Current Visible Light AO Systems and Science with MagAO and a Look to ELTs

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MagAO & MagAO-X teams

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So Why bother with the Visible…

Visible has many scientific advantages over NIR

1. **Better Science detectors (EMCCDs, QE~98%):**

- **-- Much** Lower dark current (by >10x)
- -- Lower readnoise (<1 e- typical now)
- -- better cosmetics (zero bad pixels)
- -- Better QE ~100%
- --warm is OK, just need TE cooling!
- --Compact: Science cameras can be smaller than WFS

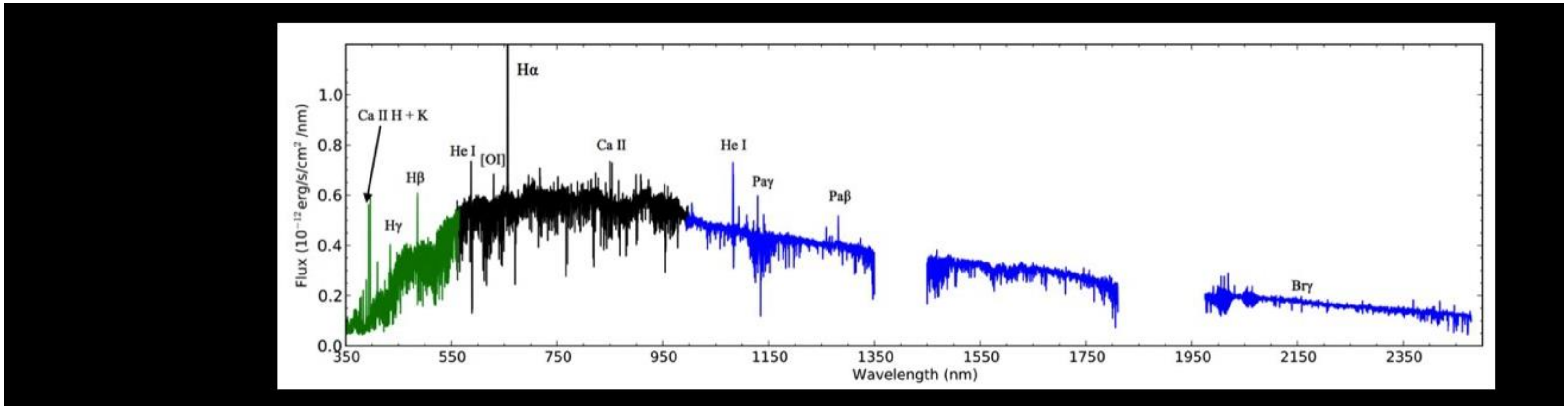
2. Much Darker Backgrounds

(>1000x darker at K compared to V) skies too…

This is important ---especially for extended objects.

Visible has many scientific advantages over NIR

3. **Strong Emission lines:** access to the primary recombination lines of Hydrogen (Hα 0.6563 μm) --- most strong emission lines are in the visible: (Case B recombination yields factor of ~20x brighter than BrGamma)



