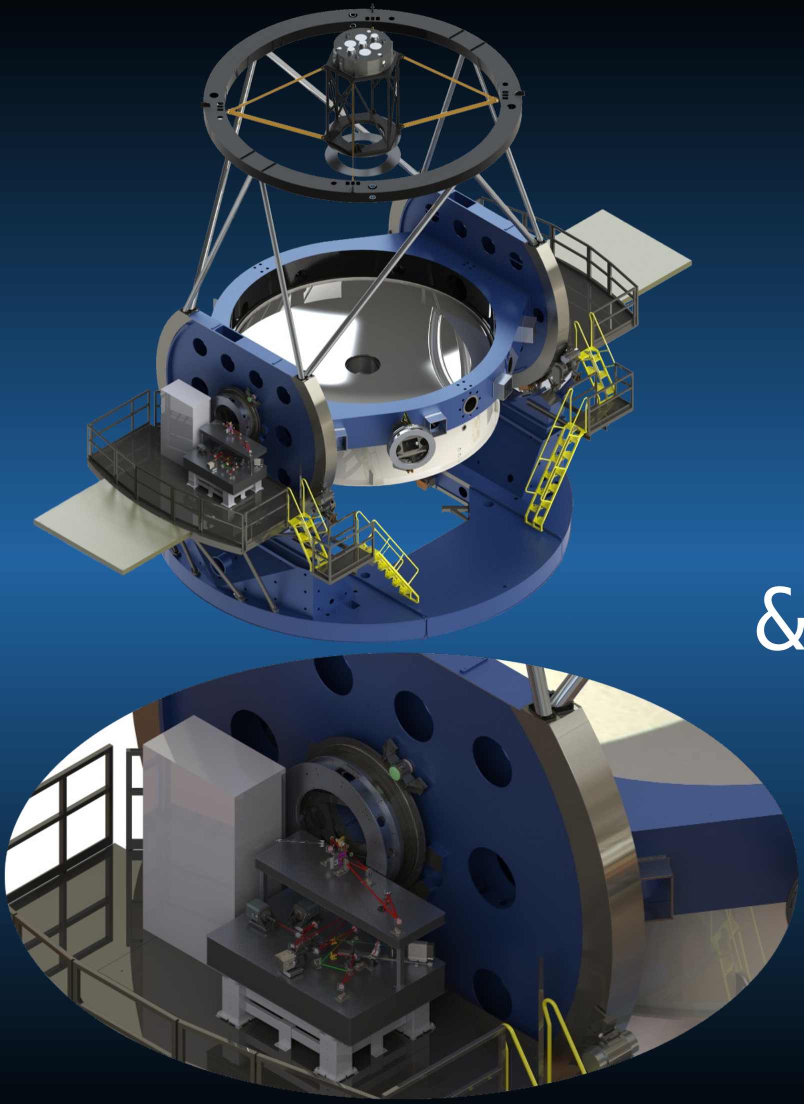


MagAO-X

Project Status & First Laboratory Results

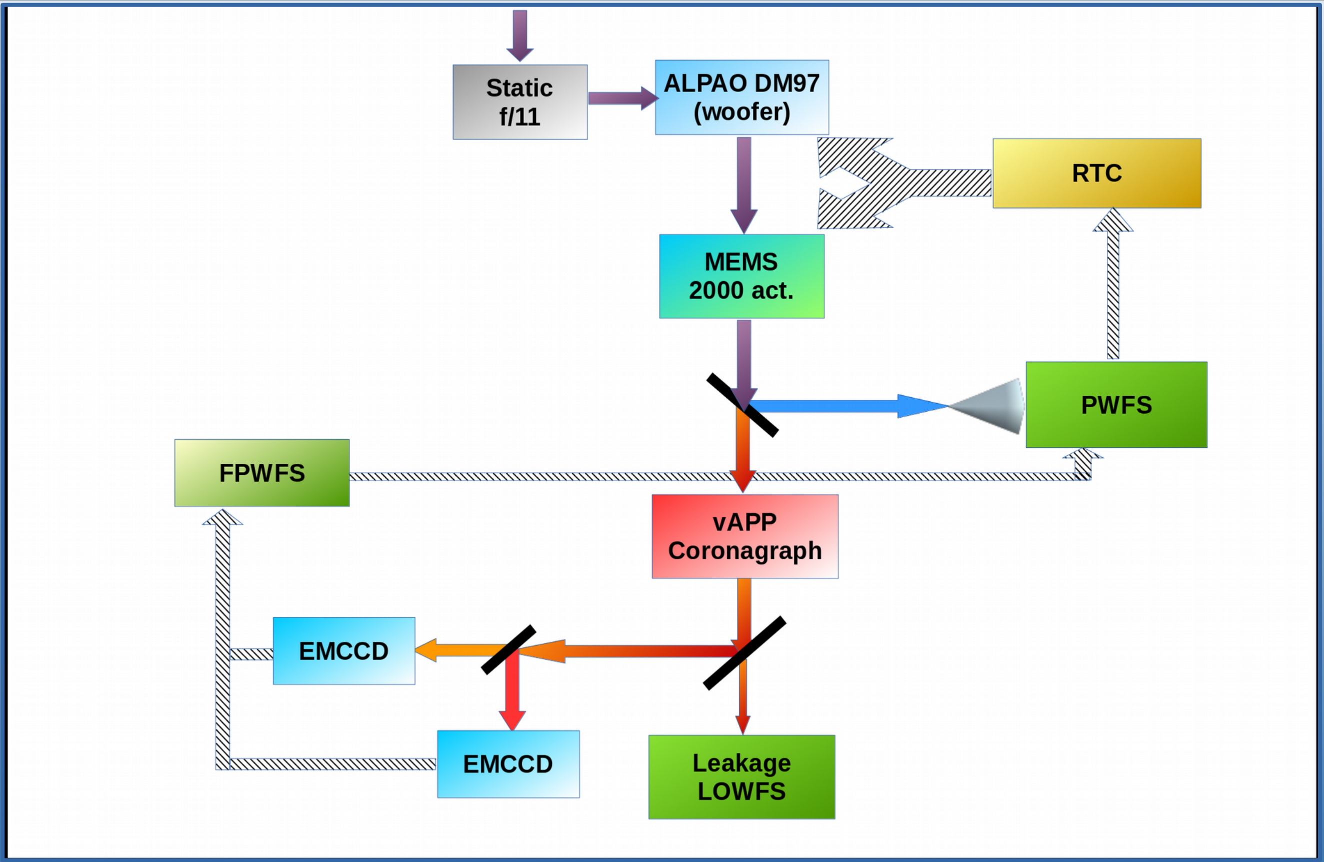
Jared R. Males, Laird M. Close
Chris Bohlman, Al Conrad, David Doelman, Ewan Douglas, Oli Durney, Victor Gasho, Olivier Guyon, Phil Hinz, Alex Hedglen, Michael Ireland, Madison Jean, Maggie Kautz, Christoph Keller, Matt Kenworthy, Justin Knight, Joseph Long, Jennifer Lumbres, Ben Mazin, Kelsey Miller, Katie Morzinski, Jamison Noenickx, Kevin Perez, Alex Rodack, Anna Sanchez, Corwynn Sauve, Lauren Schatz, Frans Snik, Kyle Van Gorkom, Alycia Weinberger

MagAO-X

- MagAO-X:
  - An entirely new AO system for the 6.5 m Magellan Clay Telescope
  - 2040 actuator MEMS deformable mirror
  - 3.6 kHz Pyramid WFS
  - Optimized for visible-wavelength coronagraphy and high-contrast imaging.
- History:
  - Proposed to Magellan SAC in Spring 2015
  - CoDR in Fall 2015 @ AO4ELT Lake Arrowhead
  - Proposed to NSF MRI Jan 2016
  - Funded by NSF MRI starting in Fall 2016
  - PDR passed May 2017 (external, managed by Magellan)
- Status:
  - Procurement nearly complete, main exception is delivery of MEMS (very soon)
  - Integration underway
  - Aiming for technical first light 2019A.

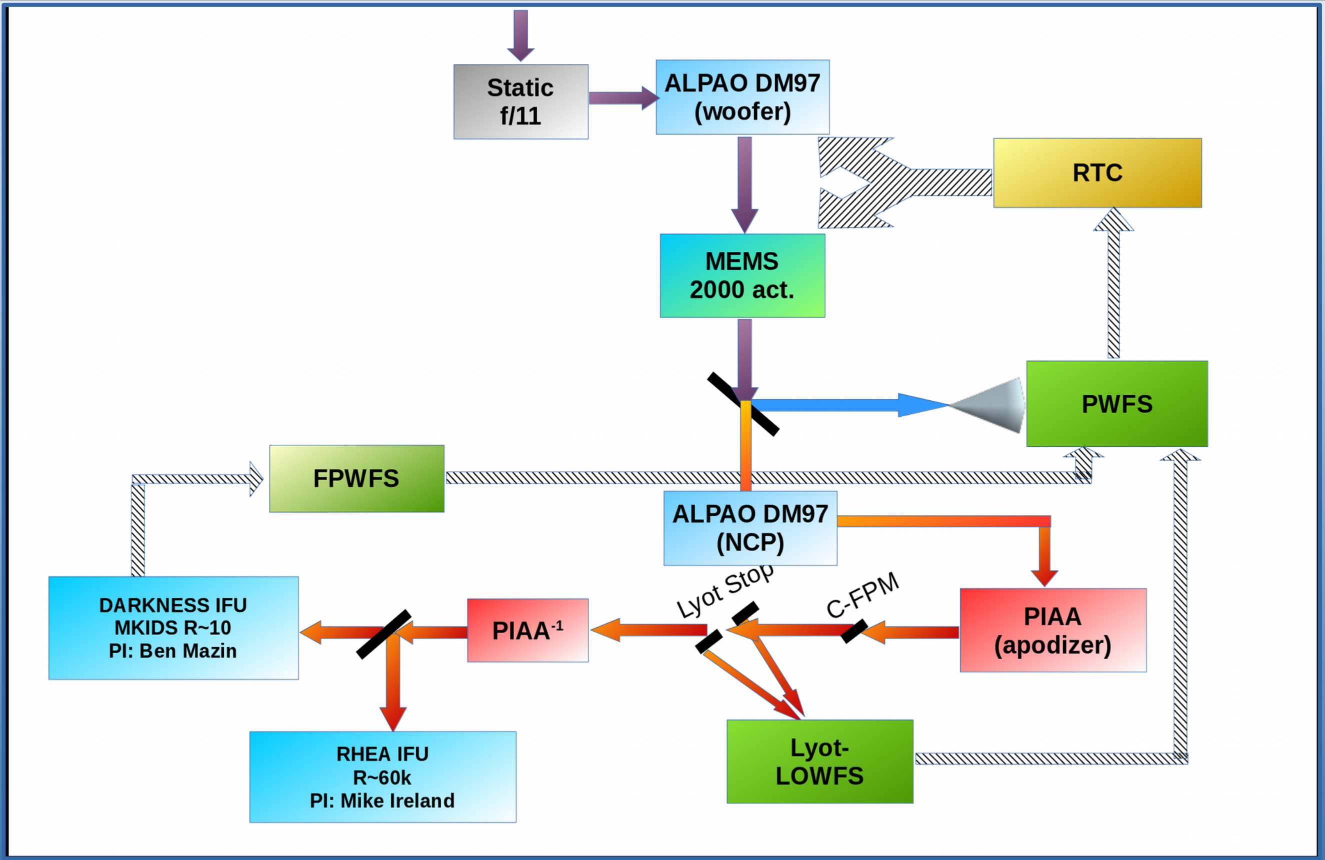
Phase I

- Original Plan:
  - Existing MagAO as 1st stage
  - Add “afterburner” MEMS
  - 3 Phase commissioning
- Current Plan:
  - Use static f/11, with on-board woofer
  - Allows internal calibration, and is operationally simpler
  - 2 phases
- Phase I:
  - New ExAO system
  - vAPP coronagraphs
  - SDI science, with vAPP-LOWFS and FPWFS



