# Subaru Coronagraphic Extreme Adaptive Optics (SCExAO): Wavefront Control Optimized for High Contrast Imaging

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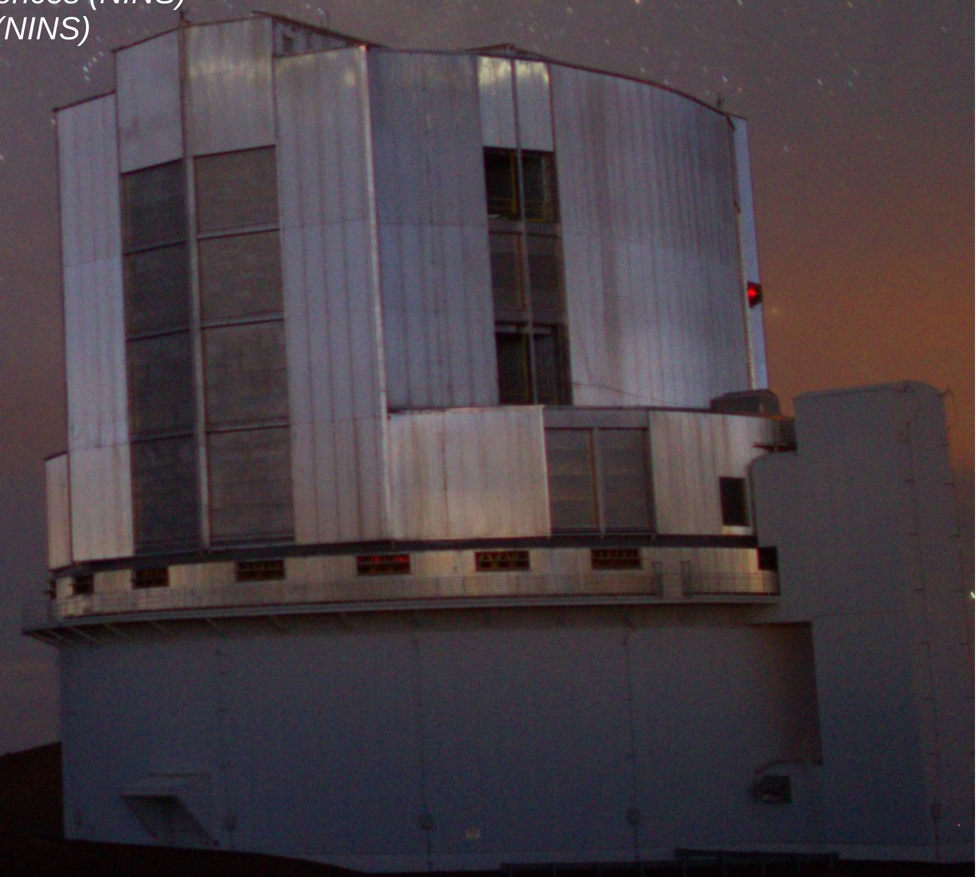
*[4] NASA Ames Research Center*
*[5] Caltech*
*[6] Observatoire de la cote d'Azur*
*[7] University of California Santa Barbara*
*[8] University of Sydney*
*[9] NASA GSFC*

***k***



SPIE, Aug 9, 2017

# 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

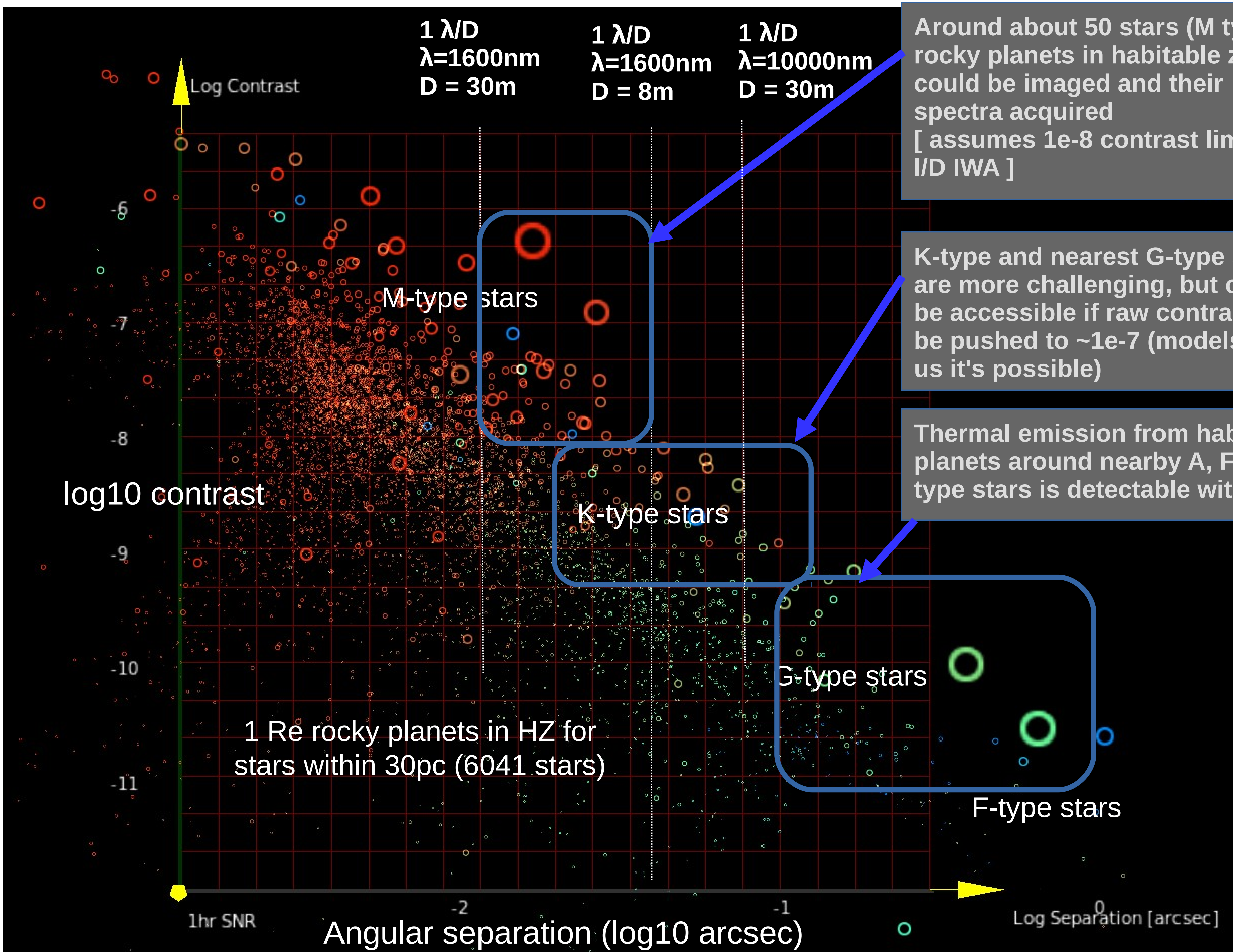
Modules/instruments funded by Japan + international partners:

- 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)

# Contrast and Angular separation

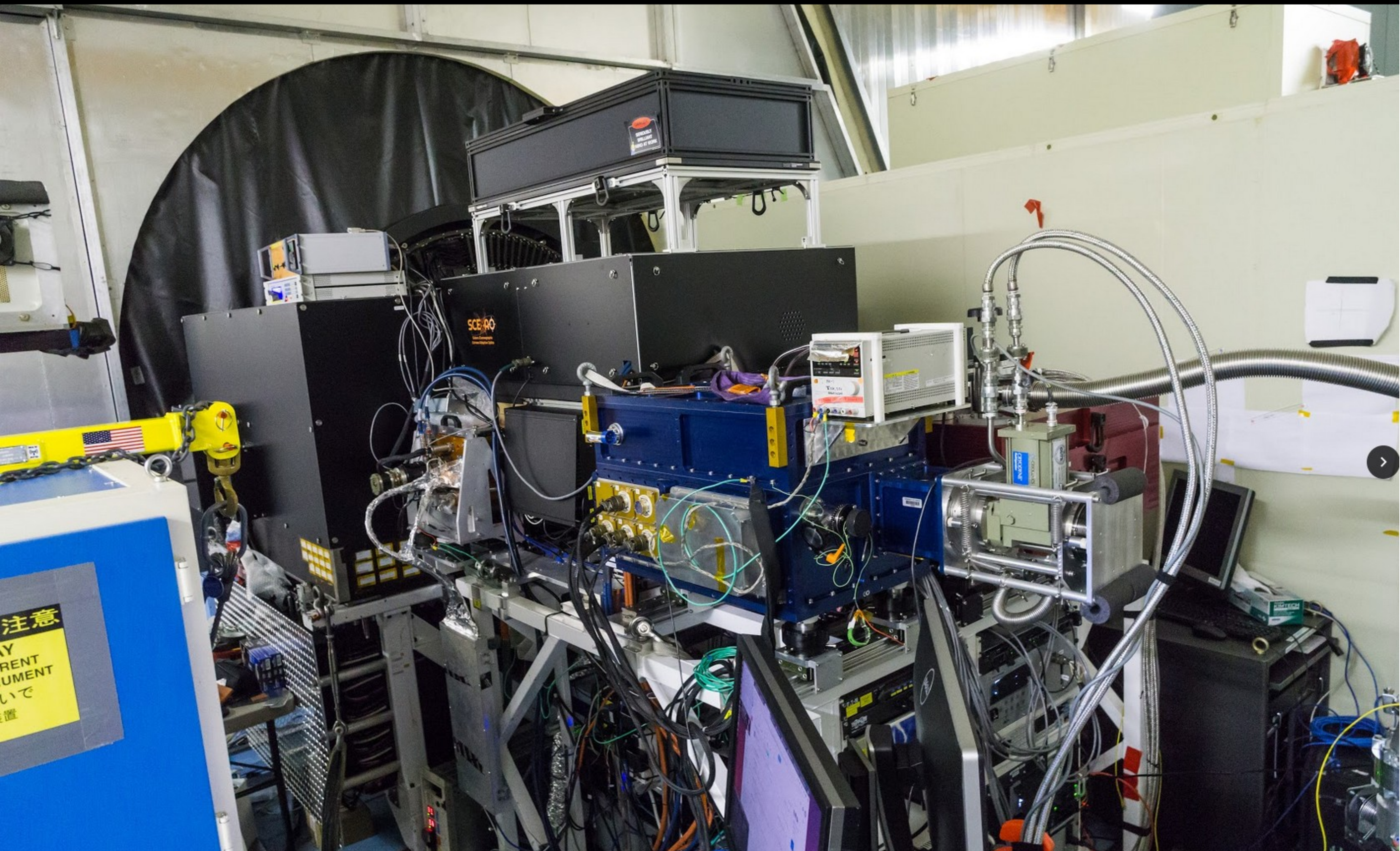



Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired
[ assumes 1e-8 contrast limit, 1 l/D IWA ]

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)

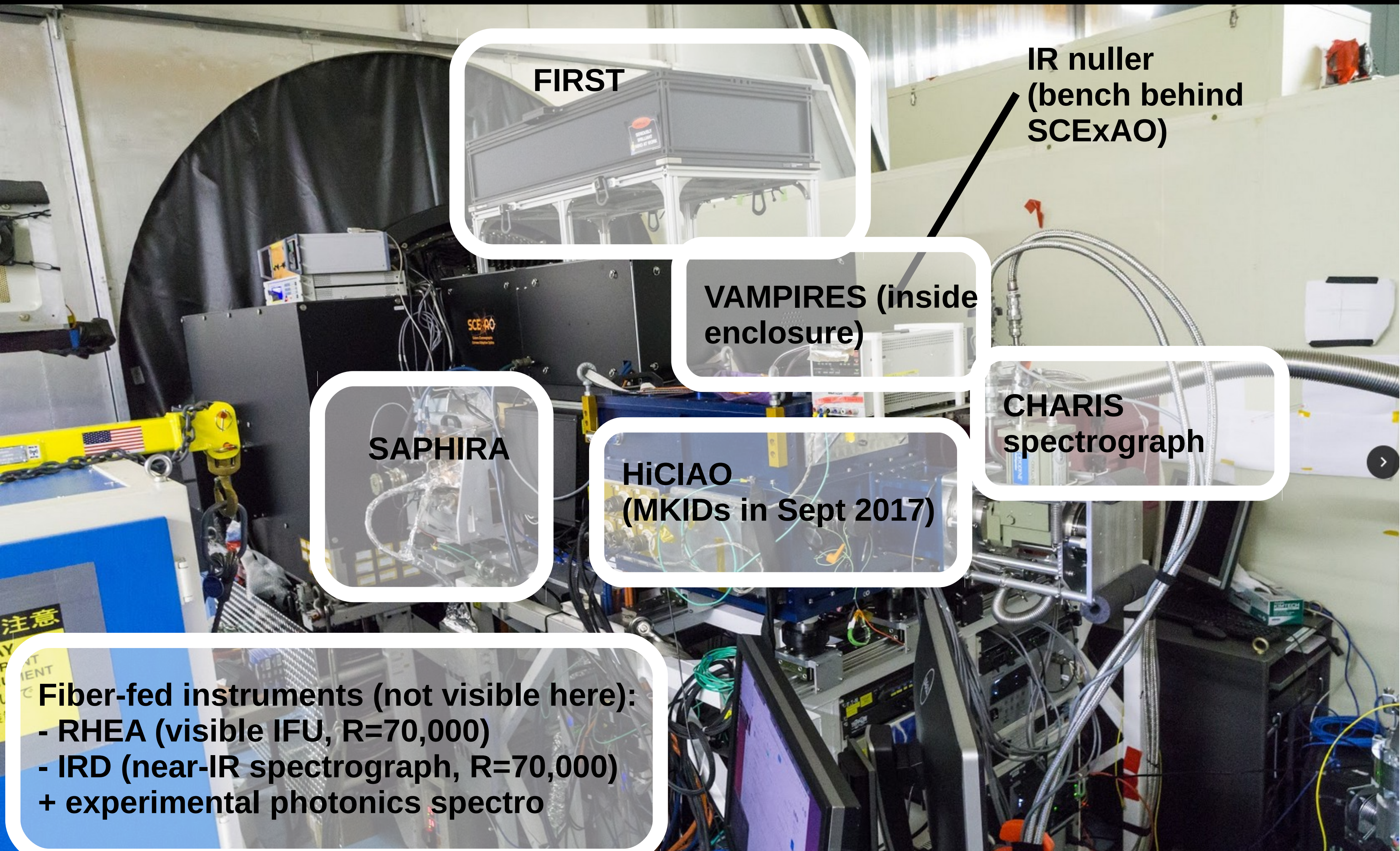
Thermal emission from habitable planets around nearby A, F, G type stars is detectable with ELTs