Visible has many scientific advantages over NIR

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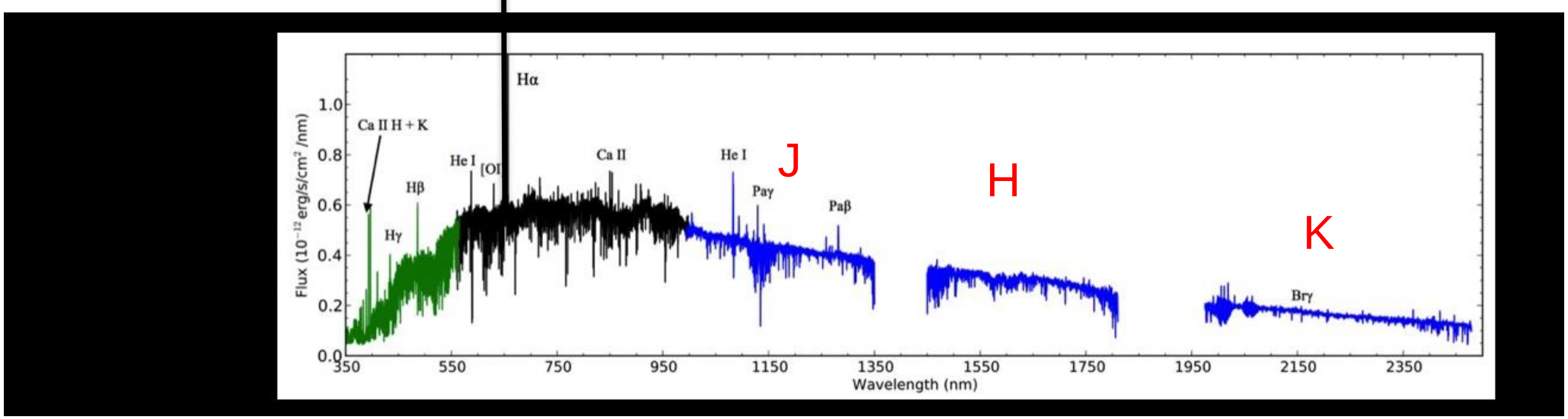
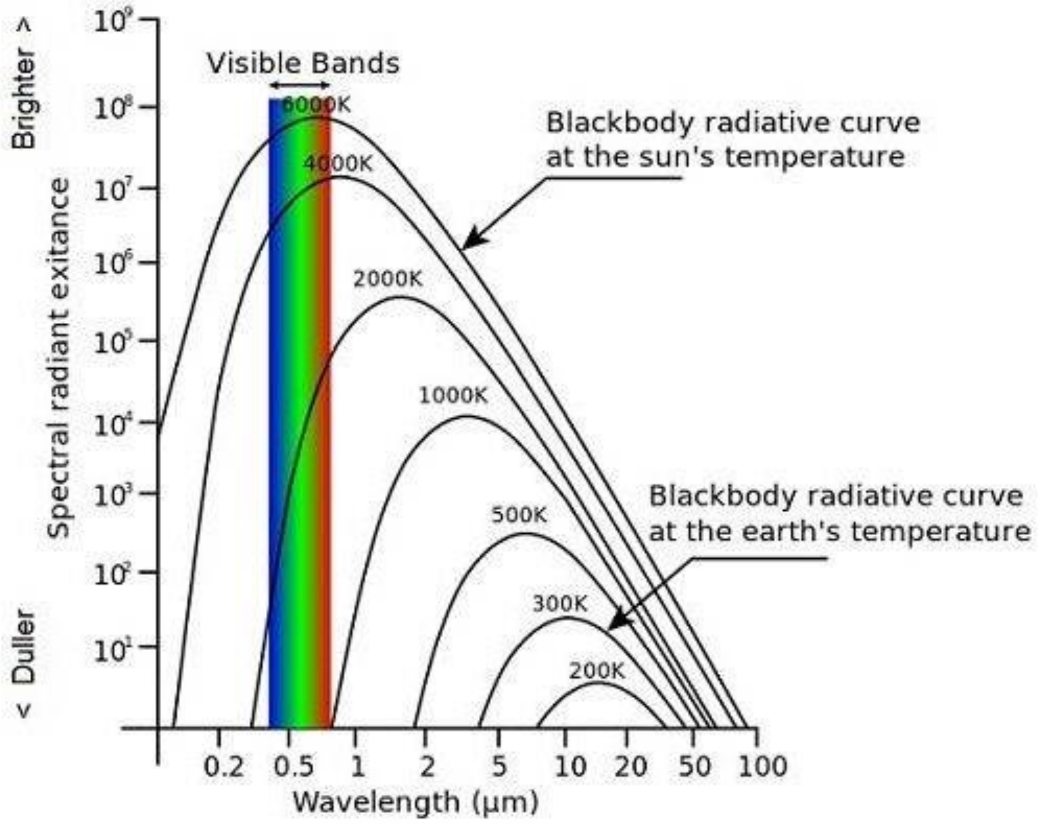
H-alpha emission (0.656 μm for typical young star (LkCa 15 A) *Whelan et al. 2015 A&A*



Visible has many scientific advantages over NIR

4. **Off Rayleigh Jeans tail**: Stars have greater range of colors in the visible (wider range color mag diagrams). Good place to measure Av, L.



Visible has many scientific advantages over NIR

-- Smaller λ :

Higher spatial resolution!

