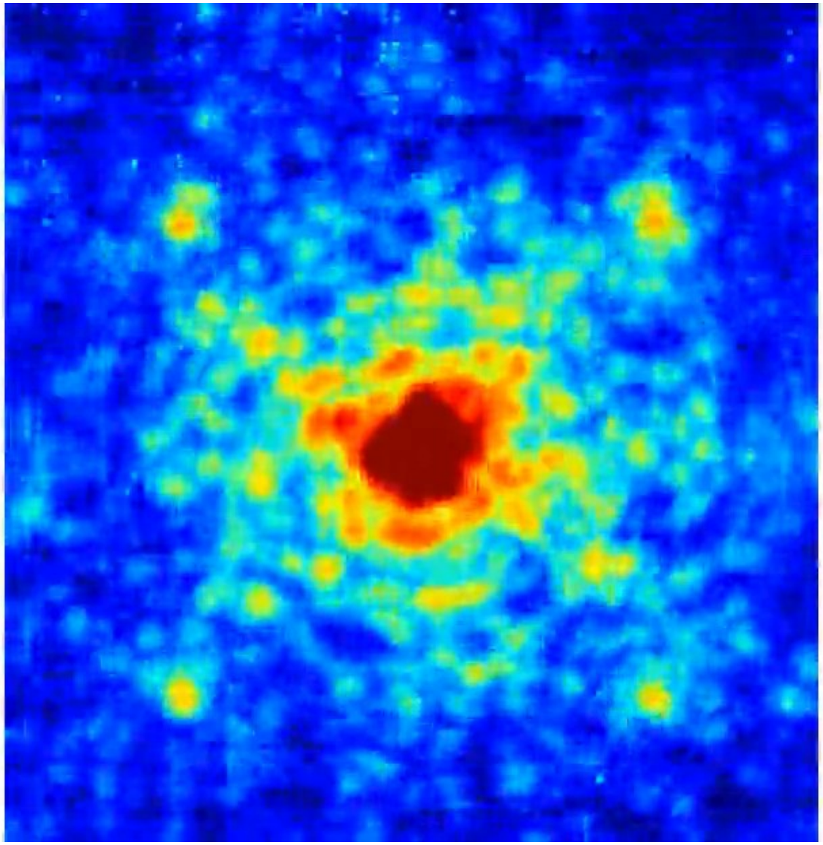
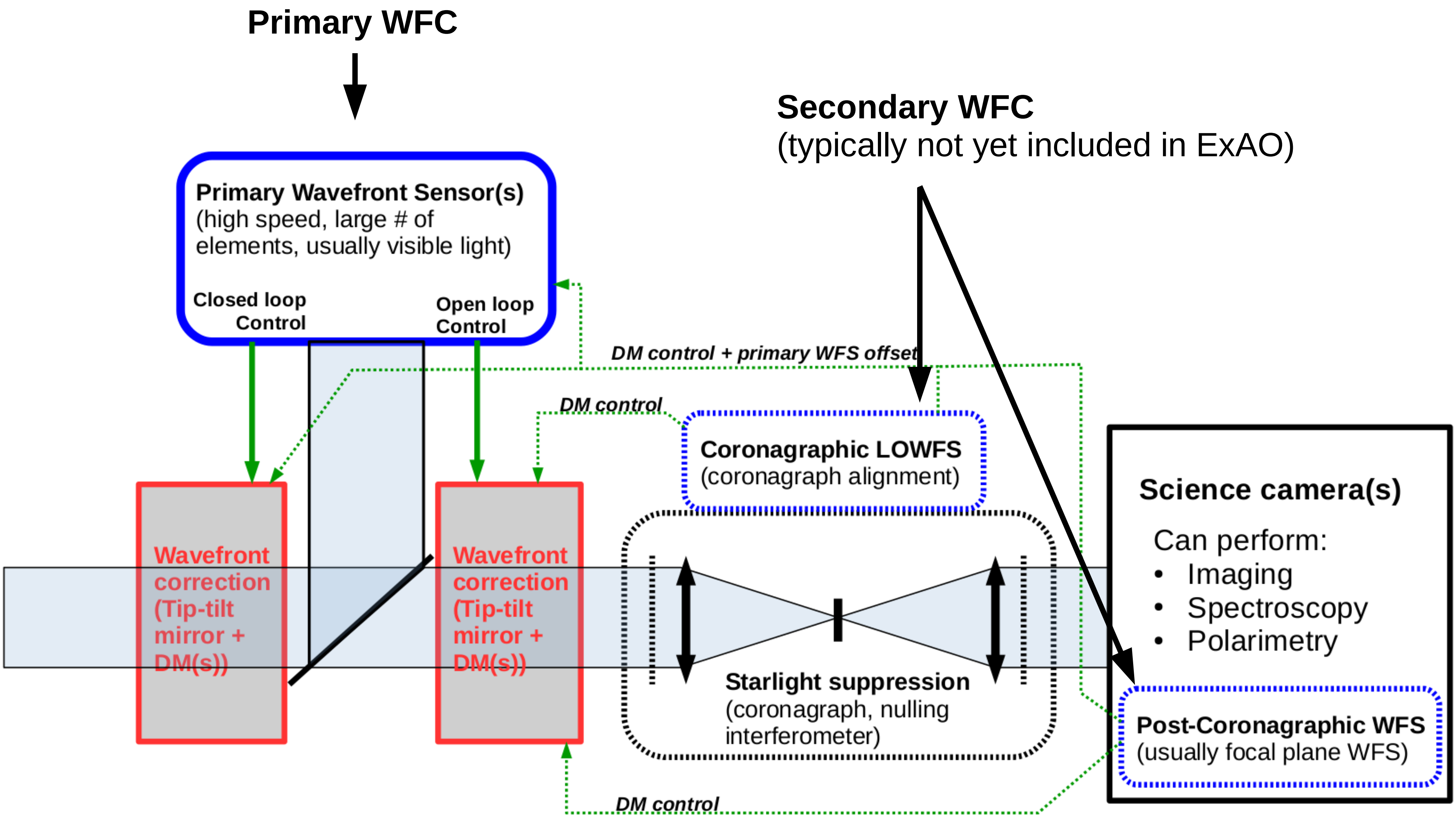
The REAL challenge: Wavefront error (speckles)



H-band fast frame imaging (1.6 kHz)

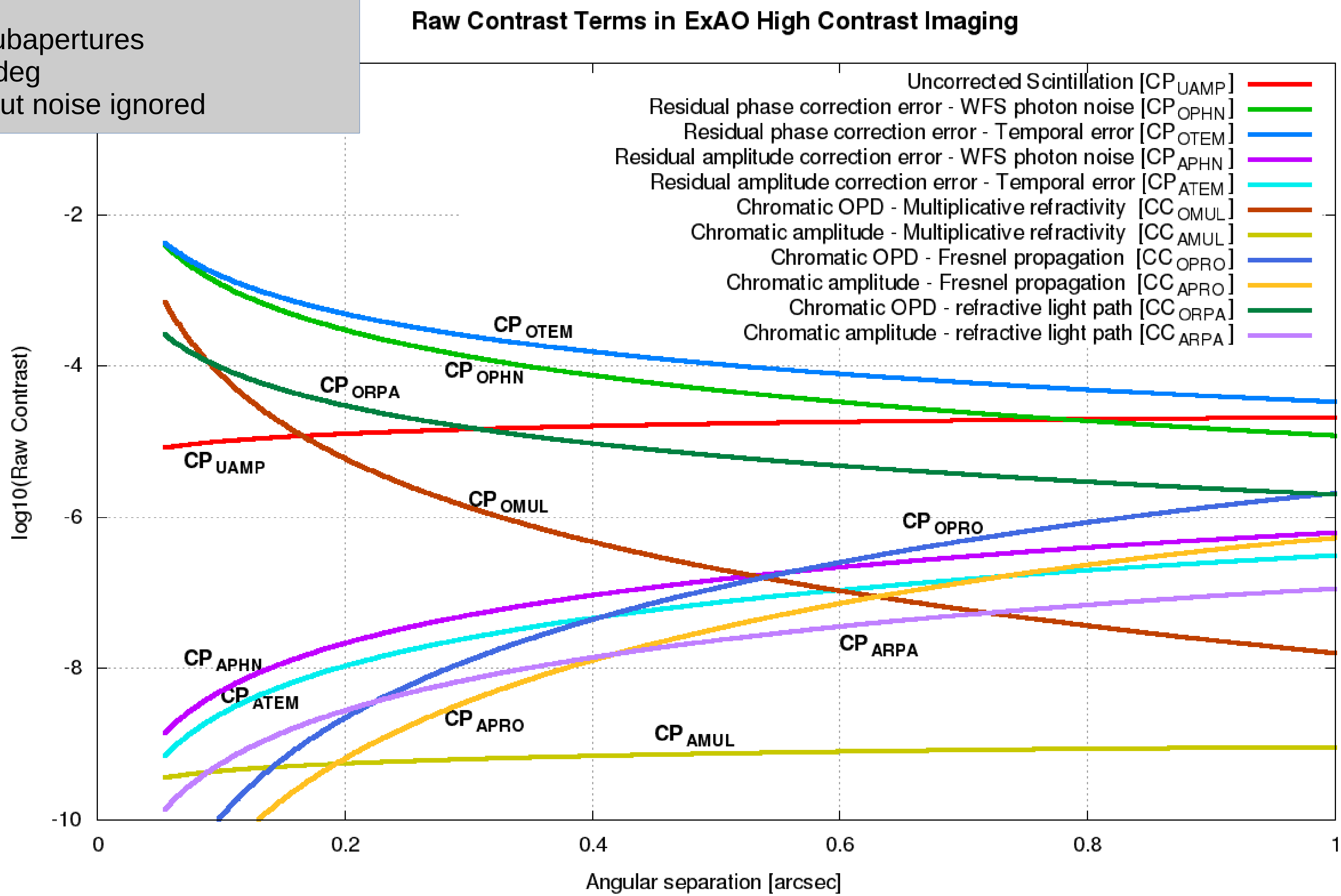


ExAO system architecture

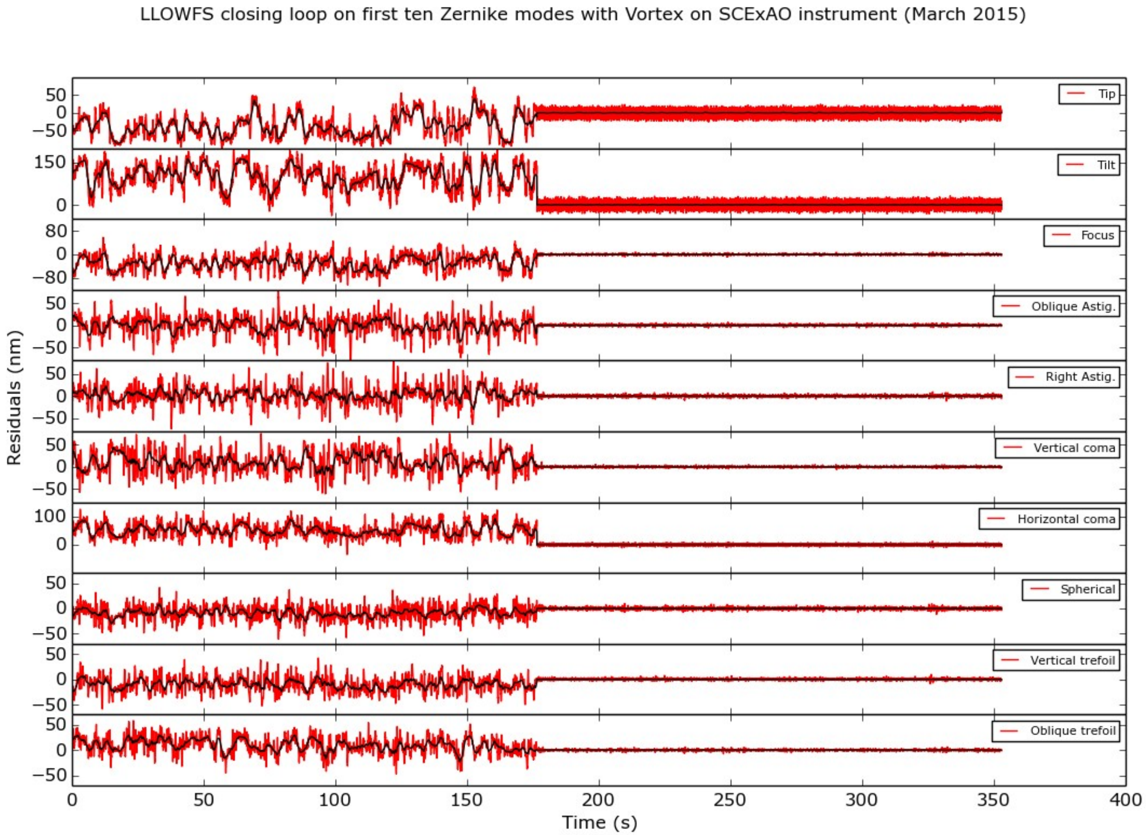


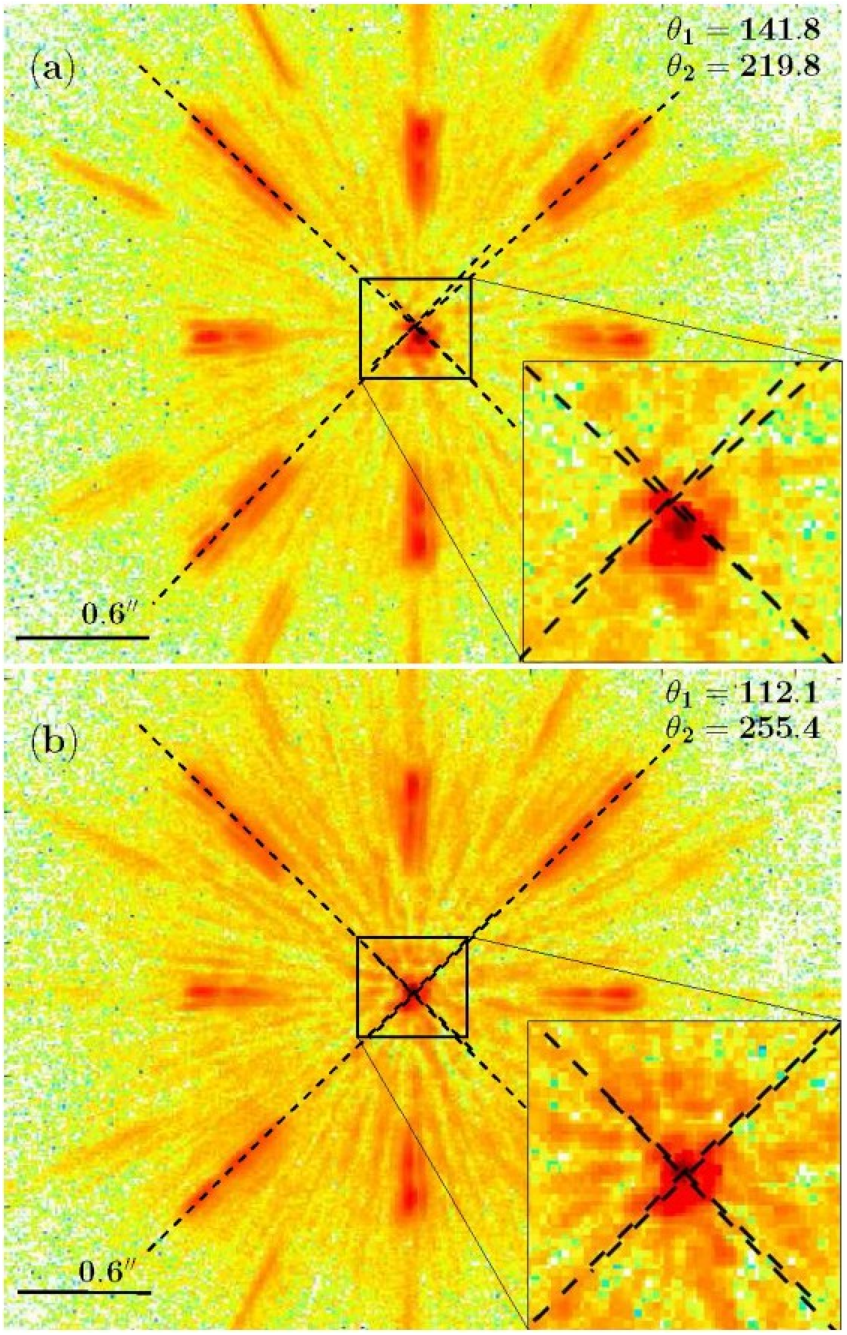
D=8m telescope
High contrast imaging at 1.6 um
Wavefront sensing at 0.8 um
30% efficiency WFS
40% wide WFS spectral band
1 kHz WFS frame rate
Integrator controller with optimal gain setting
Wind speed = 8 m/s
Fried parameter r_0 = 0.15 m at 0.5 um
m_I = 8 target
SHWFSm 15cm subapertures
Zenith angle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

Contrast Error Budget (Primary WFC)



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)

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

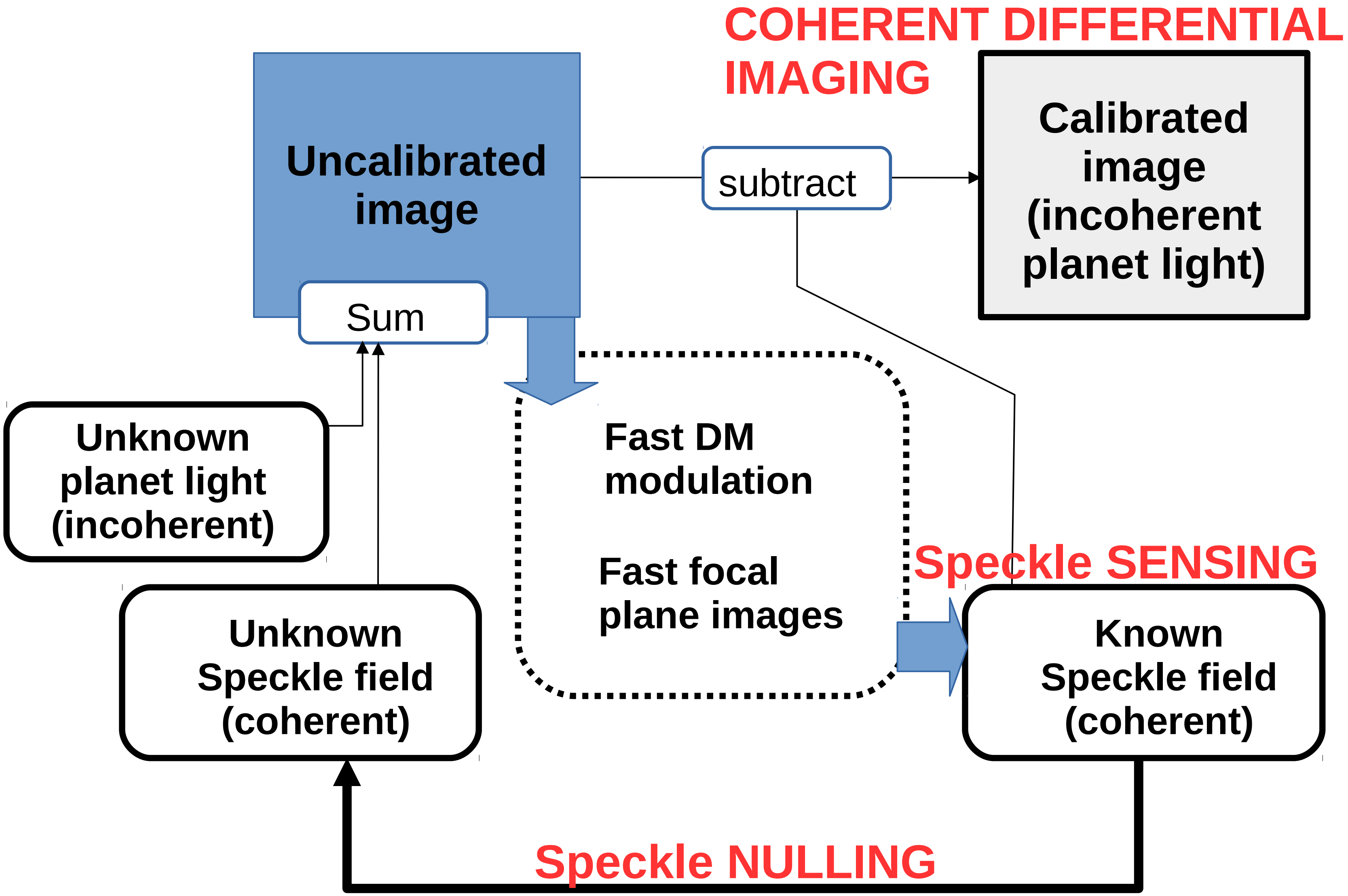
Predictive Control
Eliminates time lag, improves sensitivity