# Subaru Coronagraphic Extreme Adaptive Optics



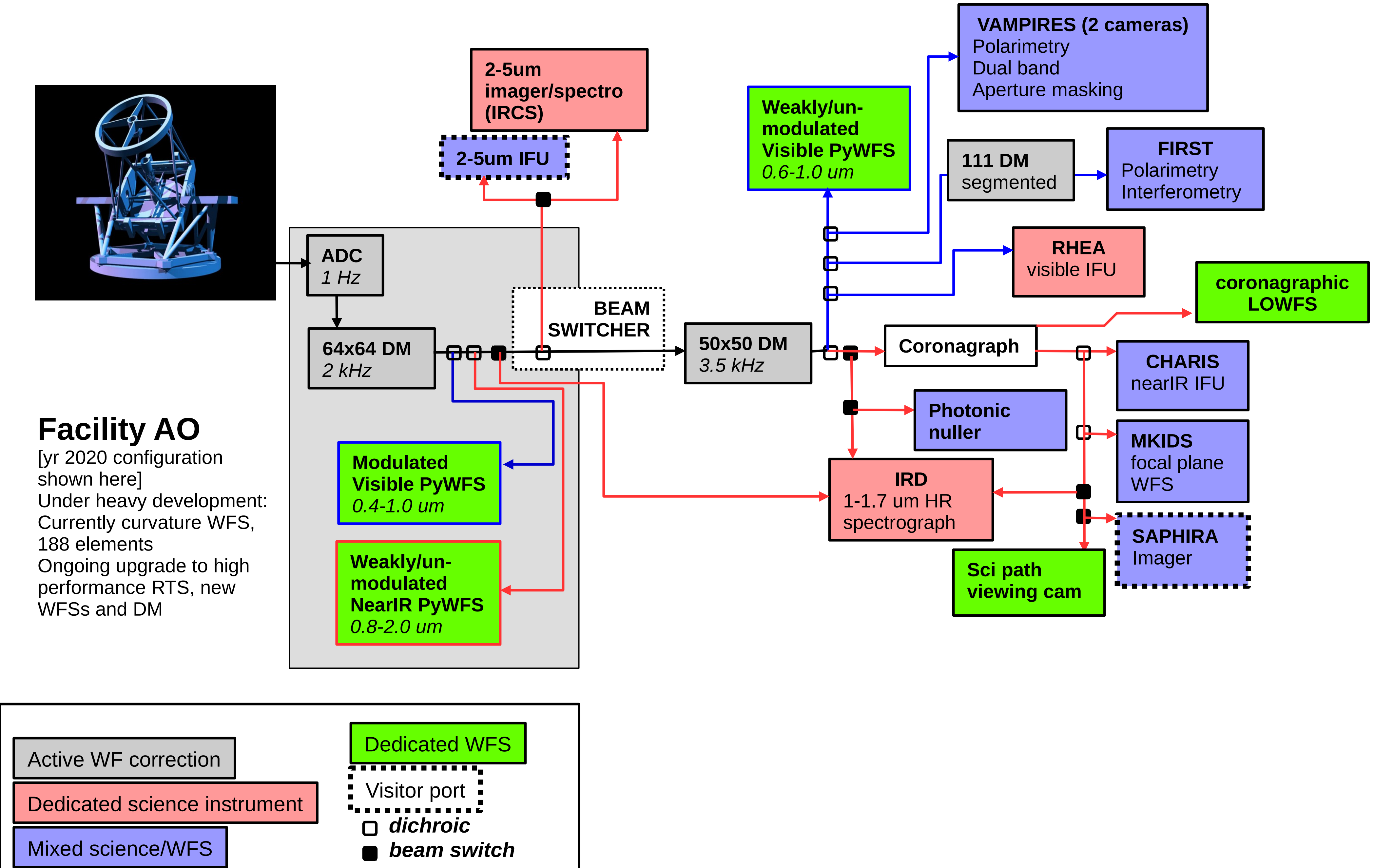
SCExAO

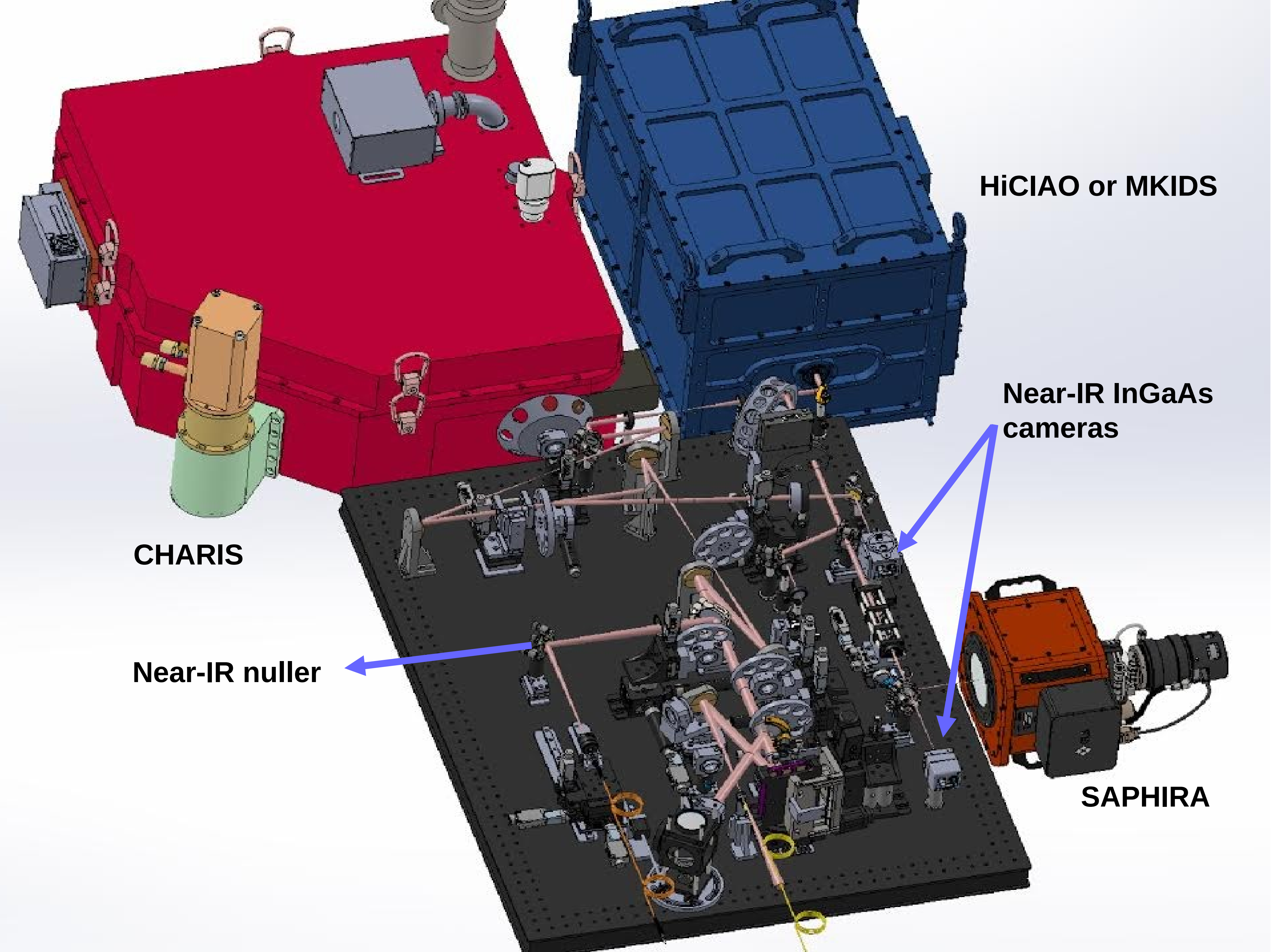
# Subaru Coronagraphic Extreme Adaptive Optics



SCExAO Subaru Coronagraphic Extreme Adaptive Optics

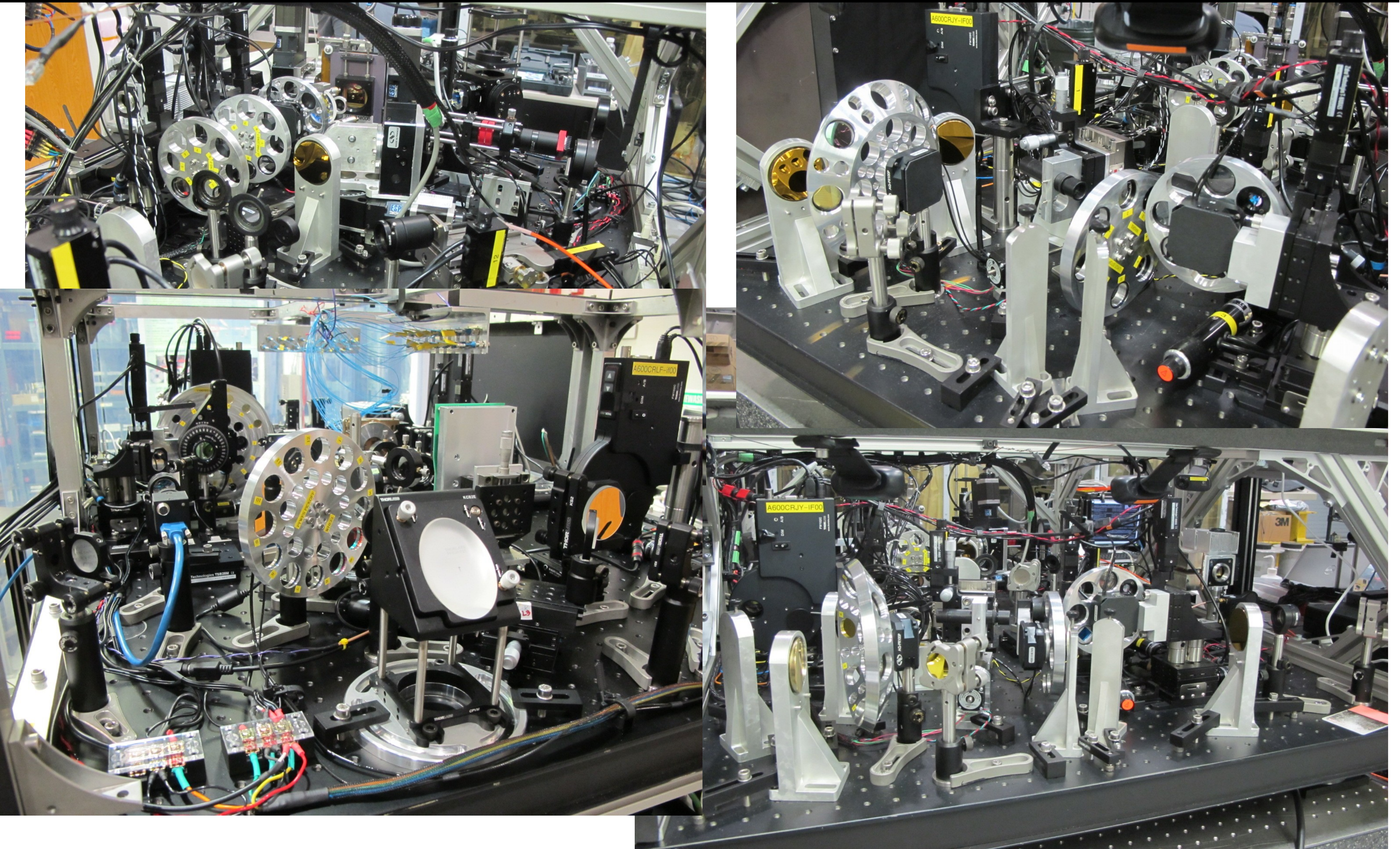
# SCExAO Light path



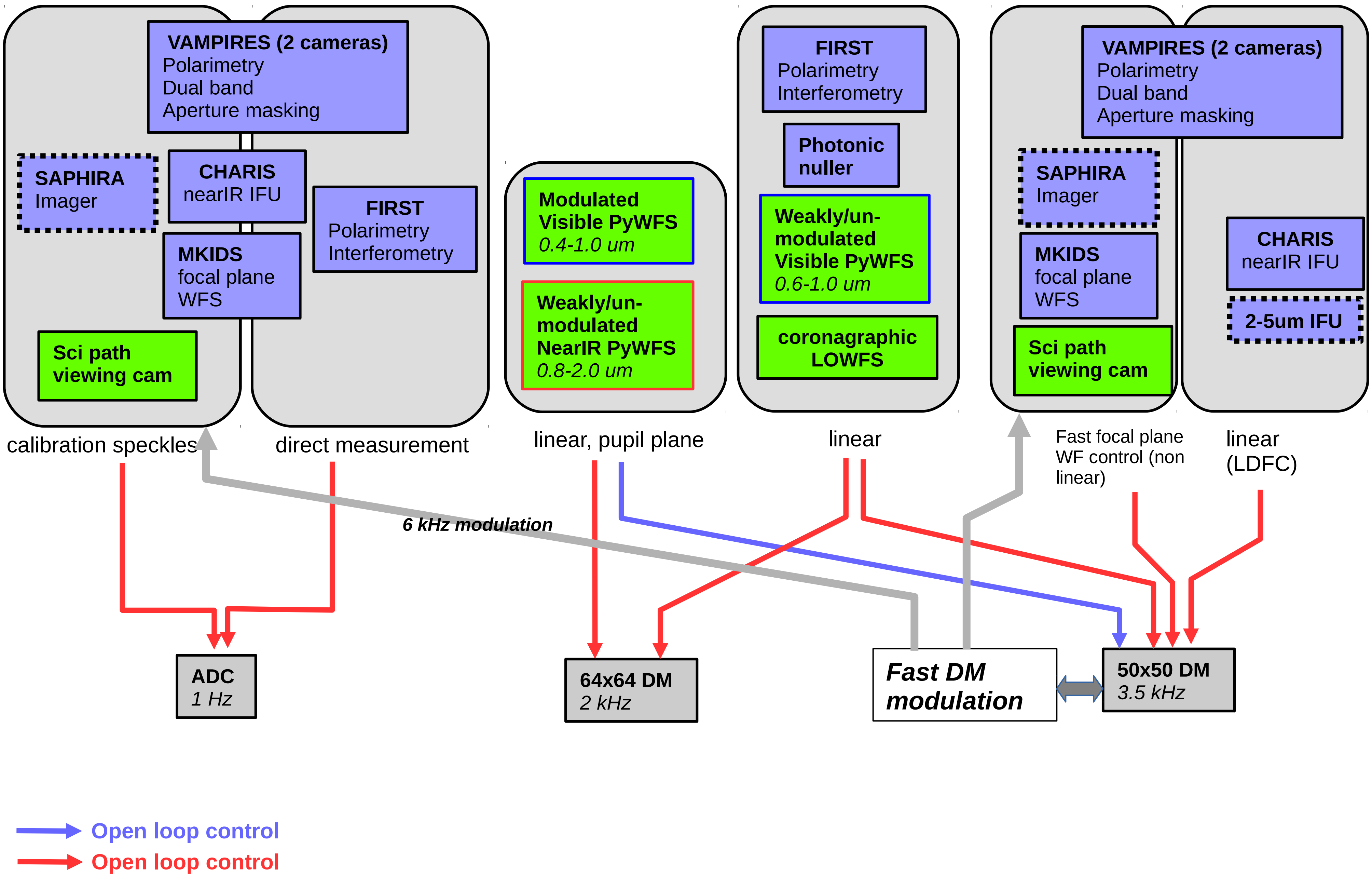

HiCIAO or MKIDS
Near-IR InGaAs cameras
CHARIS
Near-IR nuller
SAPHIRA

SCExAO

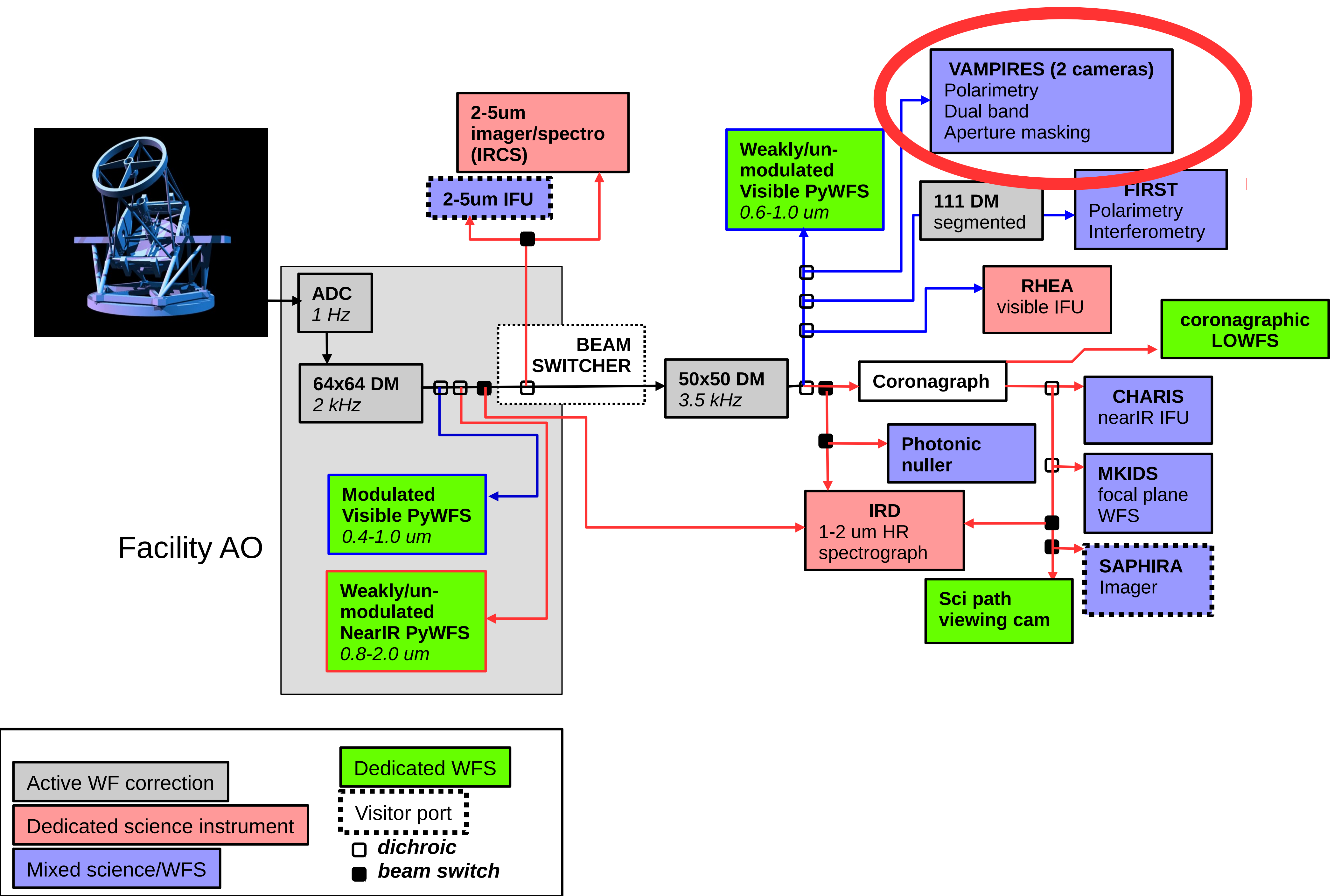
# Subaru Coronagraphic Extreme Adaptive Optics



# Wavefront Control loops



# SCExAO Light path

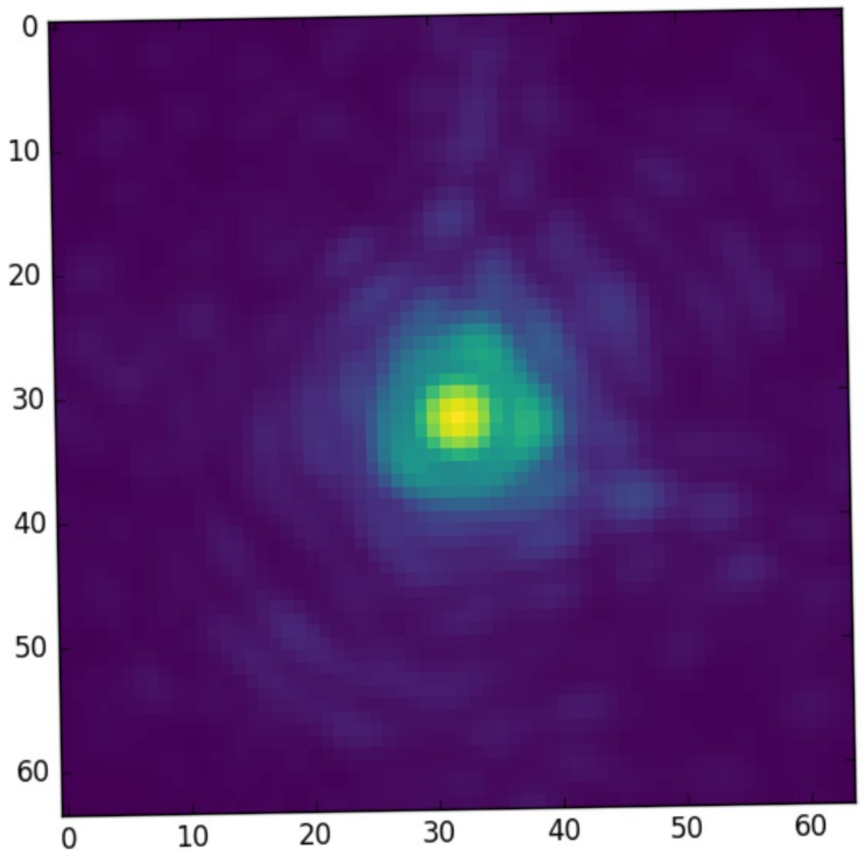


# Preliminary VAMPIRES science

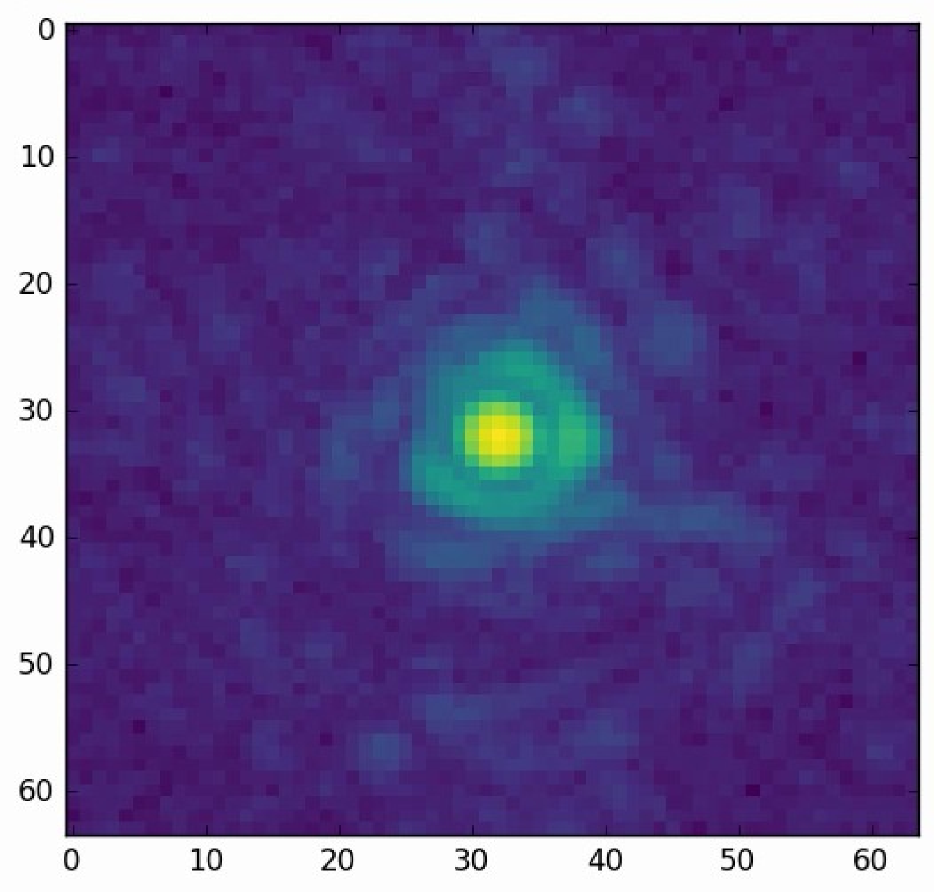
*Diffraction-limited imaging in visible light*