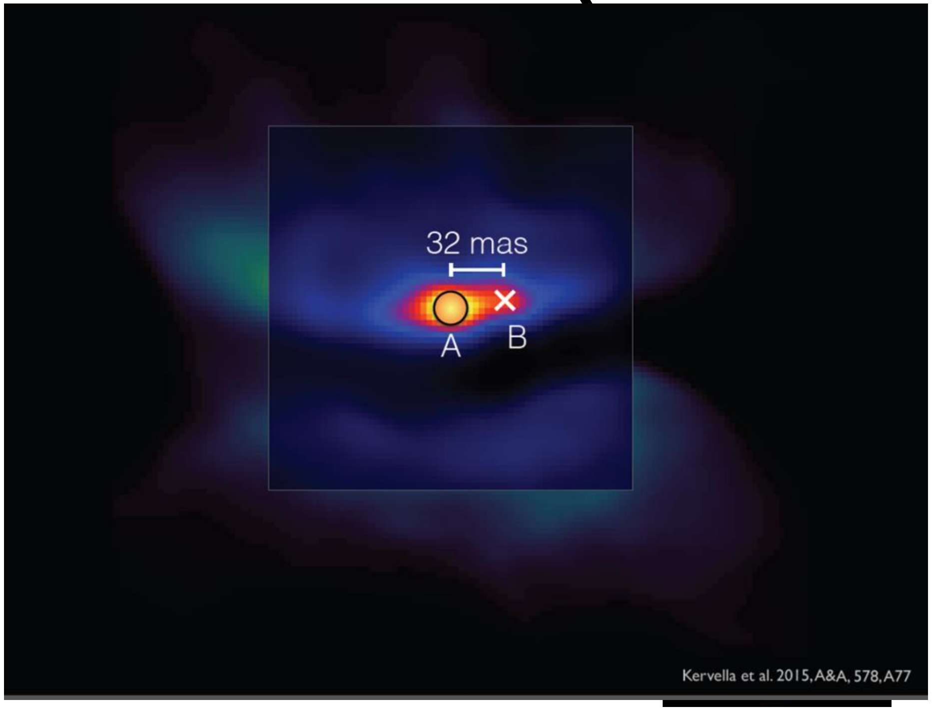
The 10-20 mas spatial resolution regime opens up on 6-8m class telescope at 0.6 microns…

ELTs could approach even higher 3-7 mas resolutions in the visible… more on that later…

MagAO

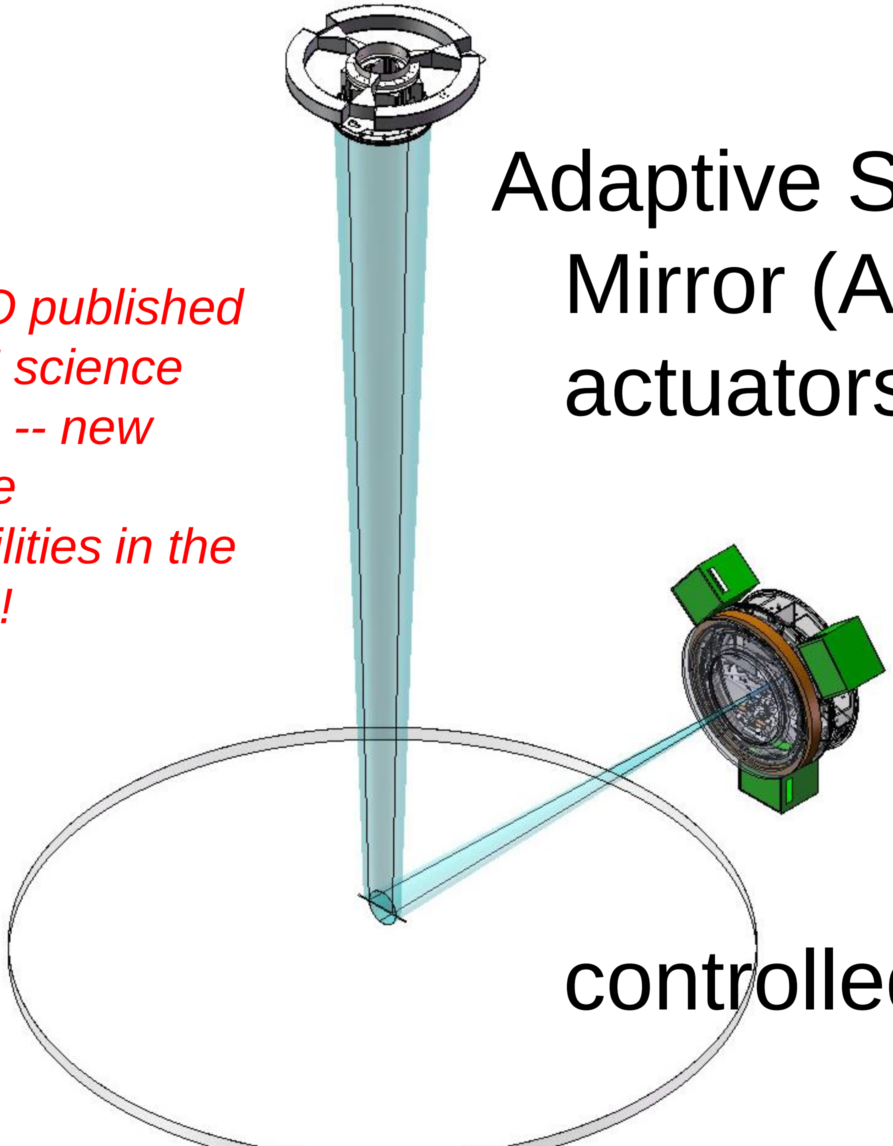
Current Visible AO systems

- **Robo-AO is running well (*automatically*) on a 1.5m scope with a UV laser** *Baranec et al.*
- *SAM GLAO system at 4m SOAR --* Andrei *Tokovin*
- ***SCExAO with VAMPIRES starting to produce visible science – the 10mas resolution of μ Cep***
- **SPHERE/ZIMPOL (in science operations at VLT)**



Sphere discovers a companion in the bipolar outflow from The Nearest AGB star: L2 Pup (Kervella et al 2015)

The 6.5m Magellan Telescope AO system (MagAO). Designed for Visible AO from start.