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

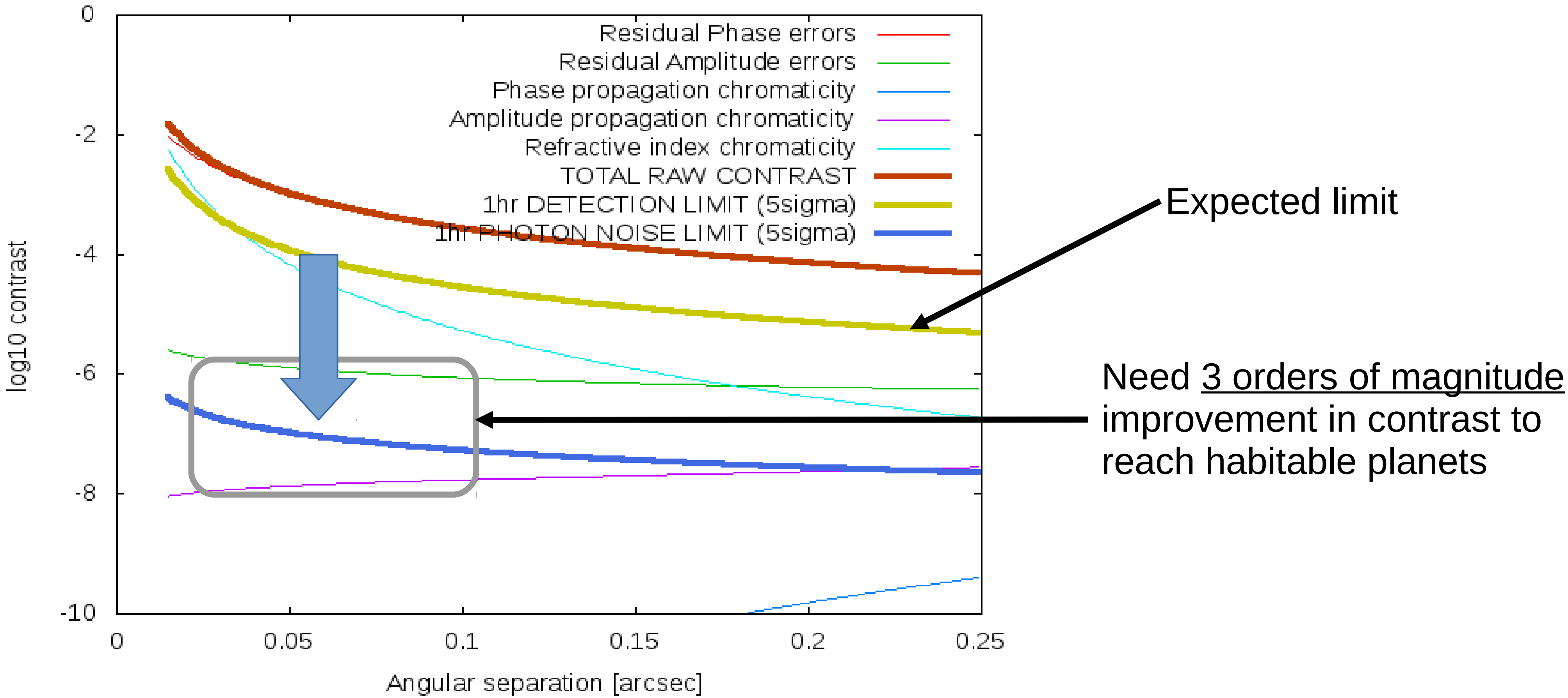
Spectral discrimination (HR)
Especially powerful at high spectral resolution

High Speed Speckle Control & Calibration



PREVIOUS technologies

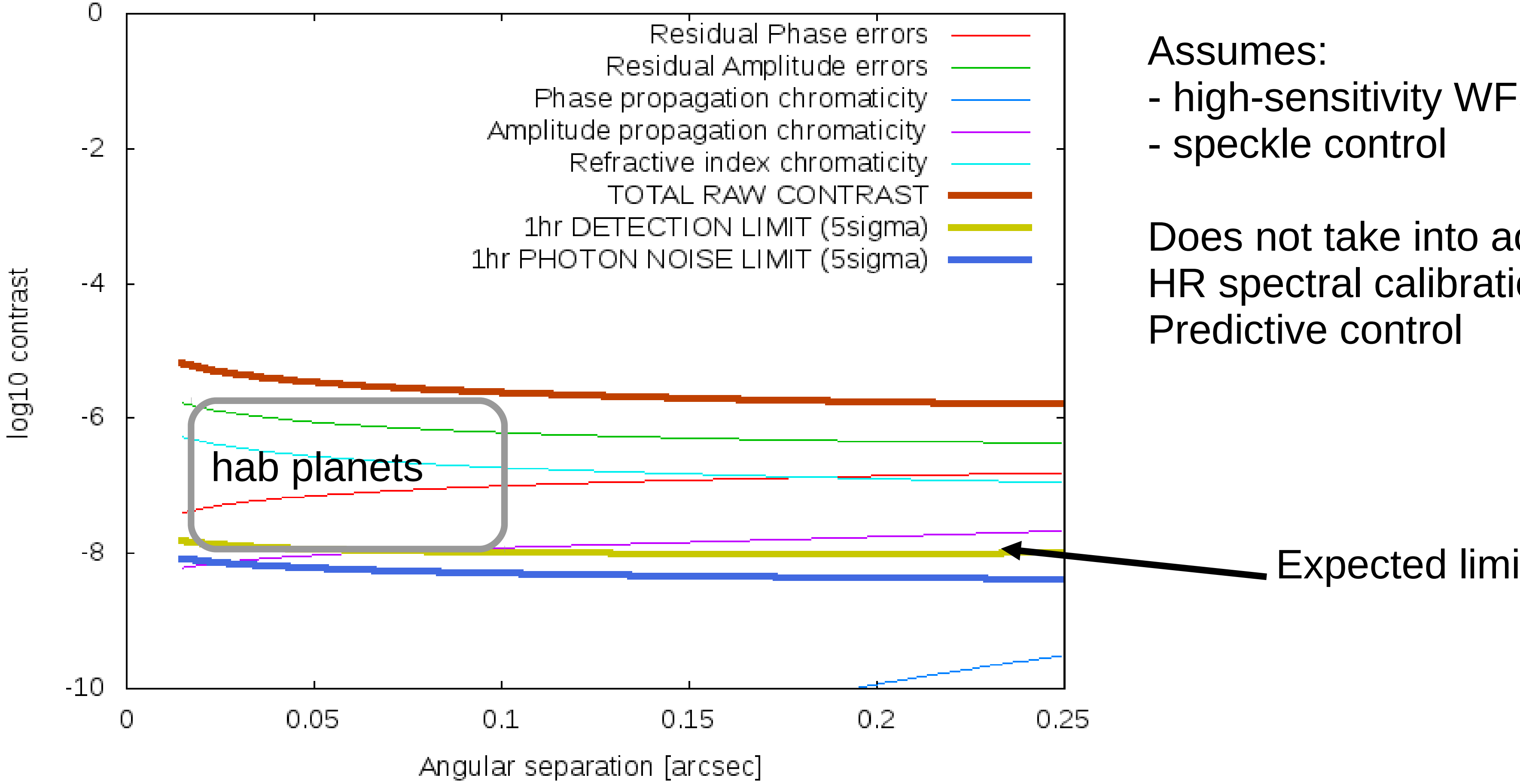
30m: SH-based system, 15cm subapertures



Limited by residual OPD errors: time lag + WFS noise
kHz loop (no benefit from running faster) – same speed as 8m telescope
>10kph per WFS required

Detection limit ~1e-3 at IWA, **POOR AVERAGING due to crossing time**

CURRENT/NEW technologies



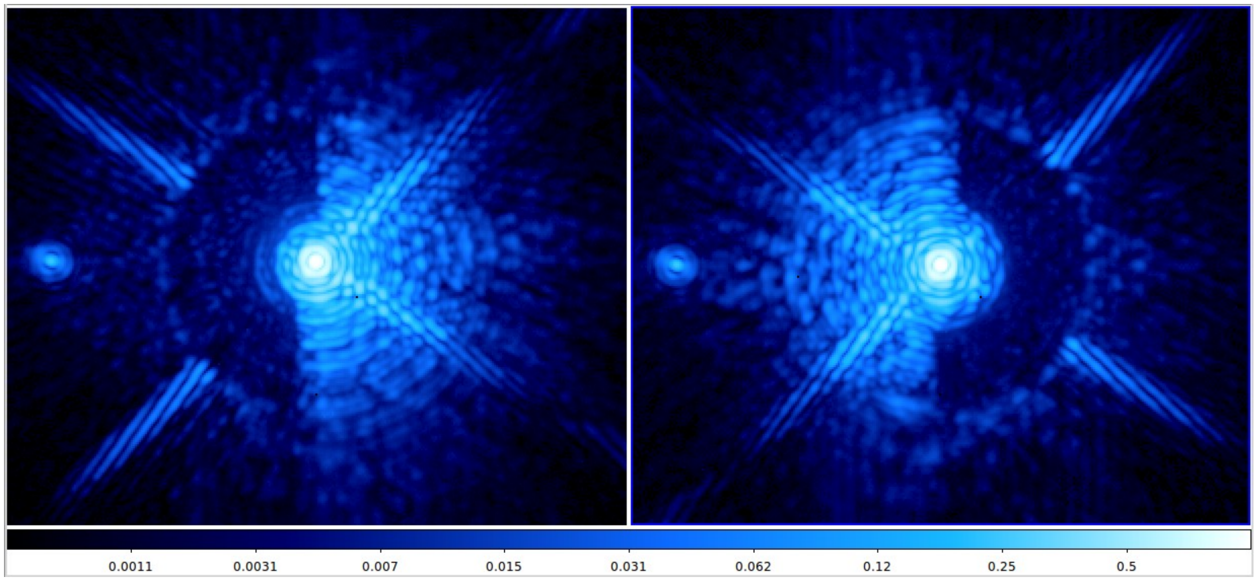
Assumes:
- high-sensitivity WFS
- speckle control

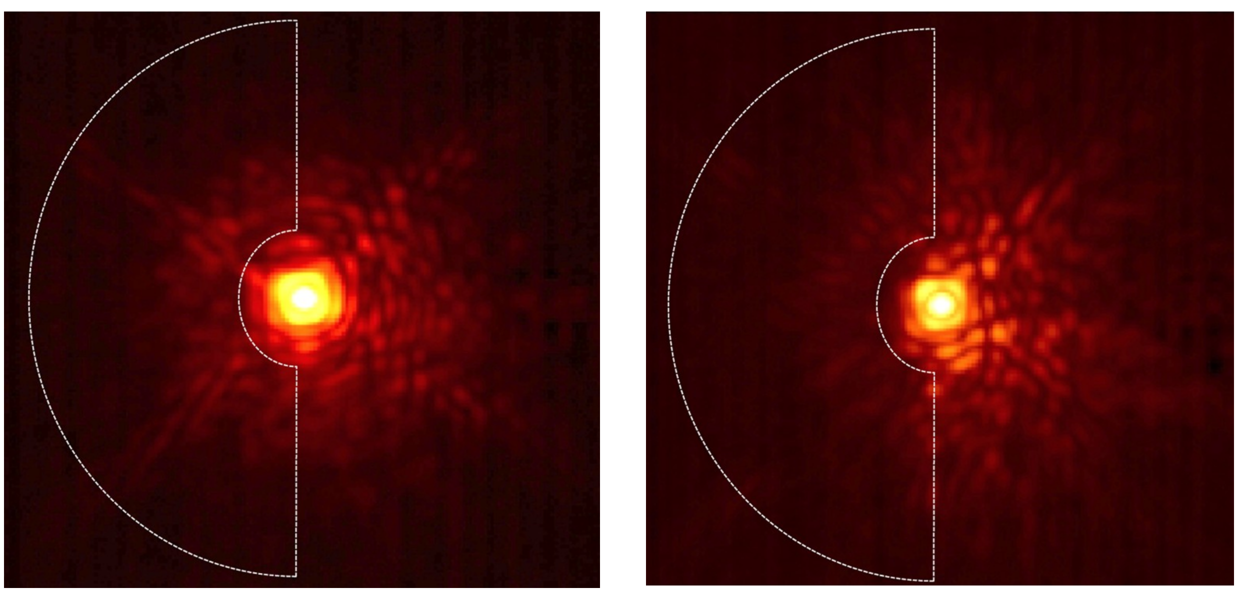
Does not take into account:
HR spectral calibration
Predictive control

300Hz speckle control loop (~1kHz frame rate) is optimal

Residual speckle at ~1e-6 contrast and fast → good averaging to detection limit at ~1e-8

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

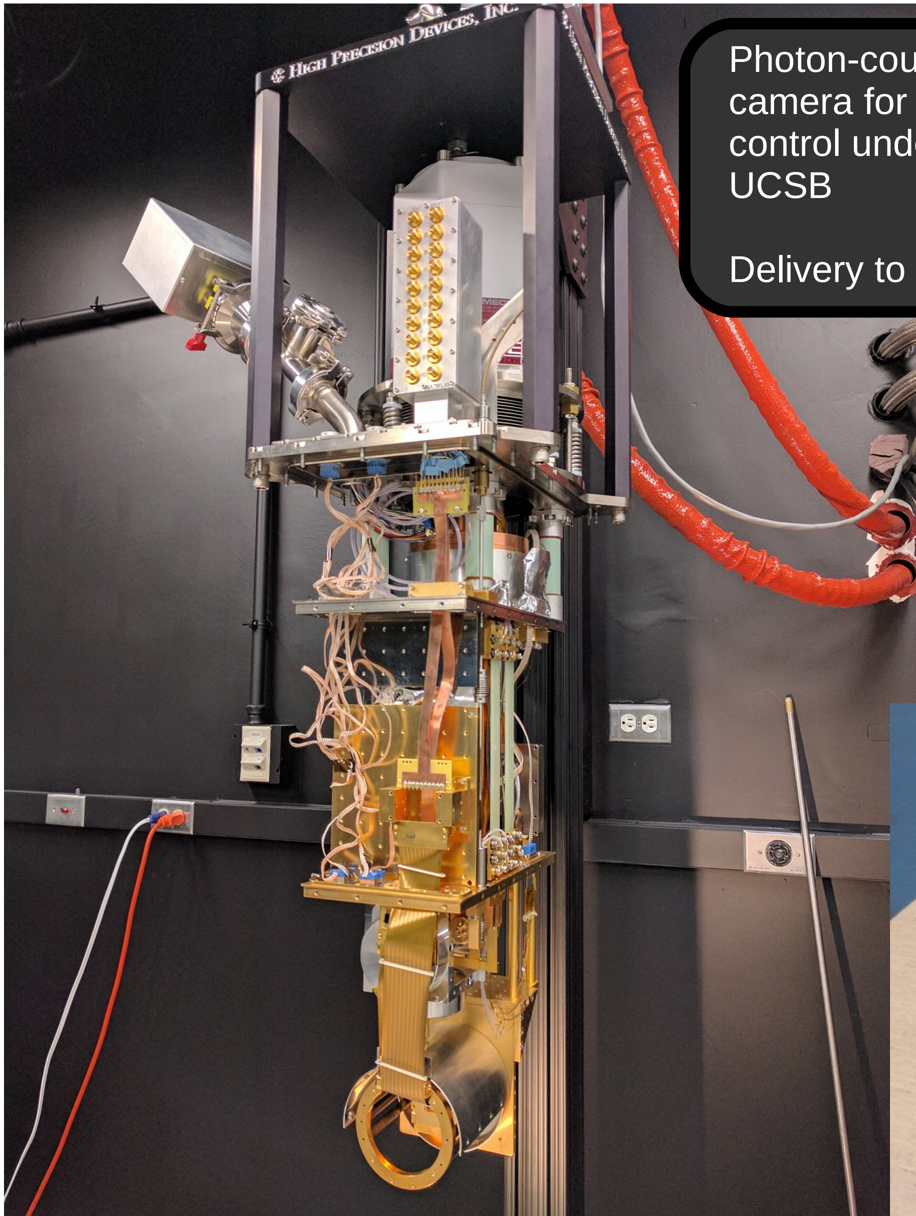
To:
- 0.8 e- RON
- 3500 Hz frame rate

Expect some updates

Observatoire de la CÔTE d'AZUR

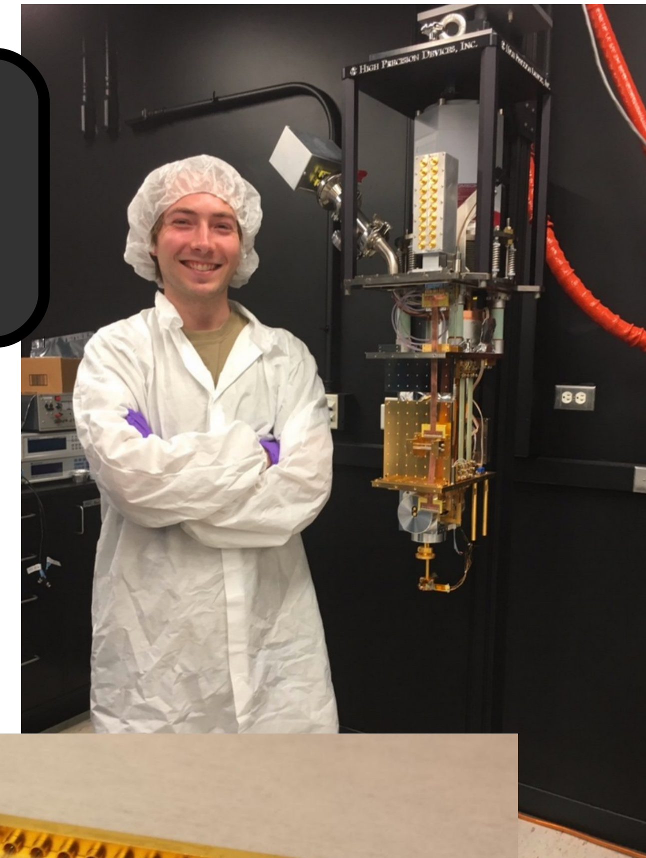
MKIDS camera (built by UCSB for SCExAO)

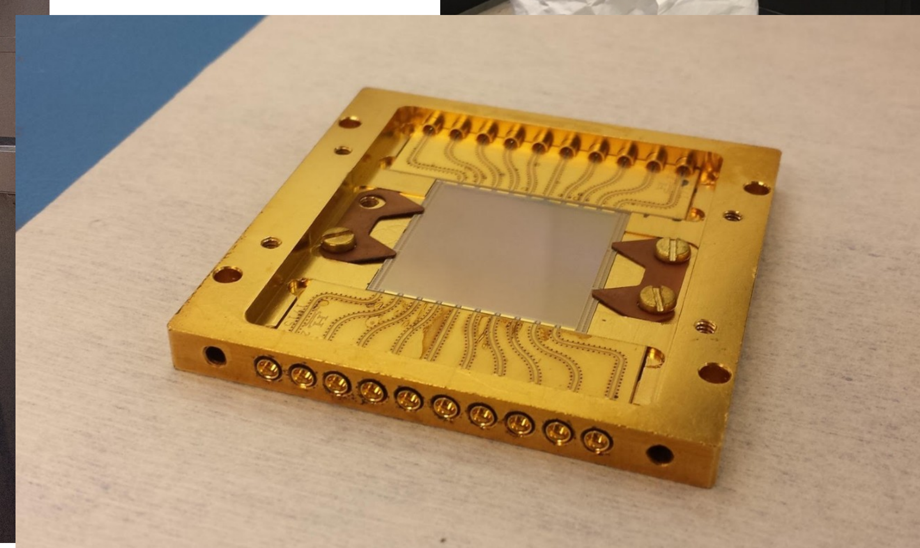
Photon-counting, wavelength resolving 140x140 pixel camera



Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB

Delivery to SCExAO in fall 2017





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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% ?)