750nm, 1kHz imaging
log scale

Summed image

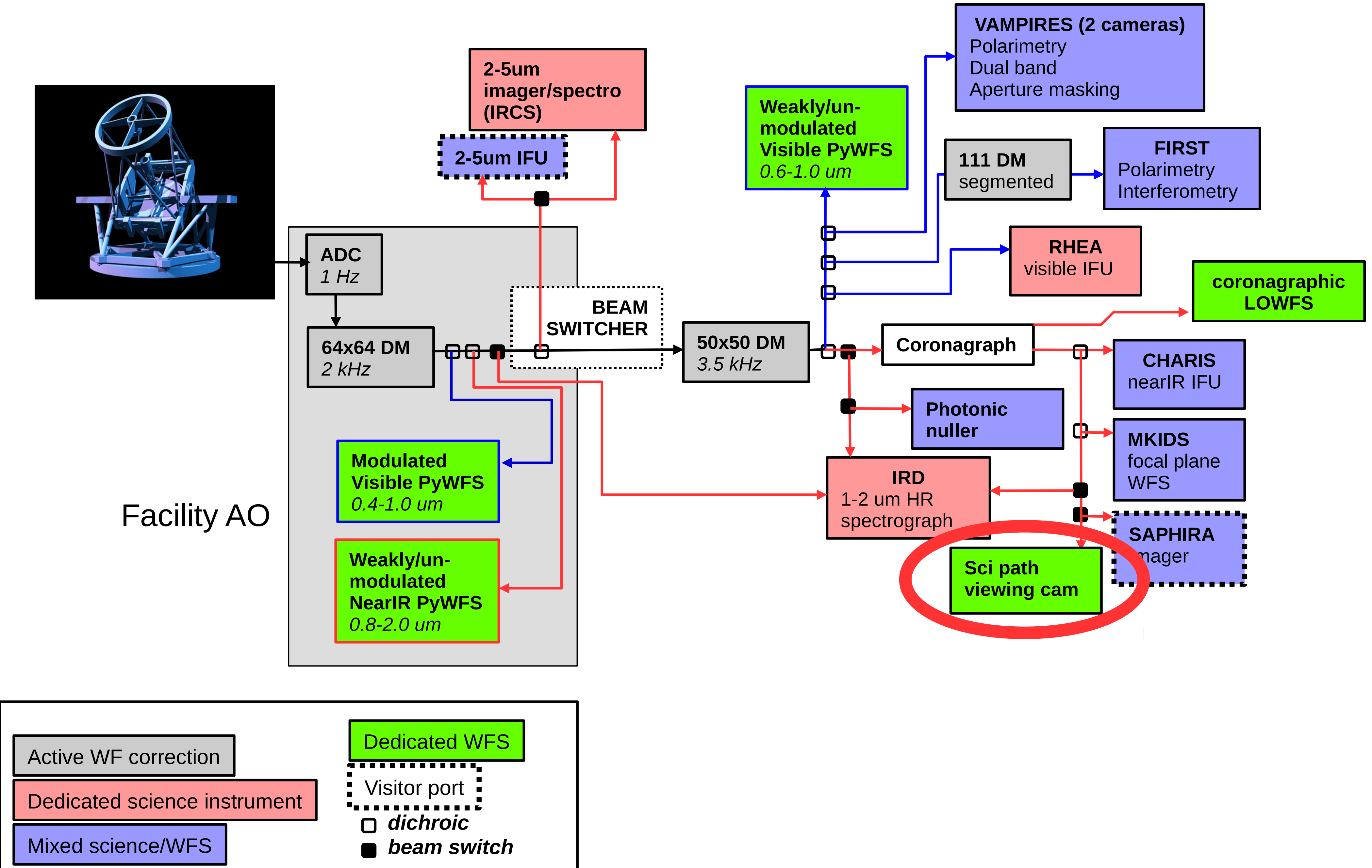



Video



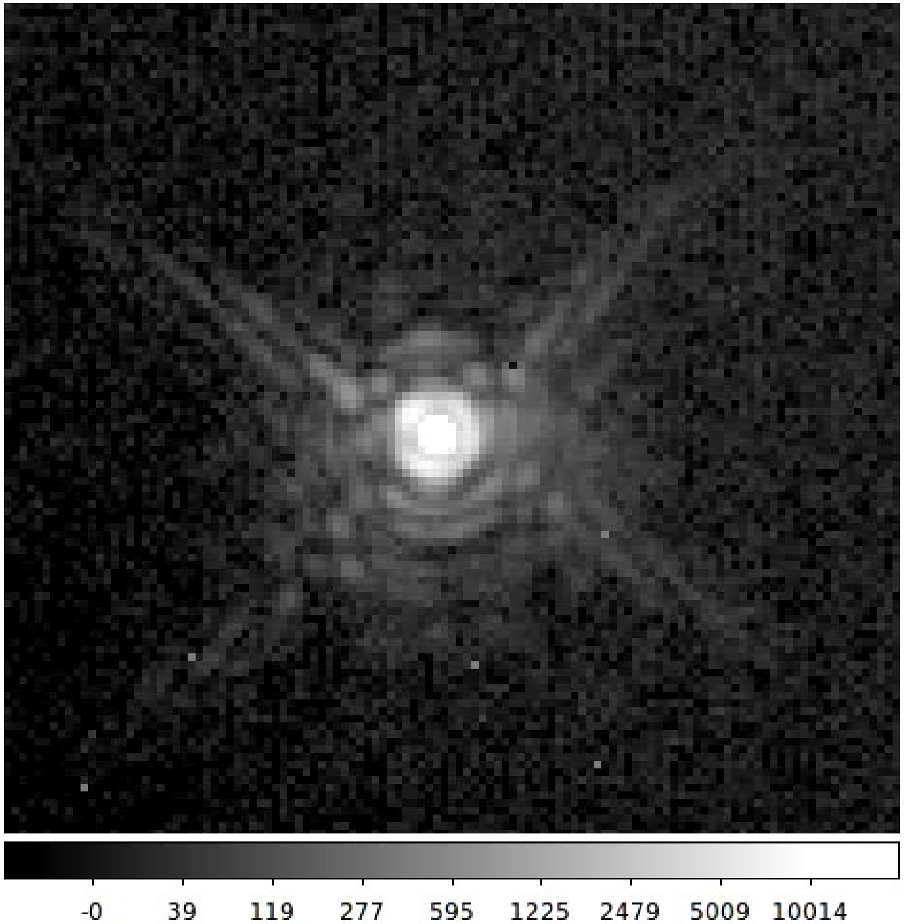
Subaru Coronagraphic Extreme Adaptive Optics