Adaptive Secondary Mirror (ASM; 585 actuators)

MagAO published 27 ApJ science papers -- new science possibilities in the visible !

Pyramid WFS 378 modes controlled at 1KHz

Some Keys to Visible AO Design

1 Good Site – Large r_o (long τ_o) + and *consistency (like clear weather) helps –clouds can ruin a long ADI dataset.*

2 Good DM and WFS fast!, <r_o sampling, no “bad” actuators!

3 Stiff “piggyback” design with Visible science camera well coupled to the WFS – *minimize non-common path optics/aberrations (NCP errors), like the ADC. Keep it Simple!*

4 Lab Testing: Lots (and lots) of “end-to-end” closed loop testing with Visible camera…

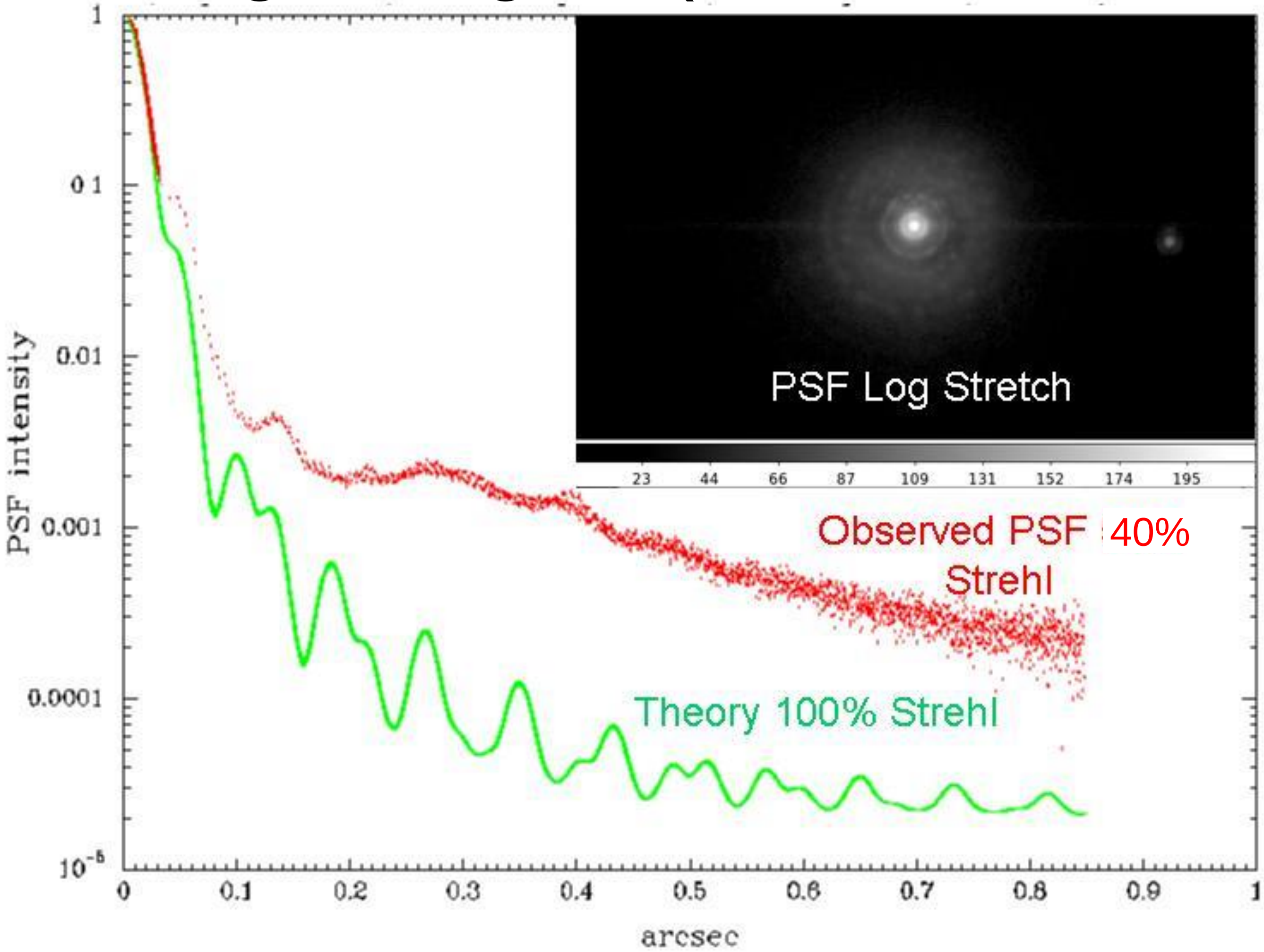
5 Modeling/Design: Well understood error budget feeding into analytical models, must have <135 nm rms WFE.