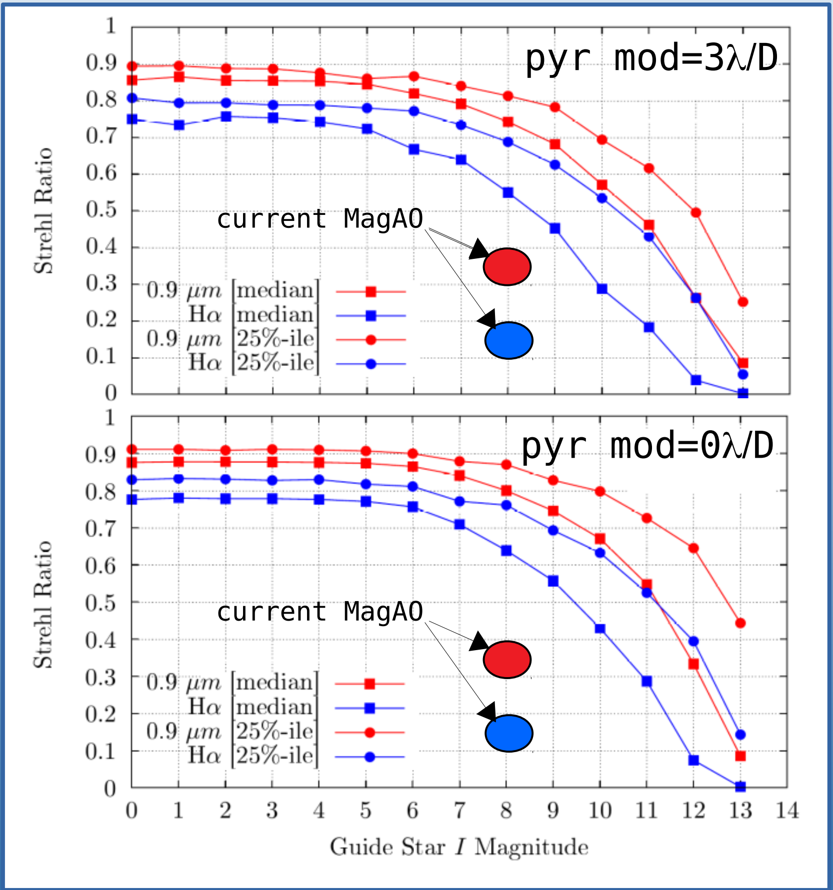
Phase II

- Phase II:
  - Add a 3rd DM for coronagraphic NCP control.
  - Add PIAACMC with LLOWFS
  - Other Lyot-type coronagraphs possible
  - Add IFUs:
    MKIDS IFU and FPWFS (PI: Mazin)
    RHEA SMF IFU (PI: Ireland)
- And beyond:
  - System designed to perform through H band
  - Eyes on GMT...



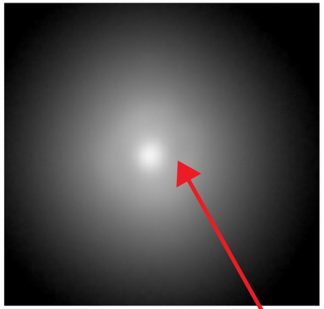
Expected Performance

- Faster, with more actuators
  - E2E simulated performance
    - Compares PyWFS mod. amp.
    - Small mod. more sensitive, but harder
- Ovals show existing MagAO performance.
  - Large gains in image quality (Strehl)



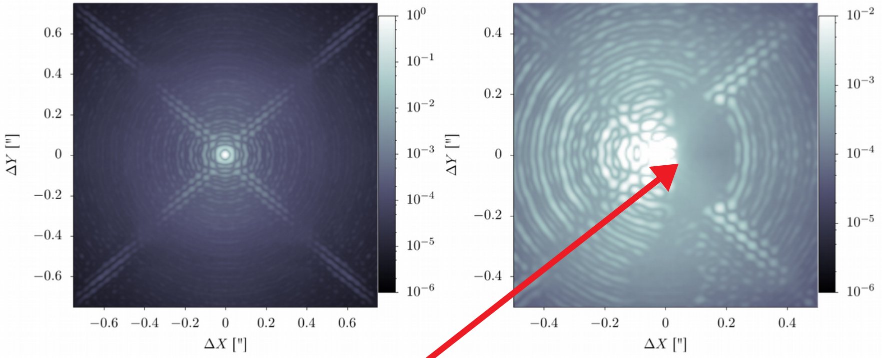
Example: LkCa 15b

MagAO



c/o Kate Follette

MagAO-X



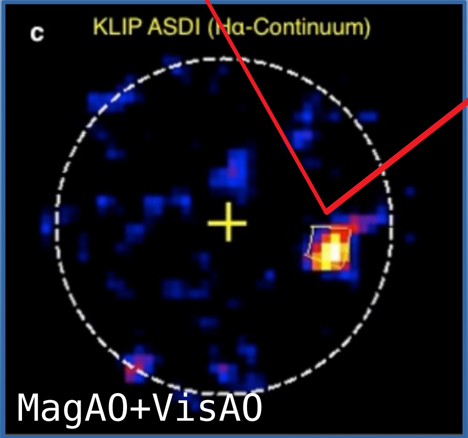
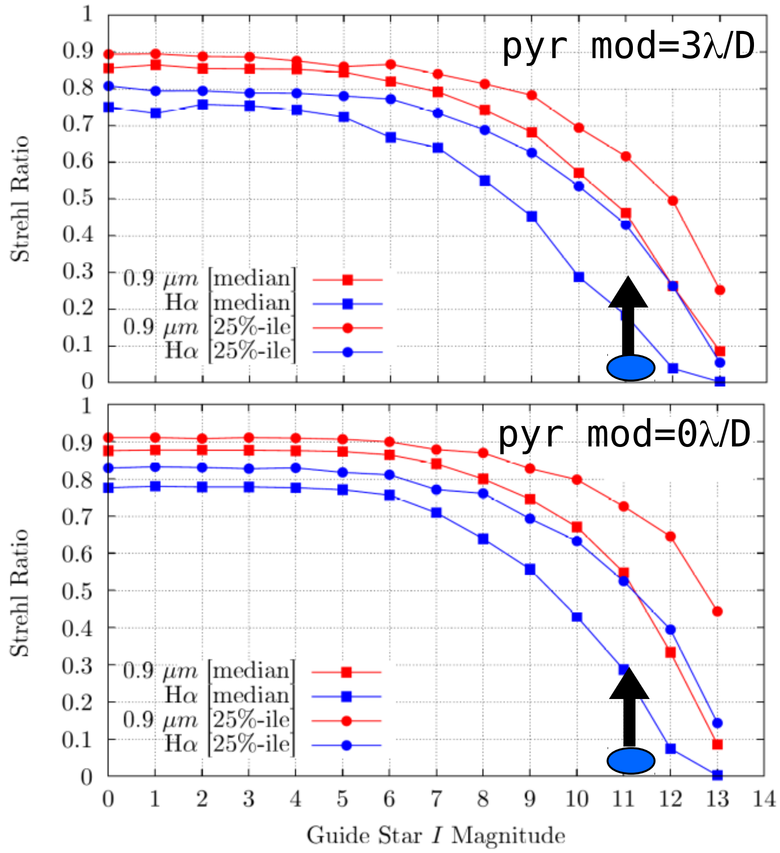


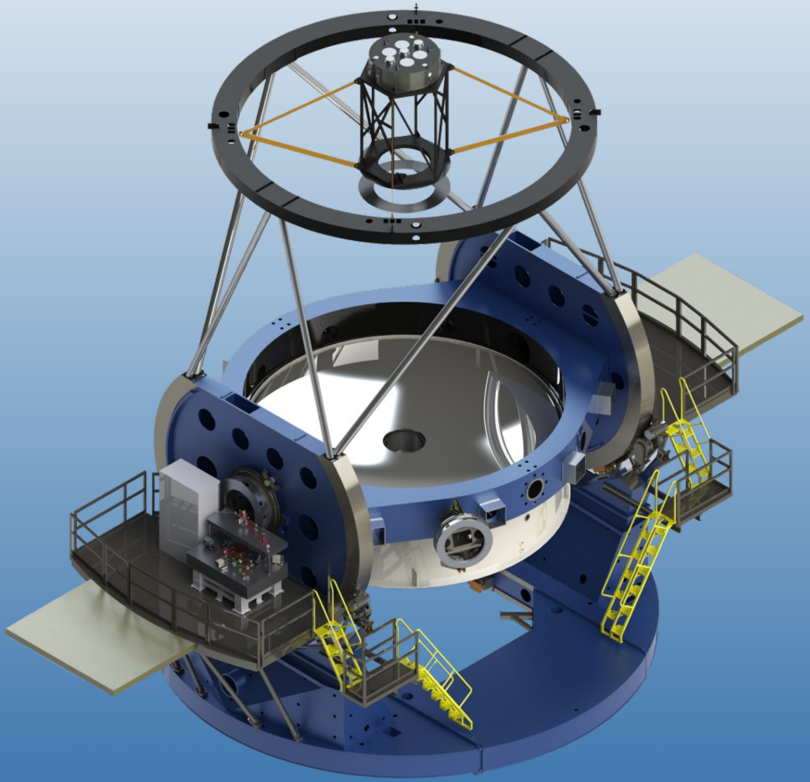
Image of LkCa 15b taken by Kate Follette (Sallum et al., Nature, 2015)

High airmass and 11th mag GS demand high performance.