# SCExAO Light path



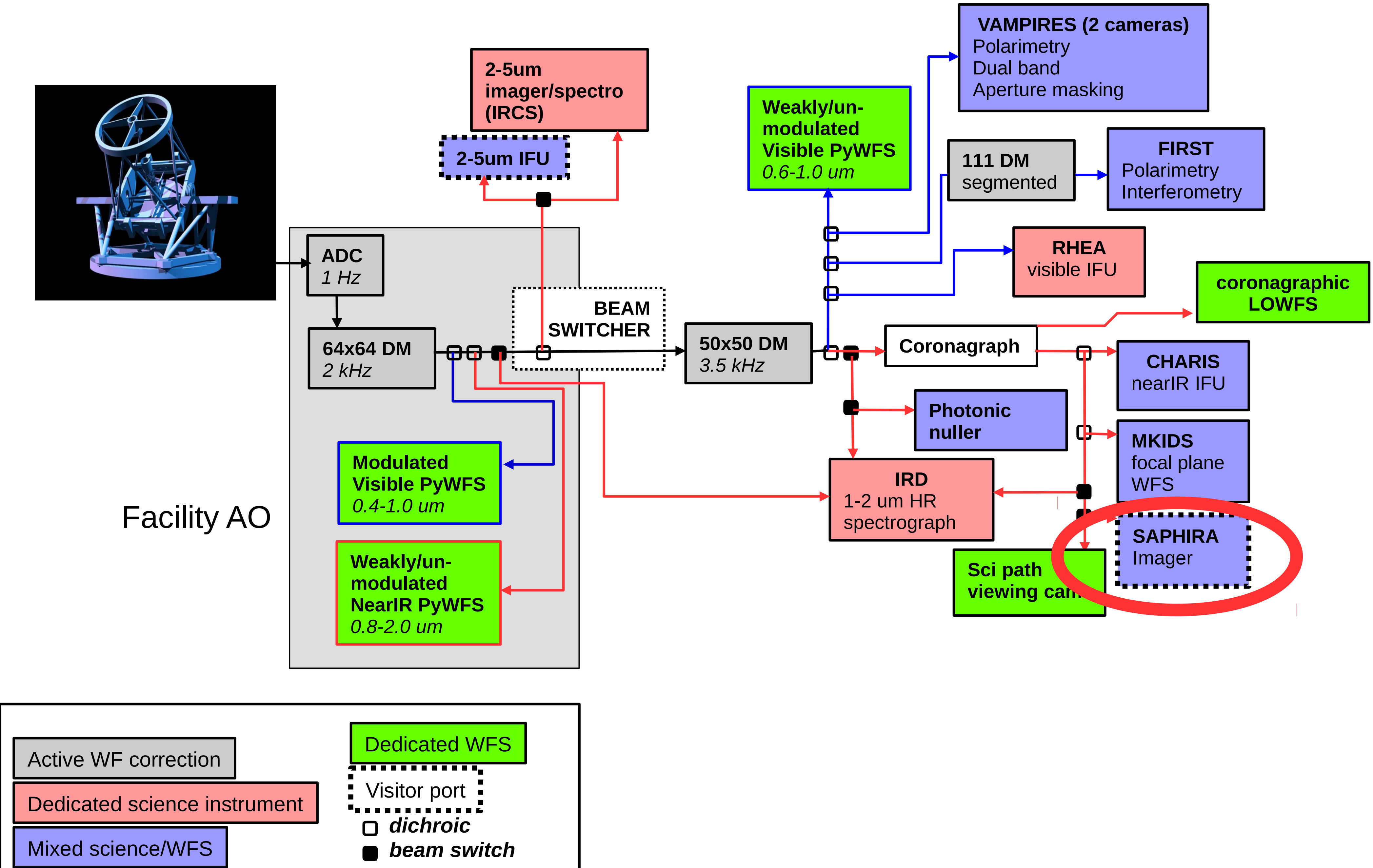
# Current PSF stability @ SCExAO

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



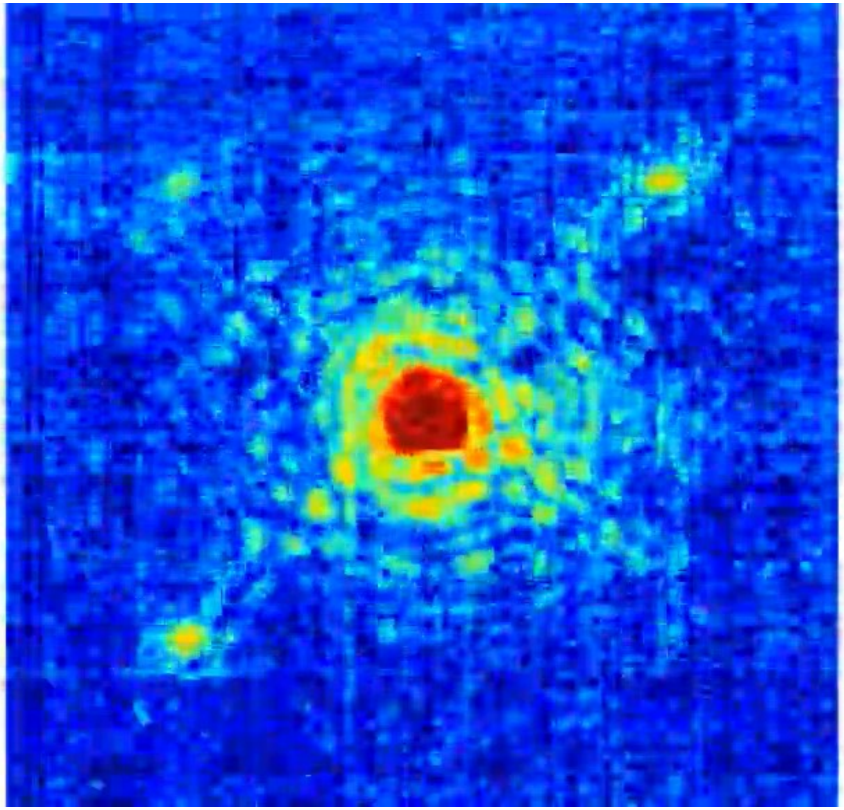

**1630nm (SCExAO internal camera)**
**3 Hz sampling**

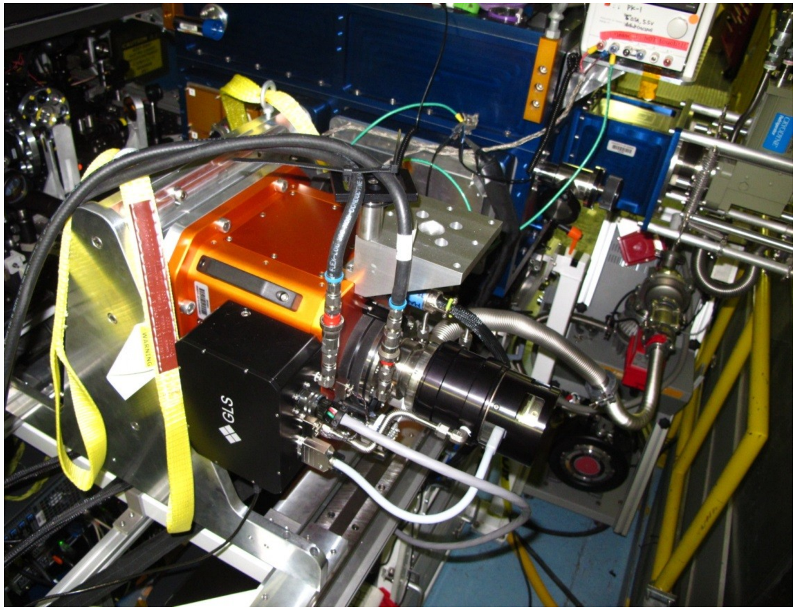
# SCExAO Light path



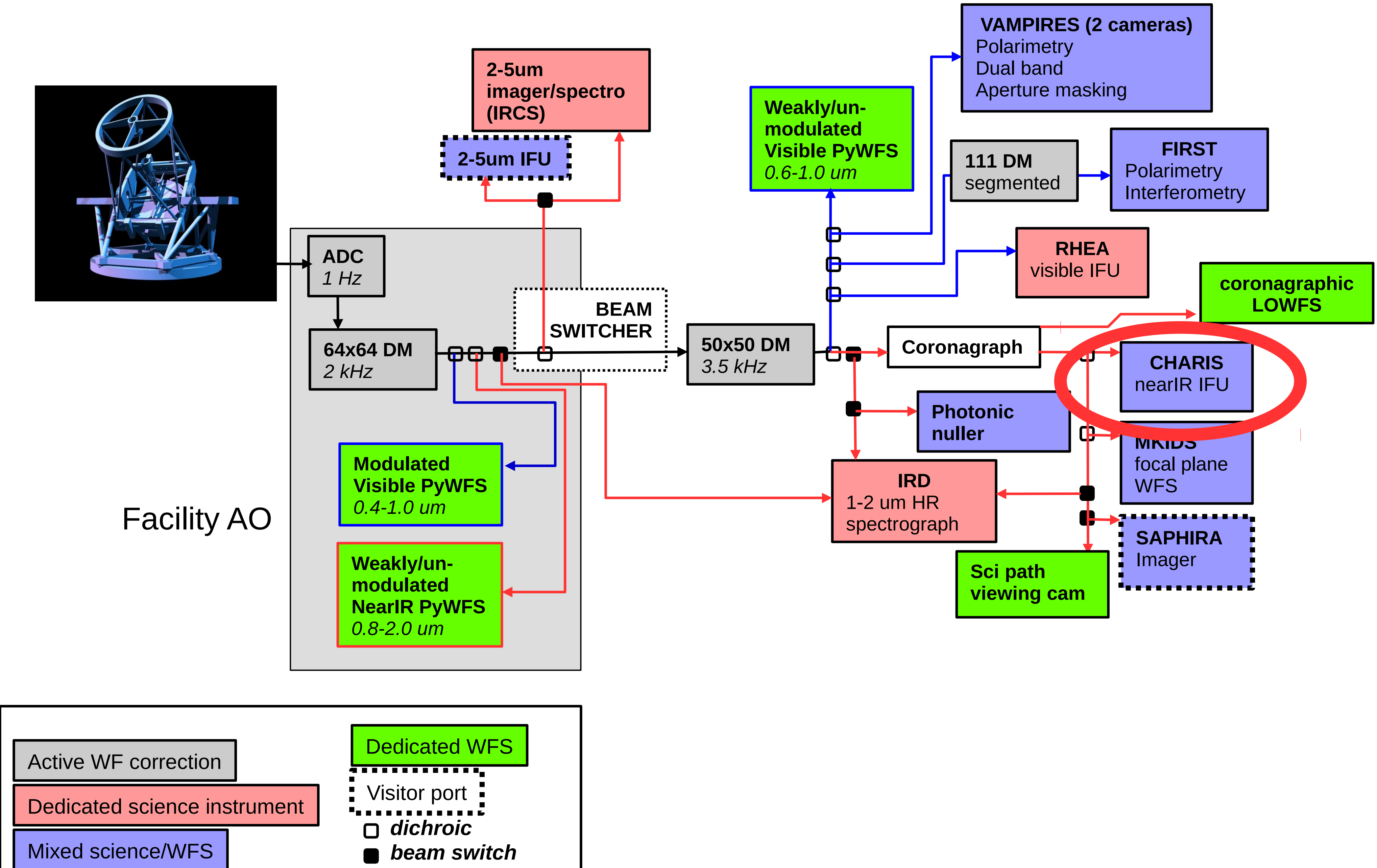
# SAPHIRA camera

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

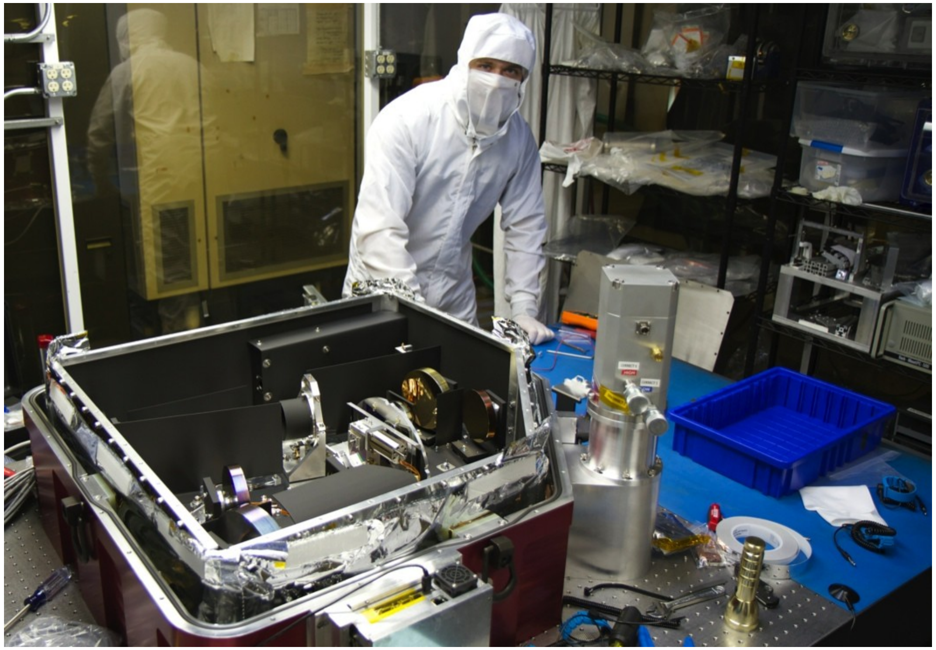


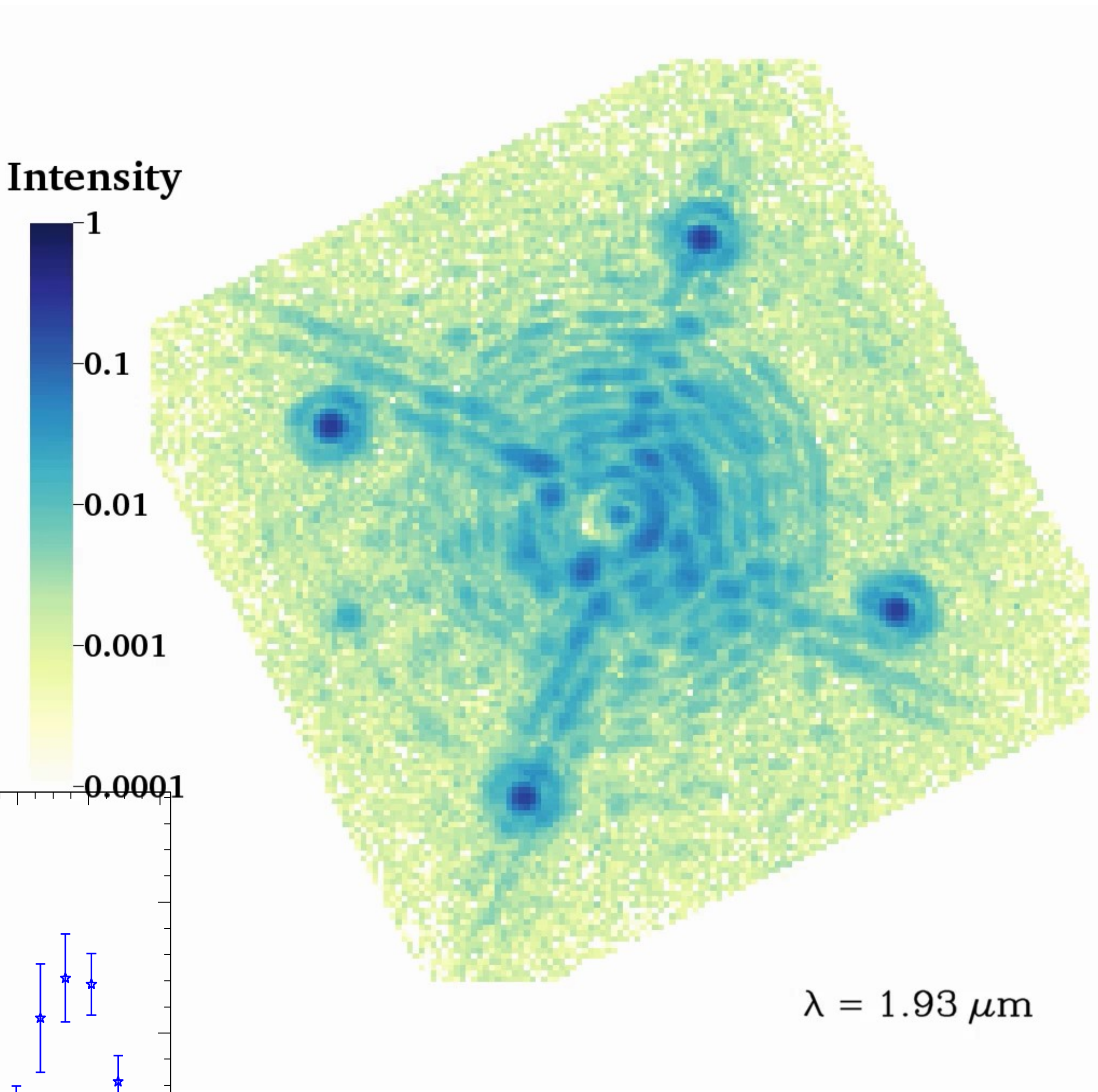


# SCExAO Light path

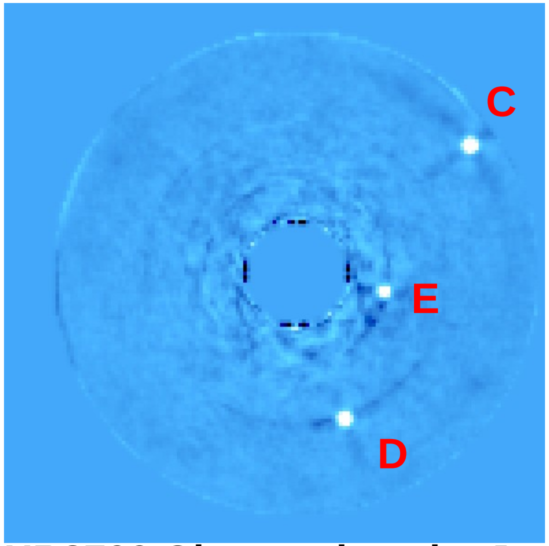


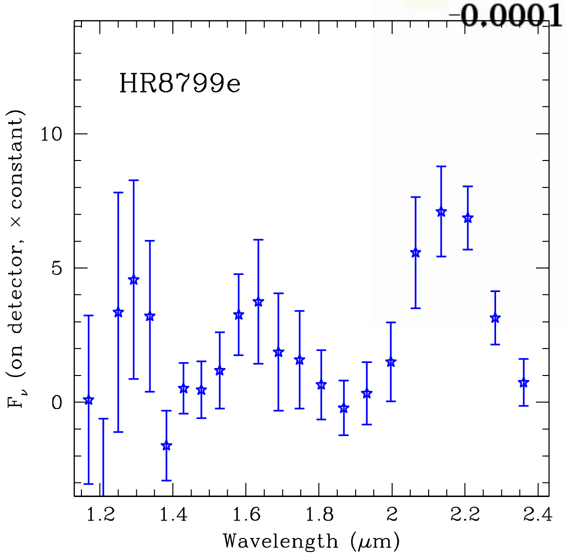
# CHARIS IFS





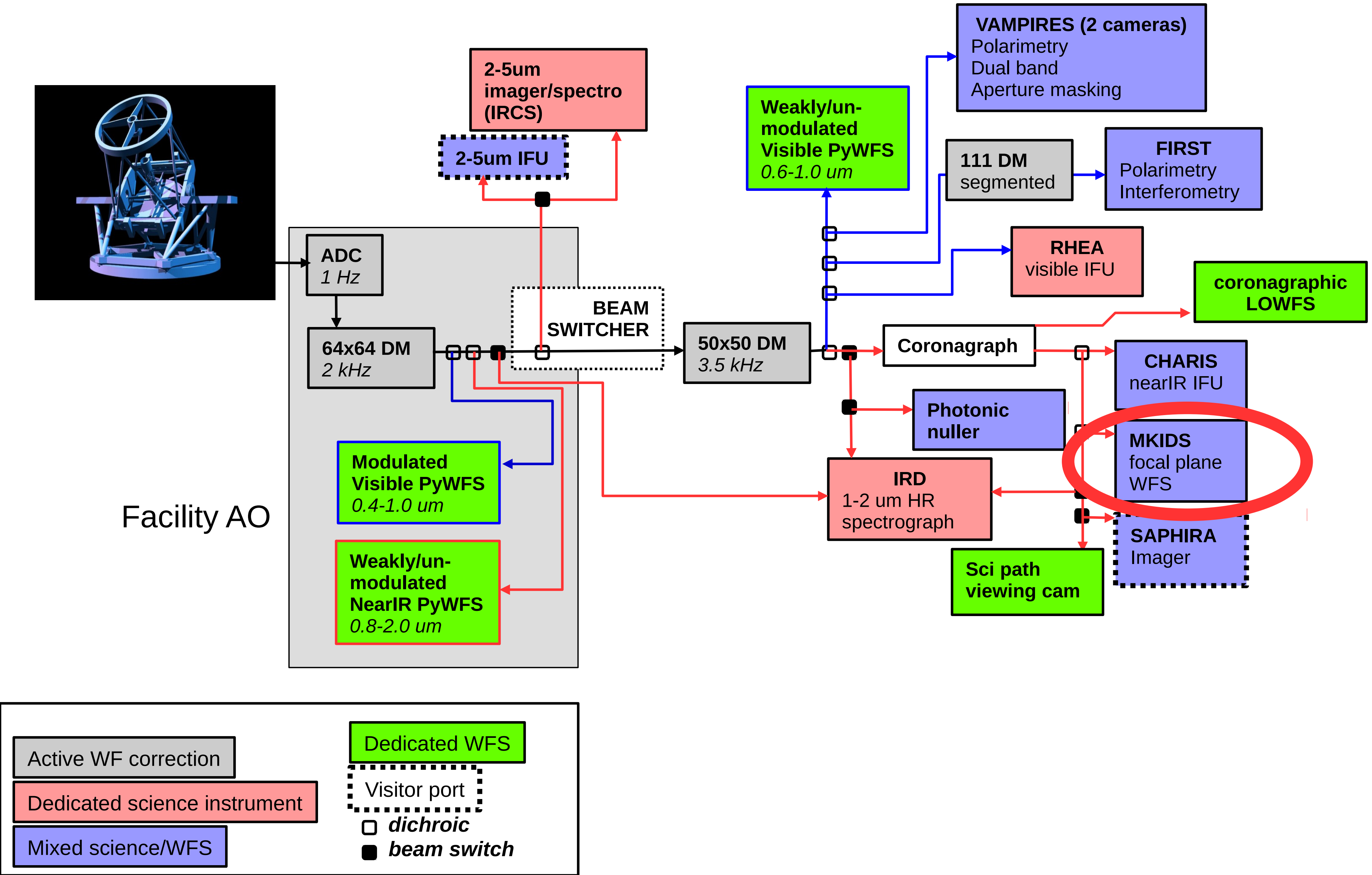

HR8799



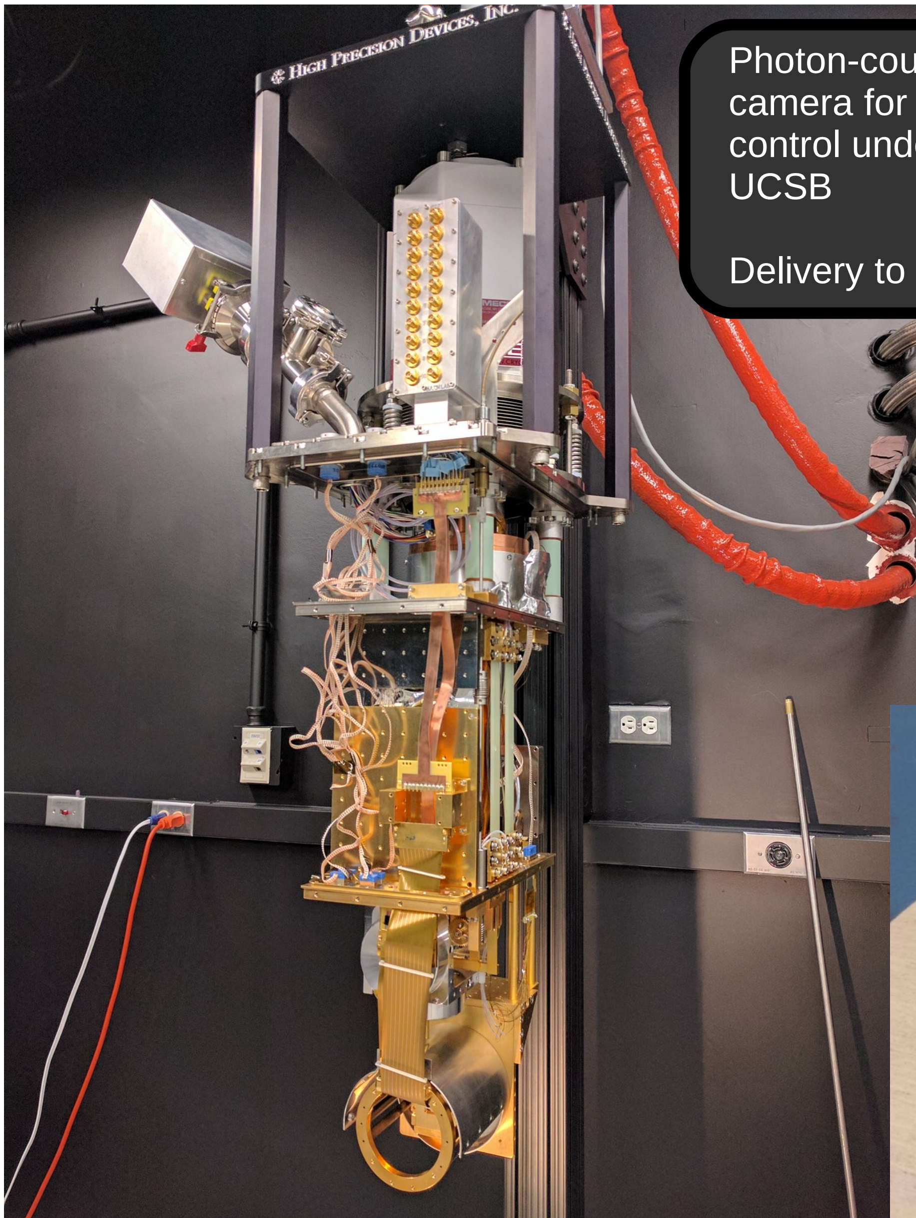

**HR8799 Observations by J. Chilcote & T. Groff preliminary data processing by T. Brandt**

# SCExAO Light path



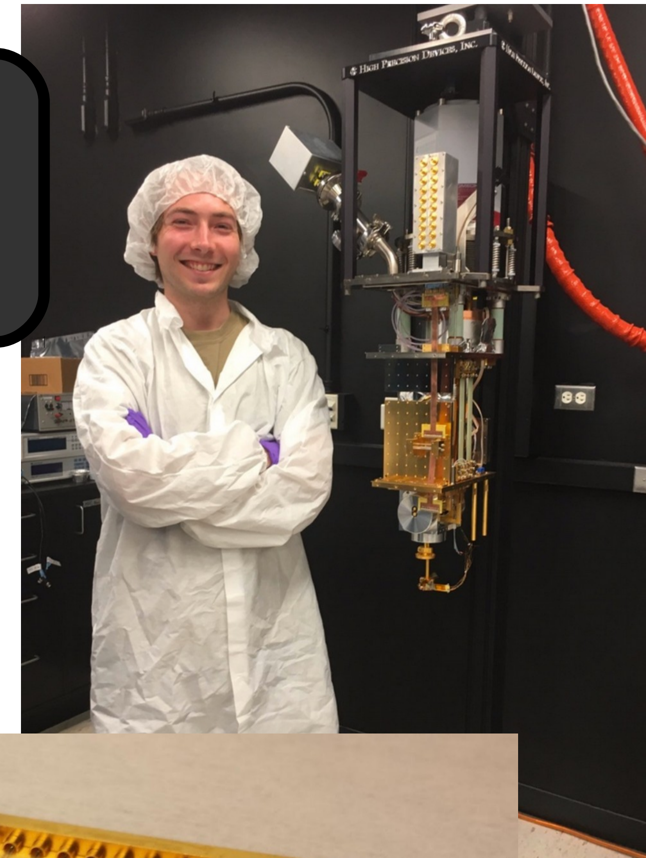
# MKIDS camera (built by UCSB for SCExAO)

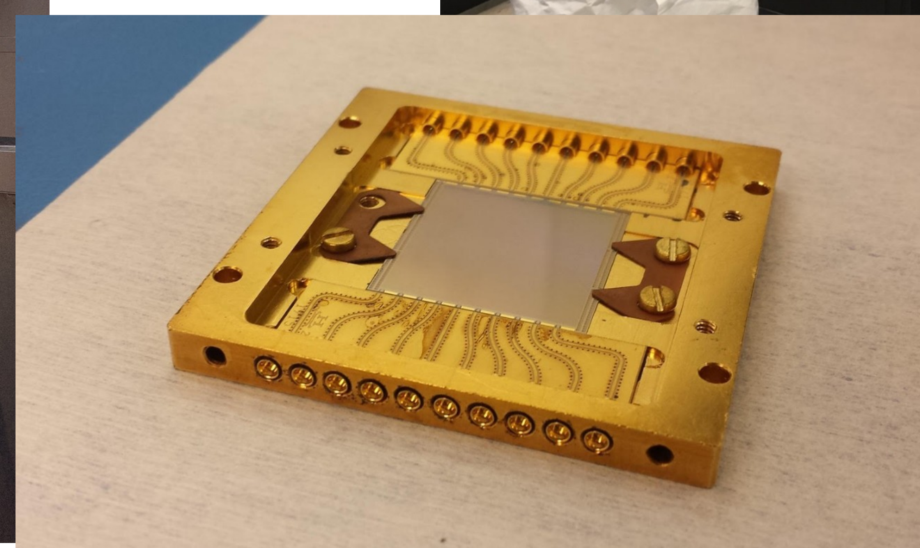
Photon-counting, wavelength resolving 140x140 pixel camera