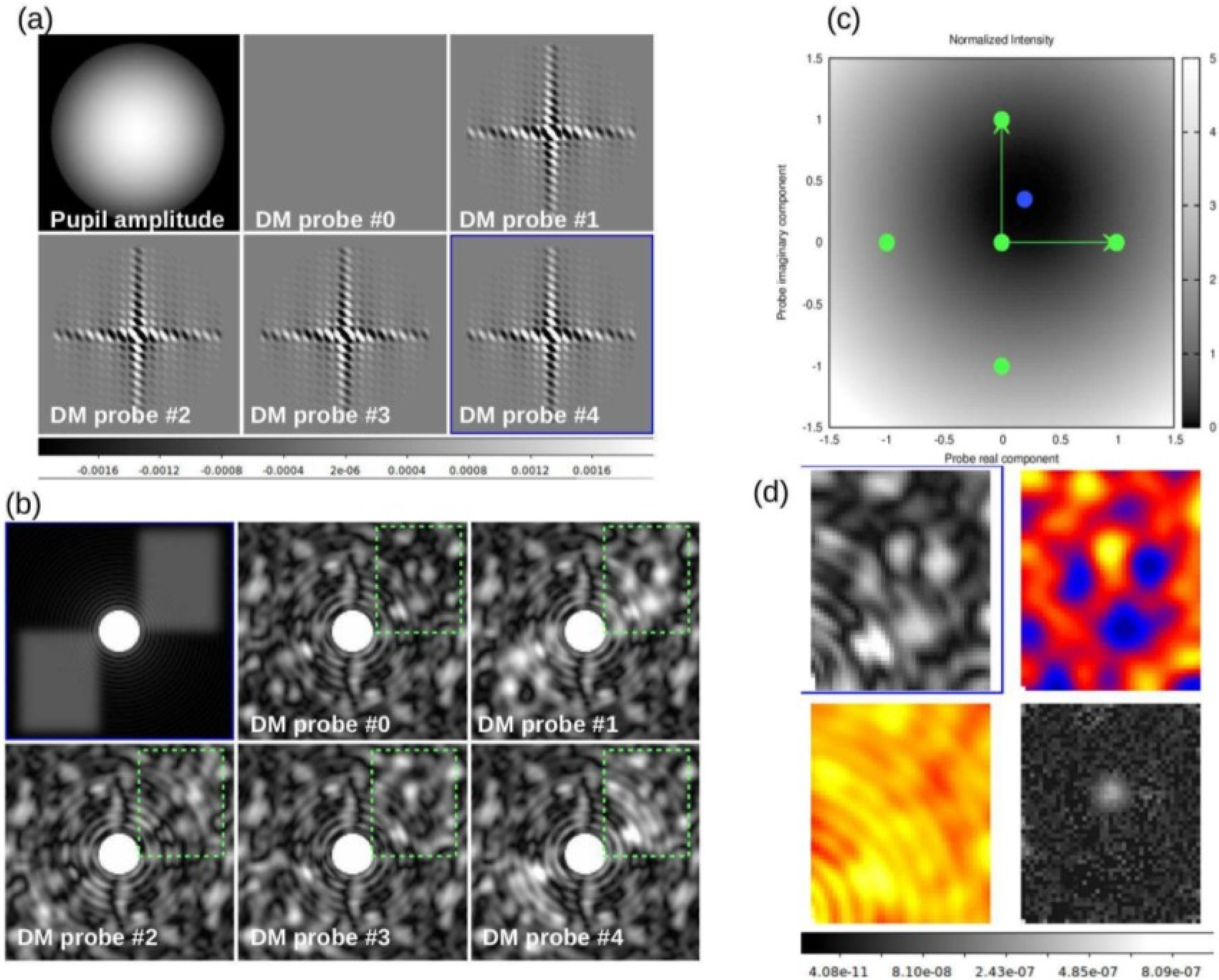
→ photon noise (from starlight) limits use

Coherent Differential Imaging

Can use 100% of light

Challenging to implement, calibration issues

Coherent Speckle Differential Imaging

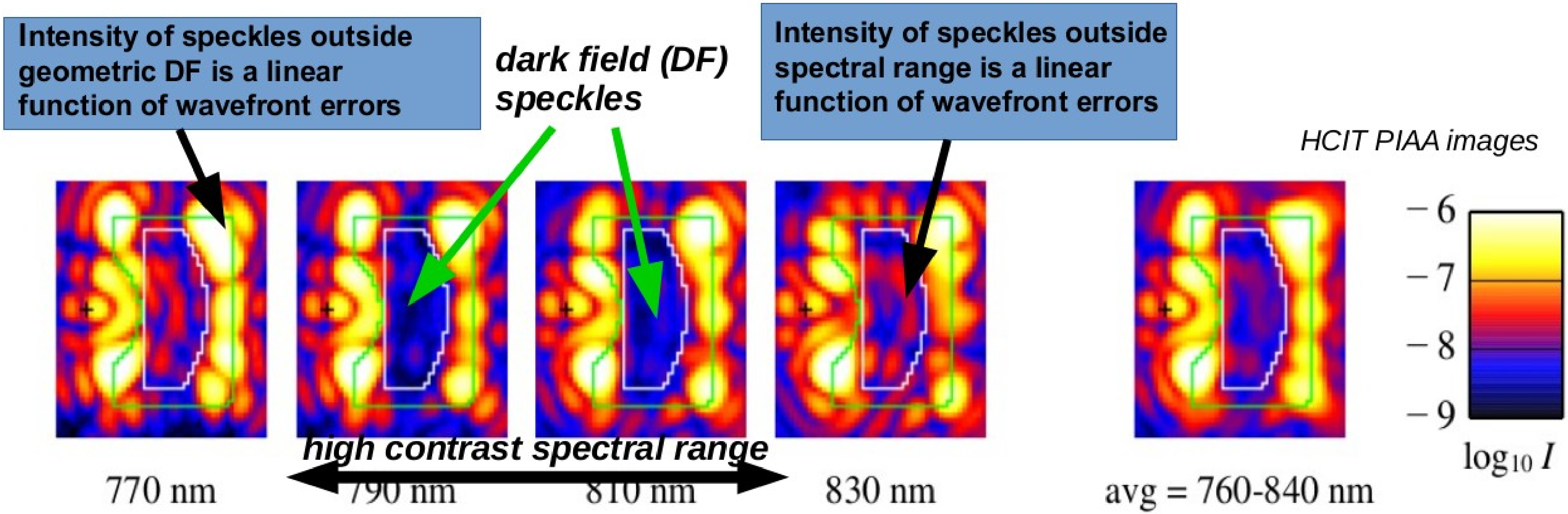


Linear Dark Field Control (LDFC)

See also: Miller et al. 2017, Guyon et al. 2017 (astro-ph)

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)

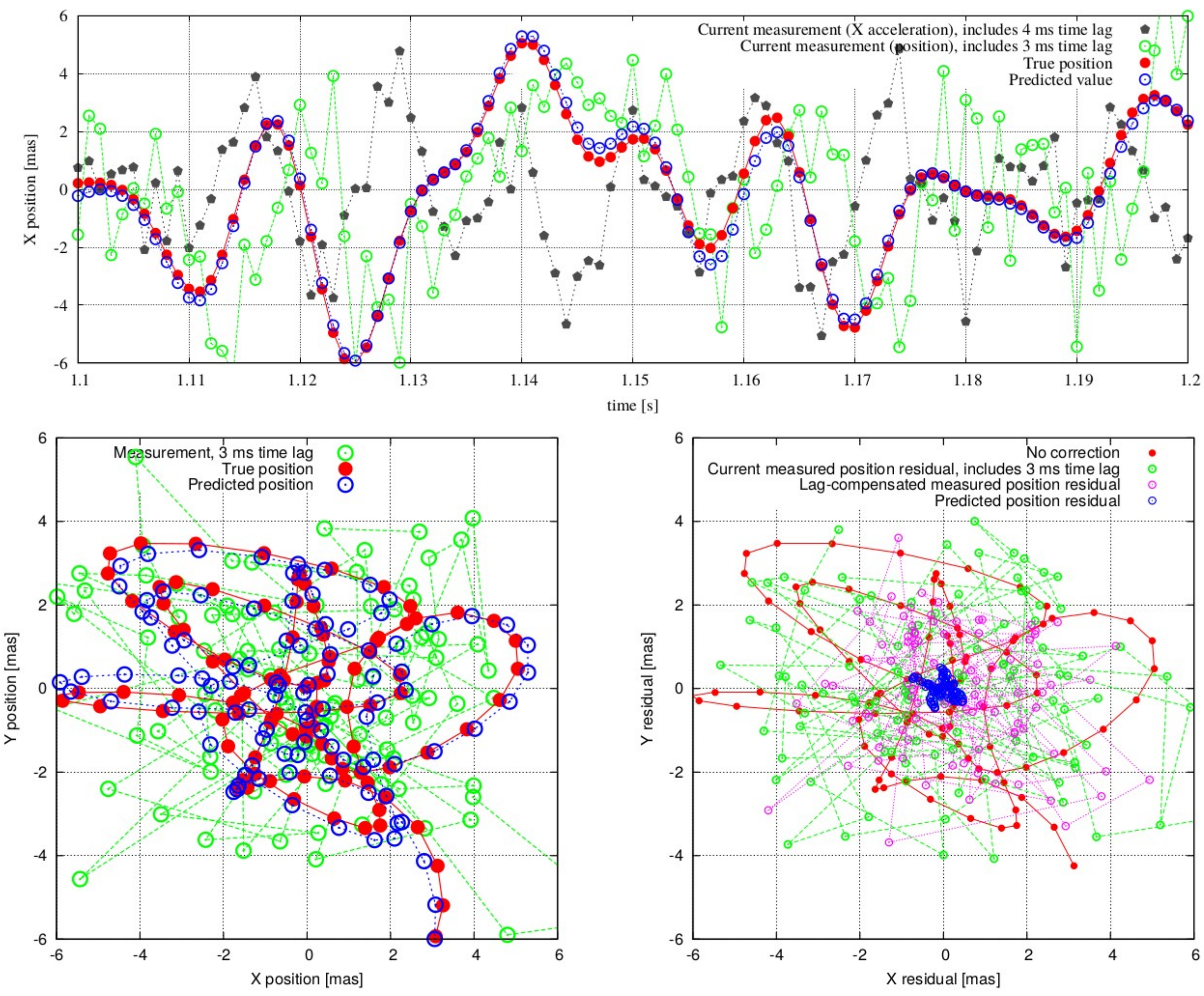
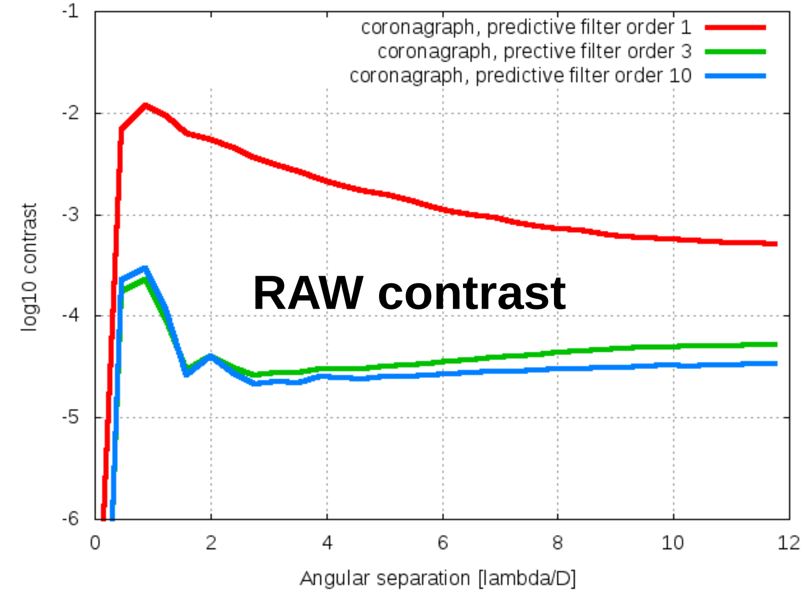
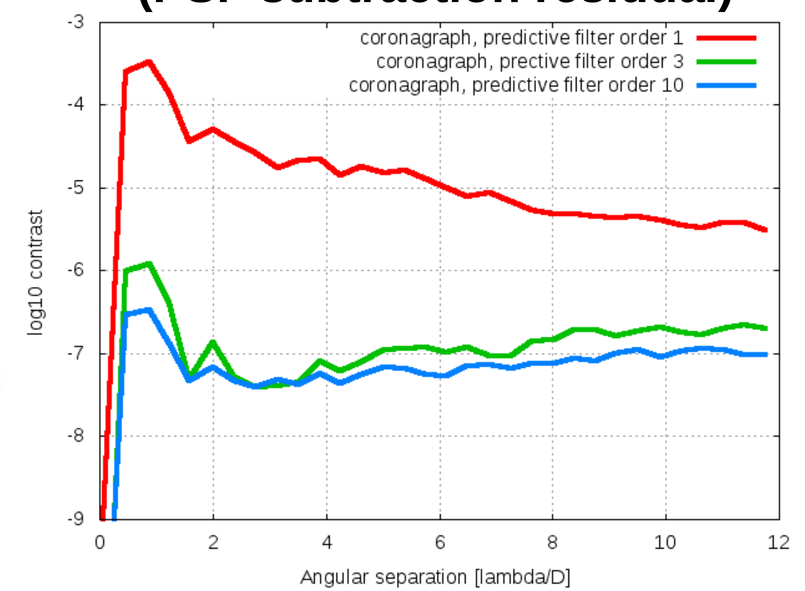


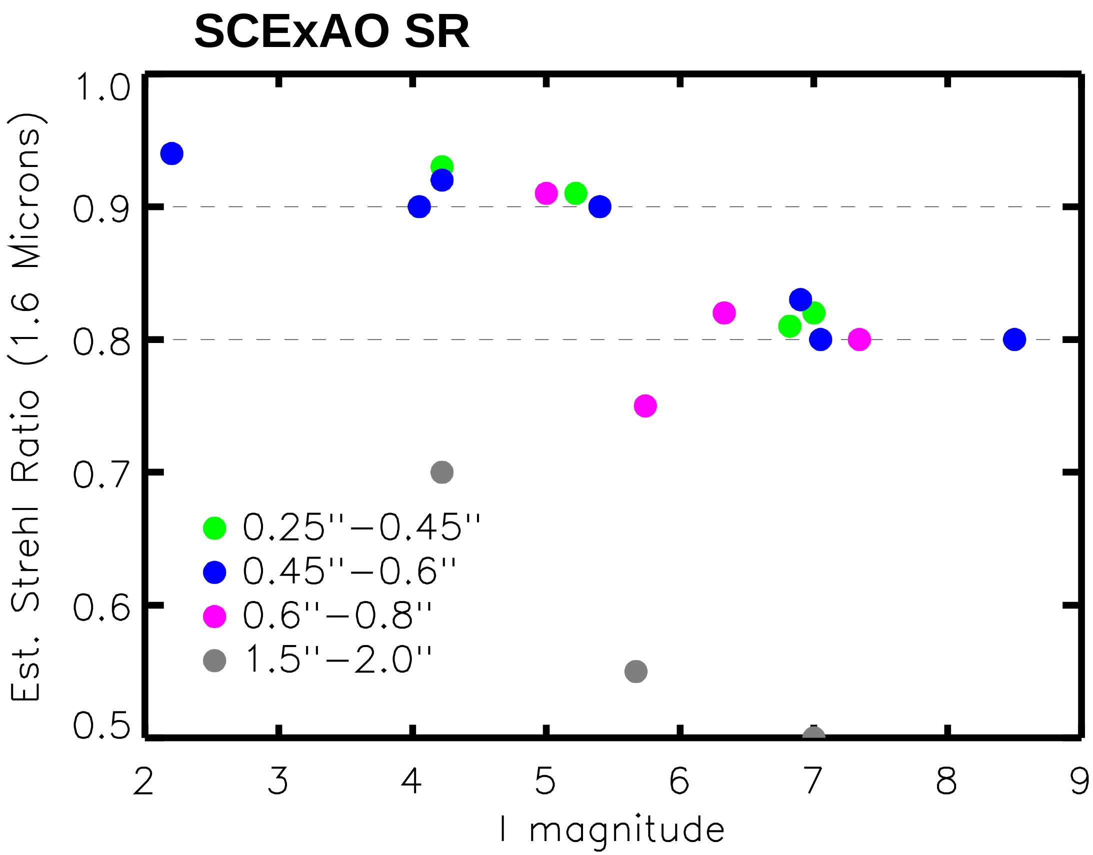
FIG. 3.— Top left: 2D-tracks for true pointing (red), predicted pointing (blue) and last measured position (green). Top right: Residual pointing error. Bottom: Single axis (x) values.

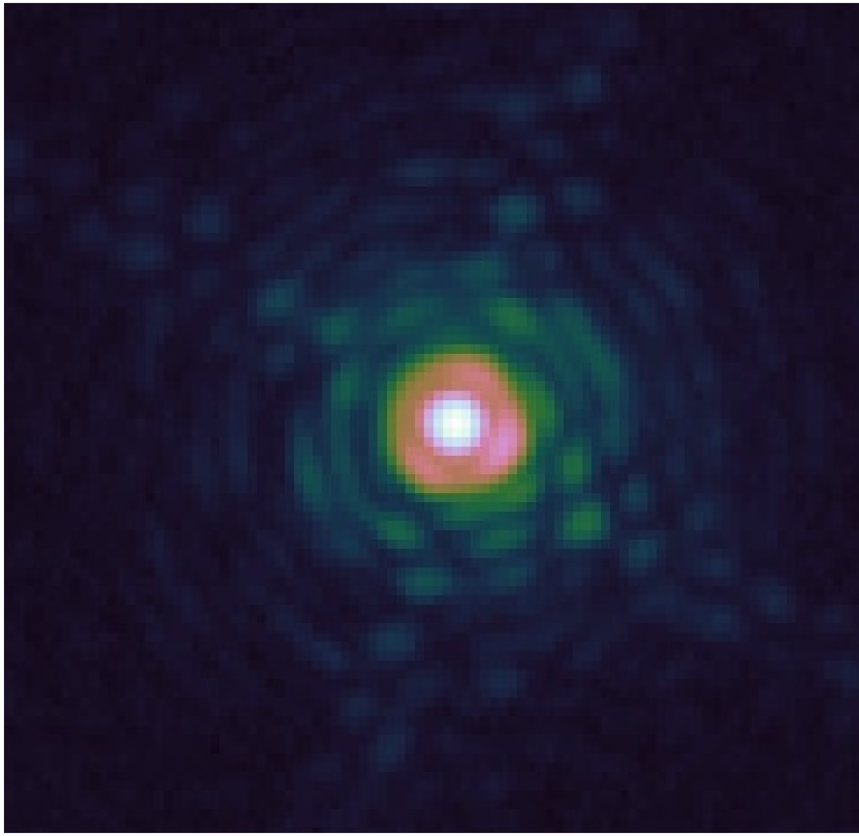


1hr detection limit (PSF subtraction residual)



Faint Star Performance





S.R. ~ 0.9 for bright stars under average to good conditions
x-AO correction demonstrated down to I ~ 9

LkCa 15:
R ~ 11.6 star, K band

SR~0.65 @ H
Predictive control ON

Outline

1. Key scientific motivations

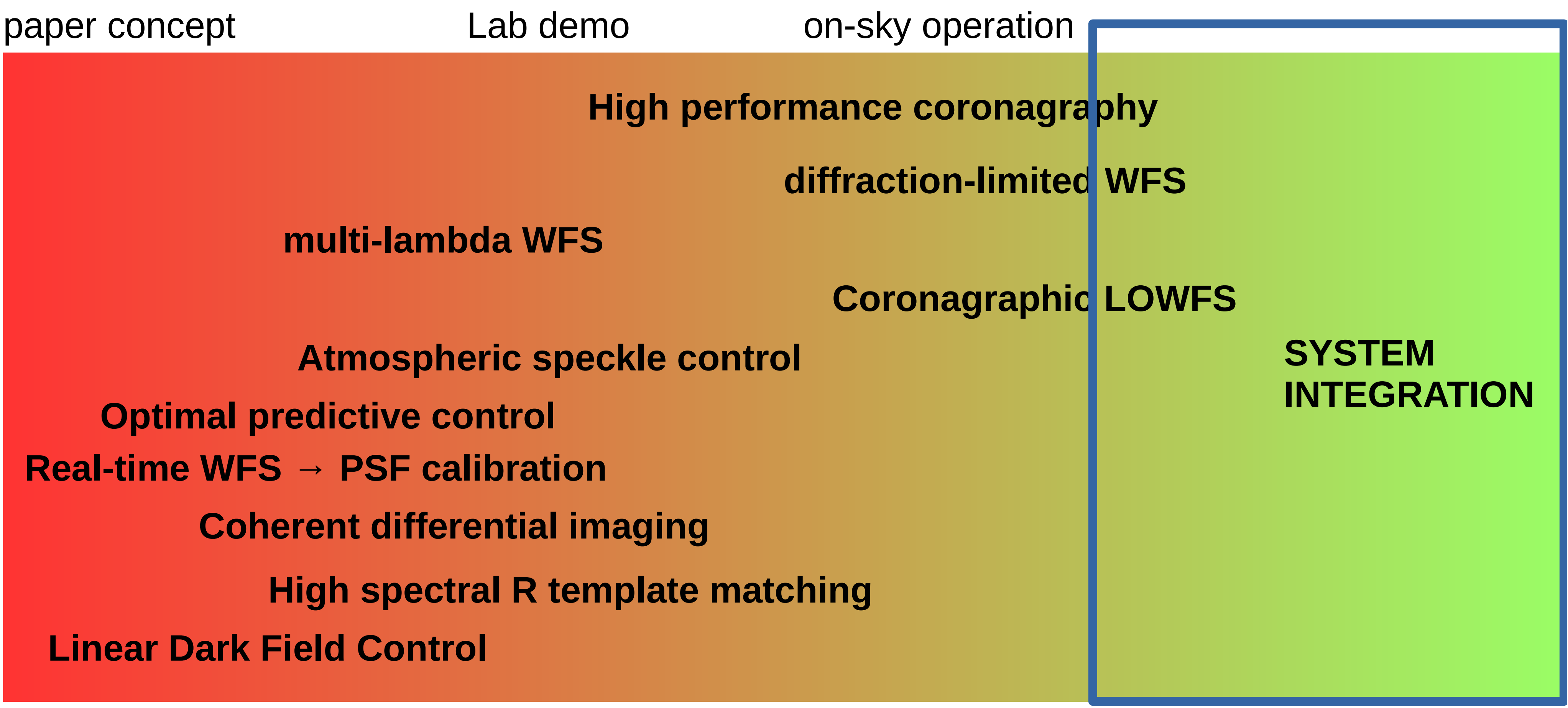
2. Coronagraph designs for ground-based systems

3. The wavefront control challenge

4. Areas of future development: where big gains are

Conclusions, Path Forward

Key technologies need rapid maturation from paper concepts to system integration



SCExAO

Subaru Coronagraphic Extreme Adaptive Optics

- **Flexible** high contrast imaging platform (Nas port)
- Meant to **evolve to TMT instrument** and validate key technologies required for direct imaging and spectroscopy of habitable exoplanets

Telescope time available to US community (Keck & Gemini time exchange) and non-US through collaborations with team