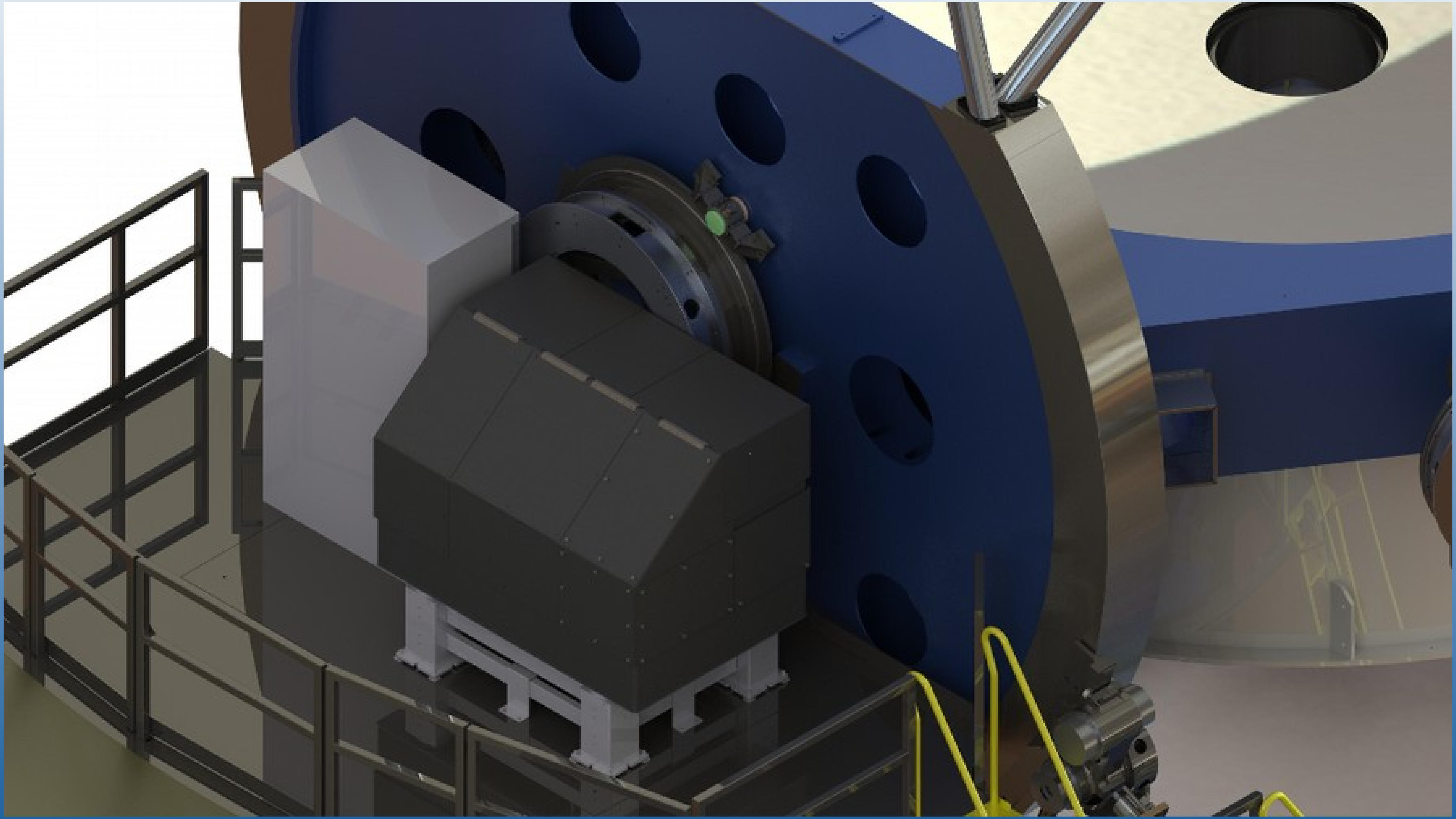


MagAO-X Optomechanical Design

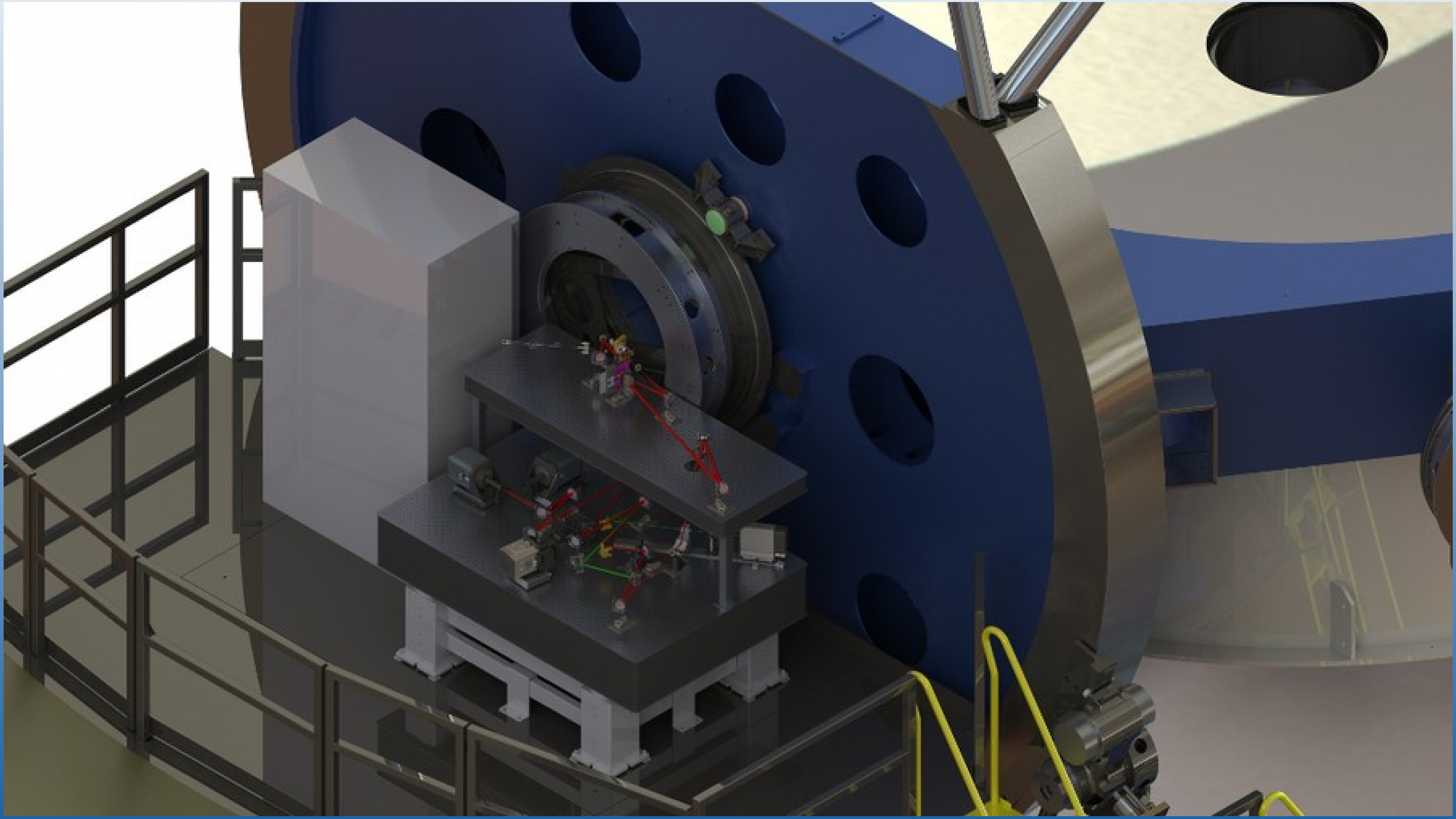
- Floating optical table on Nasmyth platform of Magellan Clay 6.5 m
  - Table is TMC with “PEPS II” active leveling and anti-vibration system
- Uses f/11 static secondary.