6 High Quality IMATs: Excellent on-scope IMATs with exact pupil (ASM helps here) – *often underestimated…*

7 IR simultaneous with VisAO: *(contingency in poor seeing)*

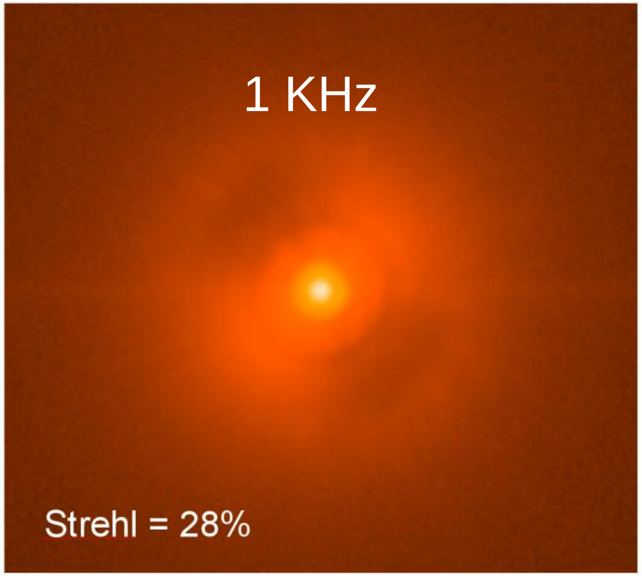
MagAO

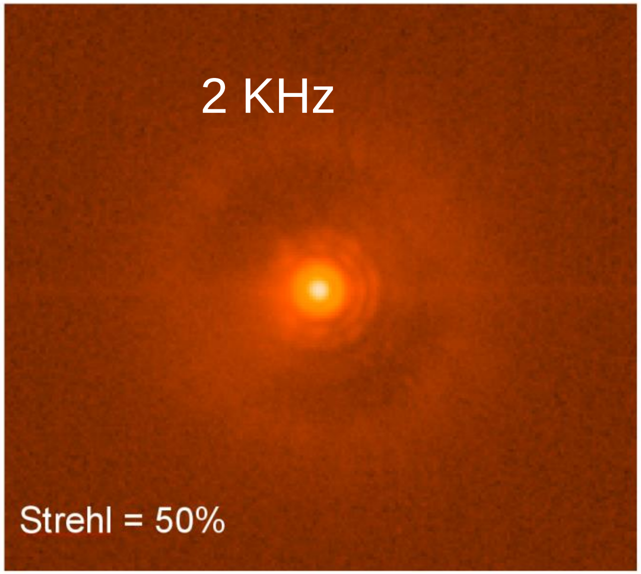
First Light MagAO (1Khz, 200 modes)



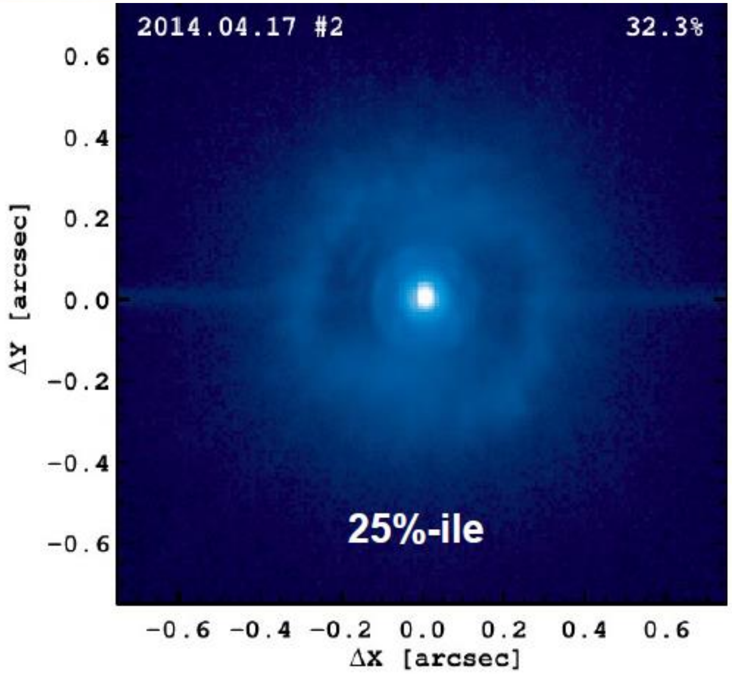
Deep 40% Strehl at 0.98 μm PSF (140 nm rms WFE with 200 modes).