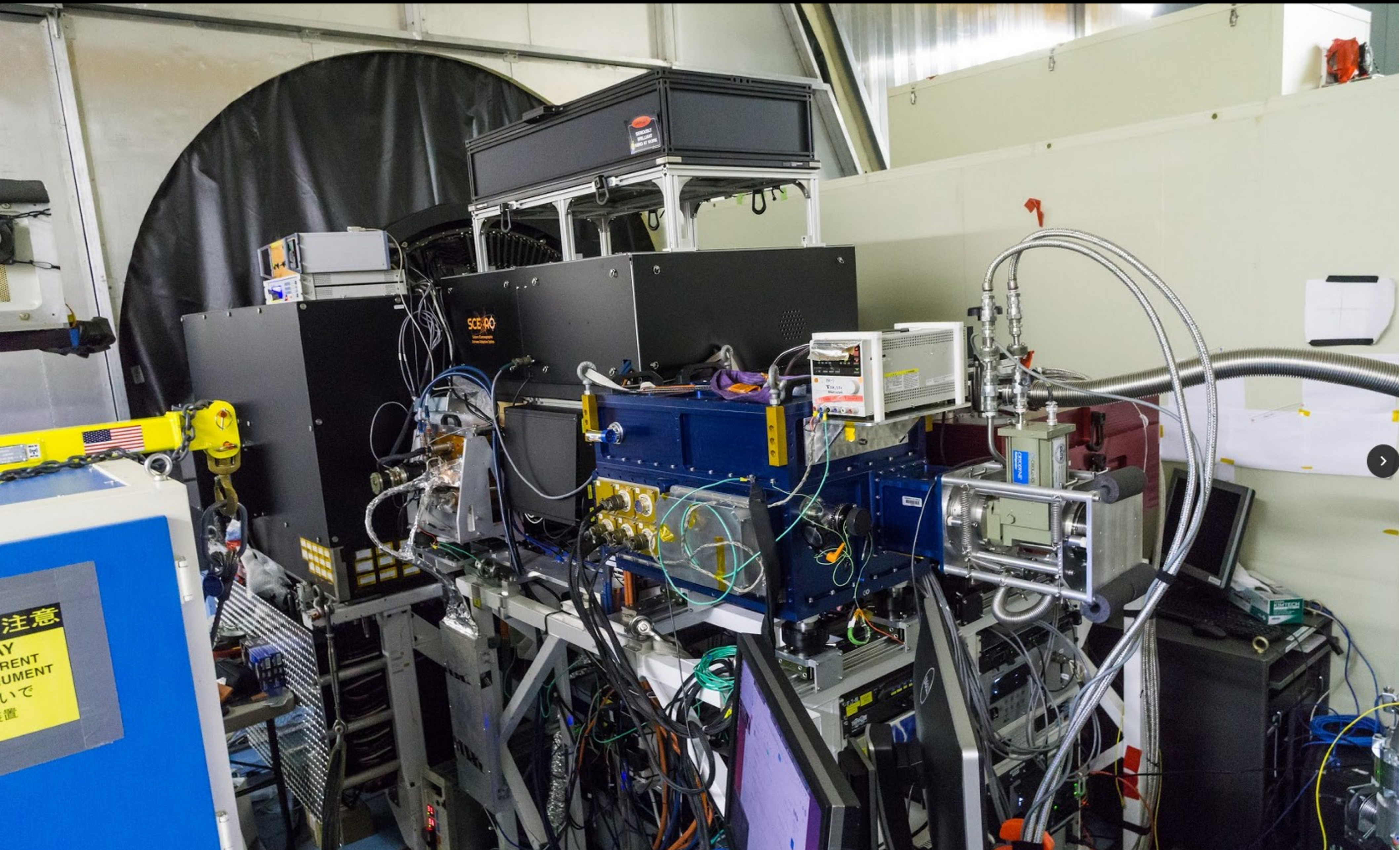
Modules/instruments funded by Japan + international partners:

- MKIDS IFU built by Princeton Univ (Japan-funded)
- MKIDs built by UCSC (Japan-funded)
- SAPHIRA camera provided by UH
- VAMPIRES instrument funded and built by Australia
- FIRST instrument funded and built by Europe
- RHEA IFU provided by Australian team

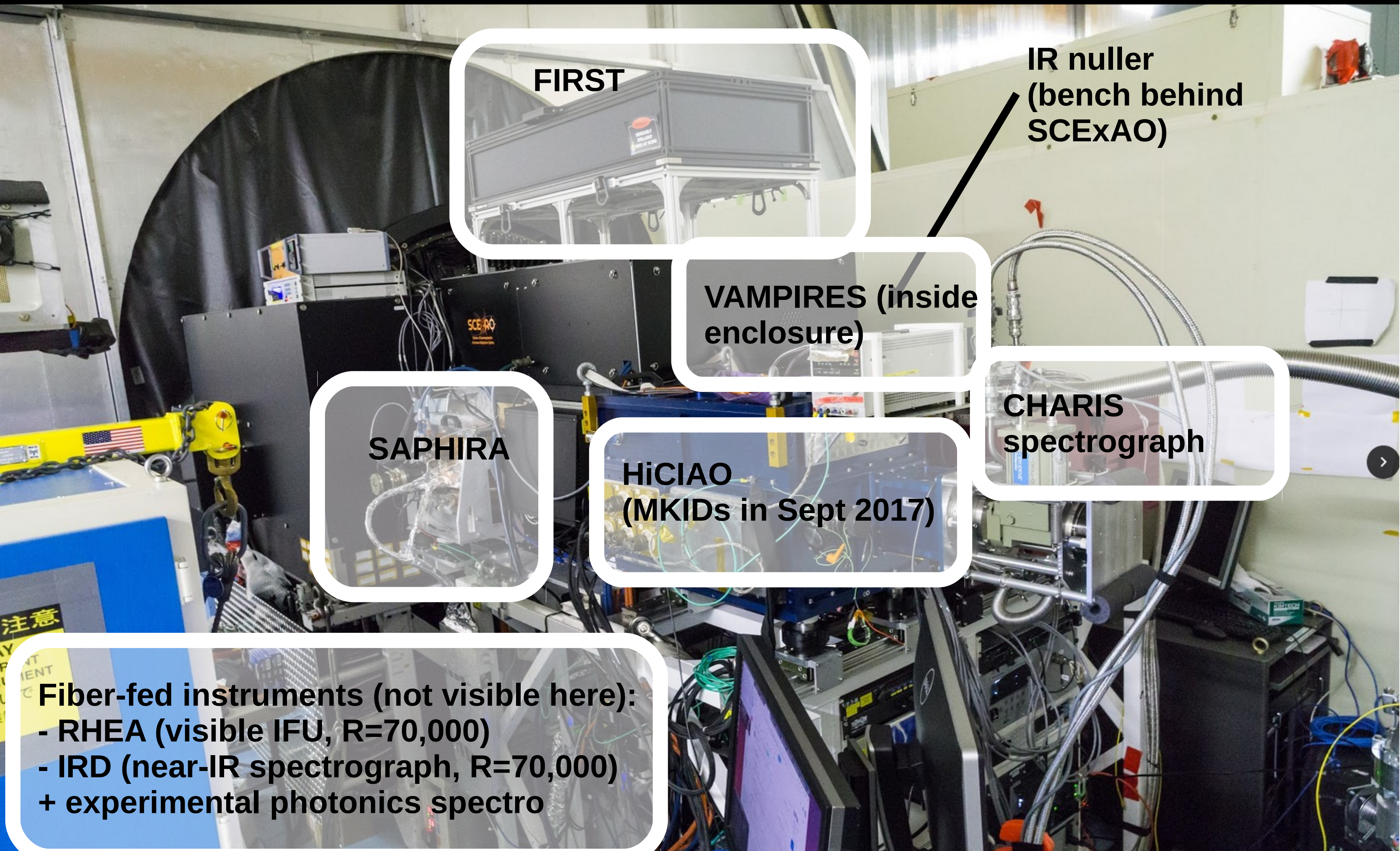
Strong research collaborations with multiple groups:

- Univ. of Arizona / MagAO(-X) (shared dev., wavefront control, coronagraphy)
- Kernel group @ Observatoire de la Cote d'Azur (wavefront control)
- Leiden Univ, JPL (coronagraphy)
- Northwestern Univ (detector dev)
- Univ. of Sydney (Photonics techs, nulling interferometry)
- Keck (near-IR WFS)

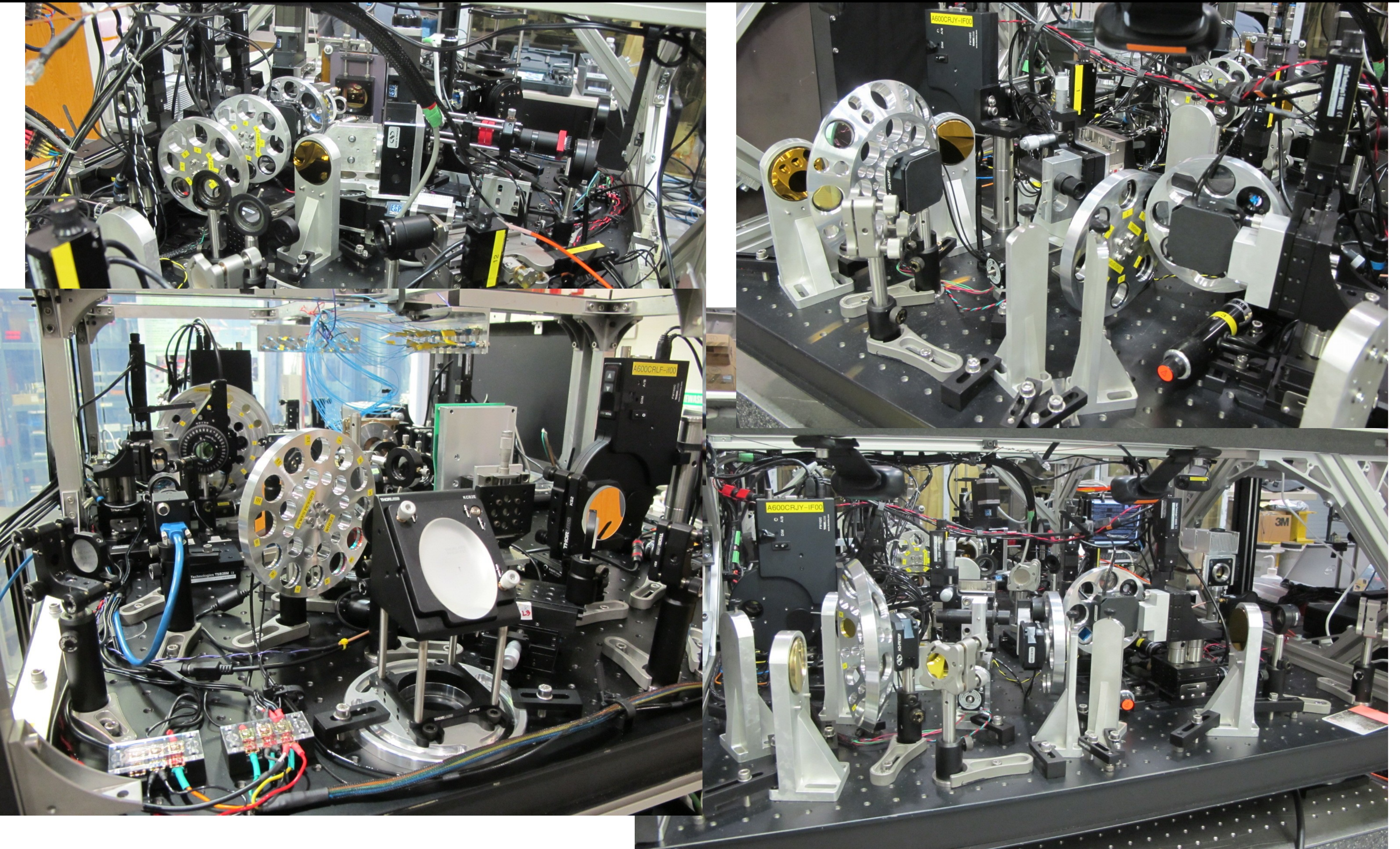
Subaru Coronagraphic Extreme Adaptive Optics



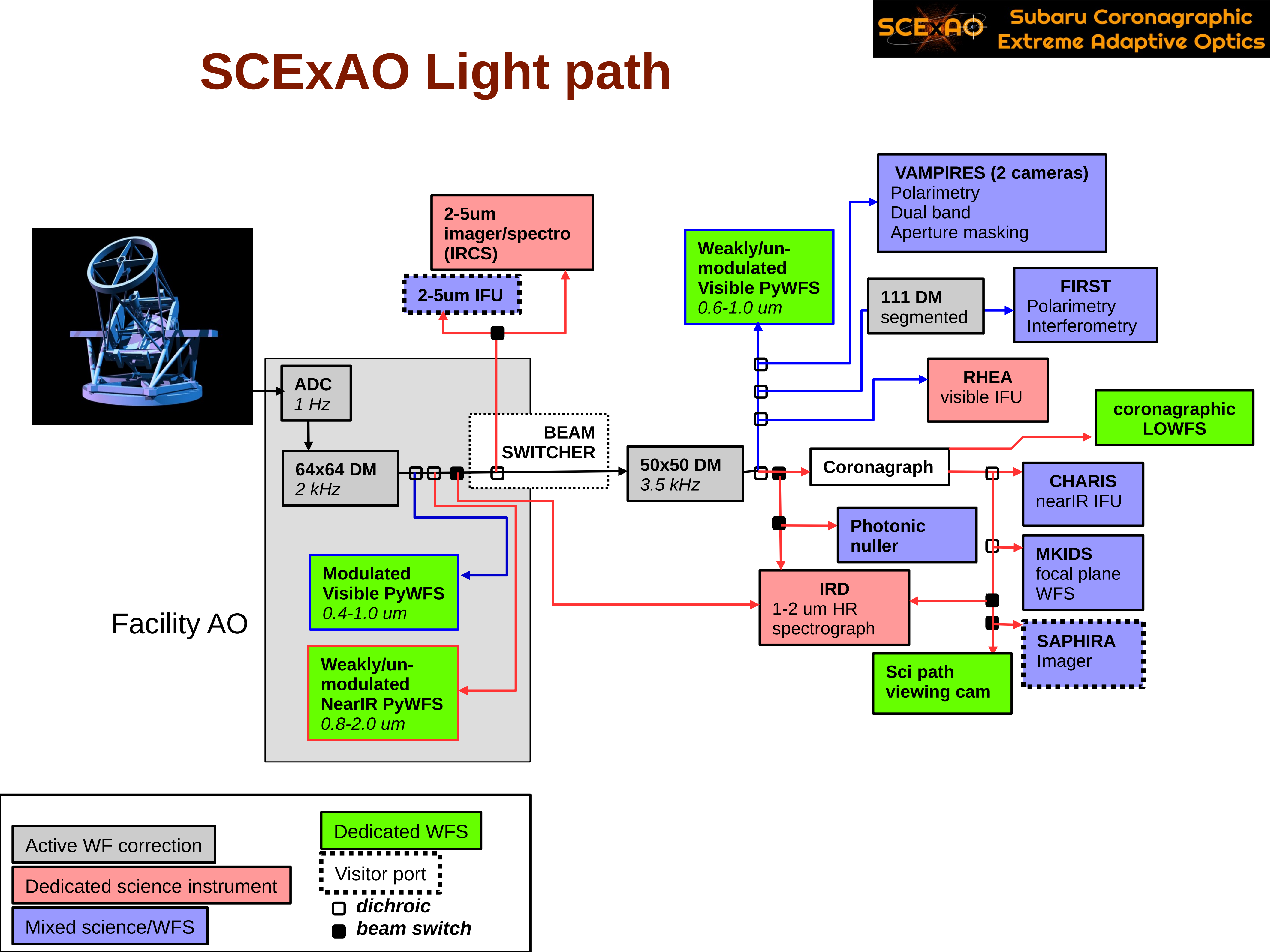
Subaru Coronagraphic Extreme Adaptive Optics



Subaru Coronagraphic Extreme Adaptive Optics



SCExAO Light path



Building community RTC / Software Ecosystem

Provide low-latency to run control loops

→ Use mixed CPU & GPU resources, configured to RTC computer system

On SCExAO, control matrix is 14,000 x 2000. Matrix-vector computed in 100us using 15% of RTC resources @ 3kHz

Portable, open source, modular, COTS hardware

→ No closed-source driver

→ std Linux install (no need for real-time OS)

→ using NVIDIA GPUs, also working on FPGA use

→ All code on github: **https://github.com/oguyon/AdaptiveOpticsControl**

Easy for collaborators to improve/add processes

→ Hooks to data streams in Python or C

→ Template code, easy to adapt and implement new algorithms

→ Provide abstraction of link between loops

→ Toolkit includes viewers, data logger, low-latency TCP transfer of streams

RTC code used at Keck, MagAO-X, OCA ...

→ community support and development

Data Stream Format

Uses file-mapped POSIX shared memory → multiple processes have access to data

Supports low latency IPC through semaphores → us-level latency

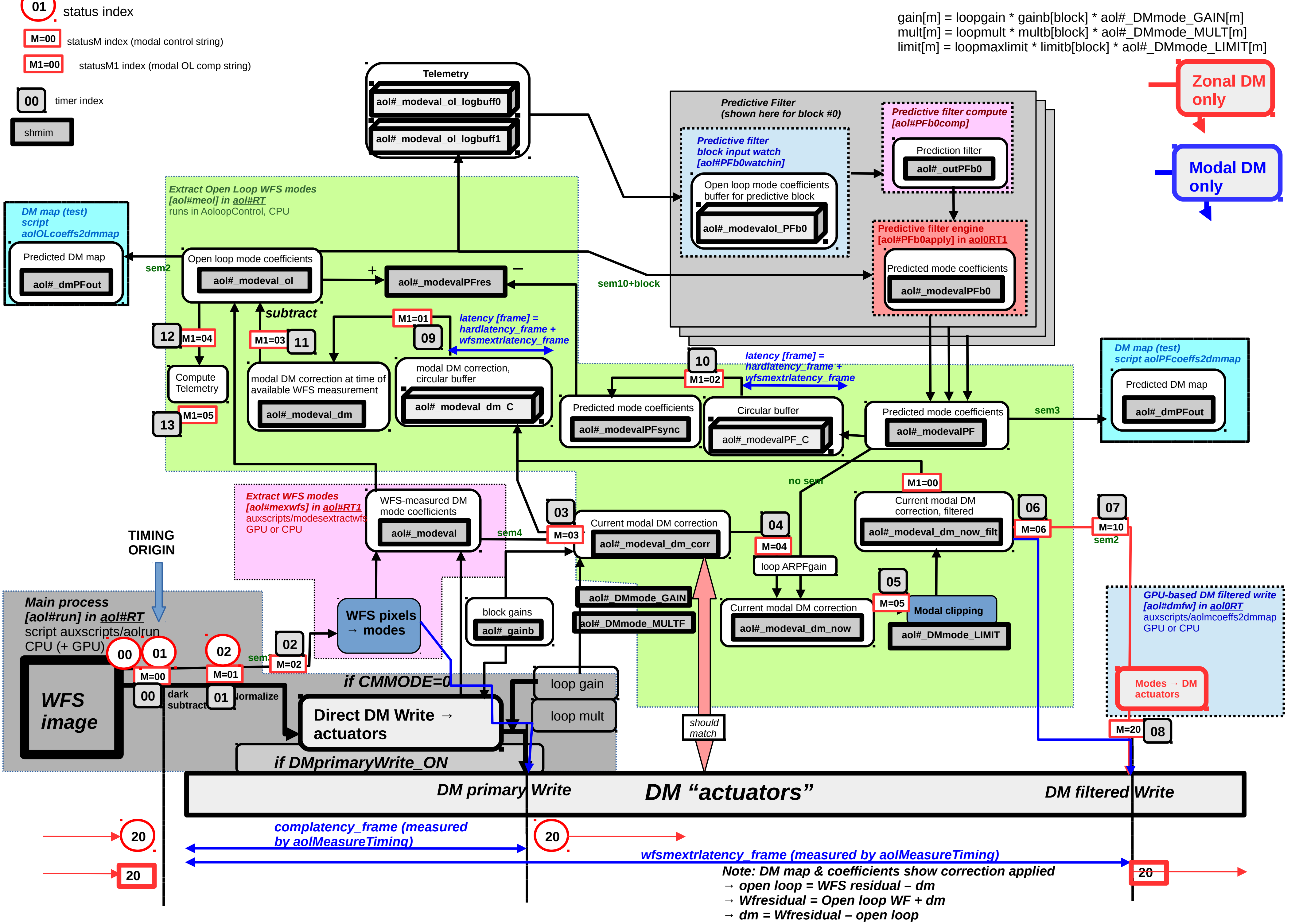
```c
typedef struct                    /**< structure used to store data arrays */
{
    int used;
    int shmfd;                    /**< if shared memory, file descriptor */
    size_t memsize;               /**< total size in memory if shared */

    IMAGE_METADATA *md;

    union
    {
        char *C;
        int *I;
        long *L;
        float *F;
        double *D;
        complex_float *CF;
        complex_double *CD;
        unsigned short int *U;
    } array;                      /**< pointer to data array */

    IMAGE_KEYWORD *kw;

    int sem;                      /**< number of semaphores in use     */
    sem_t **semptr;               /**< semaphore array */

    sem_t *semlog;                /**< semaphore for logging */


    char name[80];                /**< local name (can be different from name in shared memory) */

} IMAGE;
```

```c
typedef struct
{
    char name[80];                /**< image name */

    long naxis;                   /**< number of axis */
    long size[3];                 /**< image size */
    long nelement;                /**< number of elements in image */
    int atype;                    /**< data type code */

    double creation_time;         /**< creation time (since program start) */
    double last_access;           /**< last time the image was accessed  (since program start) */
    struct timespec wtime;

    int shared;                   /**< 1 if in shared memory */

    int write;                    /**< 1 if image is being written */
    int status;                   /**< 1 to log image (default); 0 : do not log: 2 : stop log (then goes back to 2) */
    long cnt0;                    /**< counter (incremented if image is updated) */
    long cnt1;                    /**< in 3D rolling buffer image, this is the last slice written */

    long NBkw;                    /**< number of keywords */

} IMAGE_METADATA;
```

```c
typedef struct
{
    char name[16];          /**< keyword name */
    char type;              /**< N: unused, L: long, D: double, S: 16-char string */

    union {
        long numl;
        double numf;
        char valstr[16];
    } value;

    char comment[80];

} IMAGE_KEYWORD;
```