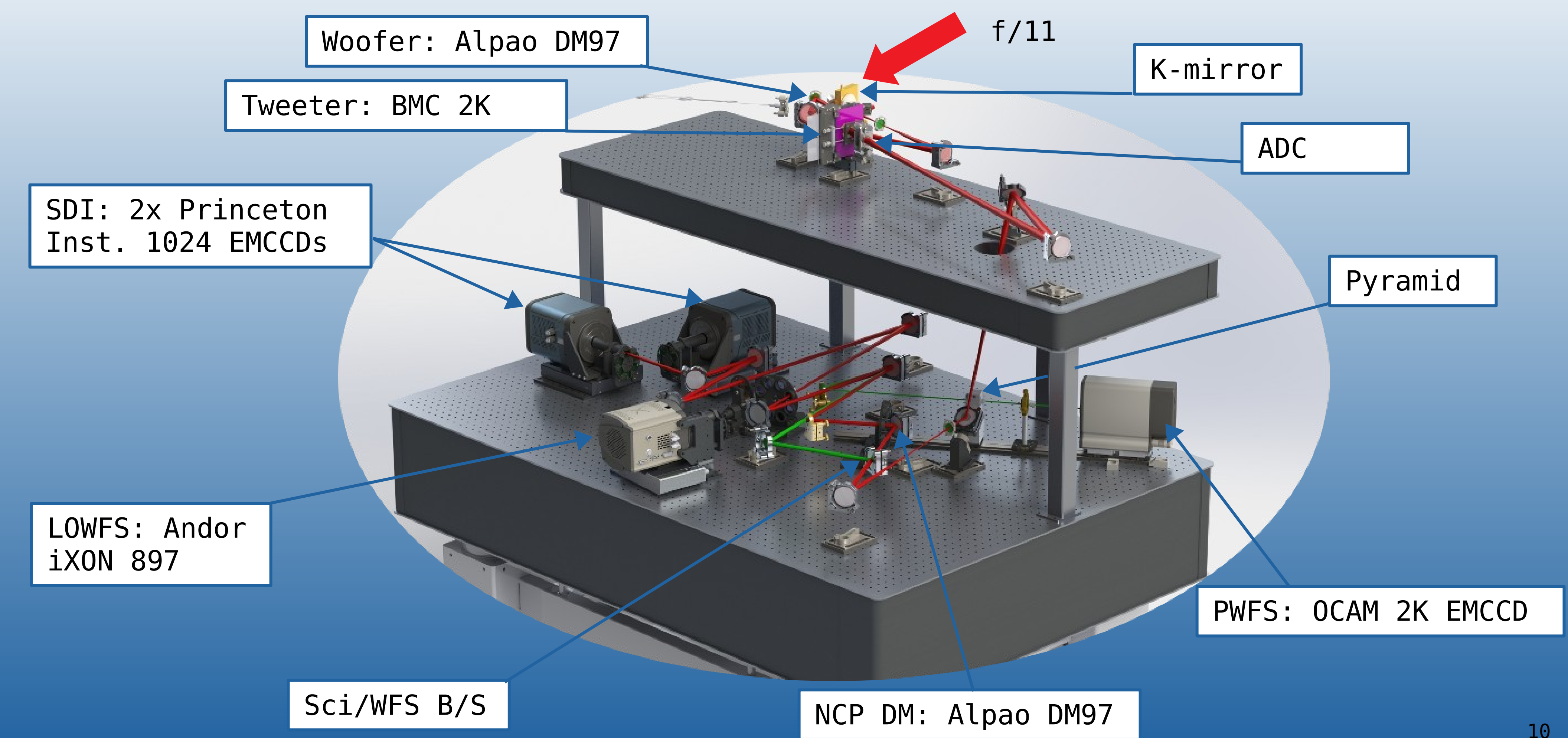
MagAO-X Optomechanical Design



MagAO-X Optomechanical Design



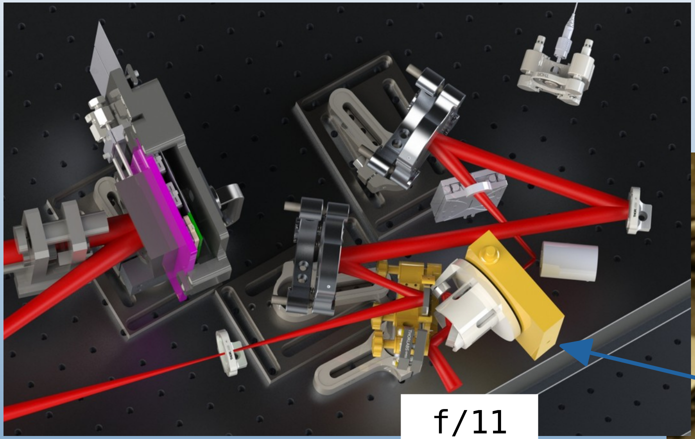
MagAO-X Optomechanical Design

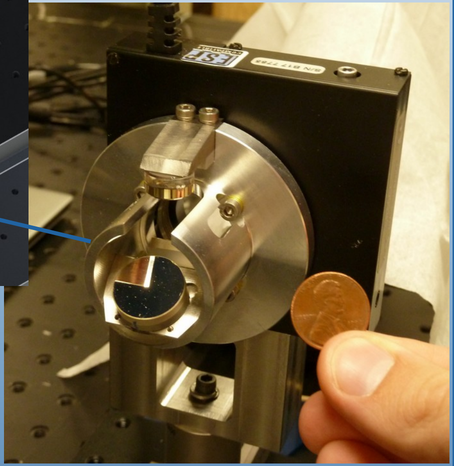


It Has Begun

See optical-mechanical design overview poster by **Laird Close** on Wednesday. [10703-184]

MagAO-X Optomechanical Design



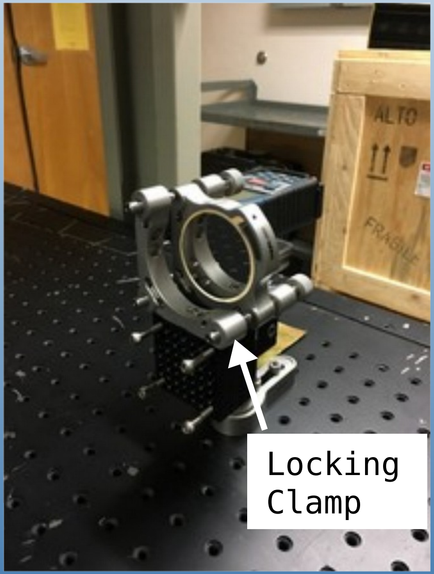


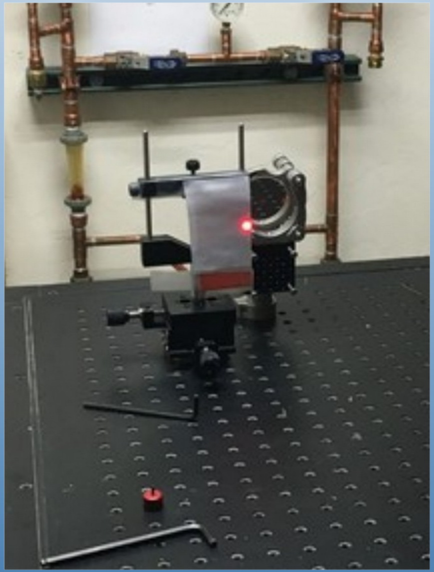
World’s smallest K-mirror!

MagAO-X will always be “pupil stabilized”

See poster by **Alex Hedglen** on Wednesday. [10703-192]

Custom locking clamps give better than 5 μm / 1° C stability, >10 times better thermal stability than best commercially available solutions

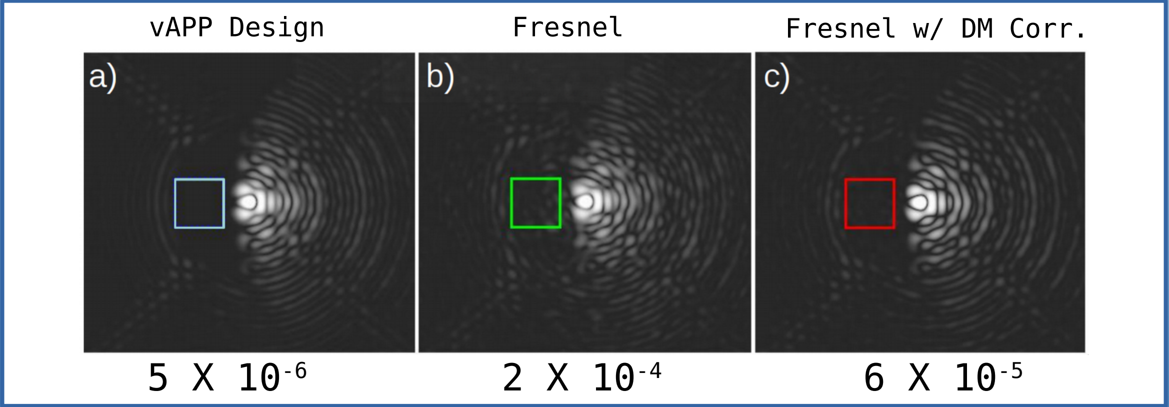




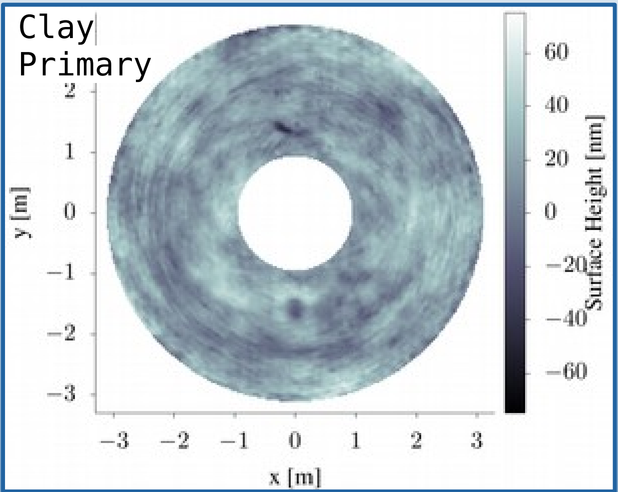
See poster by **Maggie Kautz** on Sunday. [10703-100]

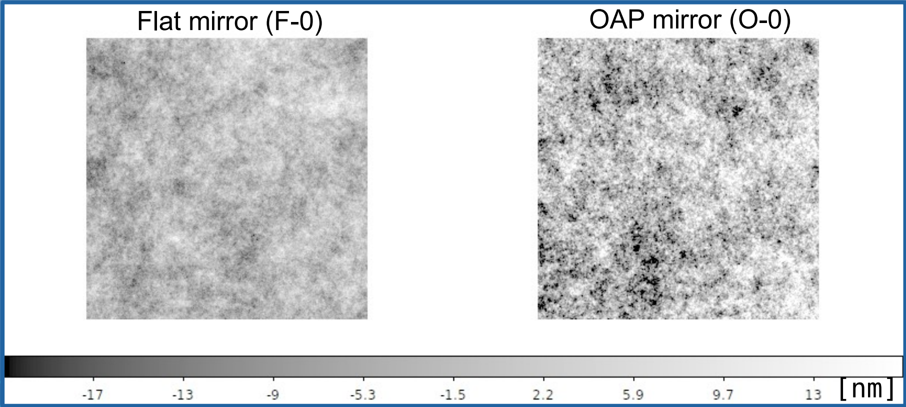
Specification of Optics

- PSD error budget established
  - Known telescope surfaces used
  - Generated flats & OAPs
- Detailed Fresnel propagation (POPPY) carried out to validate specs prior to fab.



See poster by **Jennifer Lumbres** Wednesday [10703-185].