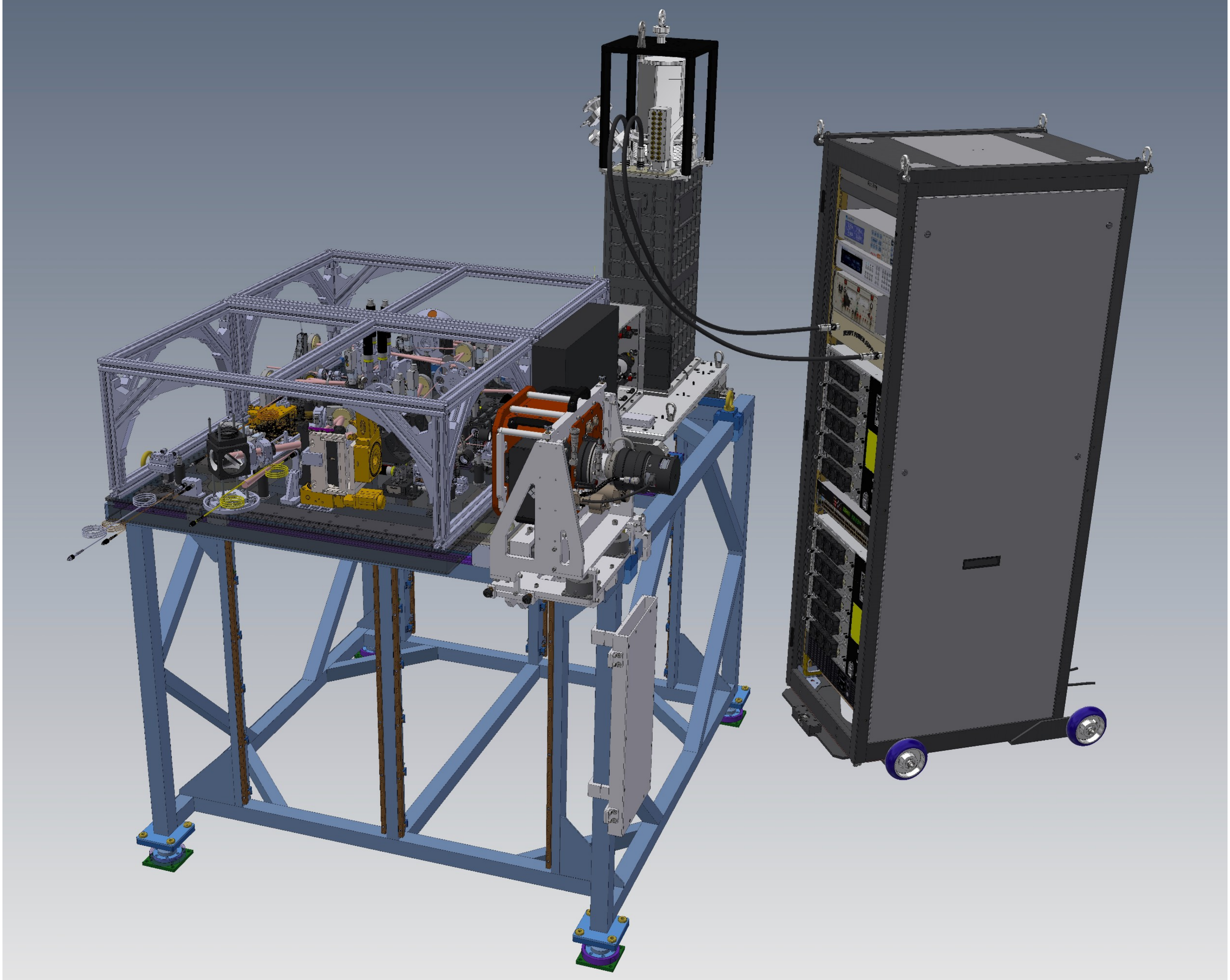



Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB

Delivery to SCExAO in sept 2017







# Building community RTC / Software Ecosystem to support WFC development

**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

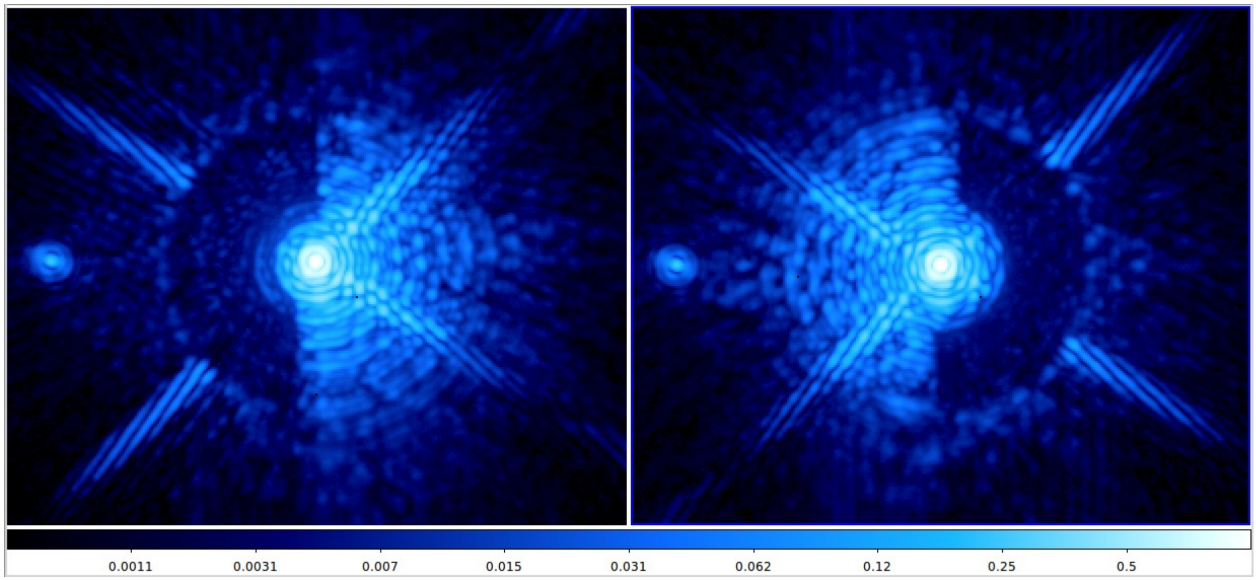
→ Provide abstraction of link between loops

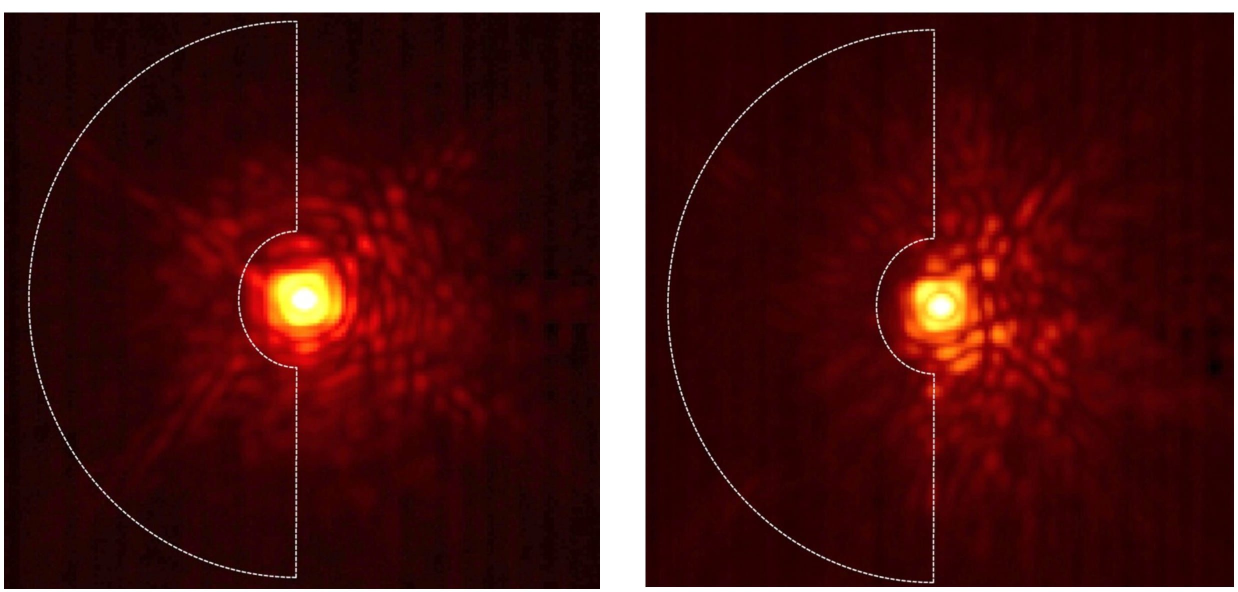
→ Toolkit includes viewers, data logger, low-latency TCP transfer of streams

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

***→ community support and development***

# Collaboration with OCA: speckle



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

Experience limited by detector readout noise and speed.

KERNEL project: C-RED-ONE camera.

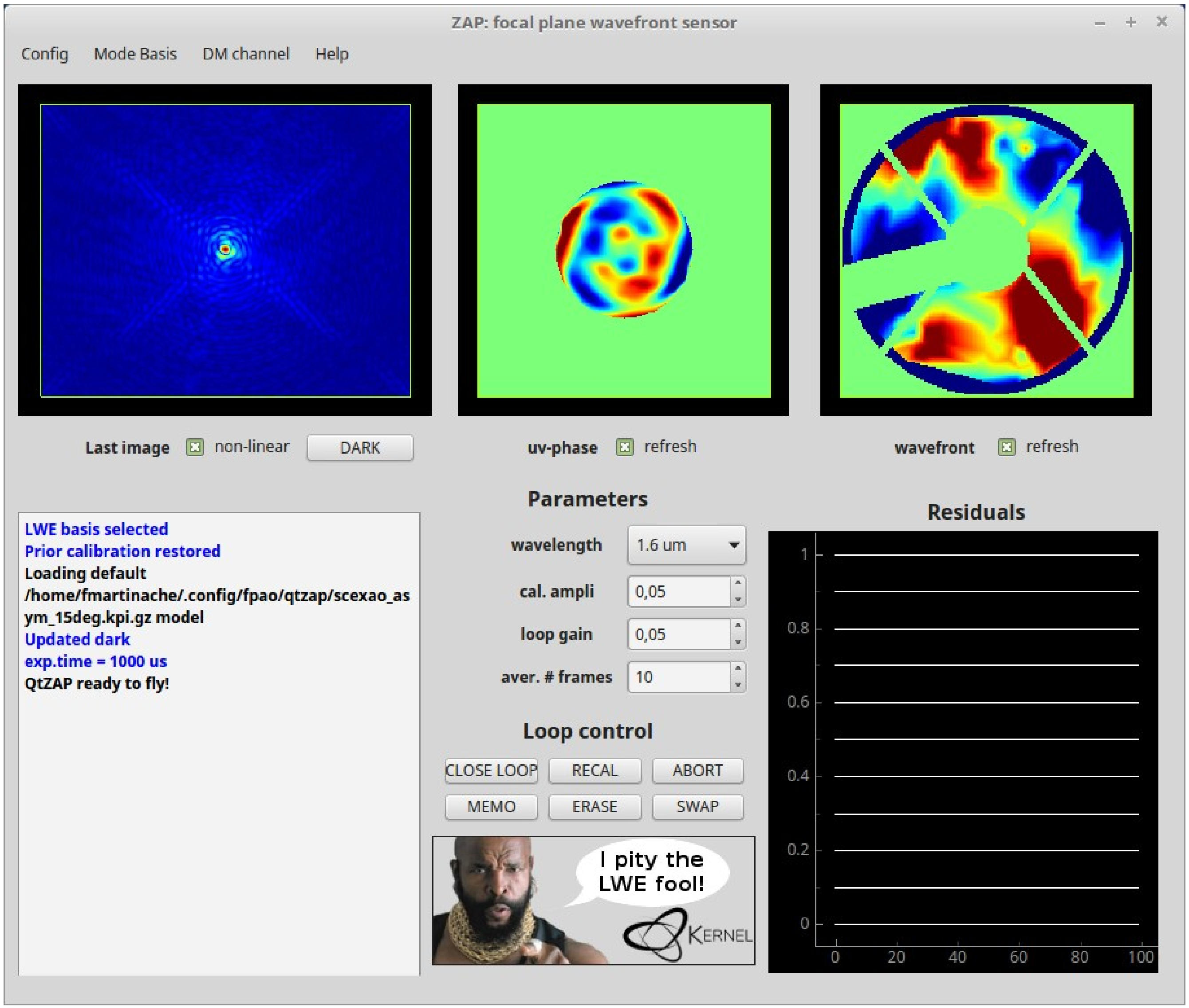
From:
- 114 e- RON
- 170 Hz frame rate

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

Expect some updates

Observatoire de la CÔTE d'AZUR

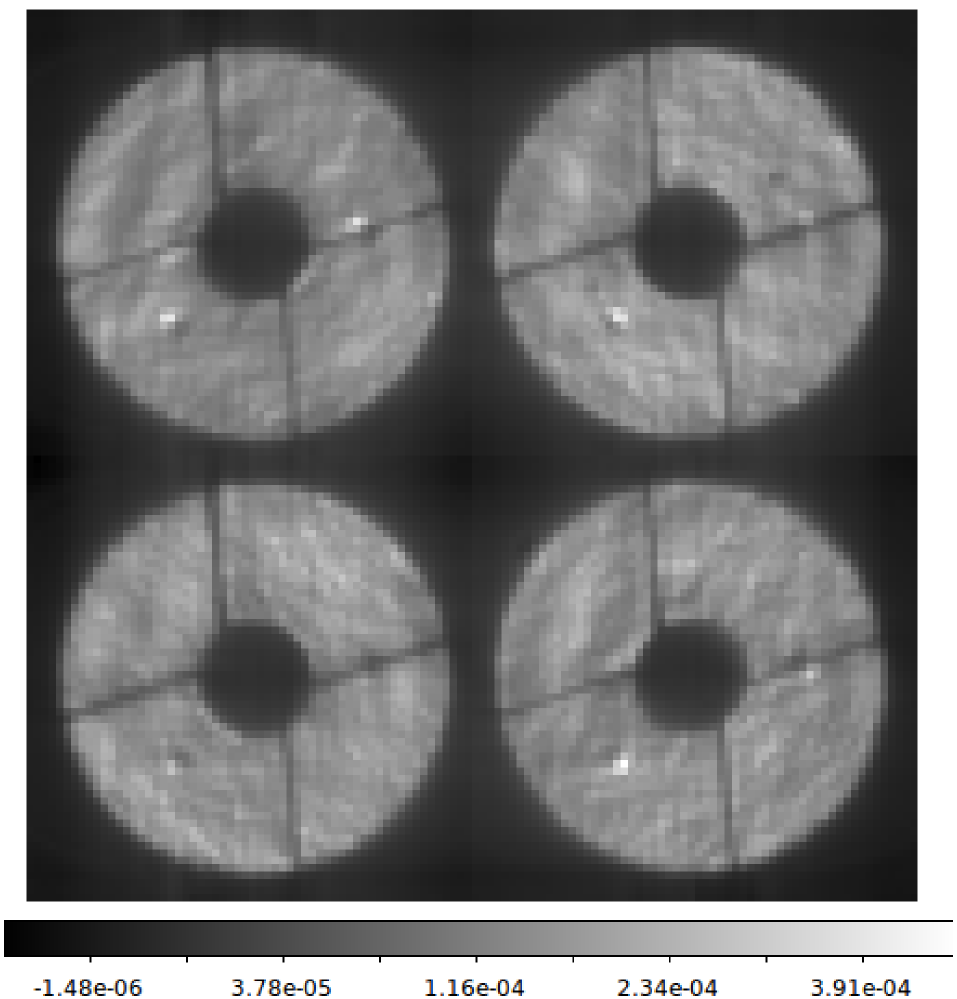
# OCA/KERNEL – developed software

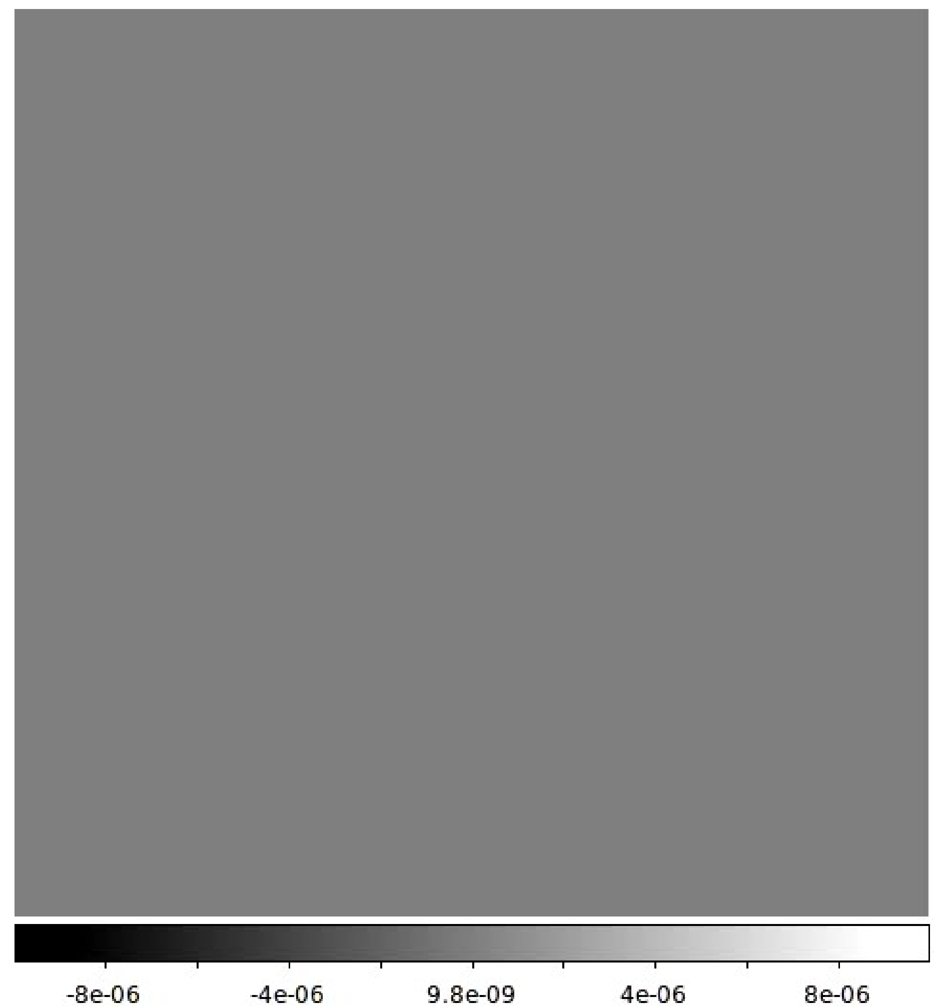



- Address NCPA
- Asymmetric mask (pupil)
- On-sky closed-loop control
- Focal plane based WFS Low-order (Zernike and LWE) modes.
- mode compatible with coronagraphy in development