Drivers written for:
OCAM2k, BMC DM, SAPHIRA camera, InGaAs cameras

Processes, output to DM (main loop)



Using SCExAO instrument

← slack channel to coordinate instrument use over multiple continents

December 19th, 2016

bnorris 1:34 AM
Crap! Yes sounds like it's best to leave it off. Well if you do go up be sure to look out for snow kangaroos. They're deadly.

olivier 1:36 AM
it's low probability that a significant leak would develop... but I prefer to play it safe

I'll go up in the day with DC if I can and then we can both test with the DM

I'm in simulator software mode, so you can use the superK as you wish

bnorris 1:38 AM
Ok cool, thx. I'll turn it off when I'm done.

olivier 1:38 AM
OK

olivier 1:45 AM
I'll try (later tonight) to run the DM at reduced voltage - this should be safe and should allow enough stroke for the dmflat

bnorris 1:49 AM
ok cool

olivier 3:20 AM
B: let me know if you need flat - I'm set it up so that is uses 80V instead of 120V. The flat may not be perfect but it's close.

bnorris 3:21 AM
It's ok for now, I don

't need it flat at the moment.

olivier 3:21 AM
OK - let me know when you need it

December 20th, 2016

bnorris 6:13 AM
Can I turn on the superk?

olivier 7:54 AM
yes... I see you just did

do you need a DM flat (I keep the DM off ... haven't been able to go to summit check things out)

bnorris 7:56 AM
Yeah that would be good. I'm going to stop in < 1 hr. Also was wondering about turb simulator.

olivier 7:56 AM
mmm... I prefer to keep the DM off for now. Can you wait another 12hr ?

bnorris 7:57 AM
Yep sure.

olivier 7:57 AM
OK - feel free to use bench as you need (without DM) for now. I am working on a "simulated" SCExAO for now.

just turn off superK when done

bnorris 7:58 AM
Ok. I like the sound of the simulated scexao - let's just use that all the time, instead of the real one.

olivier 9:15 PM
B: DM can be used safely

nem 9:15 PM
great, what was the humidity? like 2% right

olivier 9:21 PM
14%

a bit high, but safe

nem 9:22 PM
hmm, thats high for the vac pump being on

olivier 9:24 PM
B: let me know when you need DM flat

olivier 10:17 PM
OK - I'm keeping full control of DM until someone else screams

Challenges, Action Items

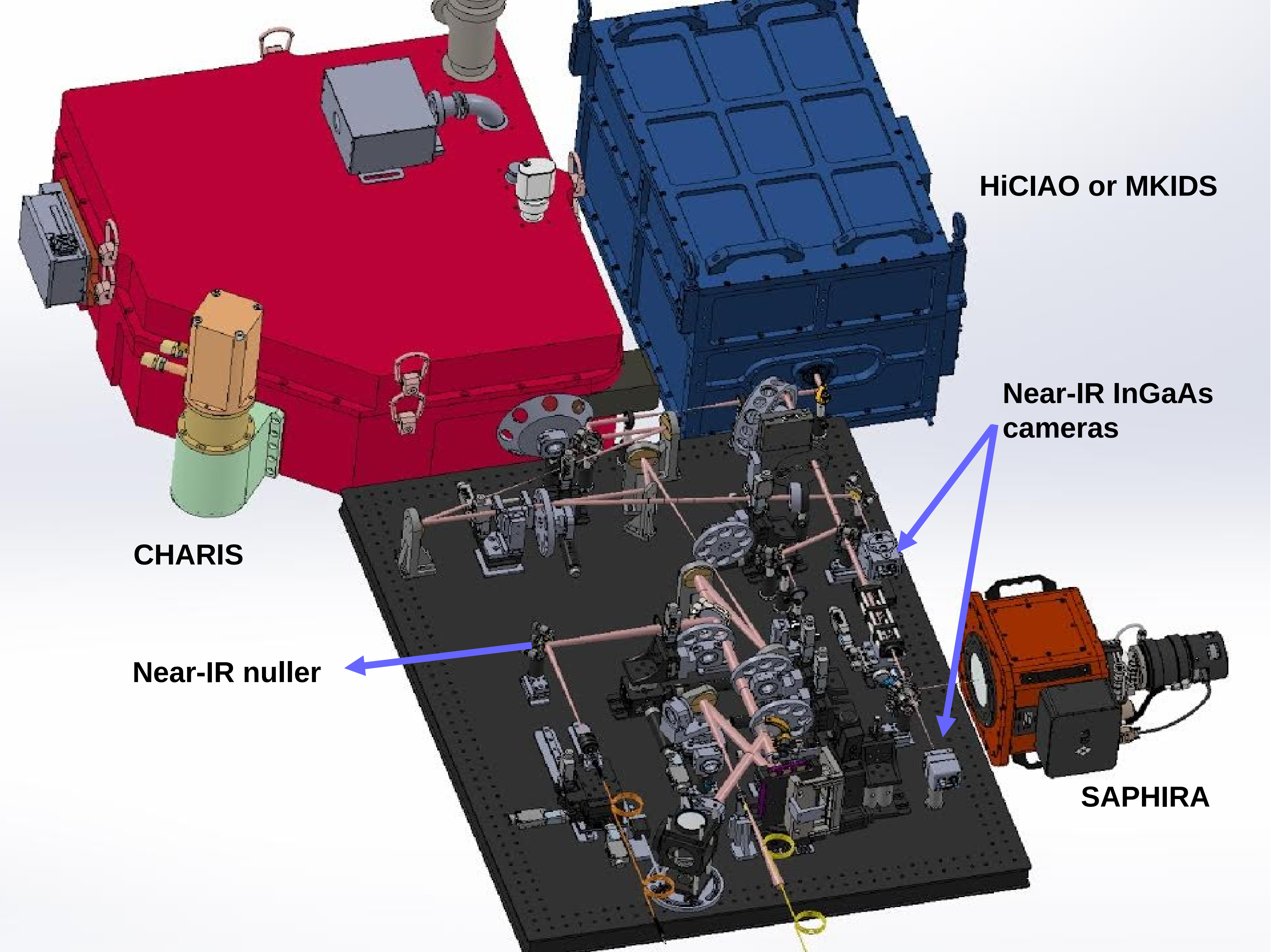
Integrating and testing secondary WFS/C to ExAO systems
- Focal plane WFS/C
- Building WFS into optics: LOWFS, “smart coronagraphs”: coronagraph modal WFS

Extending ExAO performance to fainter sources (critical for hab planet imaging)
- Diffraction-limited WFS
- Predictive control + sensor fusion

Developing real-time PSF calibration from WFS and science telemetry
- Sensor fusion
- Coherent differential imaging

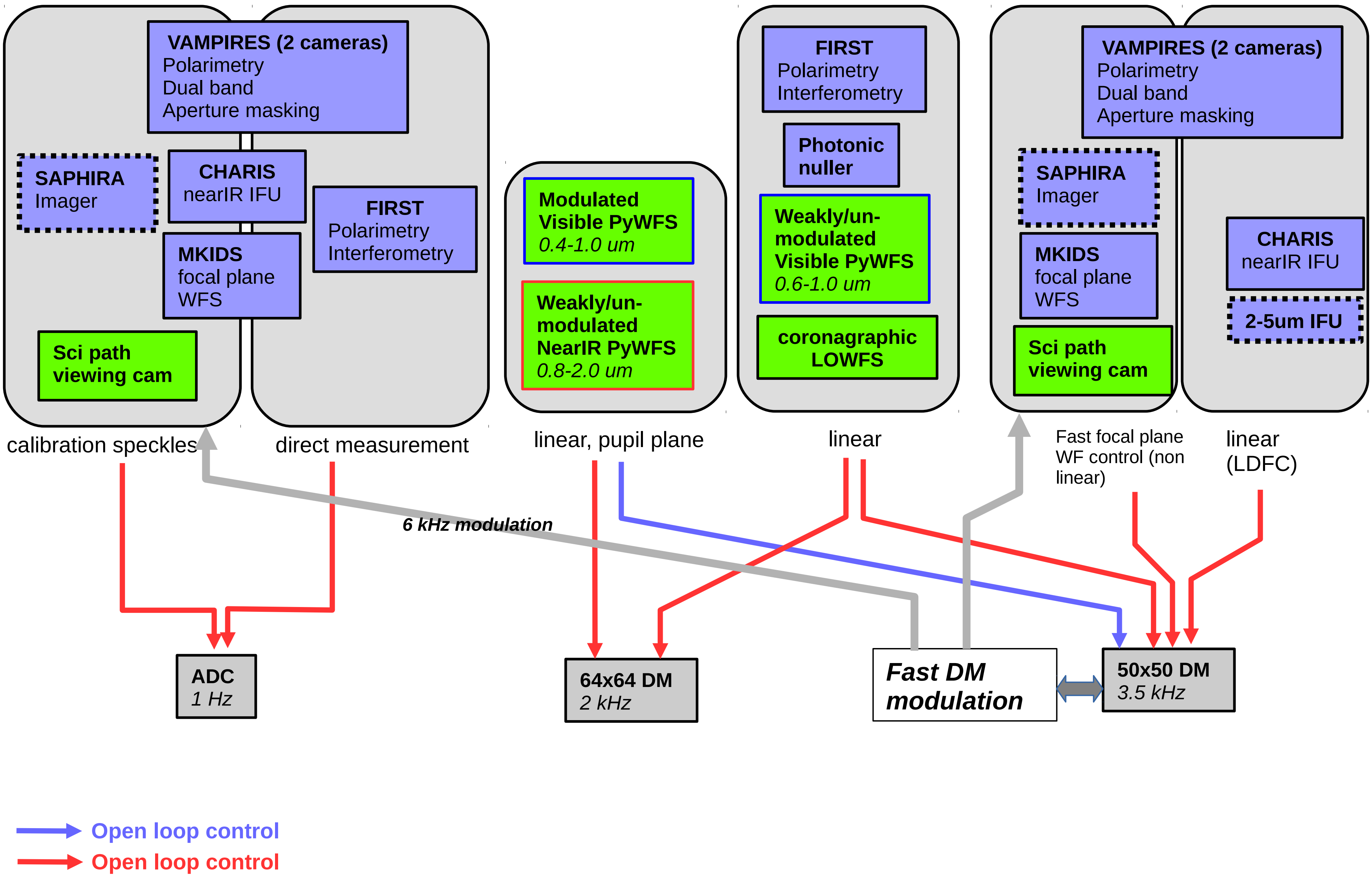
Need aggressive lab and sky testing / validation !!!
SCExAO is getting ready to support **<u>YOUR</u>** on-sky testing
Ongoing effort to develop & share common standards and code for ExAO control

Backup Slides



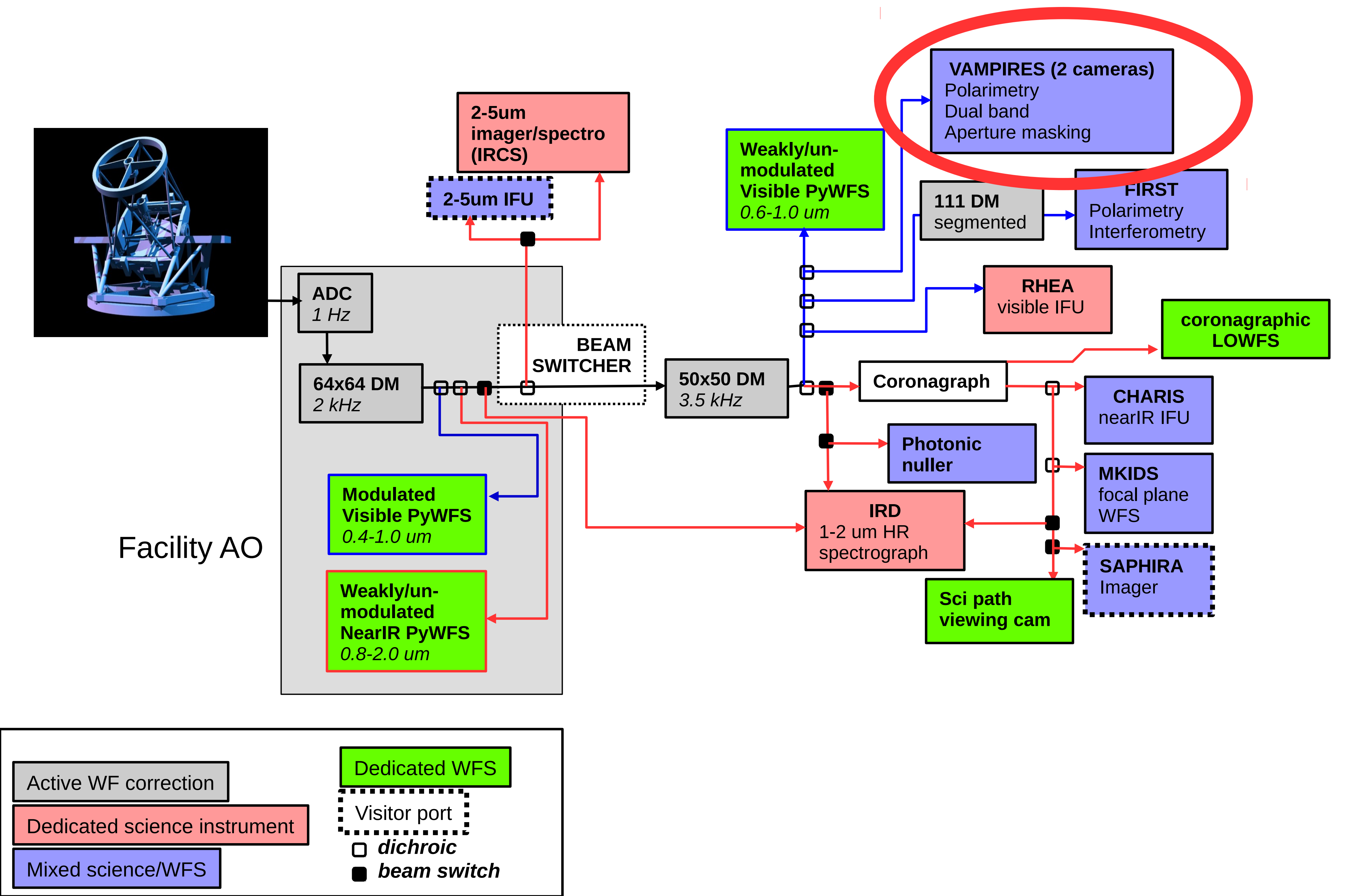
HiCIAO or MKIDS
Near-IR InGaAs
cameras
CHARIS
Near-IR nuller
SAPHIRA

Control loops



SCExAO Subaru Coronagraphic Extreme Adaptive Optics

SCExAO Light path

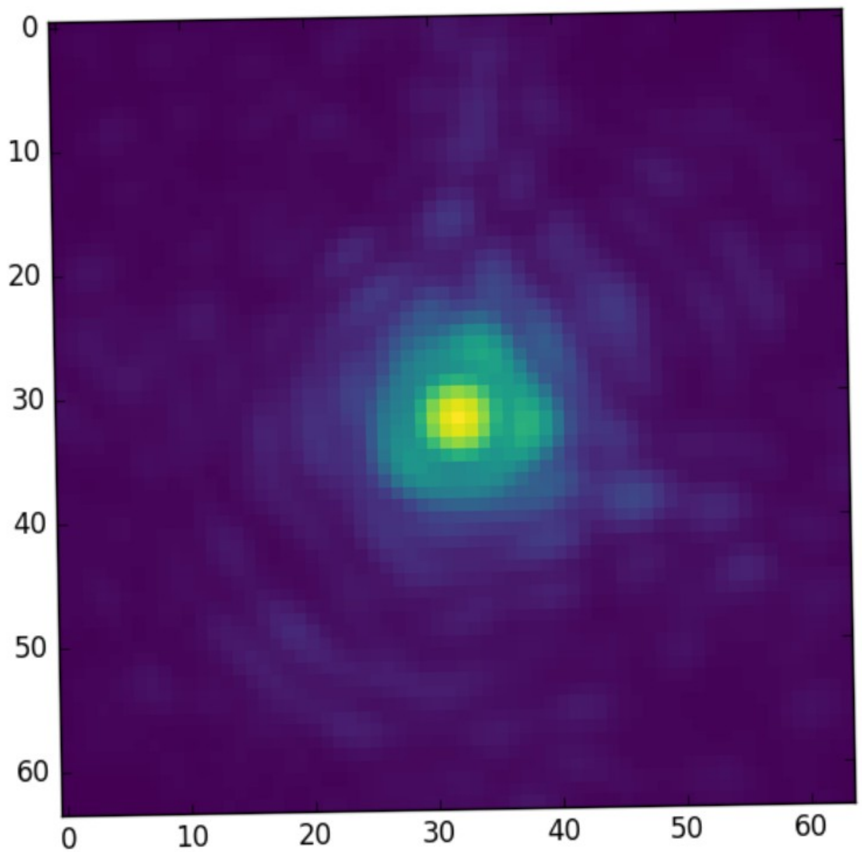


Preliminary VAMPIRES science

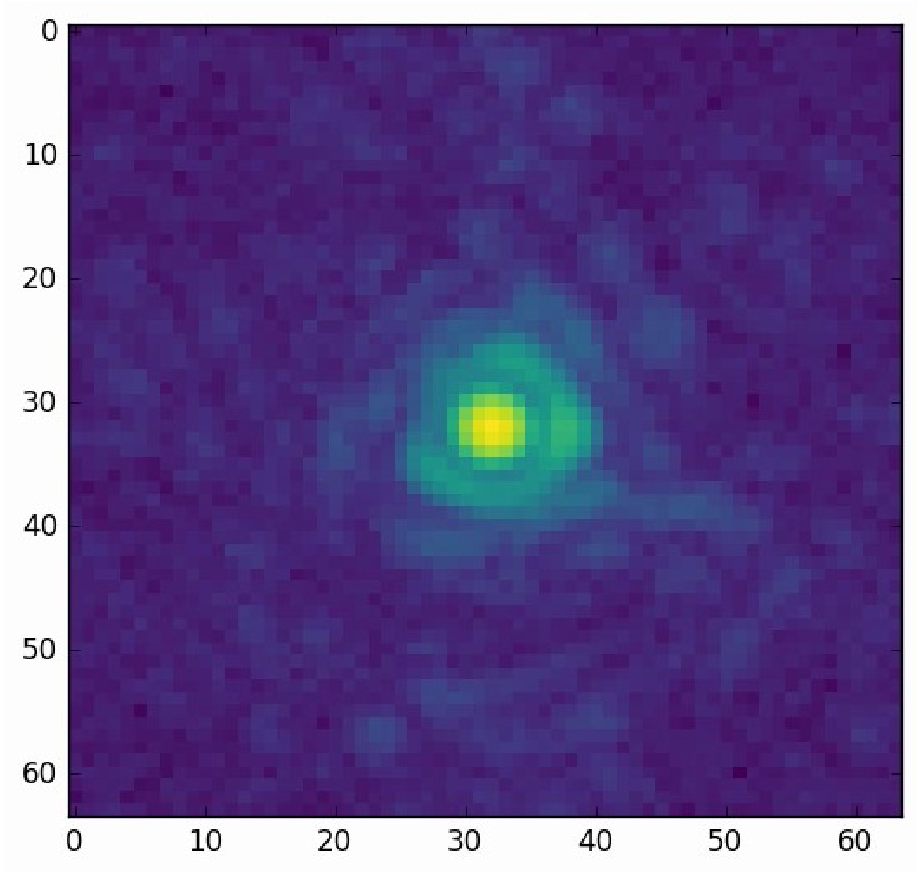
Diffraction-limited imaging in visible light