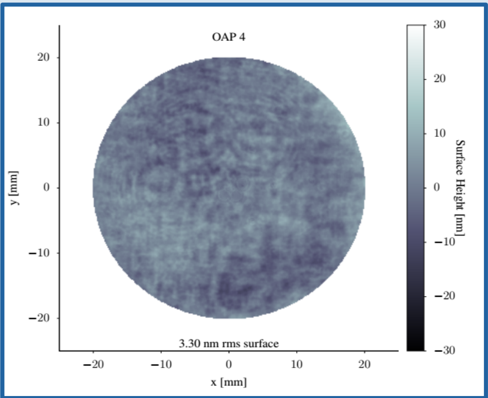




Specification of Optics

	Spec	Delivered
OAPs	12.7 nm WF	< 11 nm WF
Flats	Lambda/100 surface	in spec
DM-2K	20 nm surface	11.3 nm surface
DM-97	7 nm surface	2.2 nm surface

Totals:	
Uncorrectable (high freq) CP:	**<~35 nm**
Post LOWFS-DM NCP:	**<~20 nm**
Total instrumental:	**< 40 nm**
Instrumental Strehl Hα	**> 86%**
Fitting Error, Hα @25%-ile	**37 nm**
Total Strehl, Hα @25%-ile	**> 76%***



Example pre-coat OAP surface, 3.3 nm rms

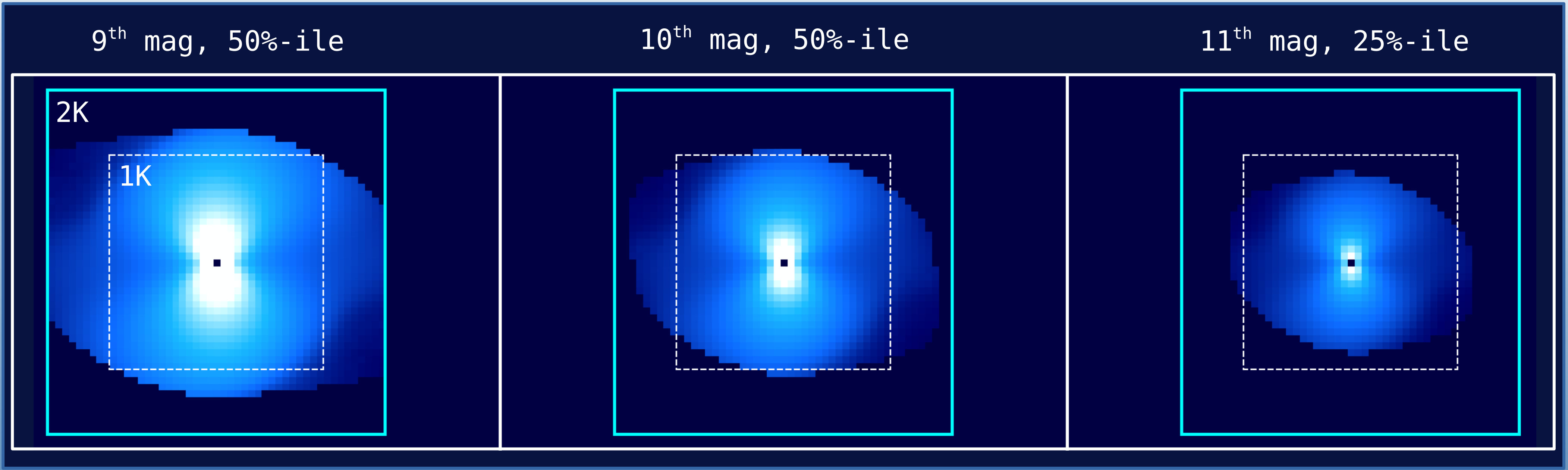
Verification in progress @UA:

Kyle, Kelsey, & Laird

Testing @UA still in progress, but results so far indicate we will exceed our design specs.

*does not include servo-lag and measurement error

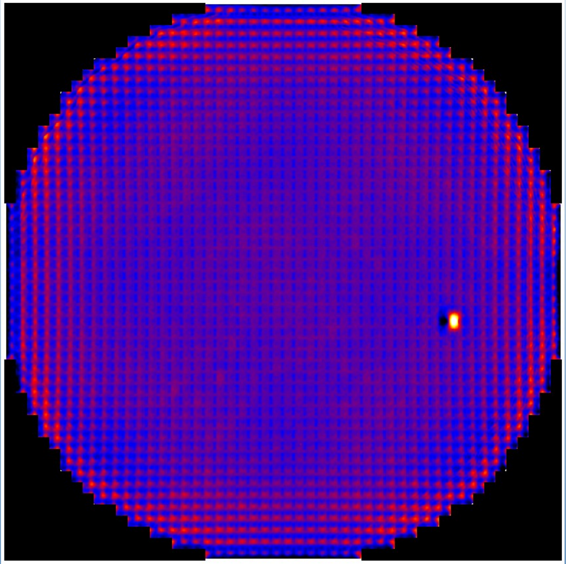
Actuator Count Requirement



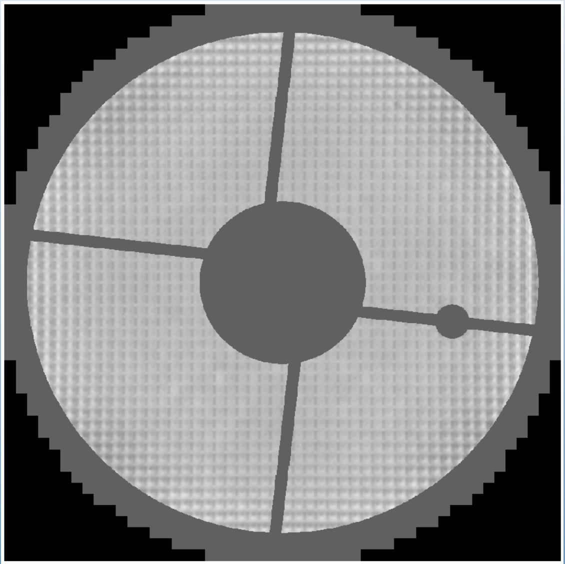
- Optimum integrator gains calculated as in Males & Guyon, 2018
  - Predictive control will apply gains to even more actuators
- The 2K MEMS is well justified by the MagAO-X science case

BMC 2K: 2040 Actuators

- Original Plan: w/ASM woofer, 100% yield 1.5 um stroke device guaranteed by BMC.
- f/11 Plan: wanted 3.5 um stroke device due to smaller woofer.
- Resulting 3.5 um device:
  - 1 major defect, a “bump” which holds surface up.
  - 1 pair coupled actuators
  - 2 more minor “bumps” that limit stroke to ~3 um in two spots.



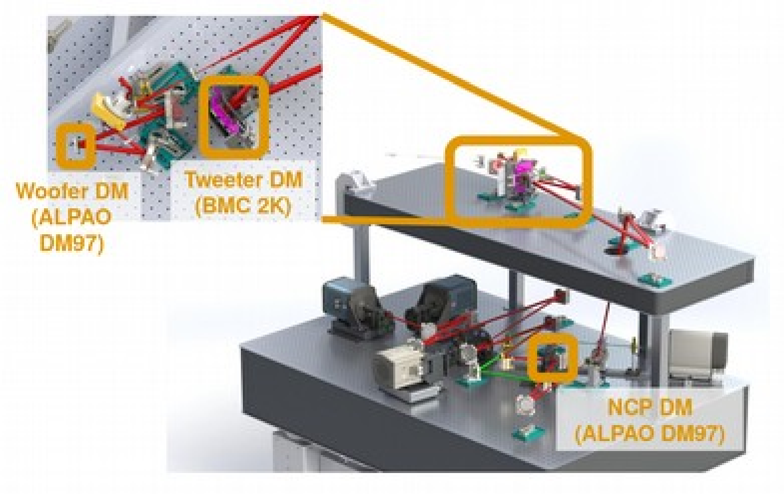
Full flat map @BMC, “bump” clearly visible.

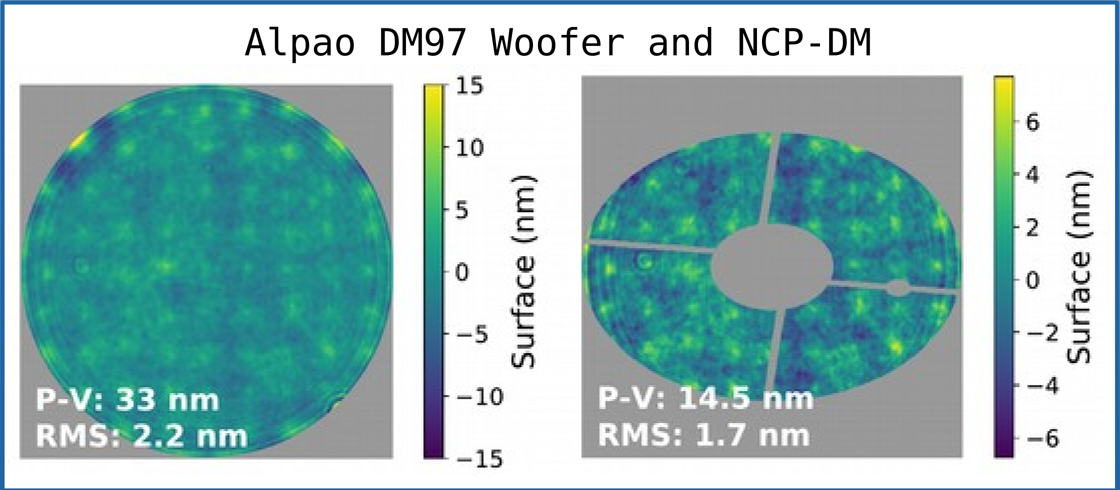


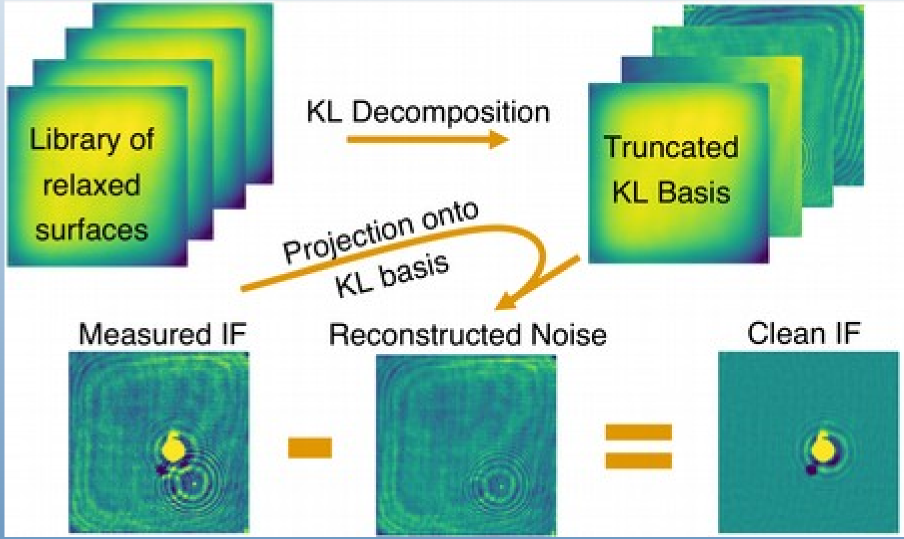
Projected MagAO-X coronagraphic pupil. 11.3 nm rms.

Soon-to-be-delivered DM exceeds our surface spec. of 20 nm rms

Deformable Mirror Characterization







See poster by **Kyle Van Gorkom** on Wed. [10703-272]

Real-Time Software

cacao : Compute And Control for Adaptive Optics

Computation engine for adaptive optics control; functions accessible through a command line interface (CLI). Holds images in RAM, with image stream support (shared memory with low-latency IPC support).

Written in C, optimized for performance. Executable launches a command line interface (CLI). Type "help" in the CLI to get started.

Uses multi-core CPUs and GPGPUs to high computing throughput.

Modular, easy to add functions, loaded at runtime as shared objects.