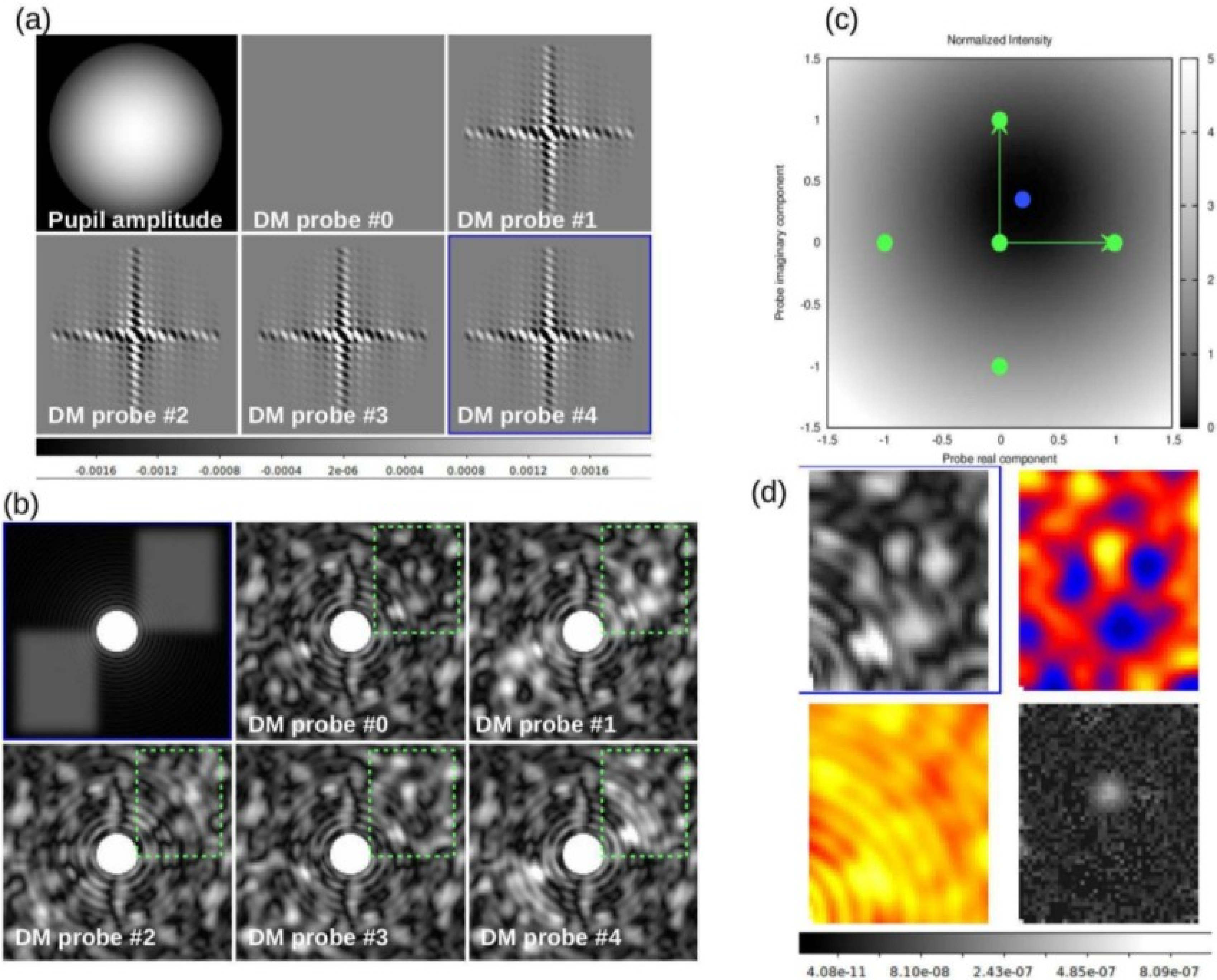
# Measuring system response matrix at 3kHz

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



# Coherent Speckle Differential Imaging

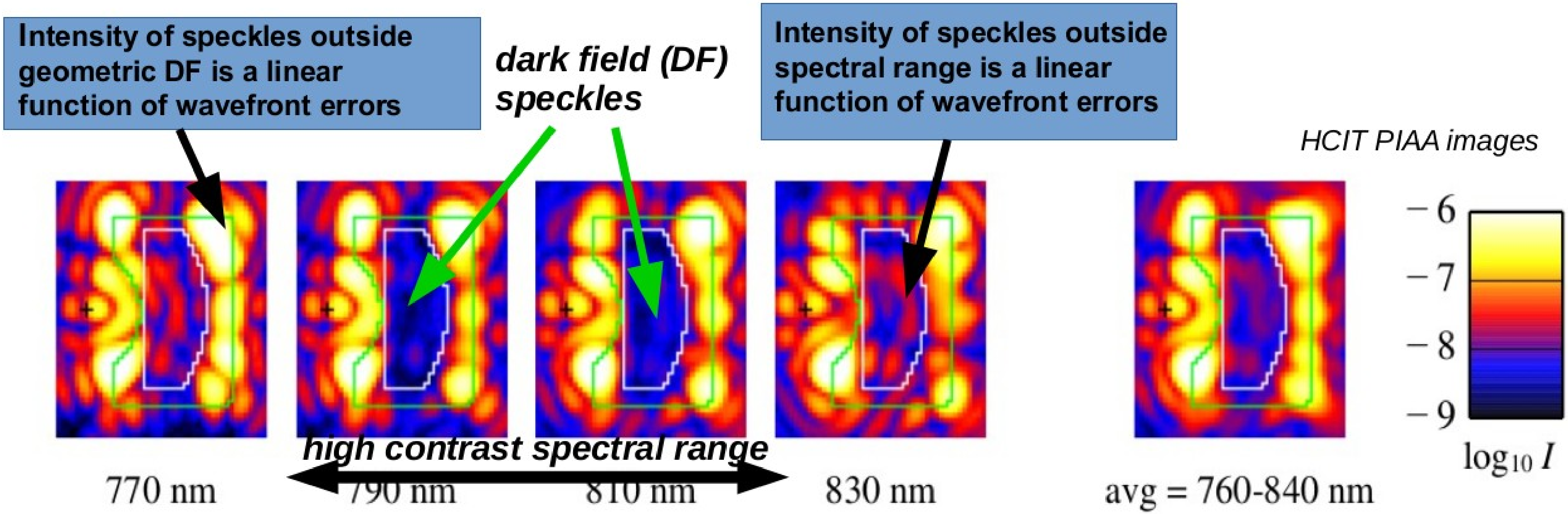


# Linear Dark Field Control (LDFC)

**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**



# 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

# Conclusions

SCExAO is a flexible platform for testing and deploying new techniques (hardware, algorithms).
Allows for smooth evolution from Daytime testing with internal source to nighttime on-sky validation

Coordinated development with MagAO-X (→GMT), Keck (→TMT), SPHERE upgrades (→ELT), + fundamental research in WFC for space missions

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

# Backup slides

# 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;
```

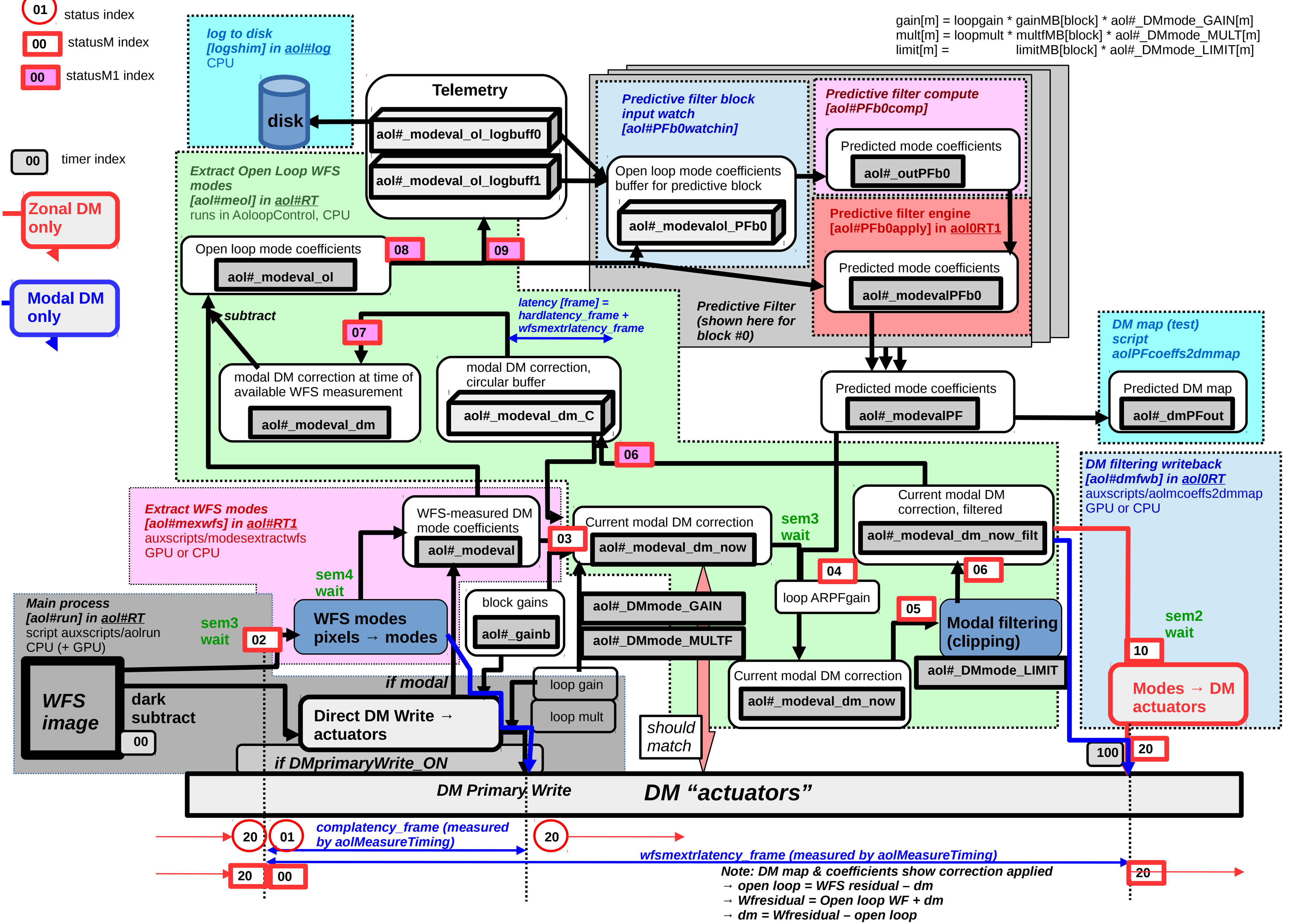
```c
typedef struct
{
    char name[80];              /**< image name */

    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

# Data flow from WFS to DM

*[process name]* (same name as tmux session)
*aol0RT* : CPU set



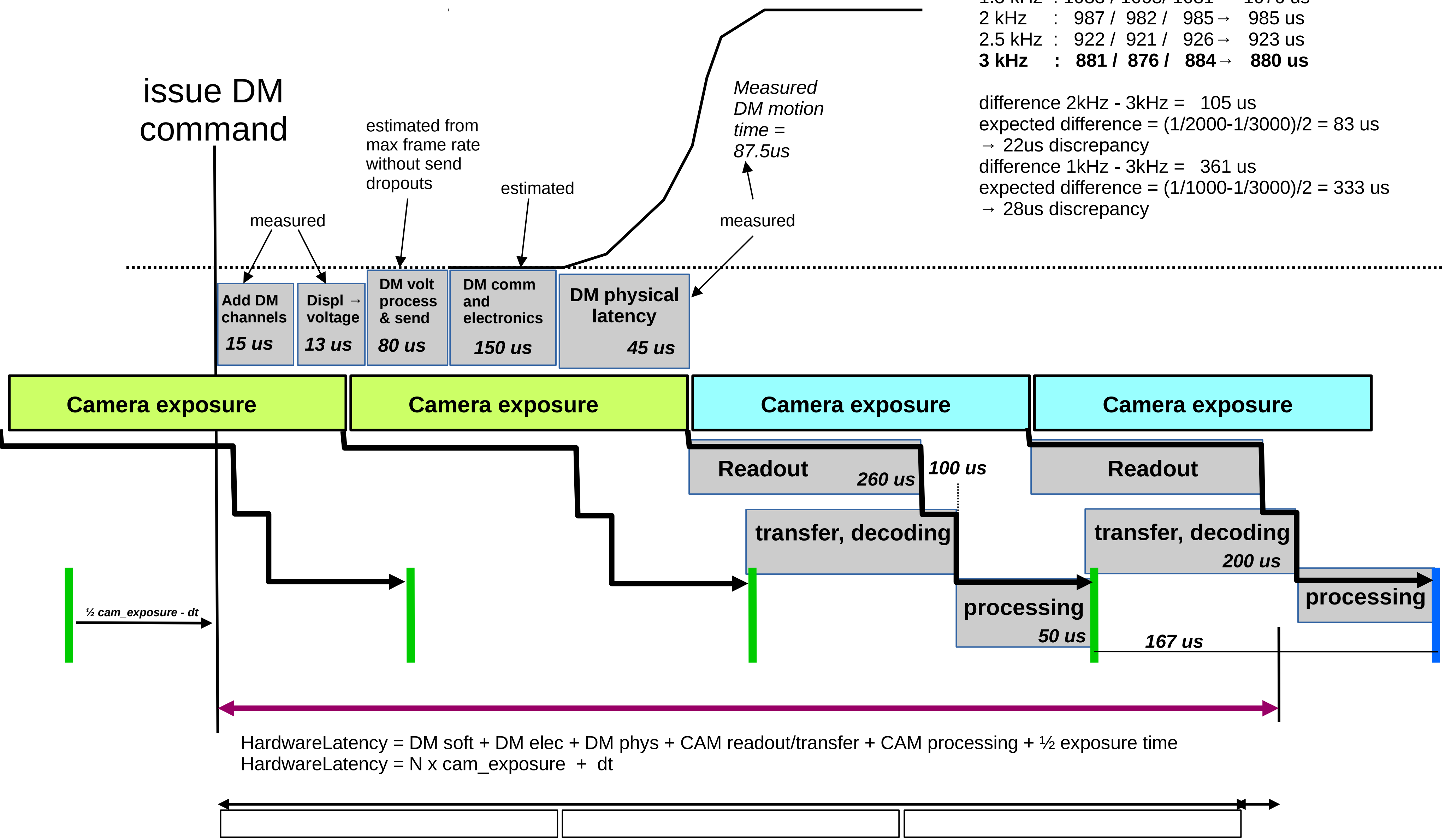
# Hardware Latency measured on SCExAO

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

SCExAO measured hardware latencies:

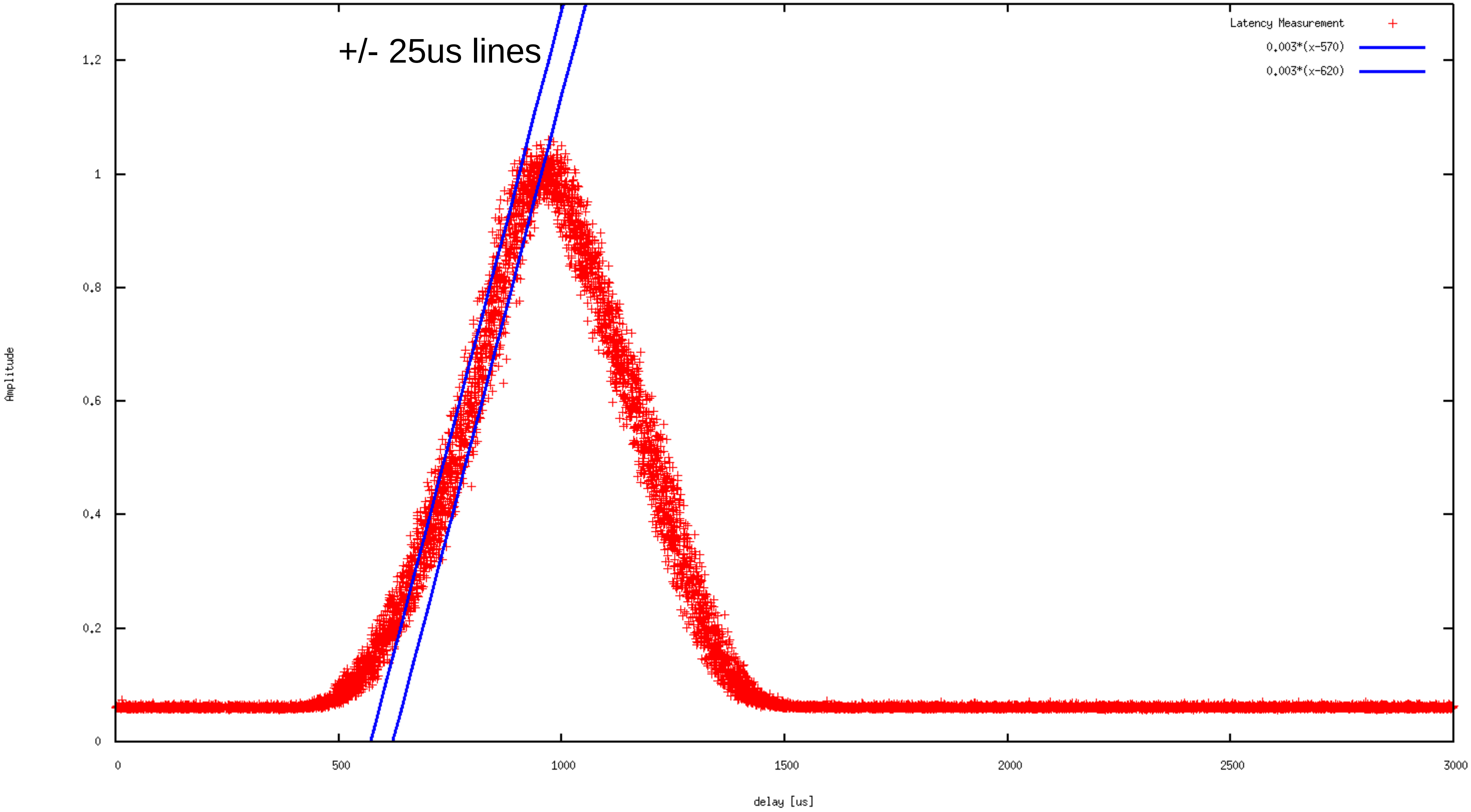
1 kHz : 1253 / 1260/ 1269 → 1261 us
1.5 kHz : 1083 / 1065/ 1081 → 1076 us
2 kHz : 987 / 982 / 985 → 985 us
2.5 kHz : 922 / 921 / 926 → 923 us
**3 kHz : 881 / 876 / 884 → 880 us**