750nm, 1kHz imaging
log scale

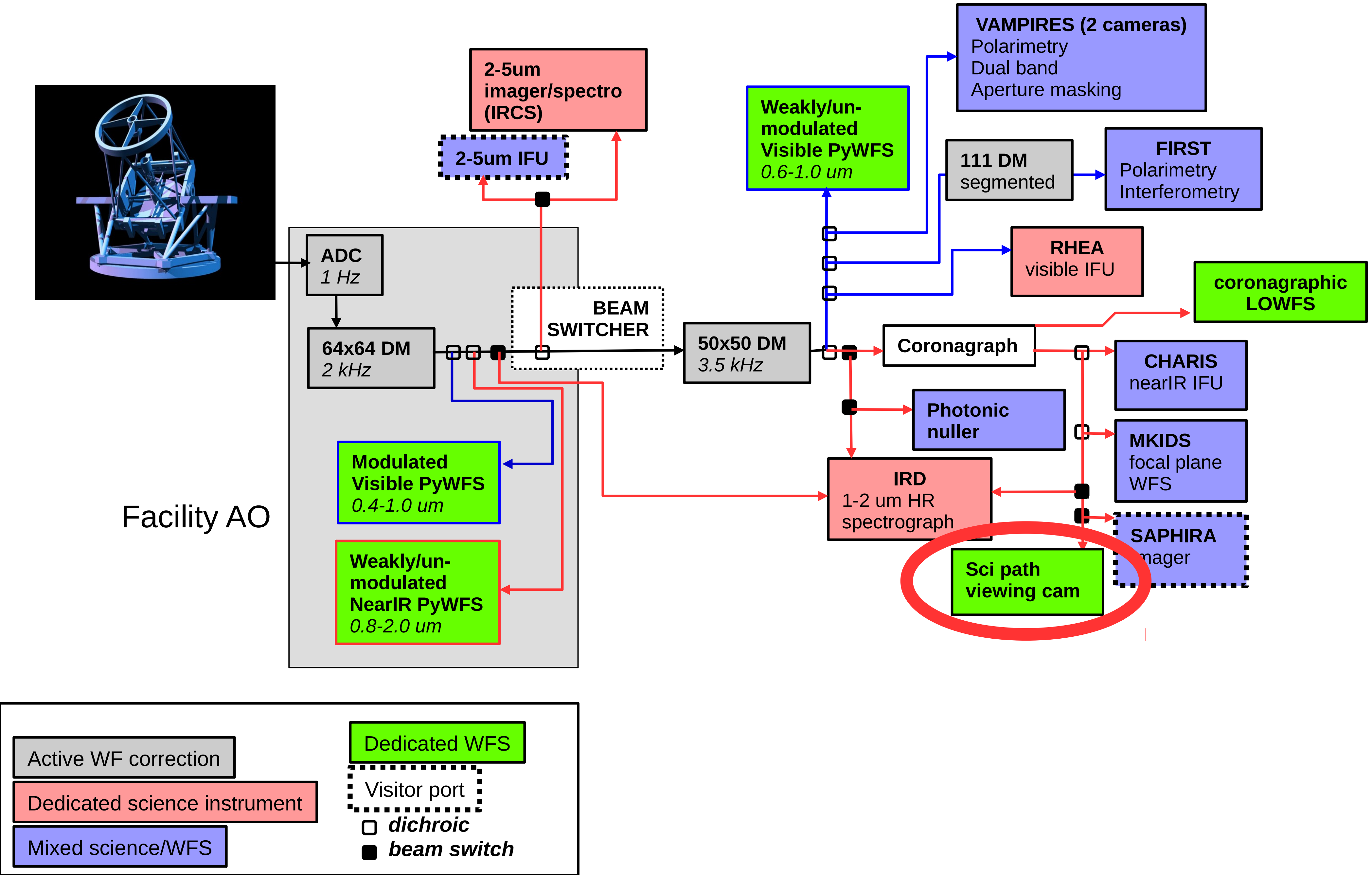
Summed image



Video

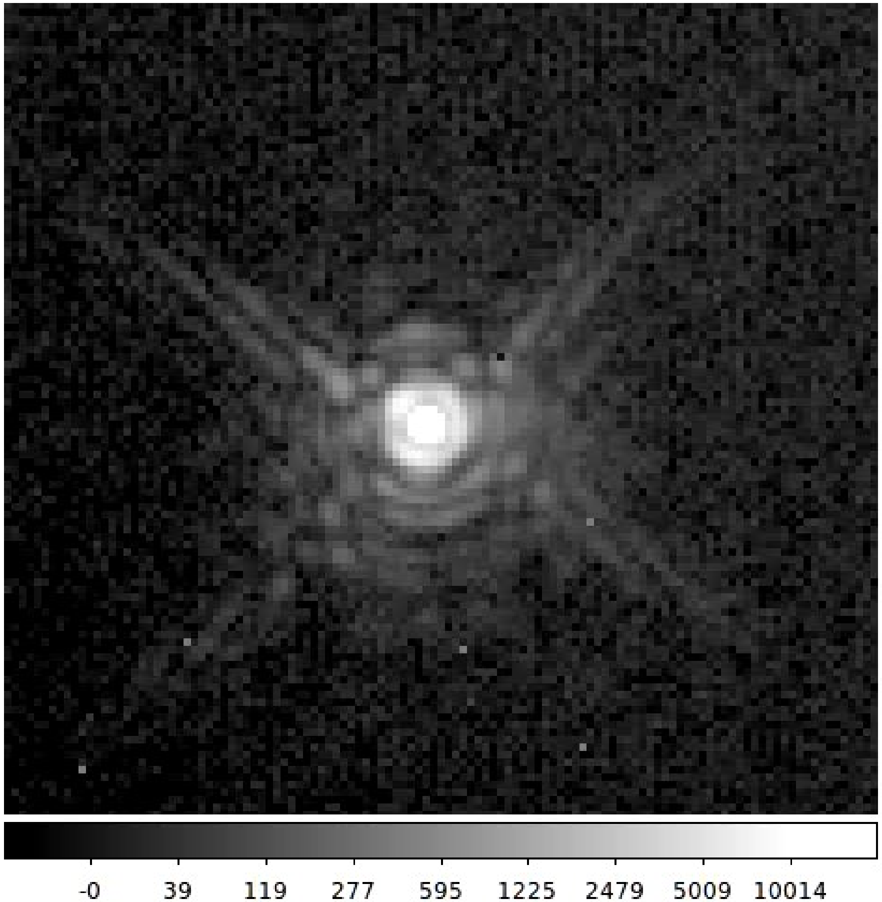


SCExAO Light path



Current PSF stability @ SCExAO

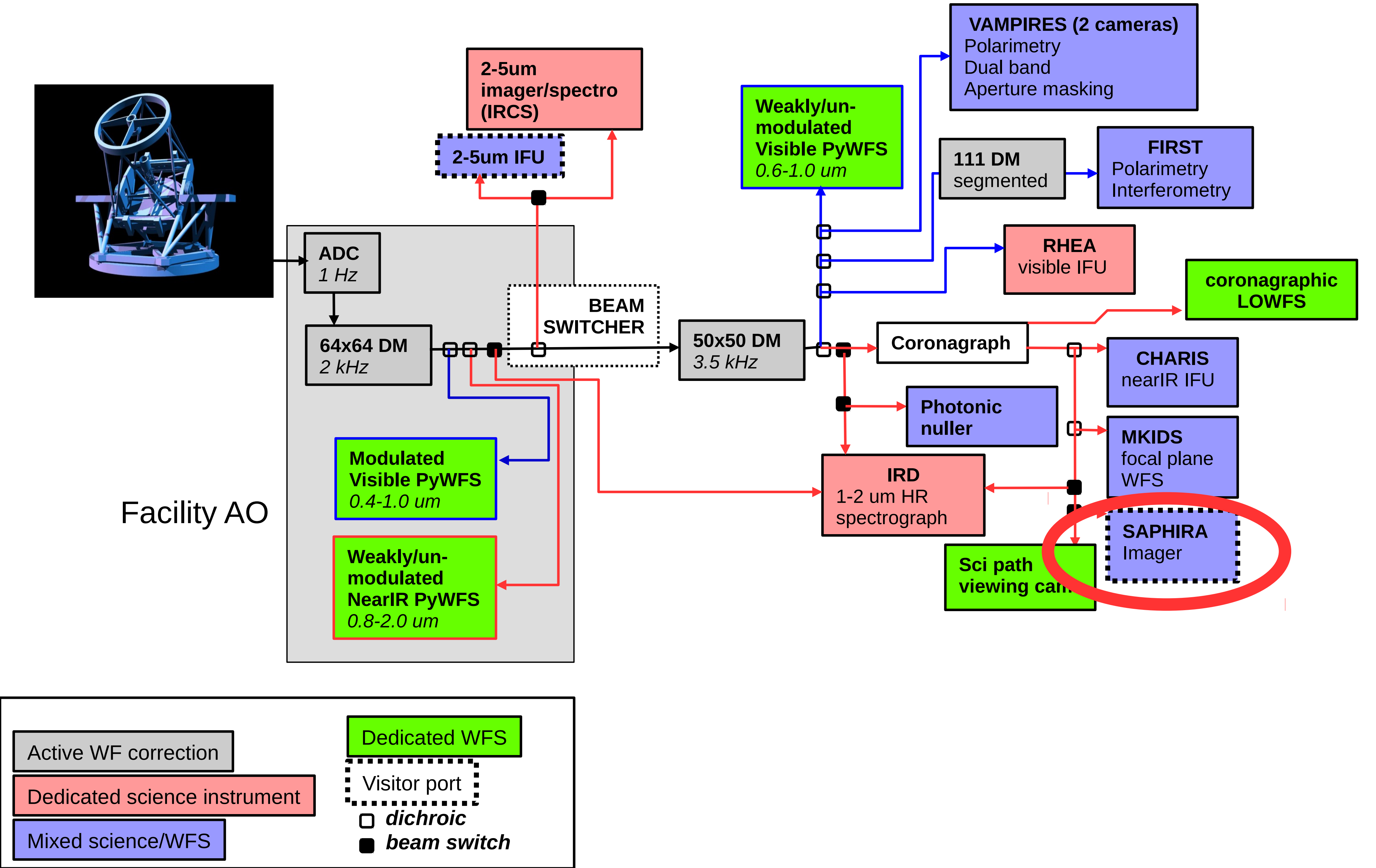
Stable PSF for coronagraphy
SCExAO provides sensing and correction at 500 Hz - 3.5 kHz
14,400 pixel WFS → 2000 actuators



1630nm (SCExAO internal camera)
3 Hz sampling

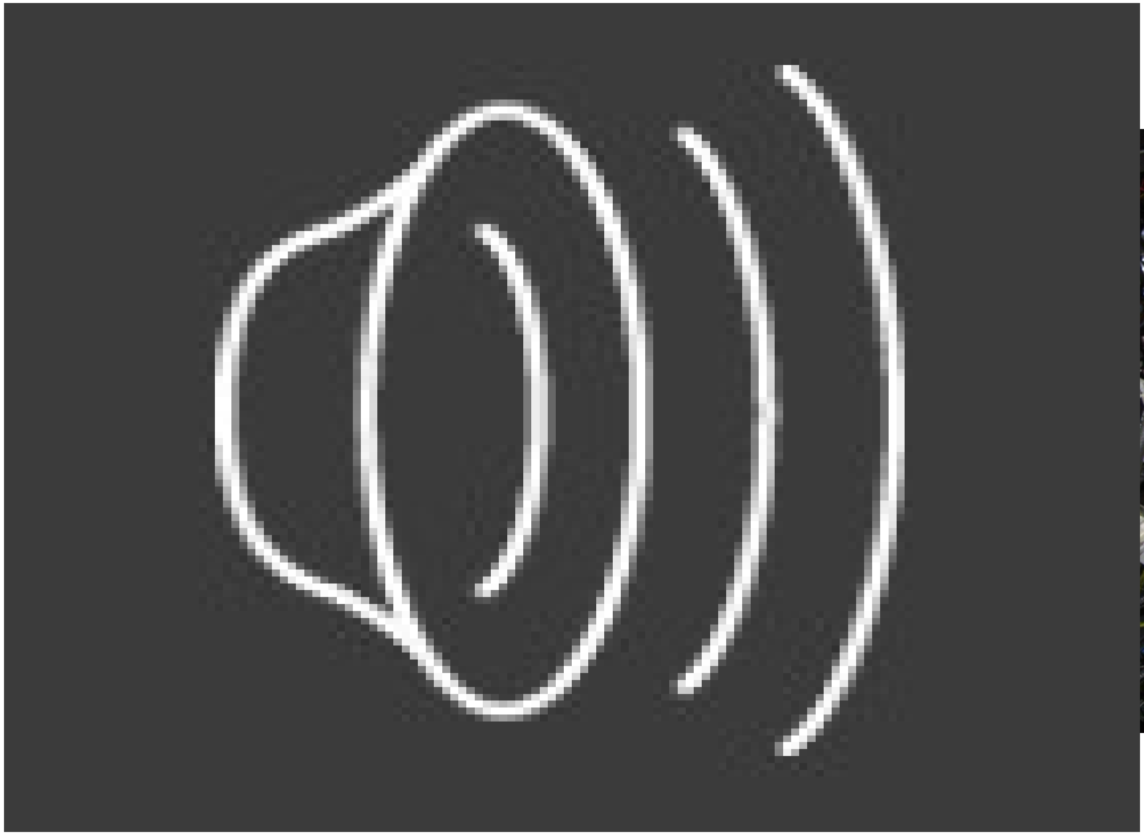
SCExAO Subaru Coronagraphic Extreme Adaptive Optics

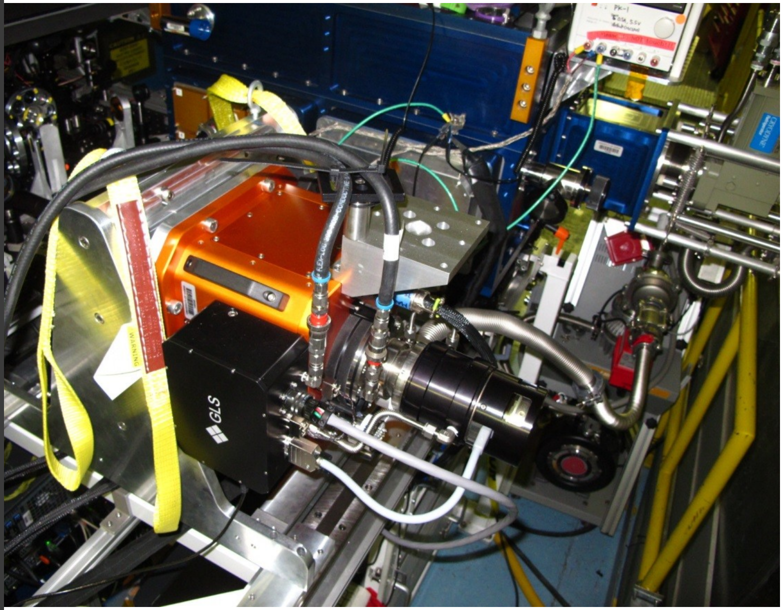
SCExAO Light path



SAPHIRA camera

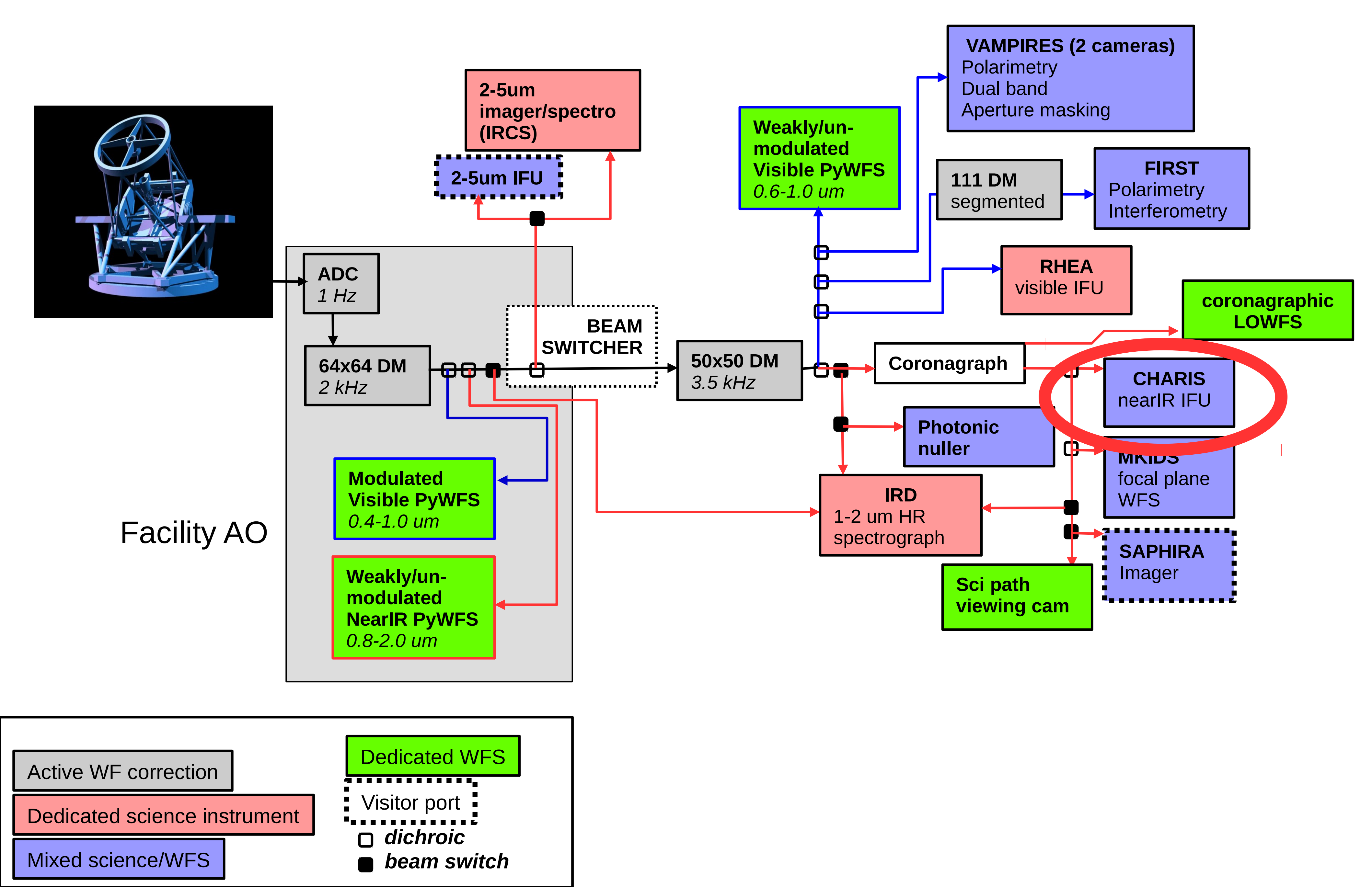
1.68 kHz frame rate, H-band
(played at 90 Hz)
SCExAO PyWFS ON → OFF



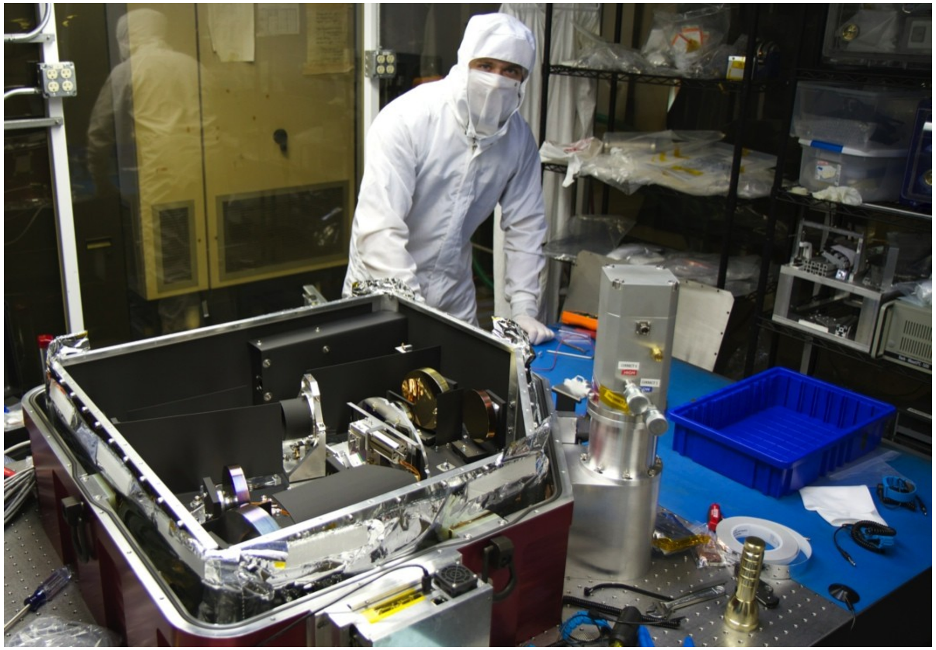


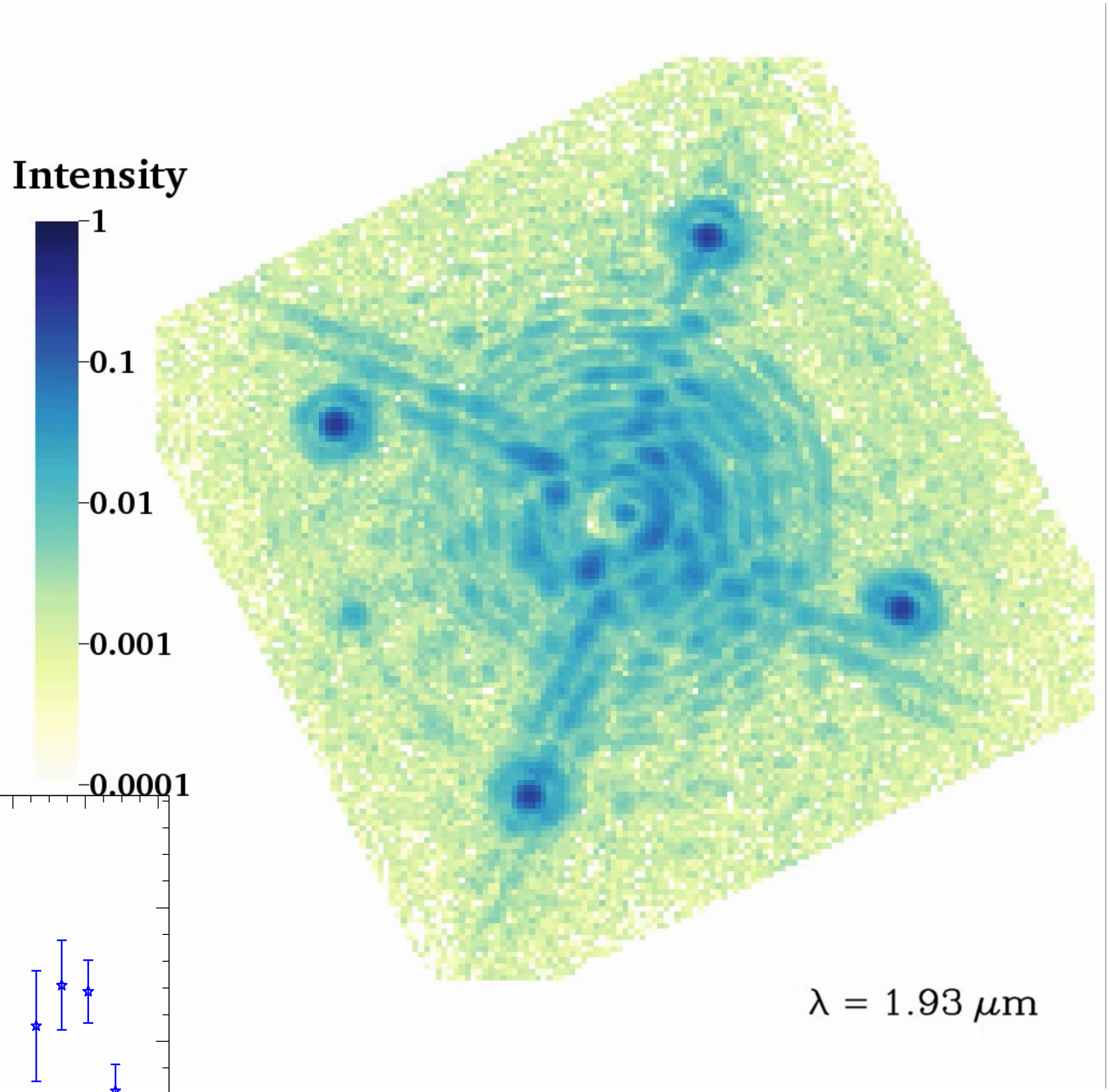
Subaru Coronagraphic Extreme Adaptive Optics