CACAO uses milk

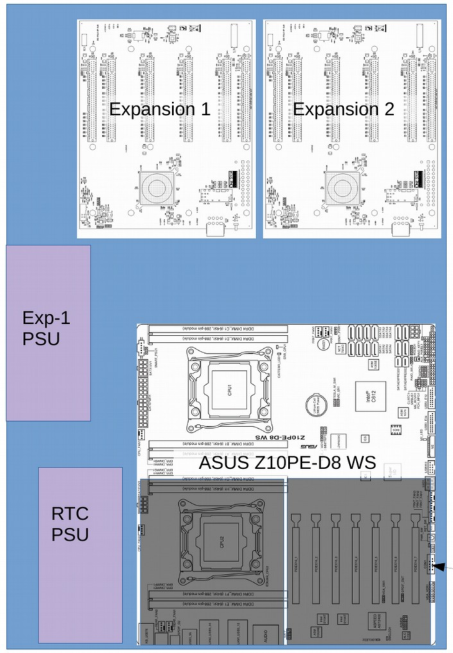
https://github.com/cacao-org/

- Using SCExAO R/T S/W developed by Olivier Guyon (CACAO).
- Already works on-sky
- Under active collaborative development and publicly available.

See talk by **O. Guyon** on Wednesday AM [10703-51]

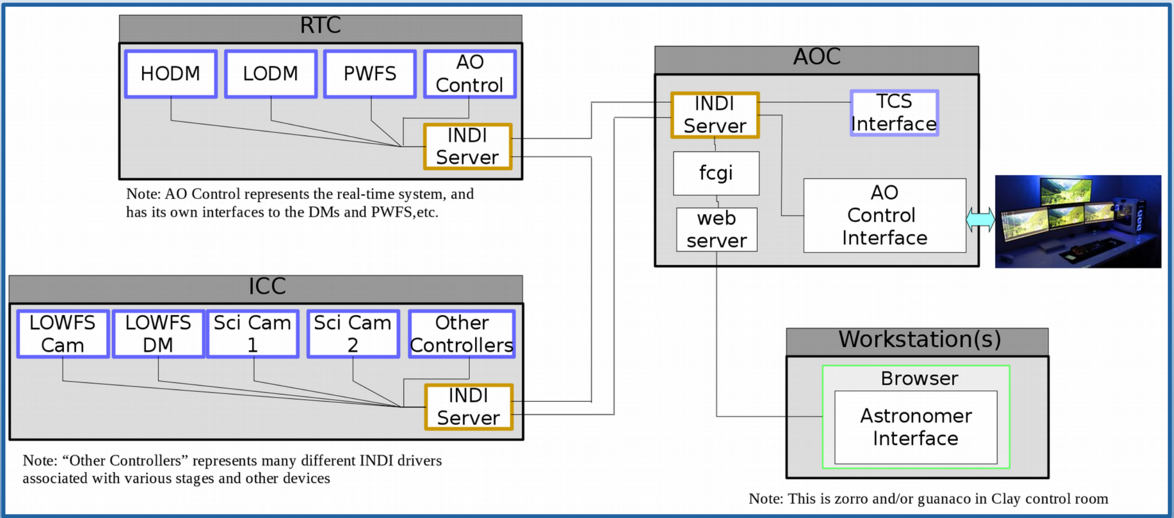
Computer Hardware

- All COTS architecture
  - Easy maintenance and upgrade path
  - Custom rack mount layouts
  - CPUs and GPUs liquid cooled
- All telemetry all the time: > 10 TB/night
  - Storage system designed to handle every bit of data available . . .
  - Transport it home . . .
  - And facilitate post-processing.



Instrument Control Software

- Instrument Neutral Distributed Interface (INDI)
  - Elwood Downey (2007)
- Decentralized communications arch. and XML-based protocol
  - Designed for astronomical inst. control
  - Publish-subscribe, no central db
- Used for LBTI, planned MMT-AO upgrade (MAPS).
  - Re-using LBTI code on MagAO-X
- Low-priority IPC
  - In parallel with CACAO R/T architecture



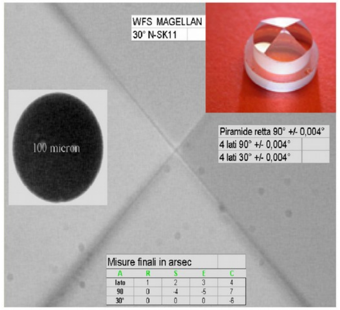
Pyramid WFS

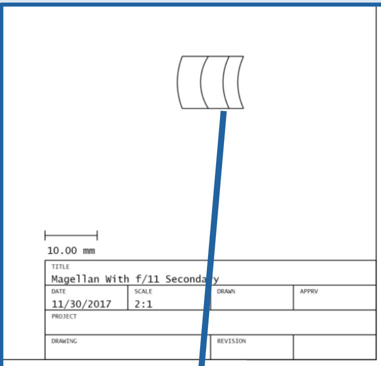
Modulated Pyramid WFS
 -Will move to unmodulated

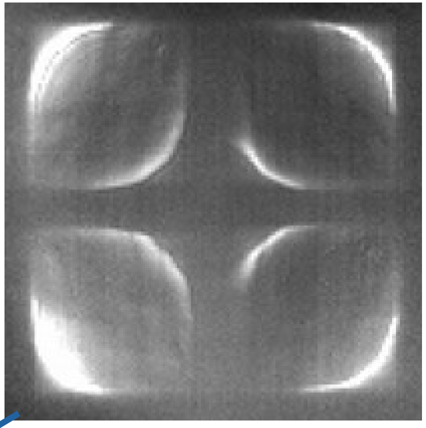
56x56 pupils (oversampled on 48x49 MEMS HODM projected pupil)

< 0.1 pixel alignment tolerance

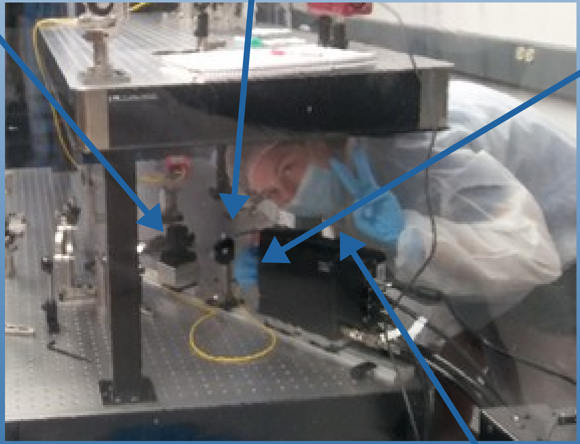
An “Arectri special” by Paolo Stefanini

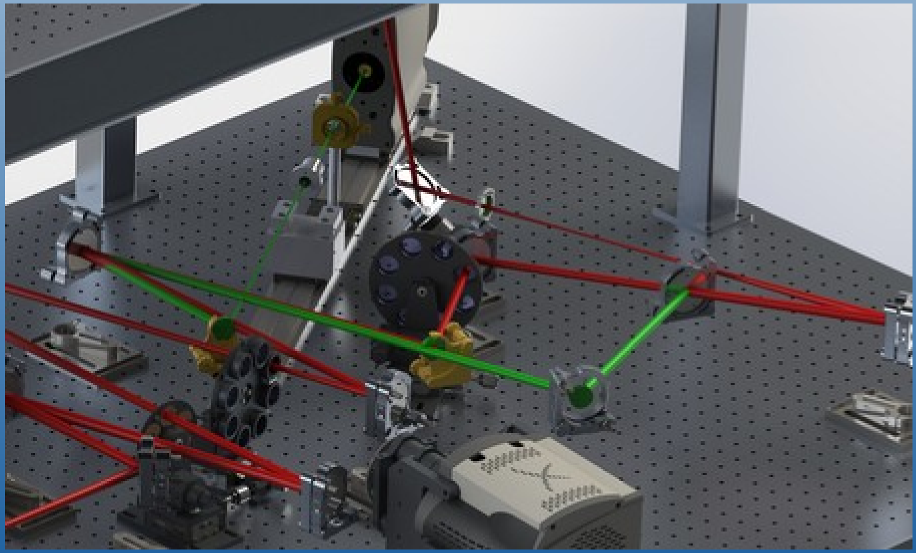






1st white-light pupils, coarse alignment, no modulation

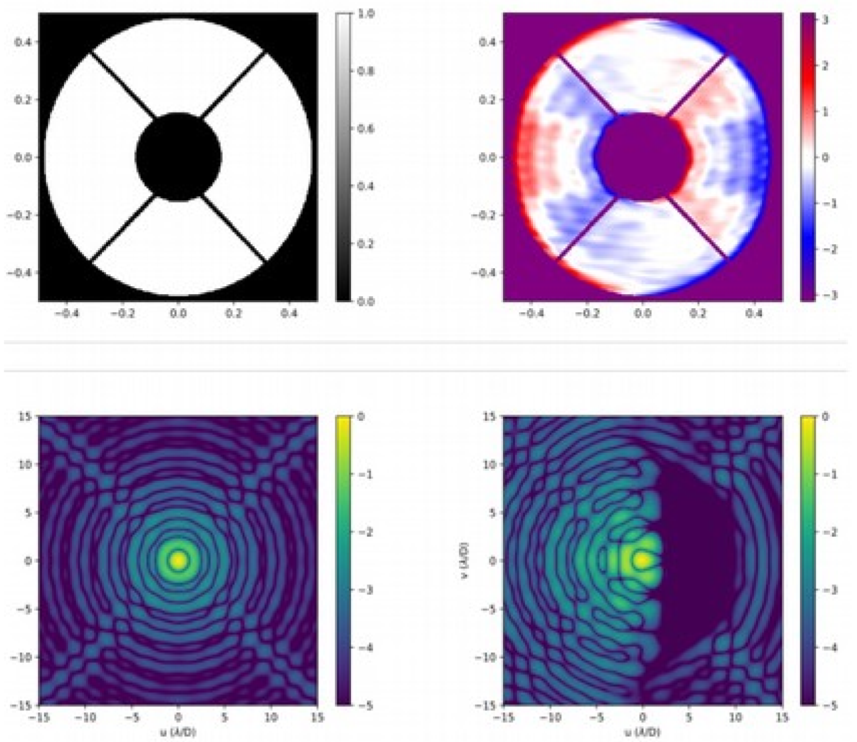




See talk by **Lauren Schatz** on Thursday [10703-74]

Vector Apodizing Phase Plate

- vAPP coronagraph will be our workhorse high-contrast imaging mode.
  - Pupil only, immune to jitter with fast camera
  - 5×10^{-6} raw contrast
  - ~2 λ/D IWA
- Will robustly enable our Hα proto-planet science case starting at first light