MagAO-2K: Better, deeper Images (2kHz, 350 modes)





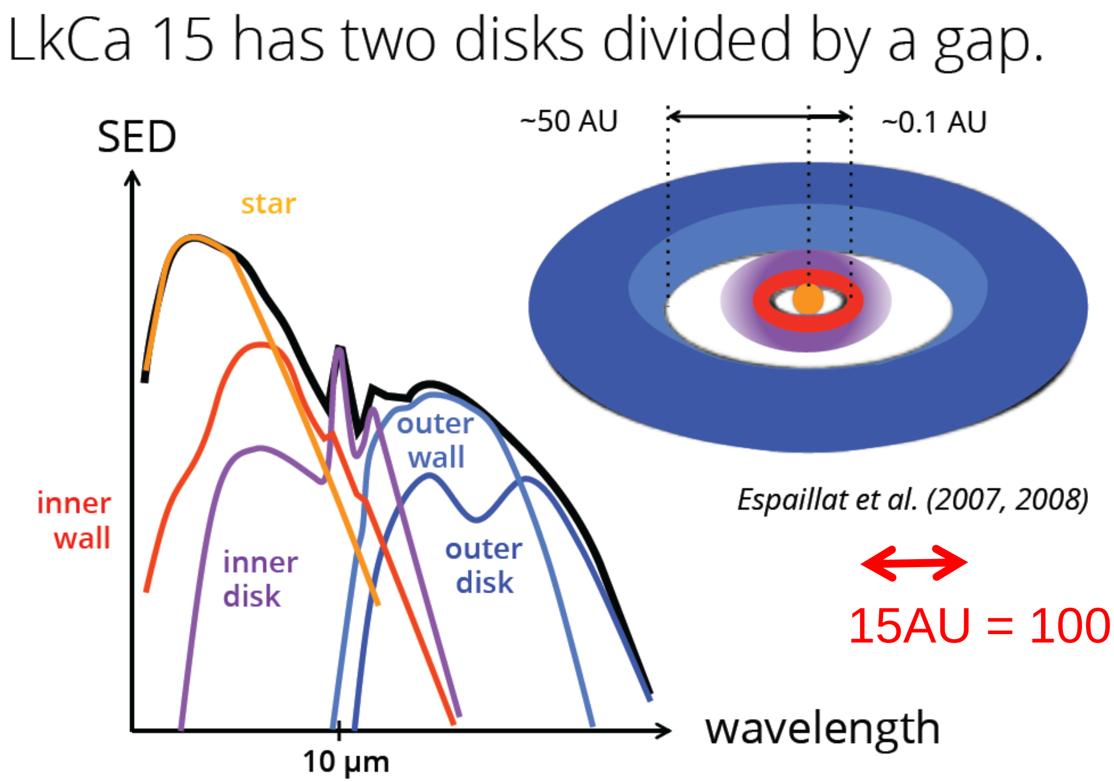
MagAO-2K improved to 102 nm rms WFE **with 350 modes now corrected at 2KHz at 0.9μm (z') in median seeing.** ***Males et al. in prep***



i' deep (2 hour) PSF Males et al 2014 (32% Strehl at 0.8μm)