SCExAO Light path

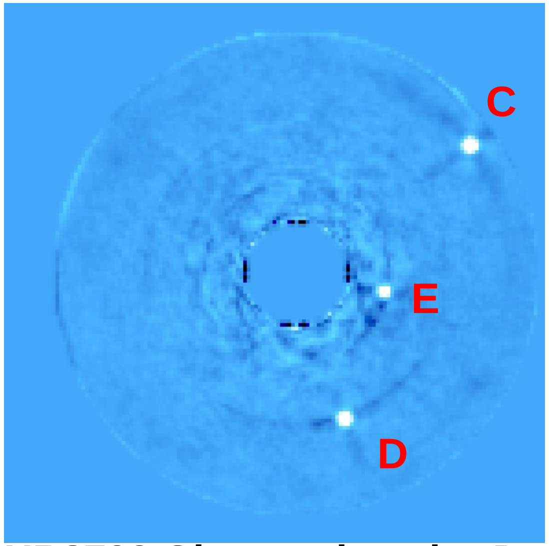


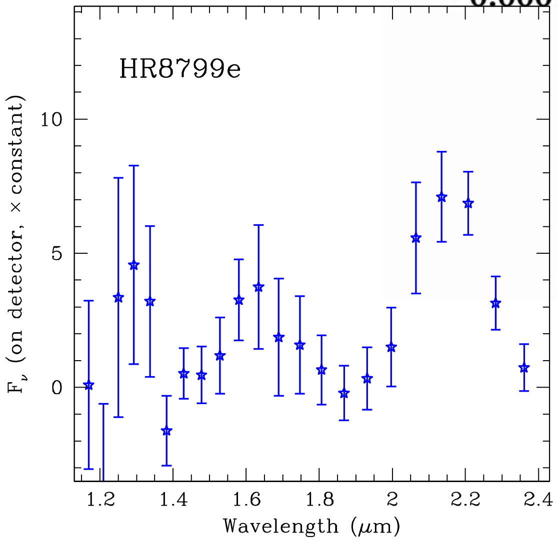
CHARIS IFS





HR8799

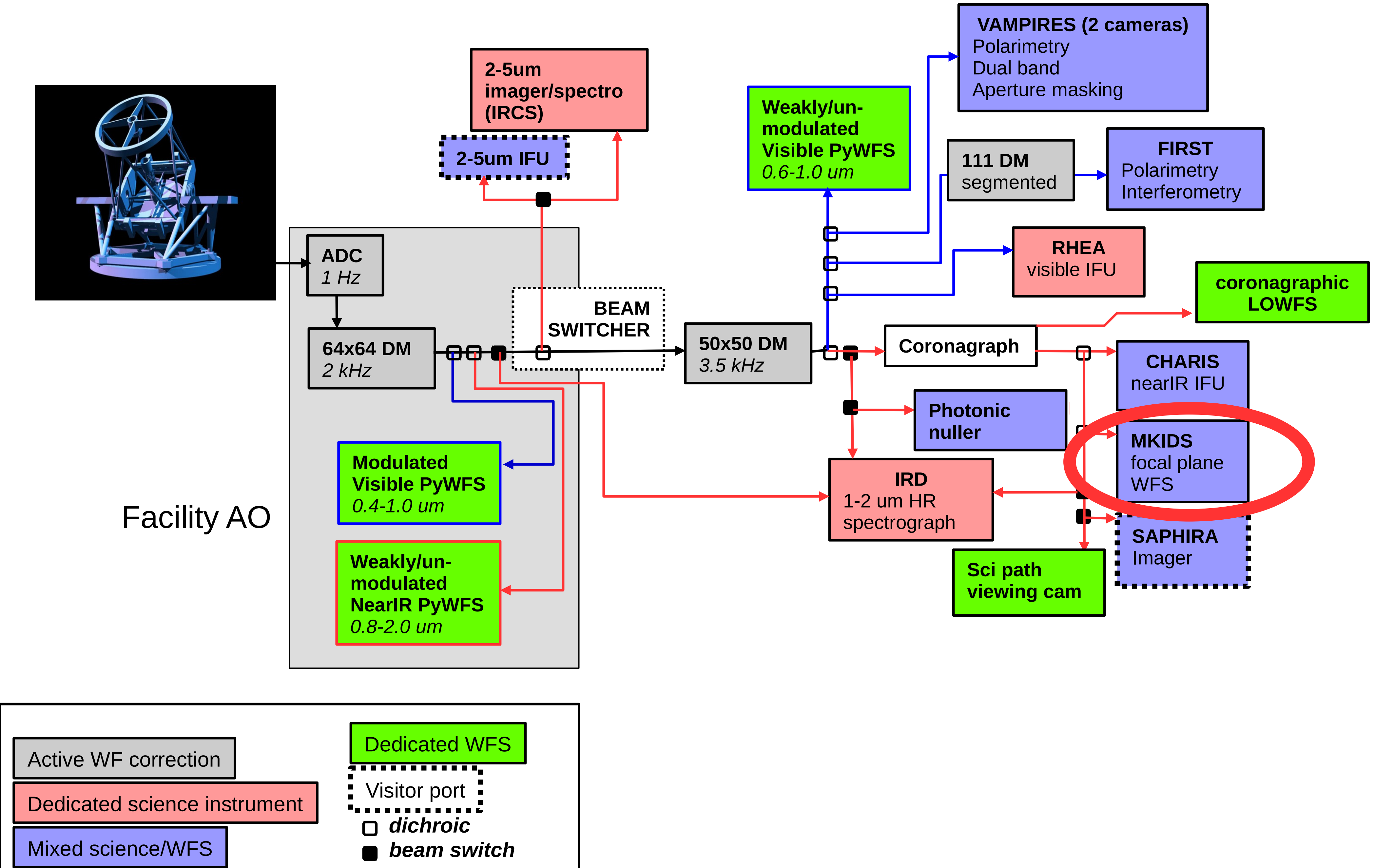


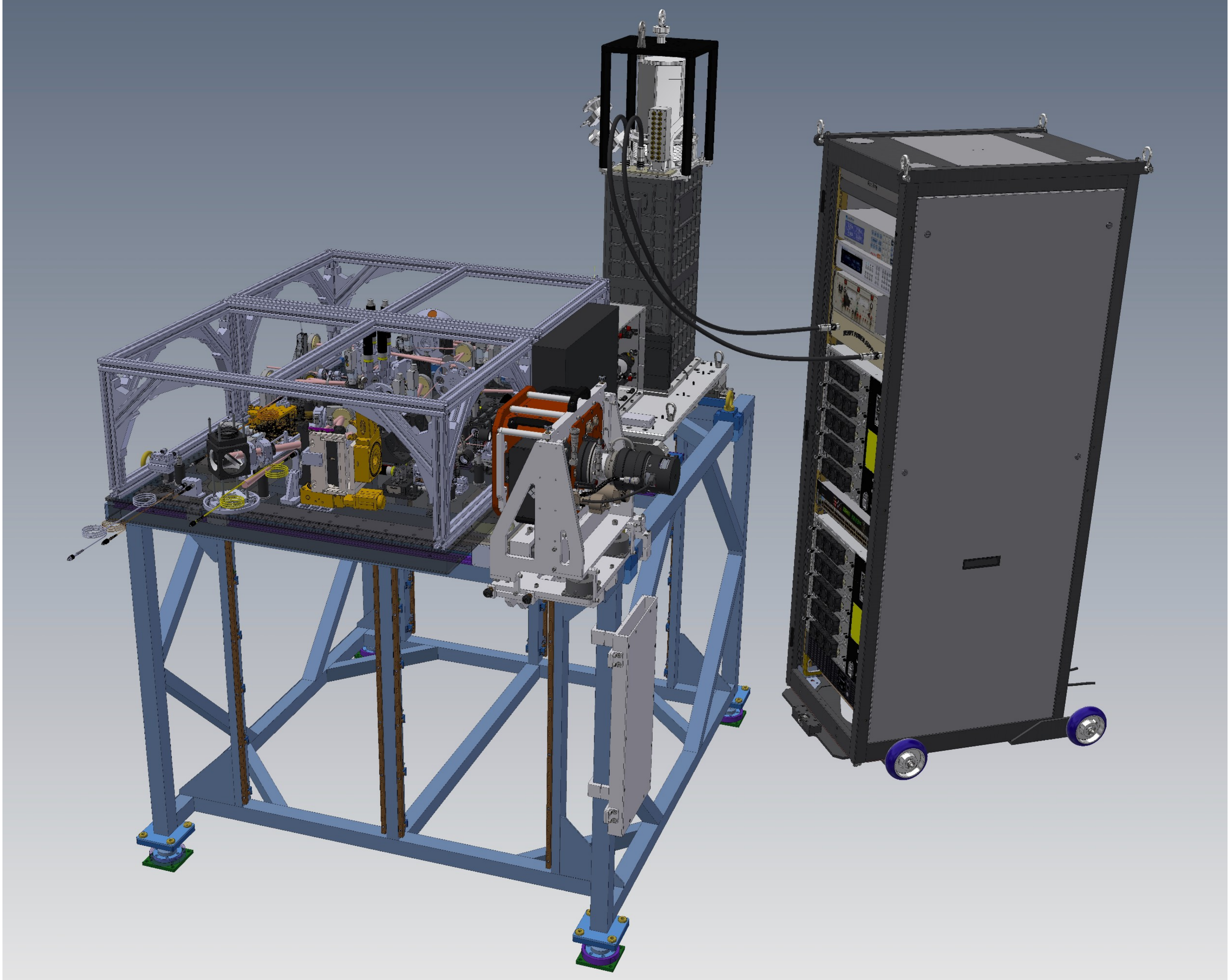


HR8799 Observations by J. Chilcote & T. Groff preliminary data processing by T. Brandt

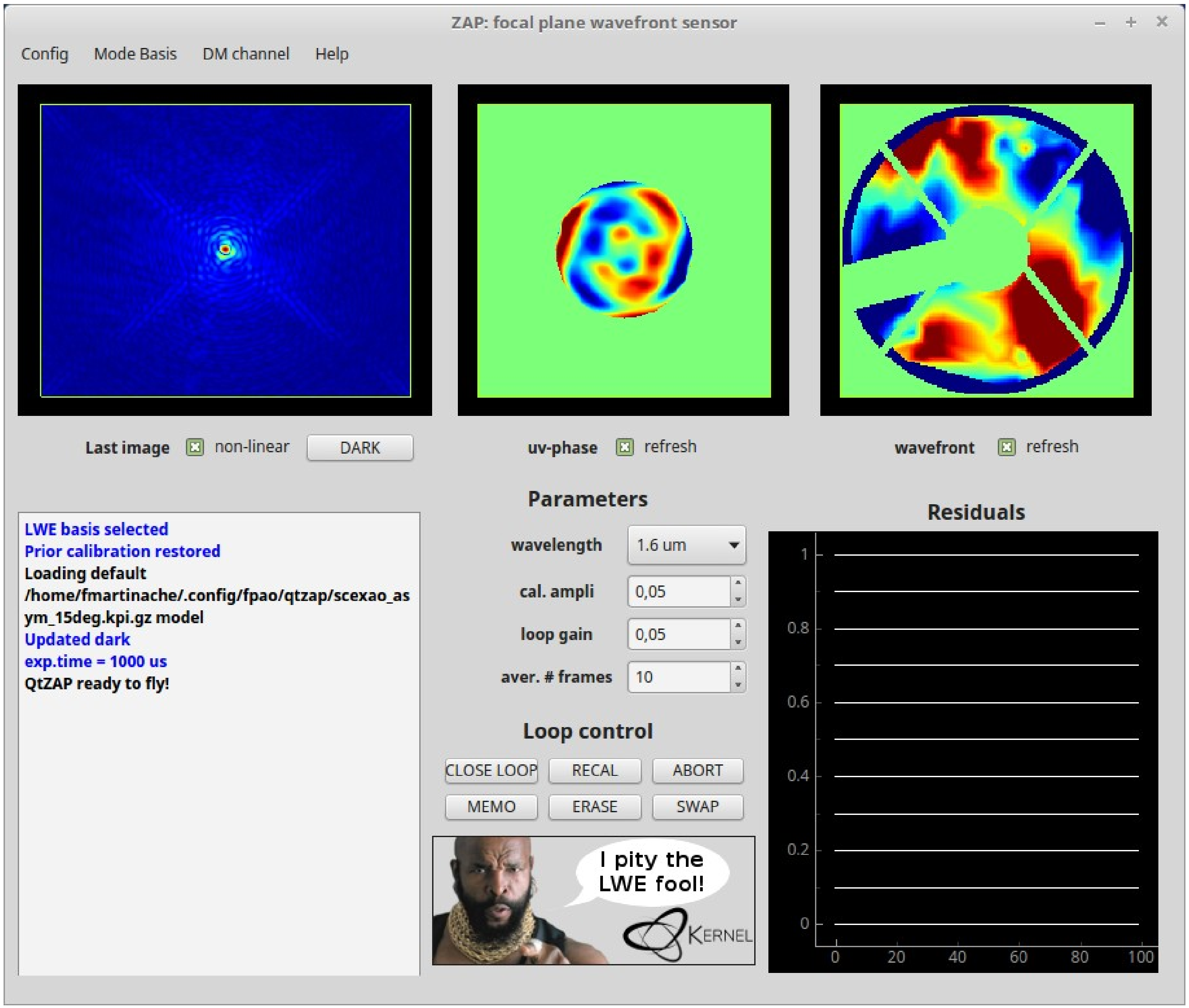
Subaru Coronagraphic Extreme Adaptive Optics

SCExAO Light path





OCA/KERNEL – developed software



- Address NCPA

- Asymmetric mask (pupil)

- On-sky closed-loop control

- Focal plane based WFS Low-order (Zernike and LWE) modes.

- mode compatible with coronagraphy in development

KERNEL

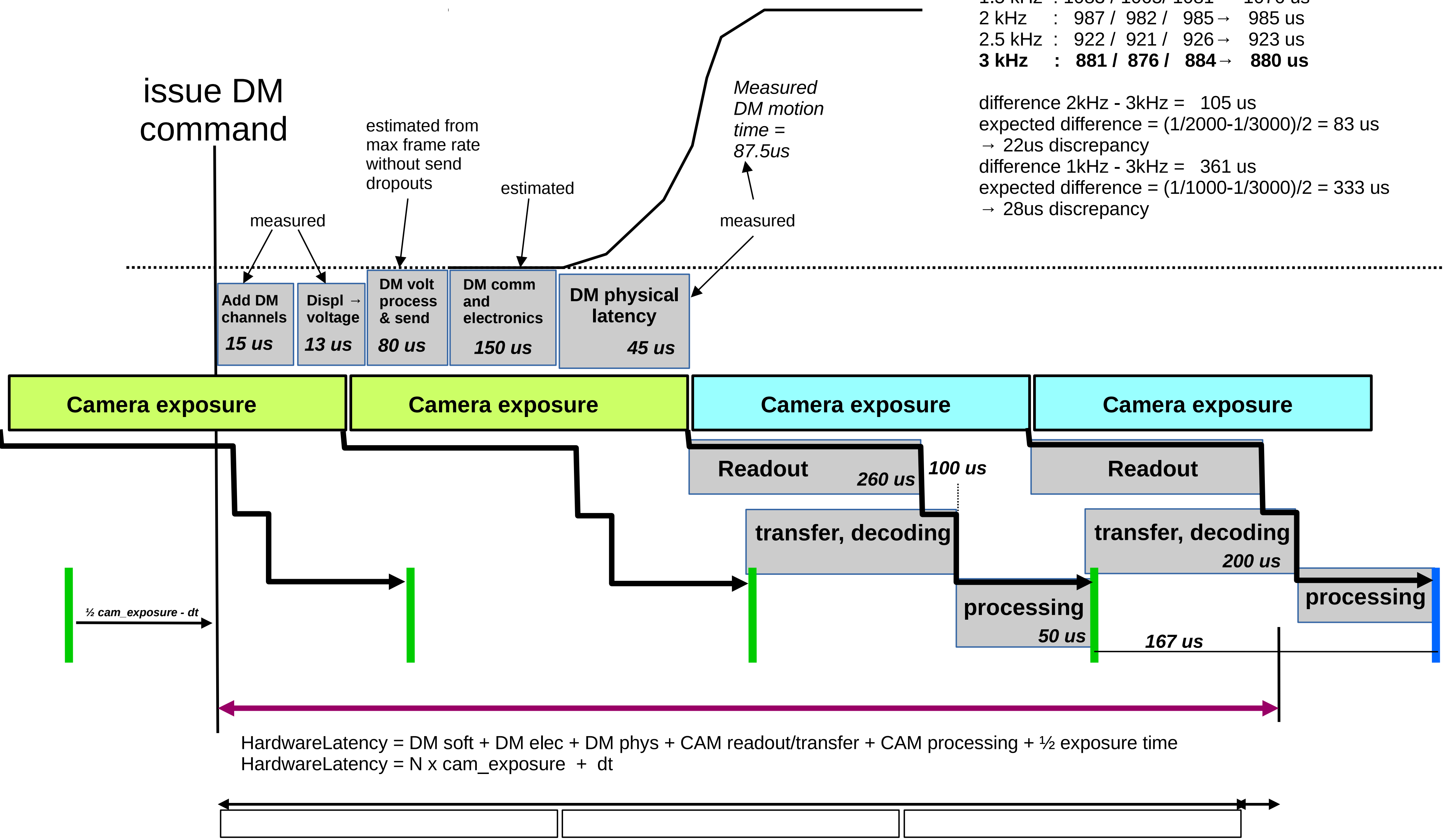
Hardware Latency measured on SCExAO

Definition:
*Time offset between **DM command issued**, and **mid-point between 2 consecutive WFS frames with largest difference***

SCExAO measured hardware latencies:

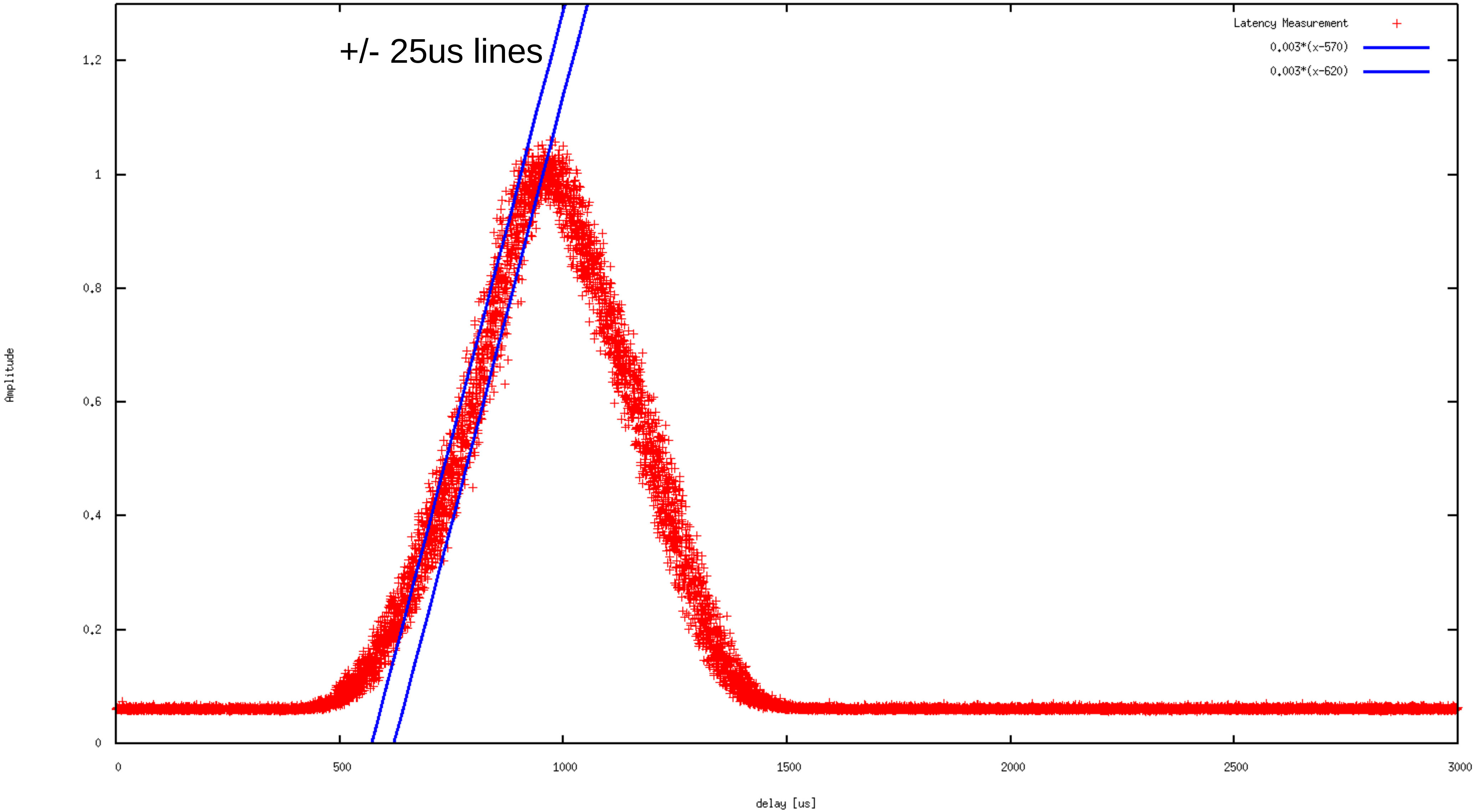
1 kHz : 1253 / 1260/ 1269 → 1261 us
1.5 kHz : 1083 / 1065/ 1081 → 1076 us
2 kHz : 987 / 982 / 985 → 985 us
2.5 kHz : 922 / 921 / 926 → 923 us
3 kHz : 881 / 876 / 884 → 880 us

difference 2kHz - 3kHz = 105 us
expected difference = (1/2000-1/3000)/2 = 83 us
→ 22us discrepancy
difference 1kHz - 3kHz = 361 us
expected difference = (1/1000-1/3000)/2 = 333 us
→ 28us discrepancy