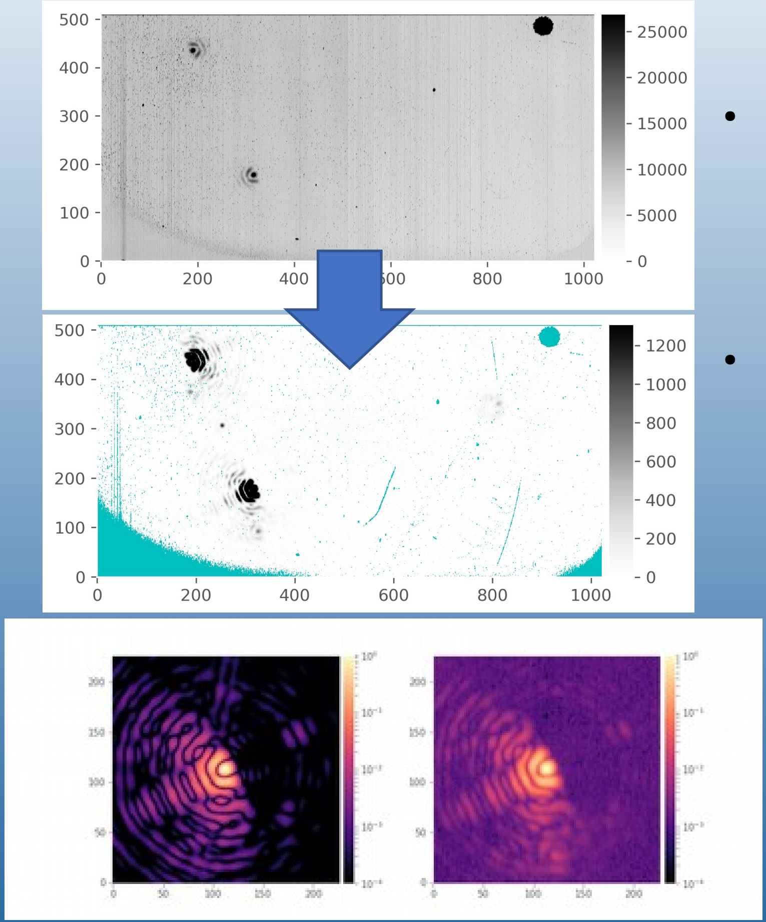
vAPP design by David Doelman, Leiden

See poster by **Frans Snik** on Monday [10702-152]

Universiteit Leiden
Leiden Observatory

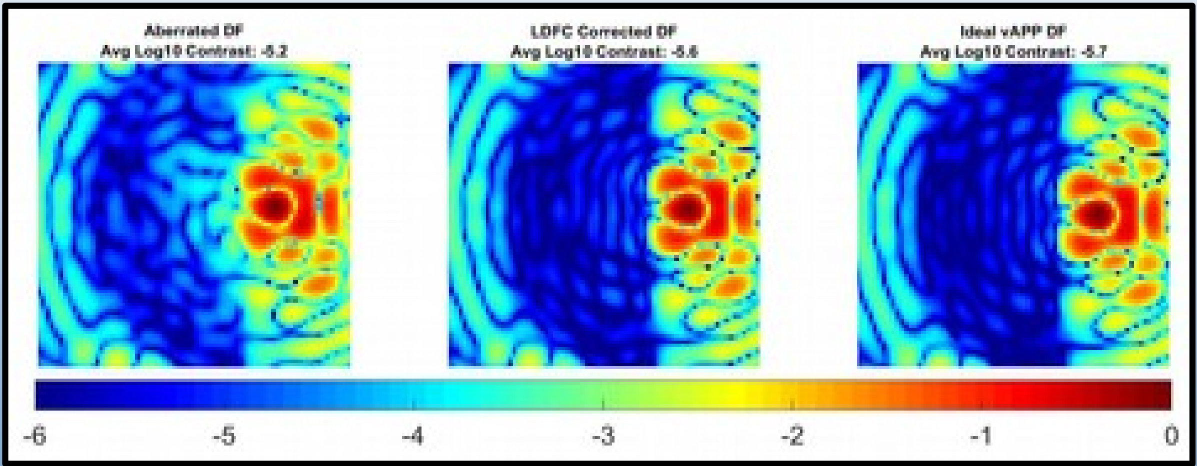
Data Reduction

- vAPPs installed on high-framerate MagAO+Clio camera allow us to start developing post-processing algorithms
- Registration and centering of vAPP PSF presents challenges (especially when saturated)
  - In this case compounded by L band background and detector
- Large dataset (~20000 frames) poses challenges for post-processing
  - We have several datasets of similar size and depth.
  - Developing the big-data connects we’ll need for MagAO-X



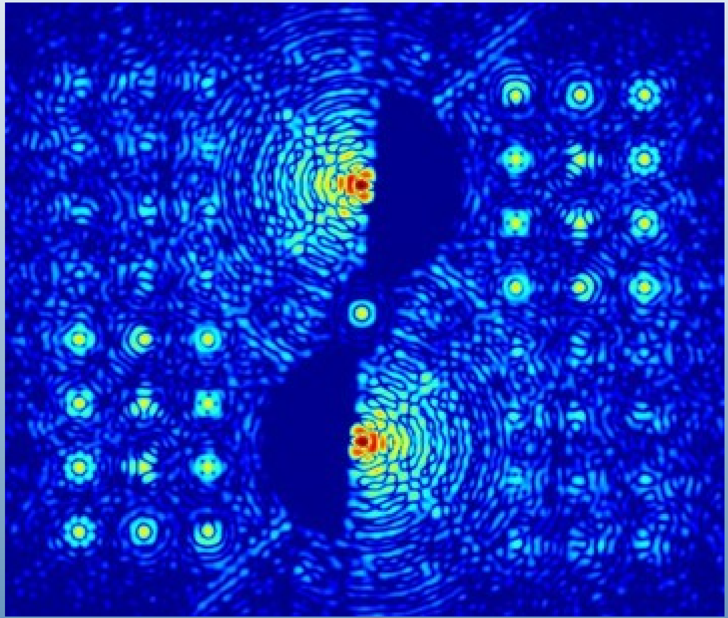
See poster about Sirius by **Joseph Long** on Sunday [10703-103]

vAPP-LOWFS



Linear Dark Field Control: using the bright field outside the dark hole to optimize contrast. Above: simulation of LDFC on a vAPP PSF.

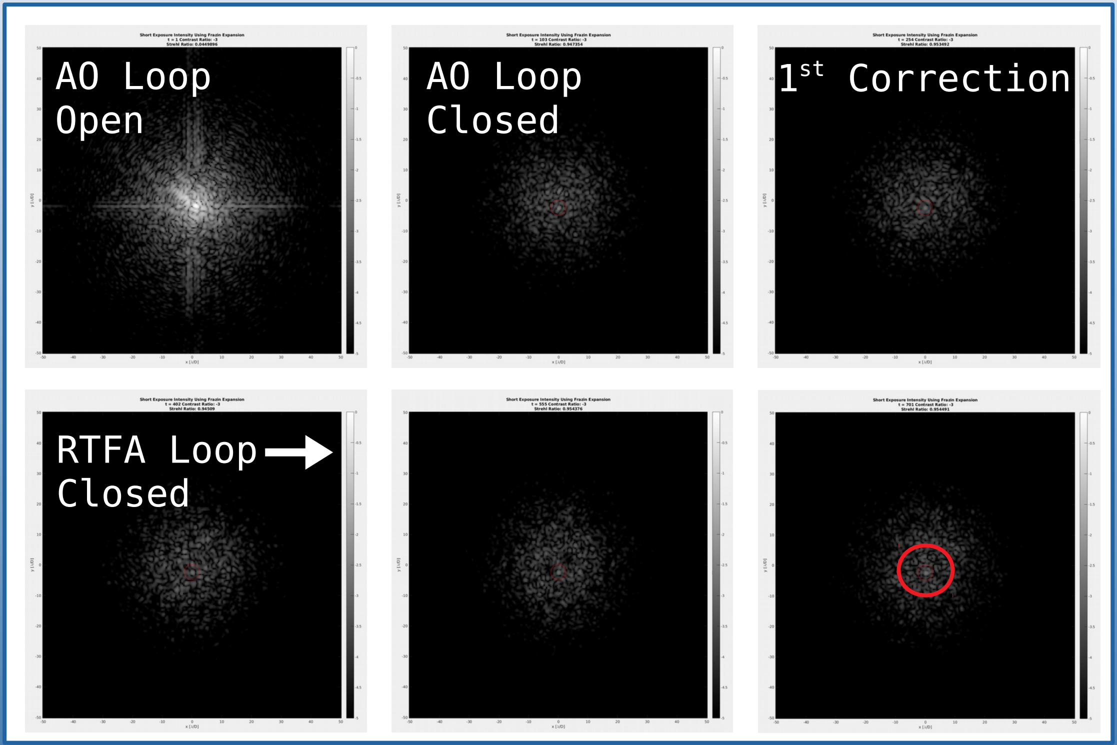
MagAO-X LOWFS design picks off the bright part of the on-axis PSF and used it for WFS&C.



Modal WFS encoded in vAPP liquid crystal mask, brightness of spot tells amplitude of corresponding Zernike

See talk by **Kelsey Miller** on Thursday AM [10703-66]

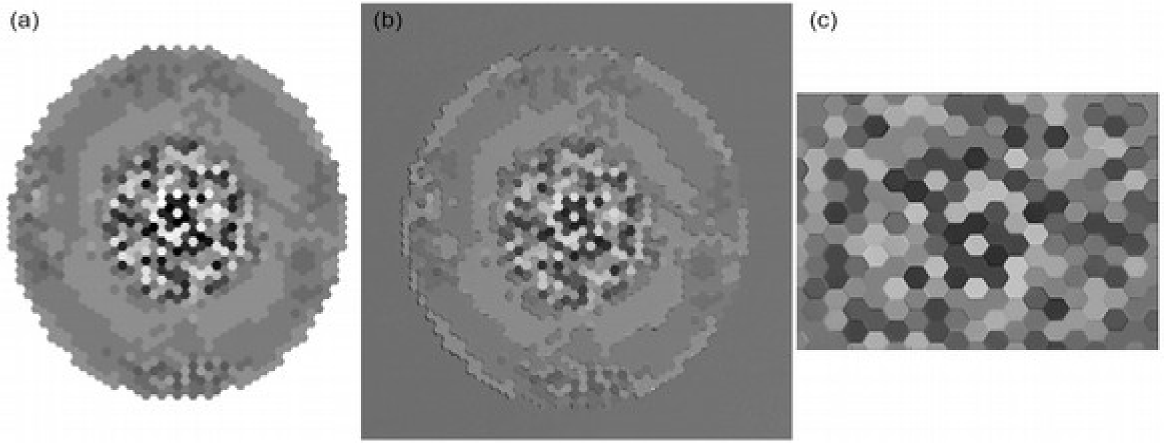
RTFA: kHZ FPWFS



- Exploring Frazin's milli-second image post-processing algorithm (ApJ, 2013)
  - kHz WFS and science (MKIDS) images, solve for aberrations
  - Can exploit MagAO-X's "all telemetry all the time" design
- Extending it to "The Real-Time Frazin Algorithm" (RTFA)
  - EFC using servo-lag as the probe
  - Why post-process it when you could correct it?