MagAO

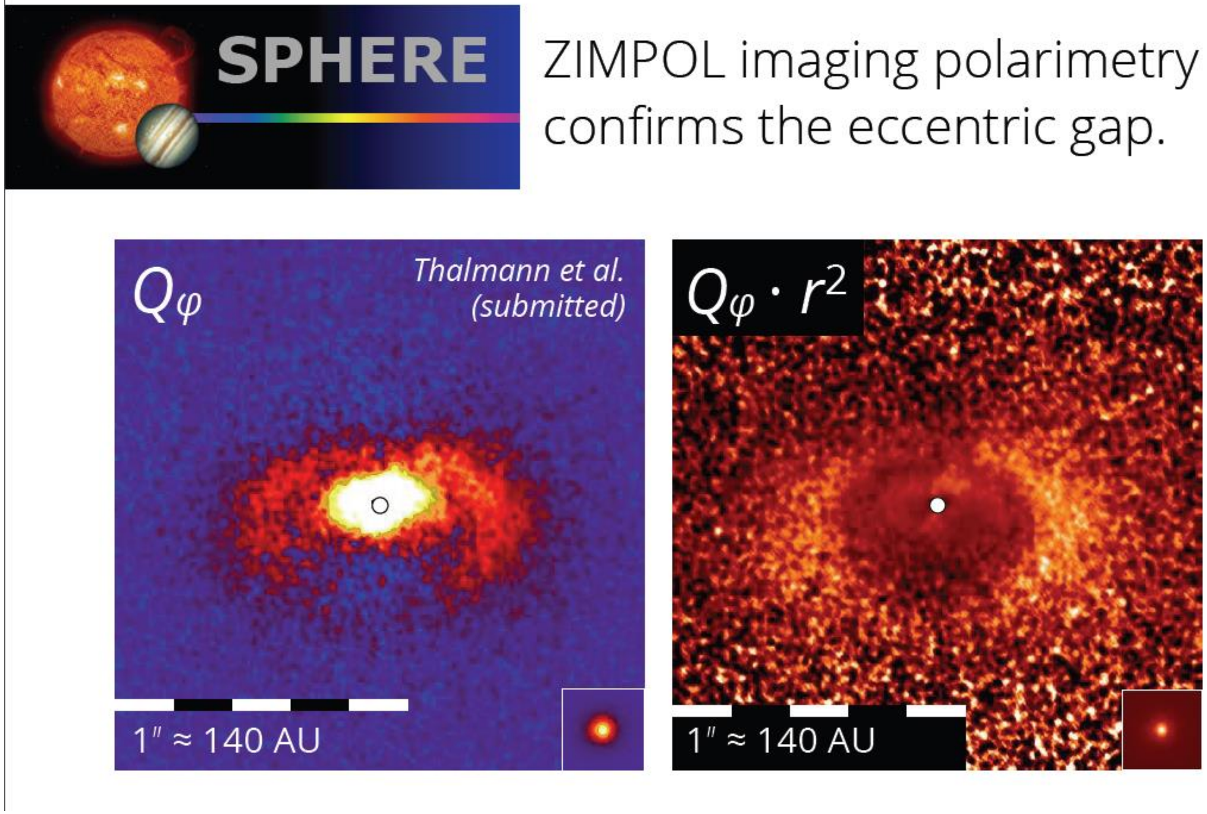
Science example: LkCa 15: The Most Famous Transitional Disk