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



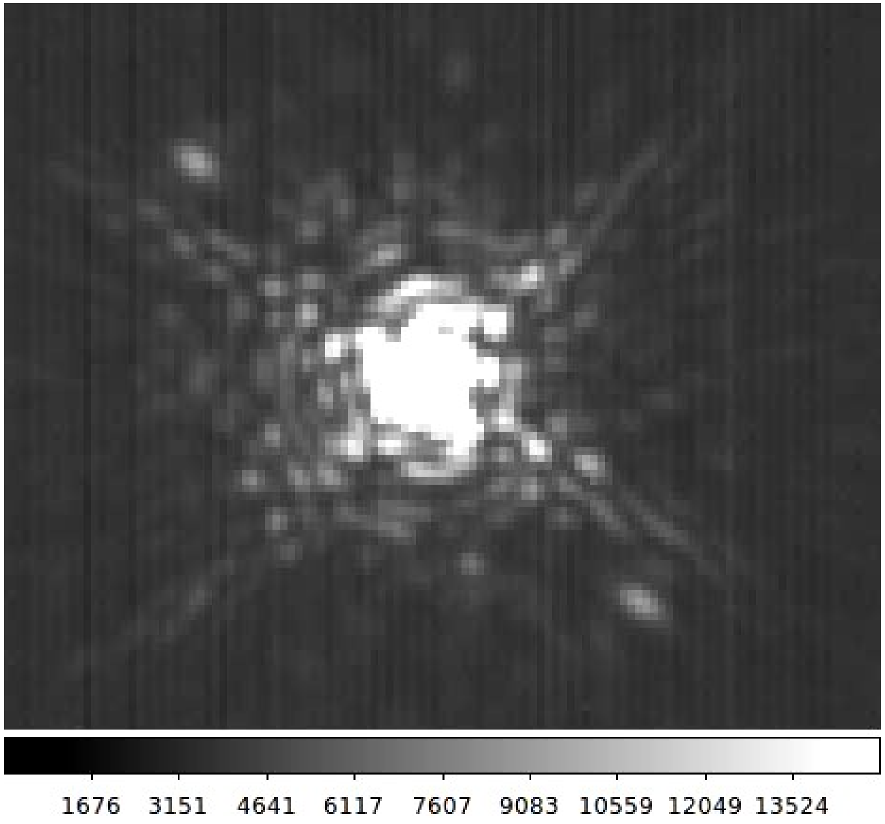
# Hardware Latency measured on SCExAO

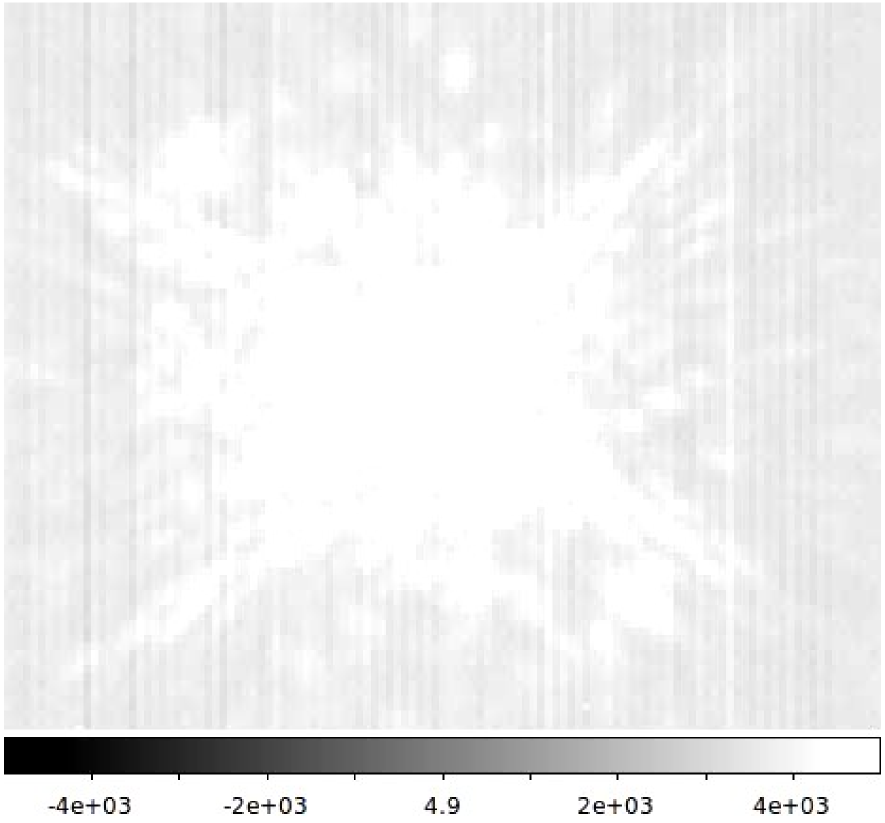
Total jitter <20us RMS = 6% of loop iteration @ 3kHz
(Camera readout + TCP transfer + processing + DM electronics)
Max jitter <40us



# Synchronizing camera stream to DM (170 Hz)

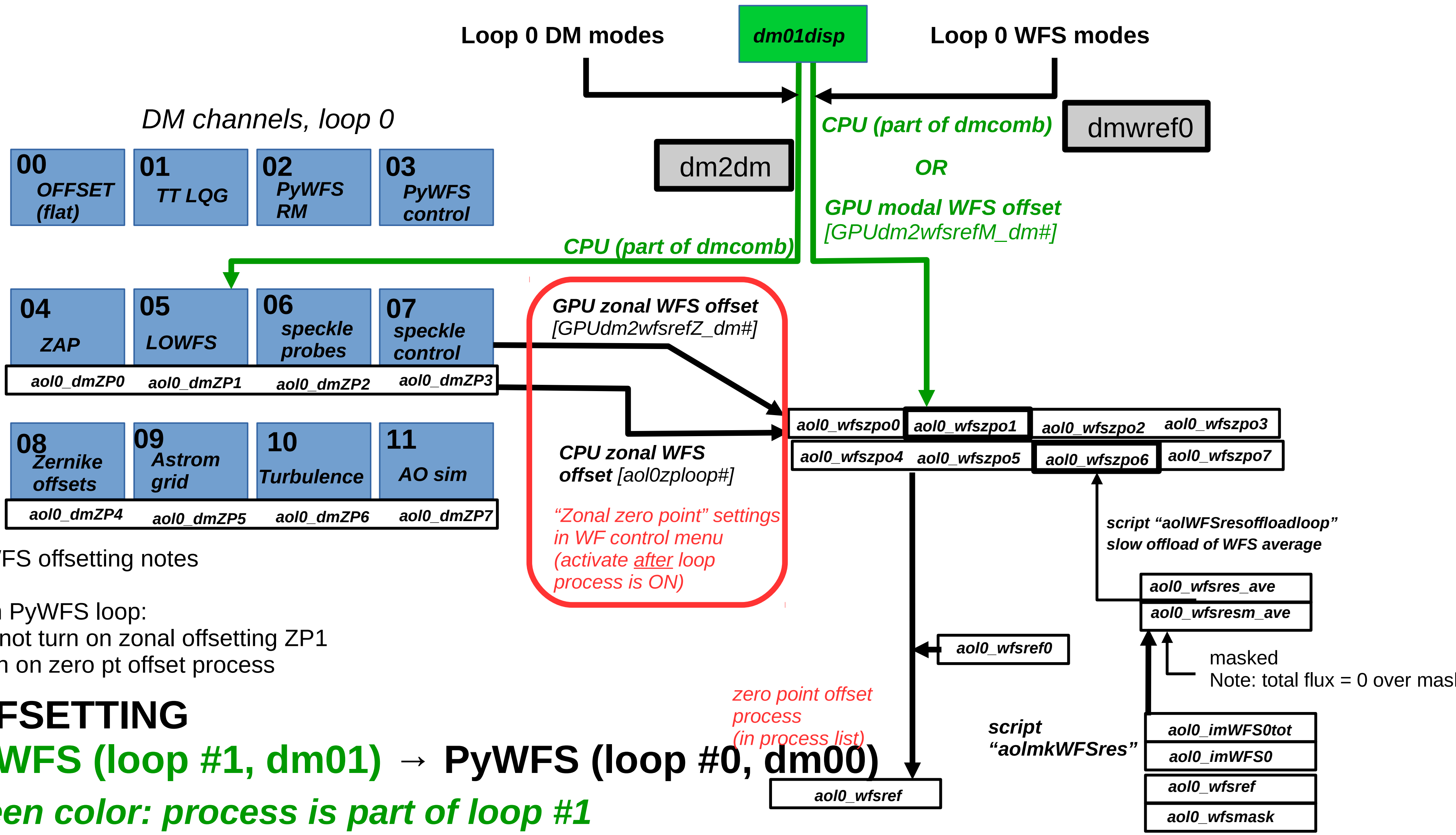
6kHz DM modulation swaps between 2 diag patterns



# 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** → <u>don't pay attention to the diagram below !</u>

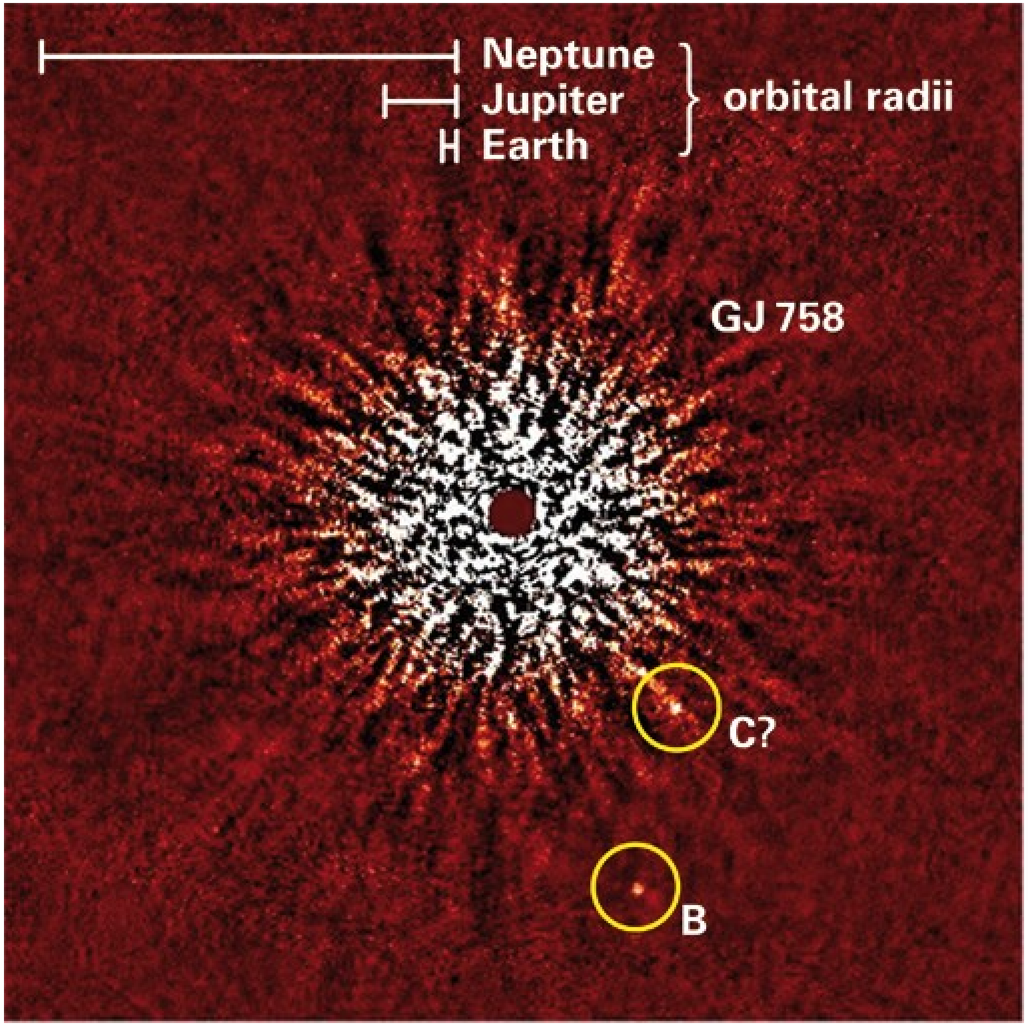



LOWFS offsetting notes

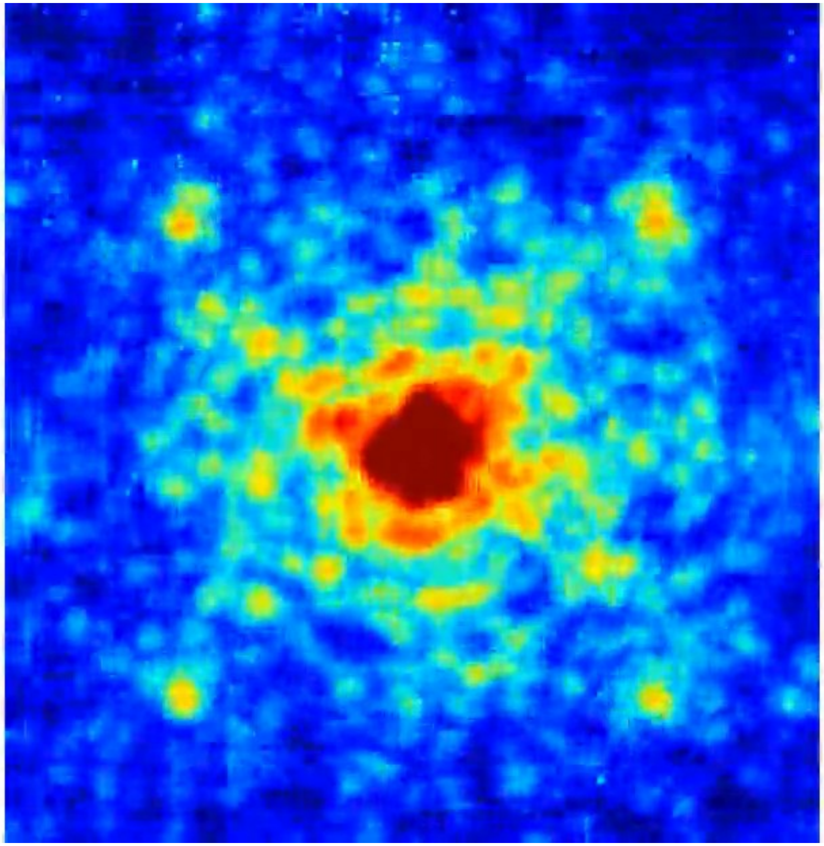
From PyWFS loop:
- Do not turn on zonal offsetting ZP1
- Turn on zero pt offset process

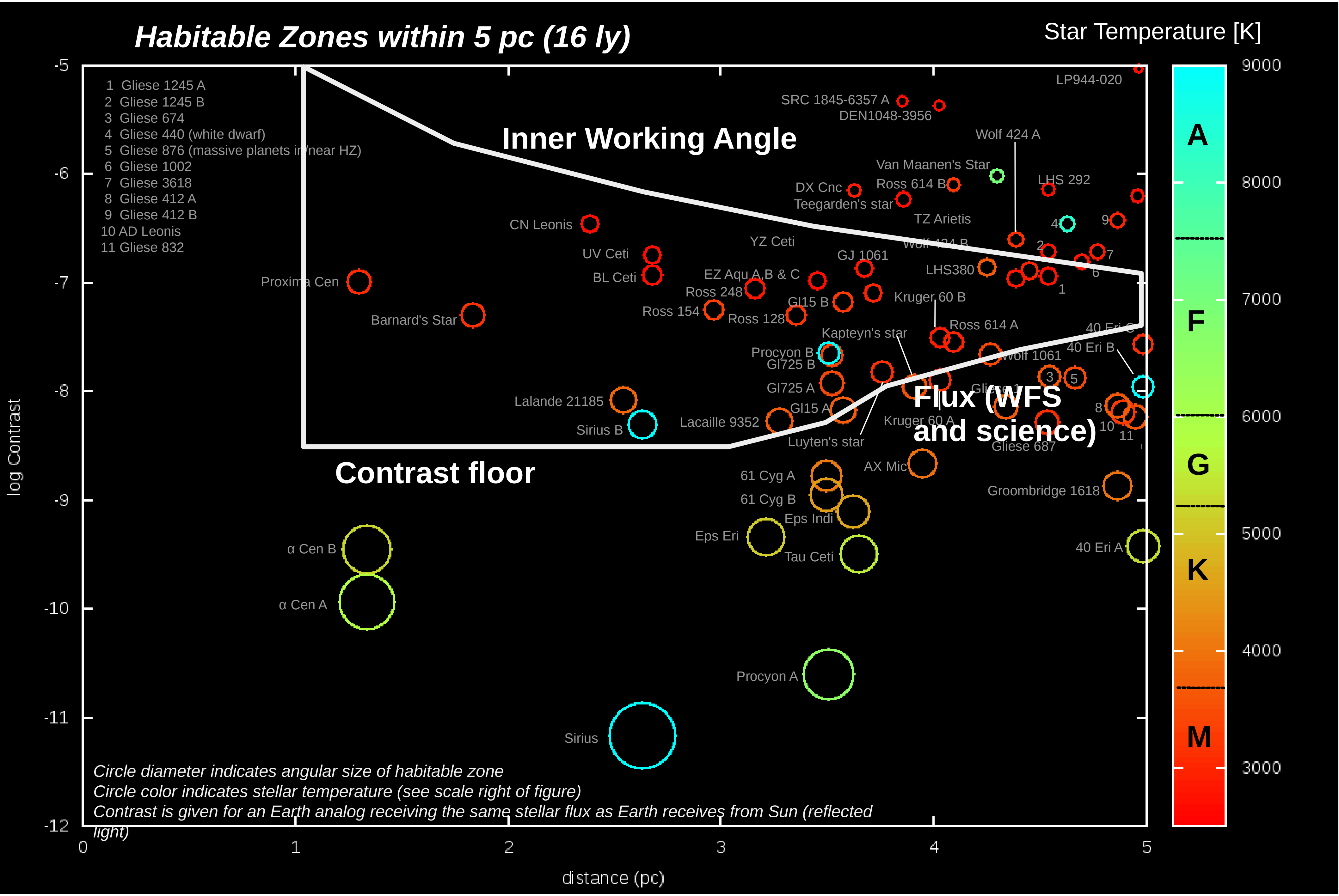
**OFFSETTING**
**LOWFS (loop #1, dm01) → PyWFS (loop #0, dm00)**
***Green color: process is part of loop #1***