See poster by **Alex Rodack** on Sunday [10703-97]

PIAACMC – Design & FPM Fabrication

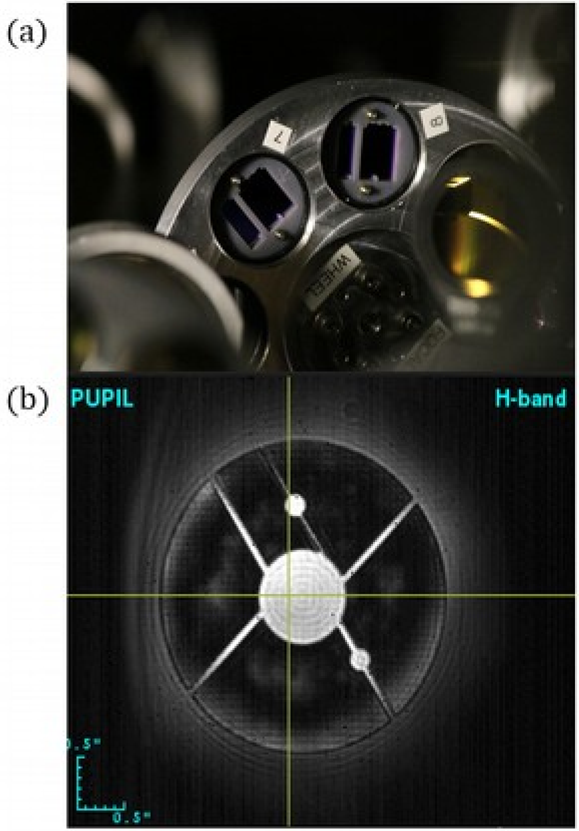


Design

Interferometric measurement on fabricated mask

See poster on mask tolerancing by **Justin Knight** on Thursday [10706-200]

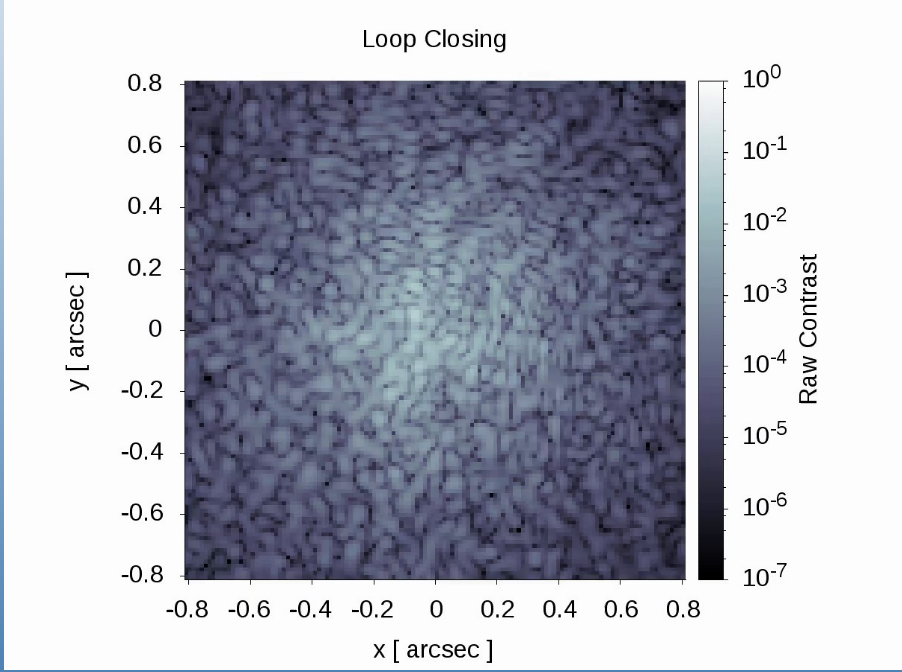
See talk on MagAO-X PIAACMC design by **Justin Knight** on Friday [10706-96]
The last talk of the conference



Demo at SCExAO: complex FPM fills the Lyot Stop

Predictive Control

A Key Technology for ground-based ExAO



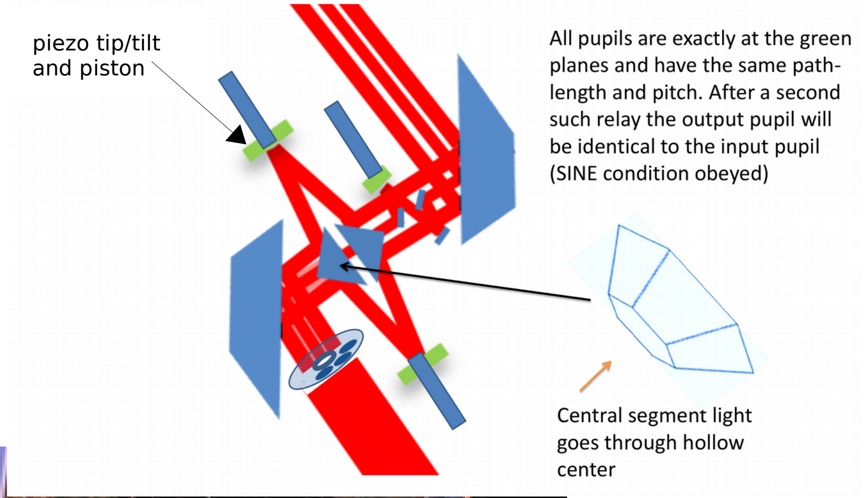
- Simulation of Linear-Predictor control on MagAO-X (Males & Guyon, 2018)
  - Very similar to PFC (Poyneer et al. 2007)
- See also DKF of Correia et al. (2018)
- Empirical Orthogonal Functions (Guyon & Males, 2017)
  - Adaptive inclusion of non-WFS data, e.g. accelerometers or stock market

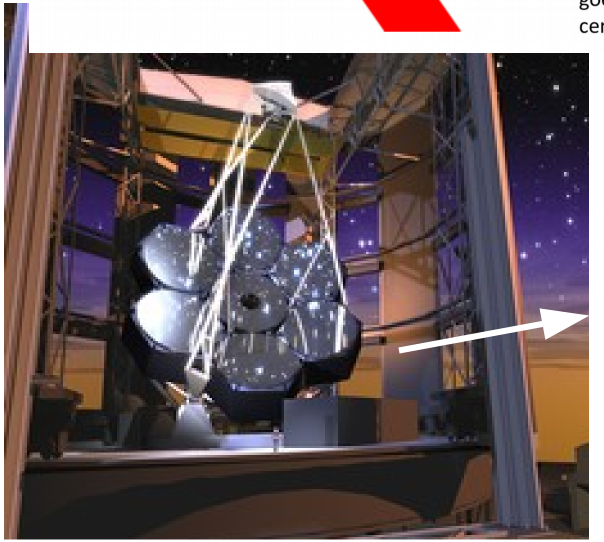
The Future

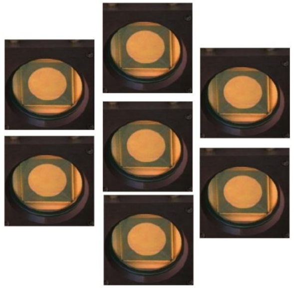
- MagAO-X is ultimately a pathfinder for GMT
  - Possible first-light AO system

- GMagAO-X: scaling MagAO-X to 25 meters
  - 7x 3000 actuator MEMS → 21,000 actuators
  - Same pitch and speed, so same ~80% Strehl in the visible on a ***25 meter telescope***

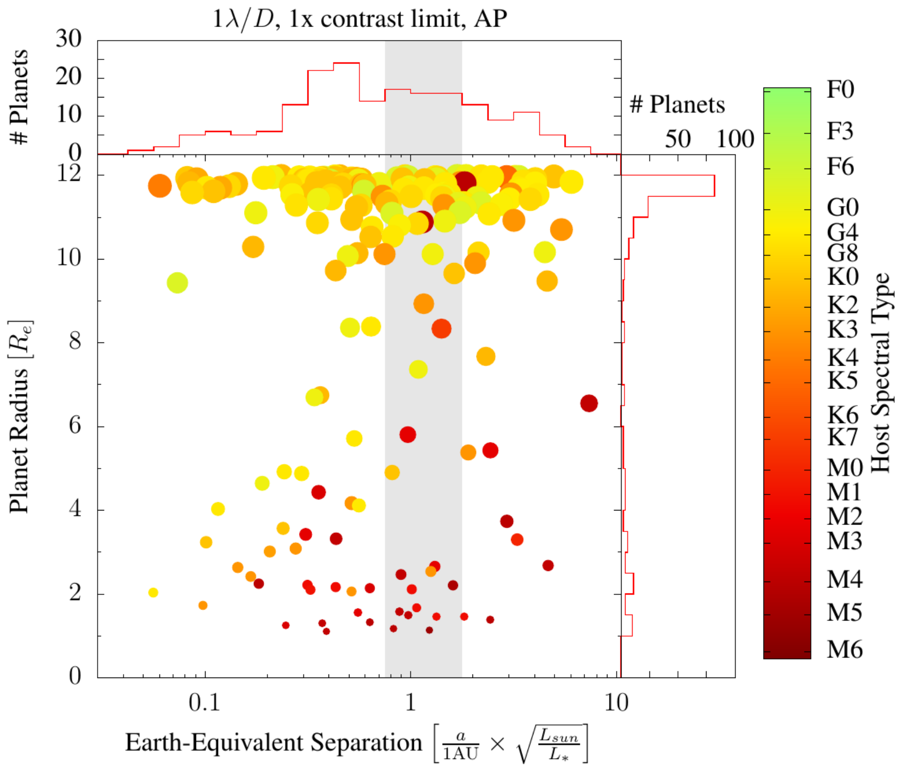
GMagAO-X







7x BMC 3Ks



Currently-known exoplanets which a fully optimized GMagAO-X could characterize in reflected light. See poster [10702-341] on Thursday...

We’re grateful for the support of the NSF MRI program (#1625441) — Thank You!