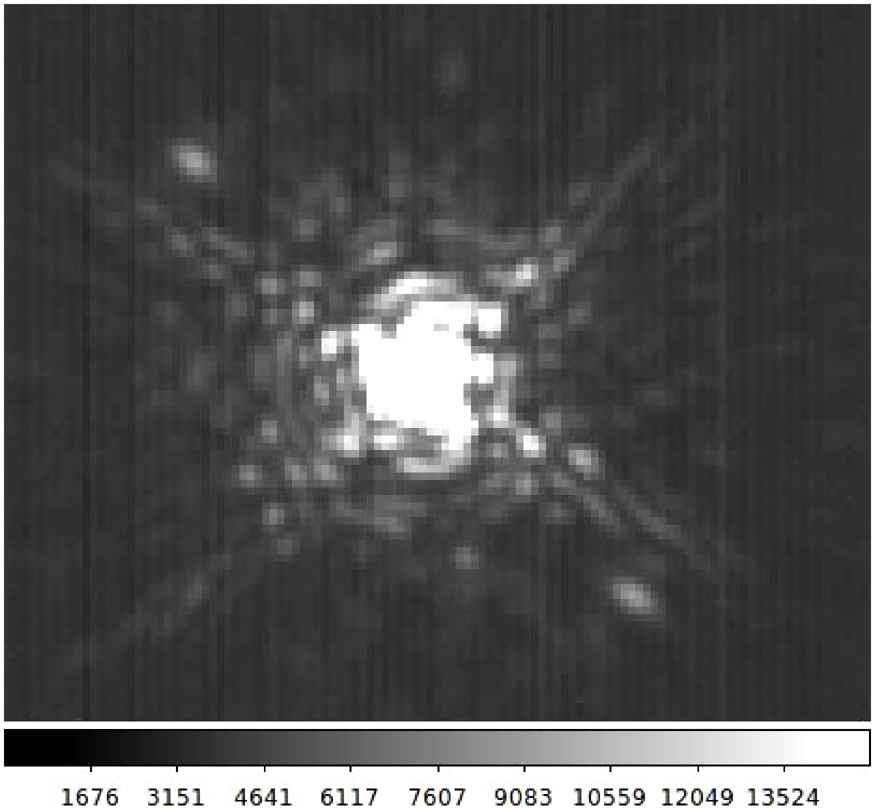
Hardware Latency measured on SCExAO

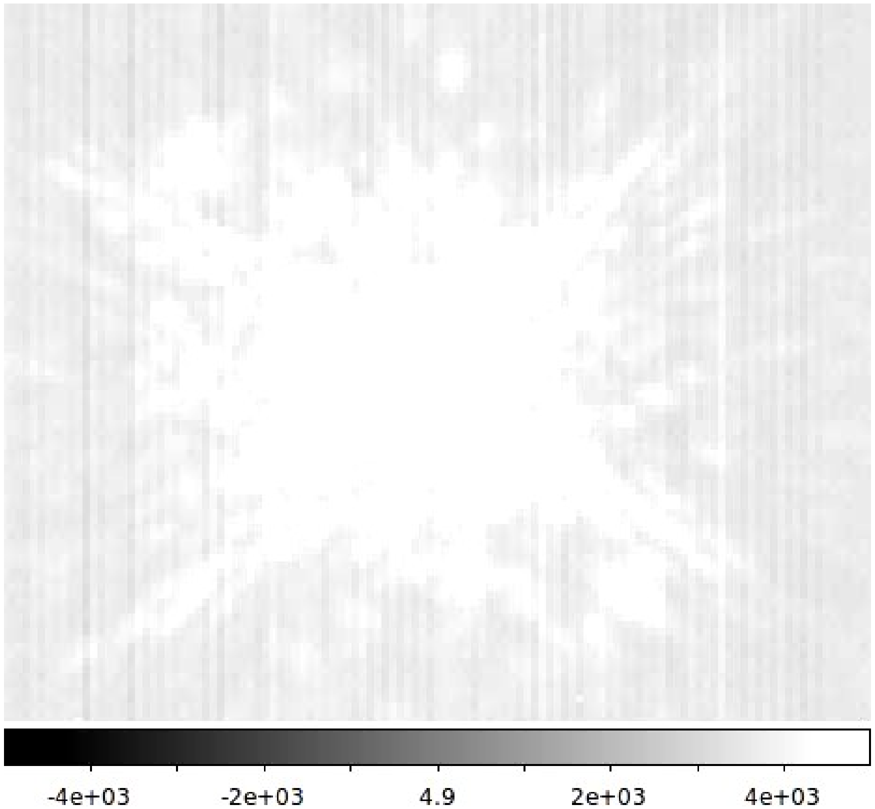
Total jitter <20us RMS = 6% of loop iteration @ 3kHz
(Camera readout + TCP transfer + processing + DM electronics)
Max jitter <40us



Synchronizing camera stream to DM (170 Hz)

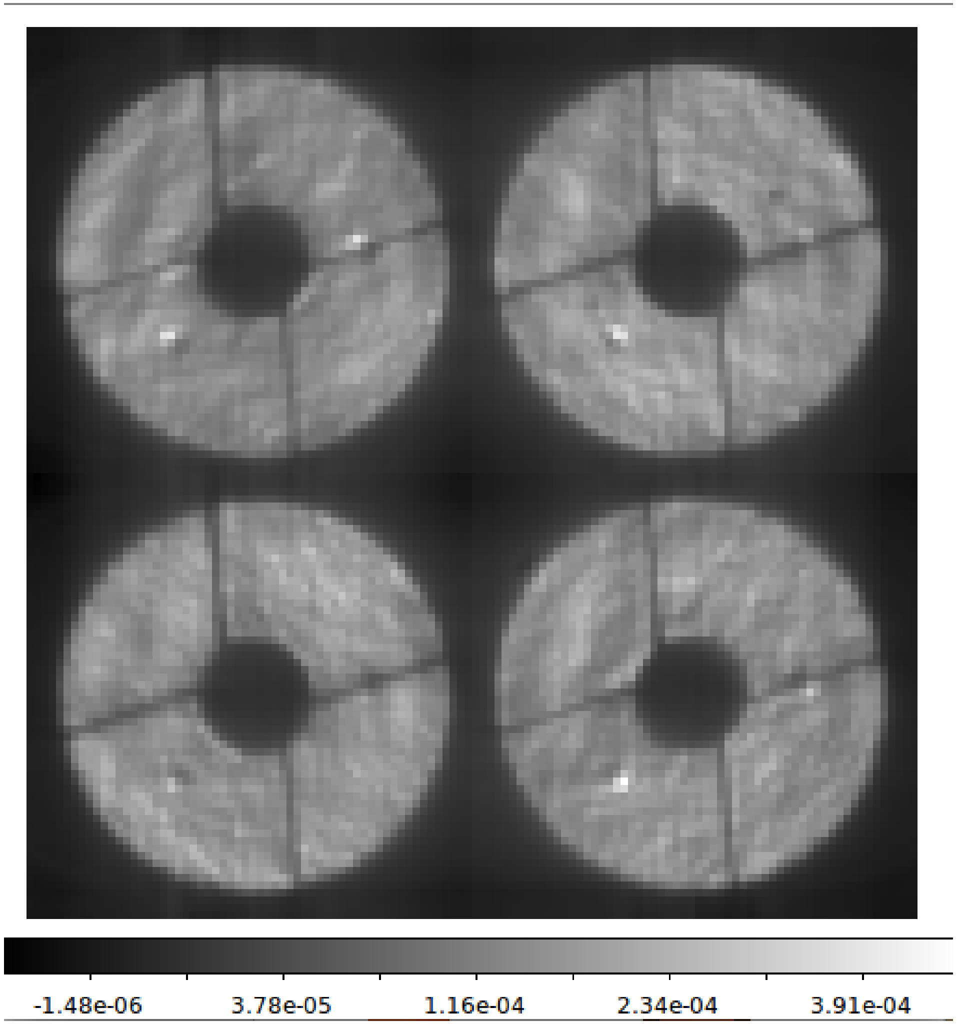
6kHz DM modulation swaps between 2 diag patterns

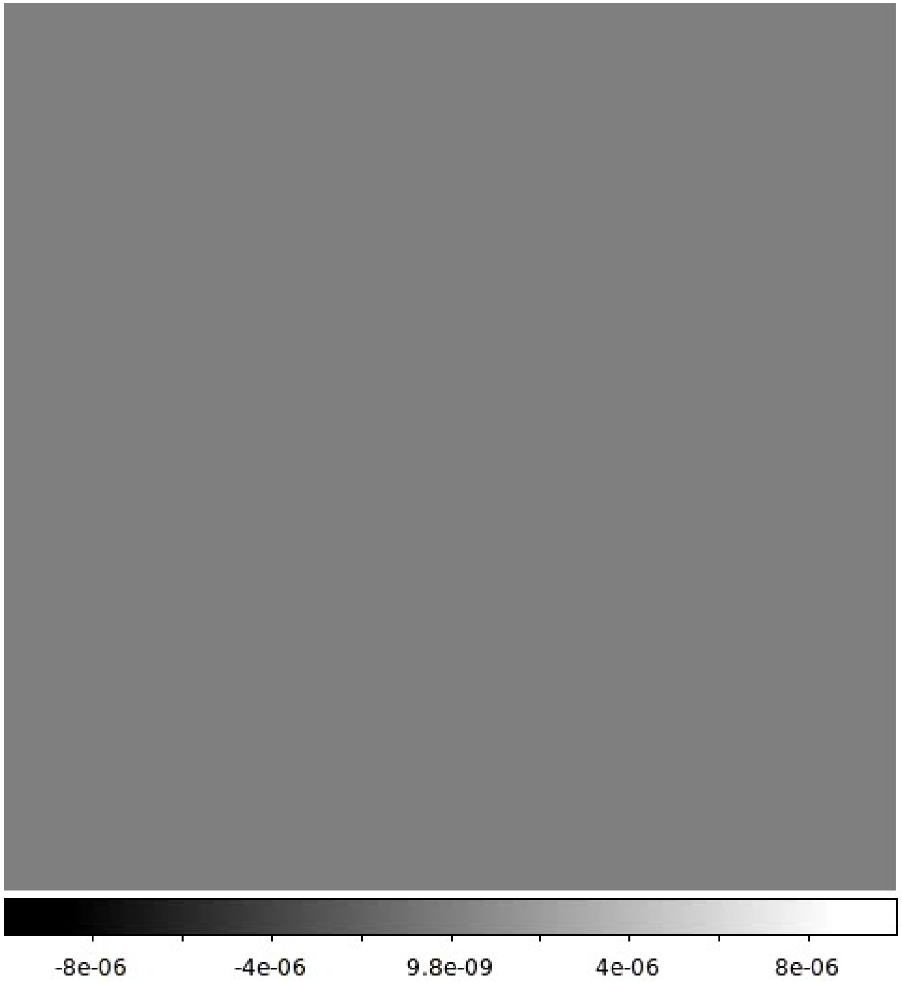




Measuring system response matrix at 3kHz

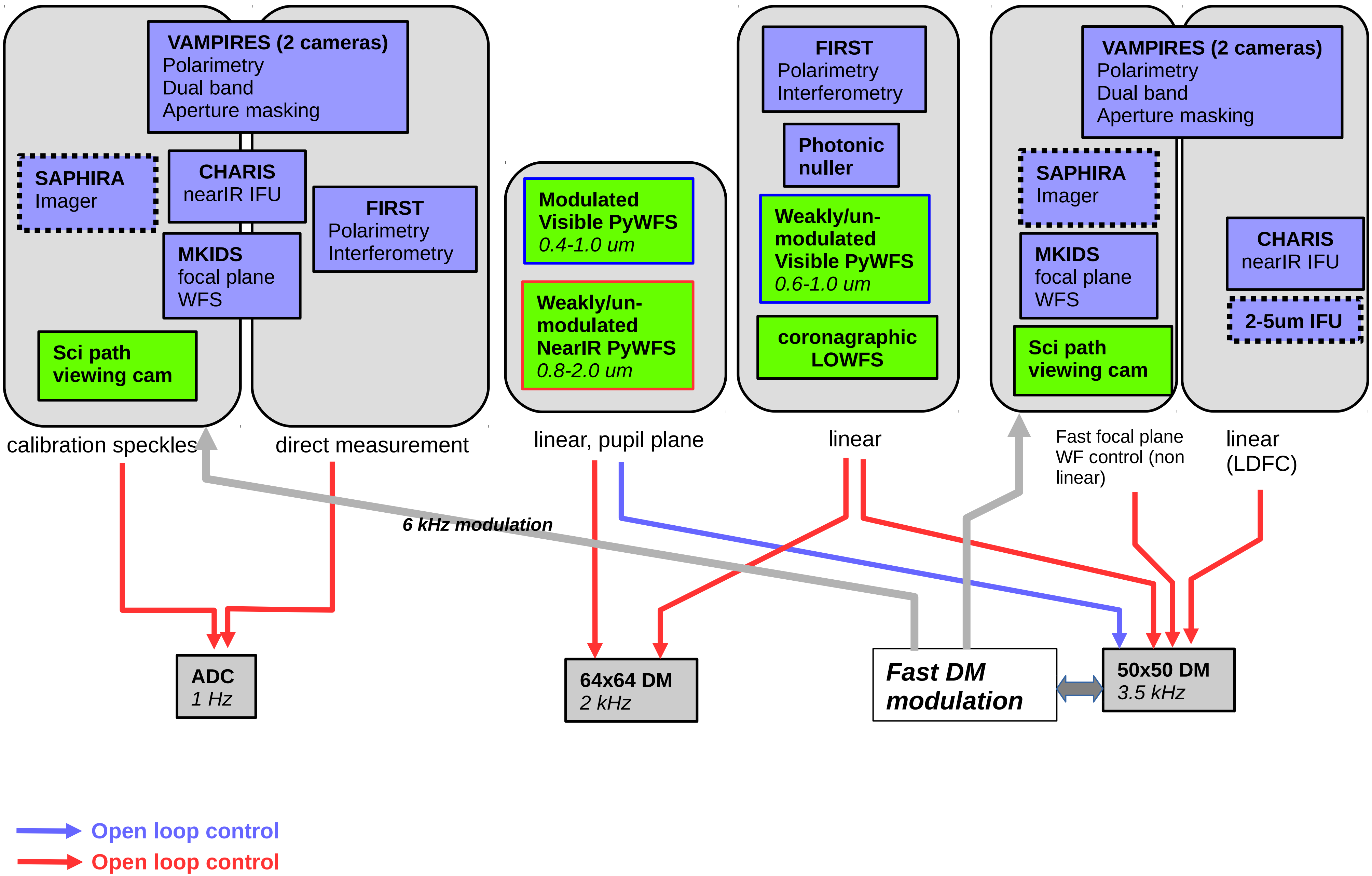
Full speed DM modulation to measure response matrix
DM motion occurs during EMCCD frame transfer
2000 modes measured in 1.33 sec @ 3kHz, 2sec @ 2kHz. Multiple cycles averaged to build up SNR





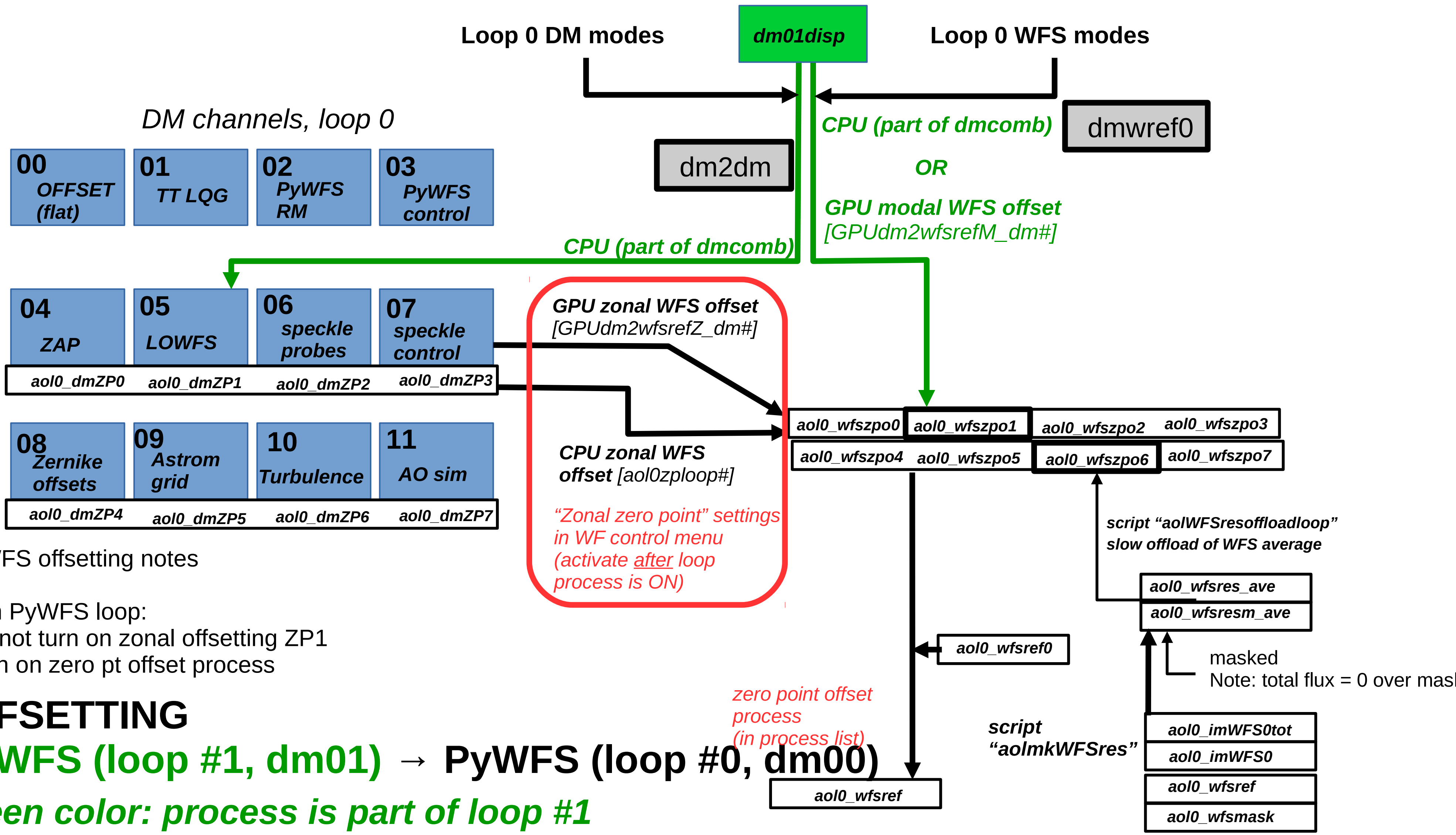
SCExAO Subaru Coronagraphic Extreme Adaptive Optics

Control loops



Linking multiple control loops (zero point offsetting)

A control loop can offset the convergence point of another loop @> kHz (GPU or CPU)
Example: speckle control, LOWFS need to offset pyramid control loop
THIS IS DONE TRANSPARENTLY FOR USER → don't pay attention to the diagram below !



LOWFS offsetting notes

From PyWFS loop:
- Do not turn on zonal offsetting ZP1
- Turn on zero pt offset process

OFFSETTING

LOWFS (loop #1, dm01) → PyWFS (loop #0, dm00)

Green color: process is part of loop #1

Conclusions

GSMTs can image and characterize habitable planets around nearby M-type stars
Significant progress is being made in high contrast imaging techniques…
→ testing on current large telescopes is critical to be ready & efficient for GSMTs era

SCExAO is a powerful platform for testing and deploying new techniques (hardware, algorithms).
Daytime testing with internal source → nighttime on-sky validation

Coordinated development with MagAO-X (→GMT), Keck (→TMT), SPHERE upgrades (→ELT)
Major ongoing effort to develop software ecosystem to facilitate algorithm development and test across observatories/instruments/labs.

Multiple opportunities to get involved:
Test algorithms, reduce data, new hardware, looking for exoplanets, cool project for postdoc fellowship ?
→ talk to us