# The REAL challenge: Wavefront error (speckles)




H-band fast frame imaging (1.6 kHz)

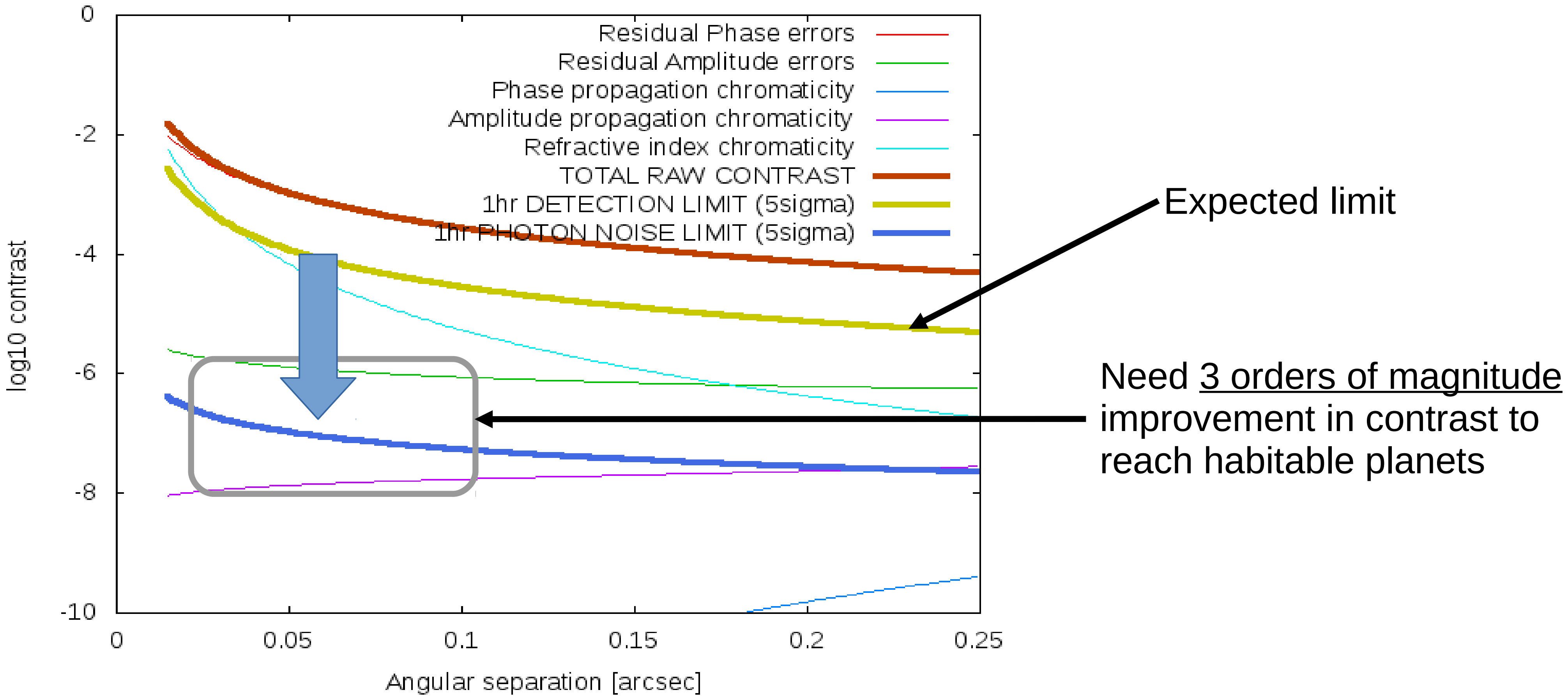




Habitable Zones within 5 pc (16 ly)
Star Temperature [K]
1 Gliese 1245 A
2 Gliese 1245 B
3 Gliese 674
4 Gliese 440 (white dwarf)
5 Gliese 876 (massive planets in/near HZ)
6 Gliese 1002
7 Gliese 3618
8 Gliese 412 A
9 Gliese 412 B
10 AD Leonis
11 Gliese 832
Inner Working Angle
Contrast floor
Flux (WFS and science)
LP944-020
SRC 1845-6357 A
DEN1048-3956
Wolf 424 A
Van Maanen's Star
LHS 292
DX Cnc
Ross 614 B
Teegarden's star
TZ Arietis
CN Leonis
YZ Ceti
UV Ceti
GJ 1061
BL Ceti
EZ Aqu A,B & C
LHS380
Proxima Cen
Ross 248
Gl15 B
Kruger 60 B
Barnard's Star
Ross 154
Ross 128
Ross 614 A
Kapteyn's star
40 Eri C
40 Eri B
Procyon B
Gl725 B
Wolf 1061
Gl725 A
Lalande 21185
Gl15 A
Kruger 60 A
Sirius B
Lacaille 9352
Luyten's star
Gliese 687
AX Mic
61 Cyg A
61 Cyg B
Groombridge 1618
Eps Indi
Eps Eri
α Cen B
40 Eri A
Tau Ceti
α Cen A
Procyon A
Sirius
A
F
G
K
M
9000
8000
7000
6000
5000
4000
3000
log Contrast
-5
-6
-7
-8
-9
-10
-11
-12
distance (pc)
0
1
2
3
4
5
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)

# PREVIOUS technologies

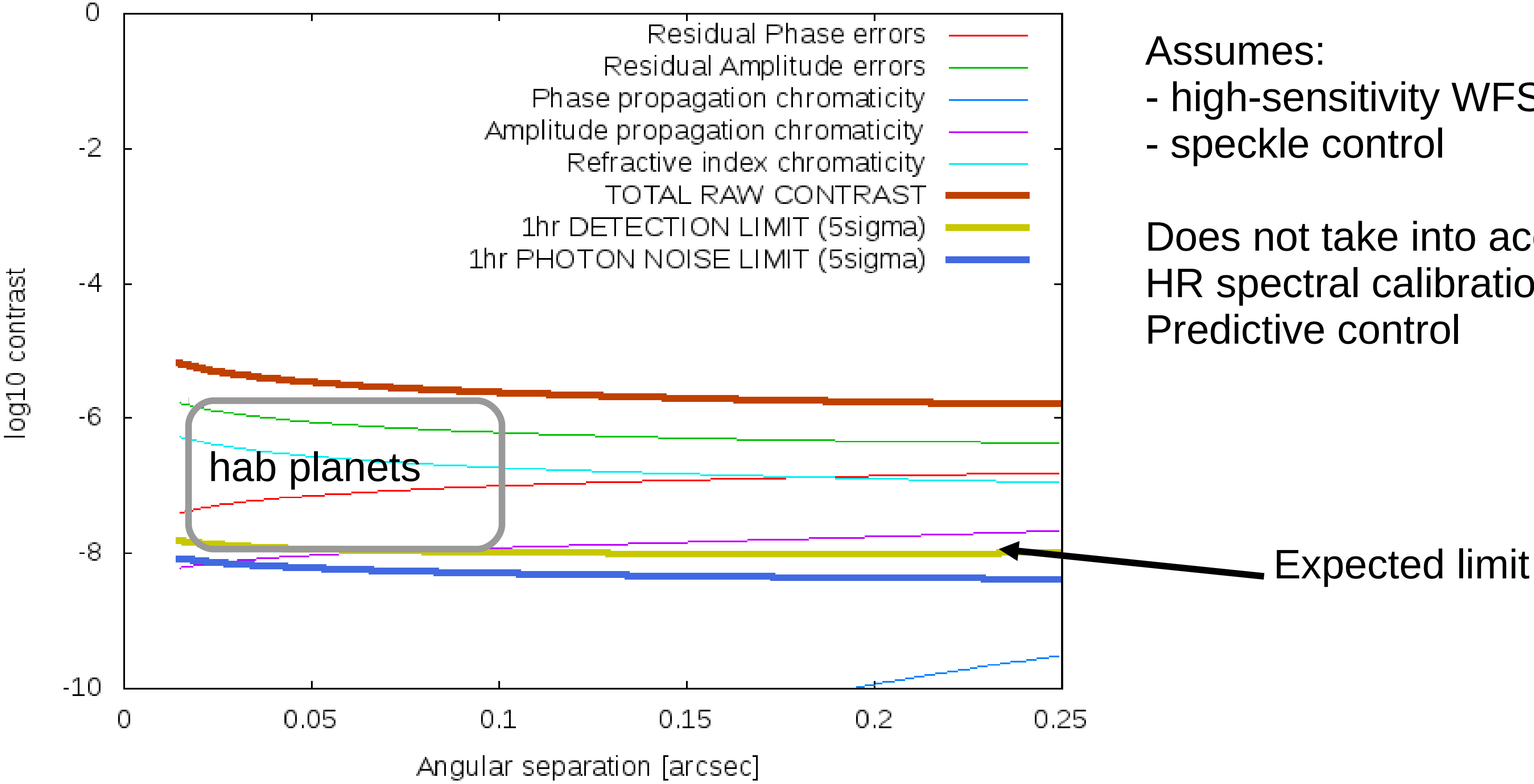
*30m: SH-based system, 15cm subapertures*




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



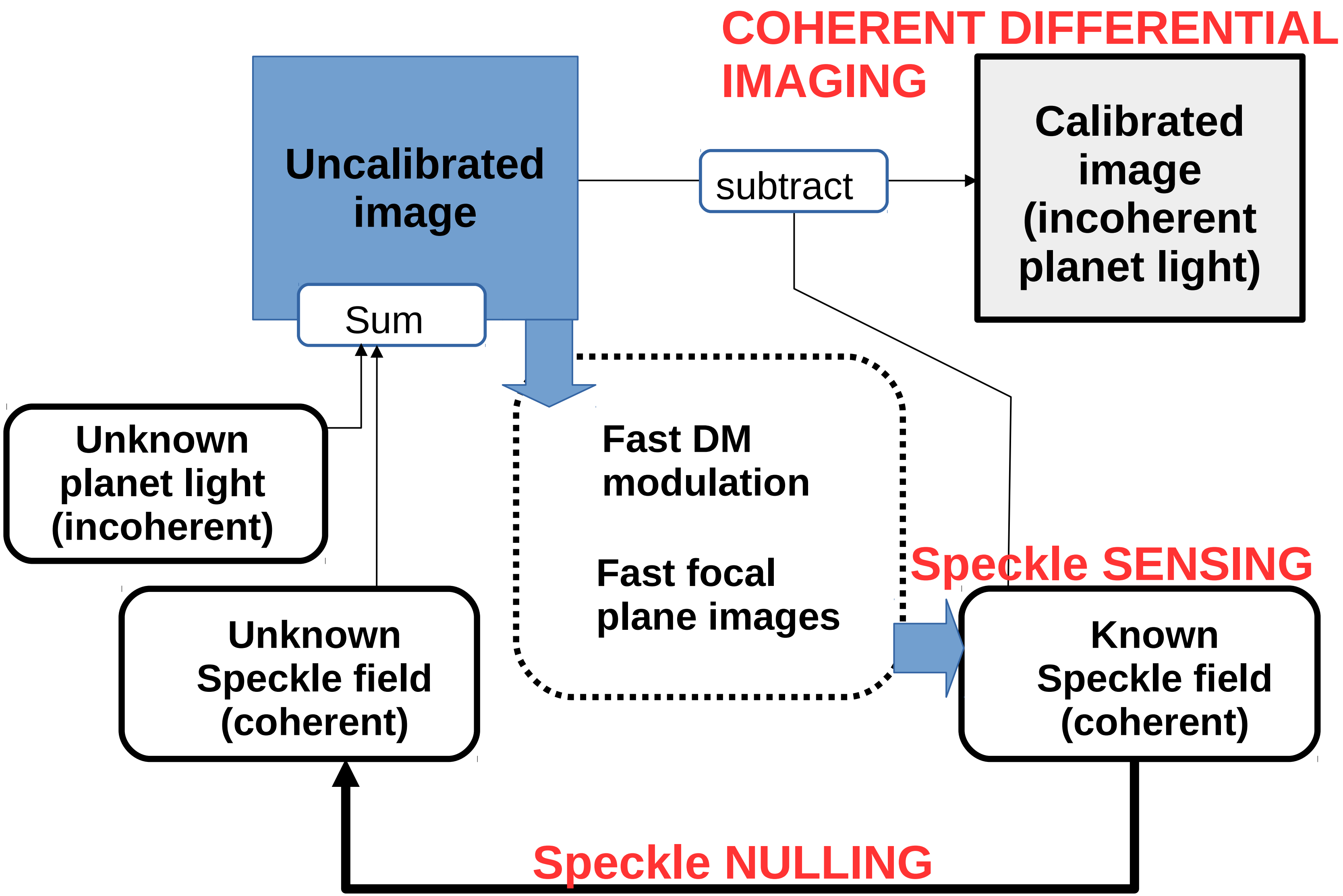

Assumes:
- high-sensitivity WFS
- speckle control

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

# High Speed Speckle Control & Calibration



# 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

# Predictive control & sensor fusion→ 100x contrast gain ?

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

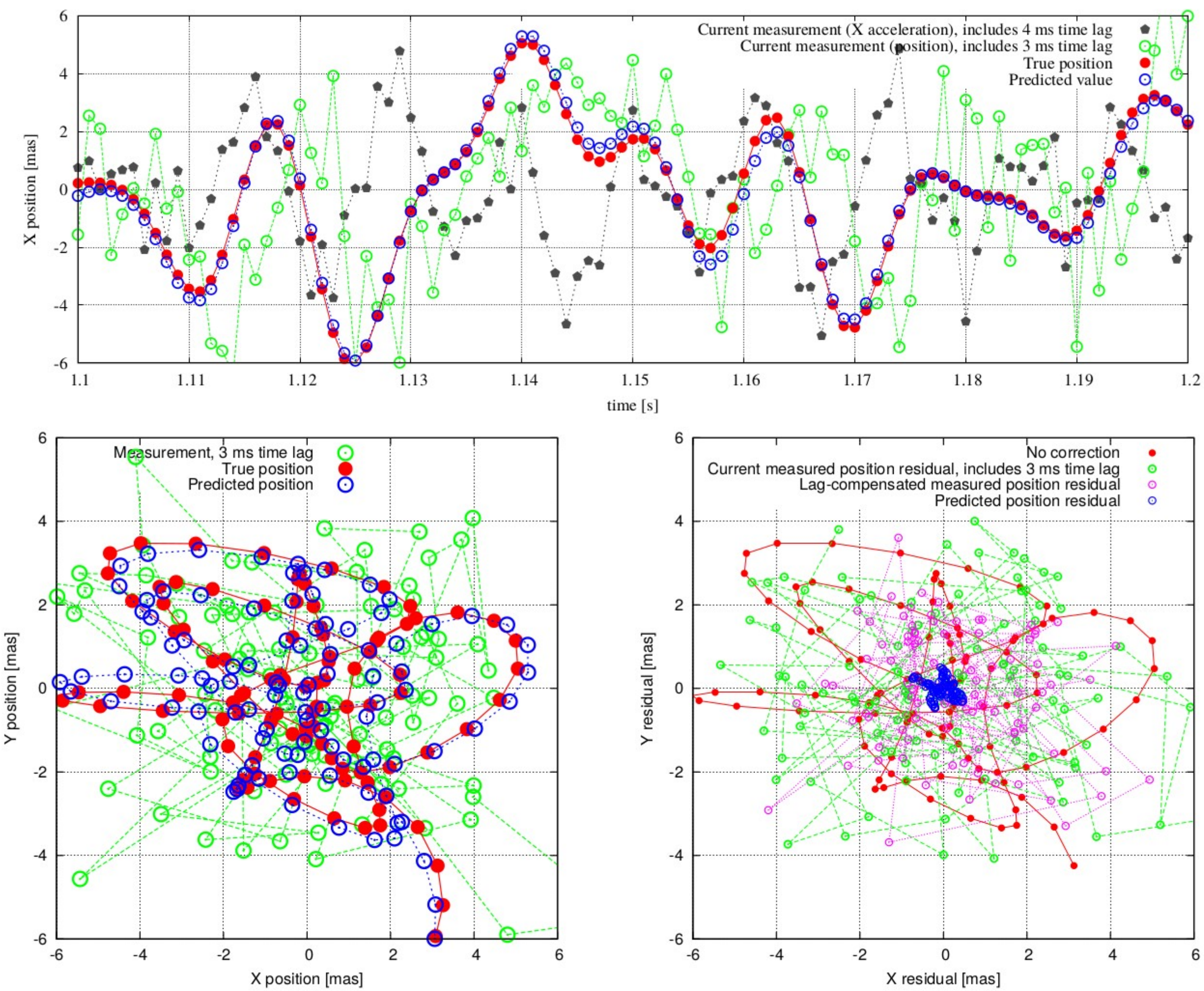
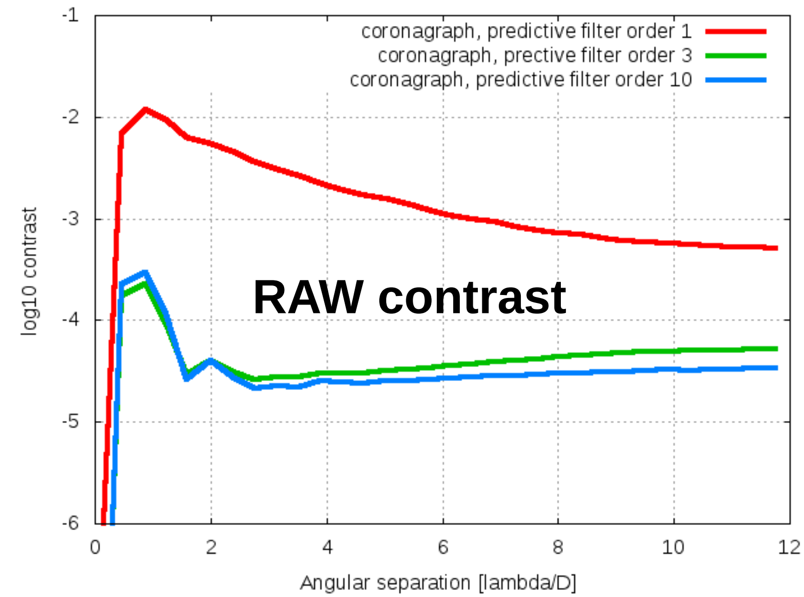



FIG. 3.— Top left: 2D-tracks for true pointing (red), predicted pointing (blue) and last measured position (green). Top right: Residual pointing error. Bottom: Single axis (x) values.




**1hr detection limit**
**(PSF subtraction residual)**