15AU = 100 mas

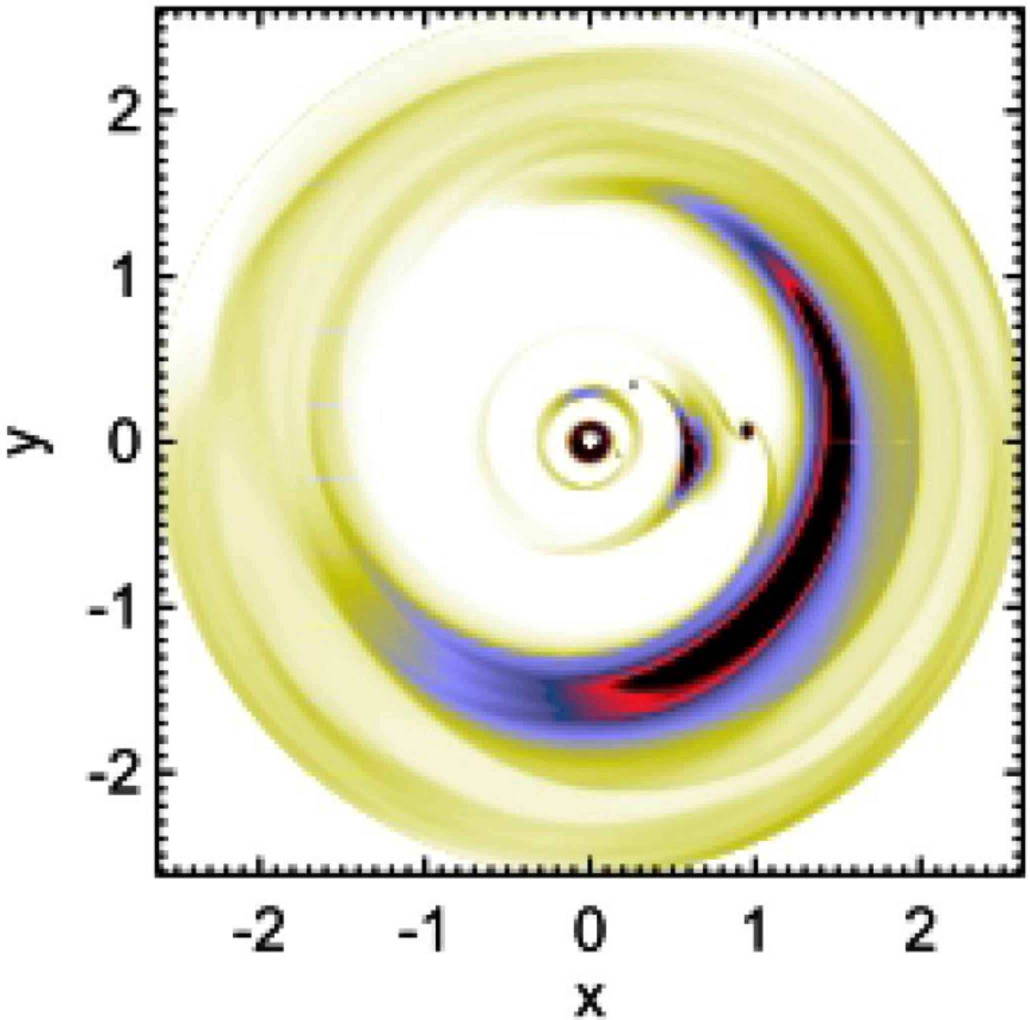
- Christian Thalmann

ZIMPOL uses the polarized nature of scattered light to constrain the geometry of Disk



- Christian Thalmann et al. 2015 A&A

GAP PLANETS We can even imagine that **multiple planets** may be needed to keep Large gaps cleared in the cases of Transitional disks like HD 142527.



Simulations of how a multiplanet system (3 in this case) can maintain a wide gap in a transitional disk (reproduced from Dodson-Robinson & Salyk 2011).

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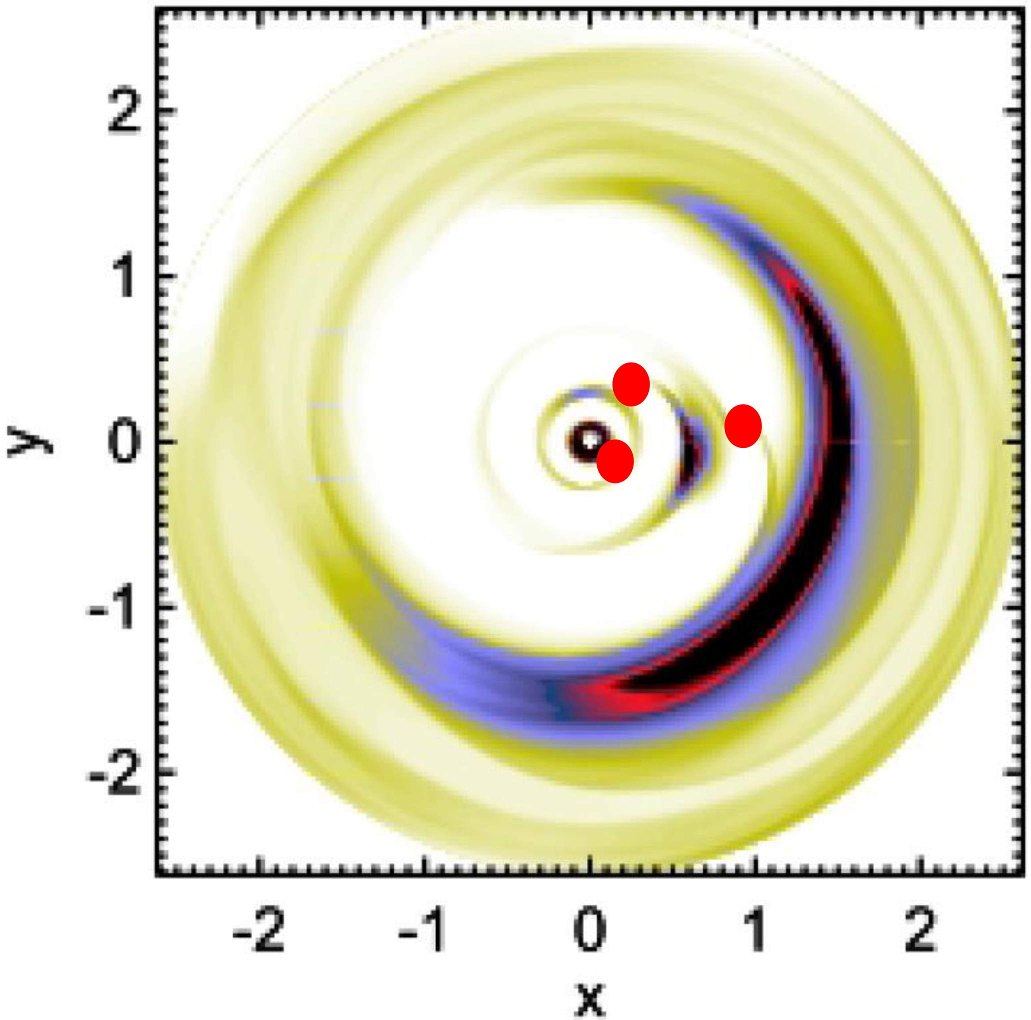


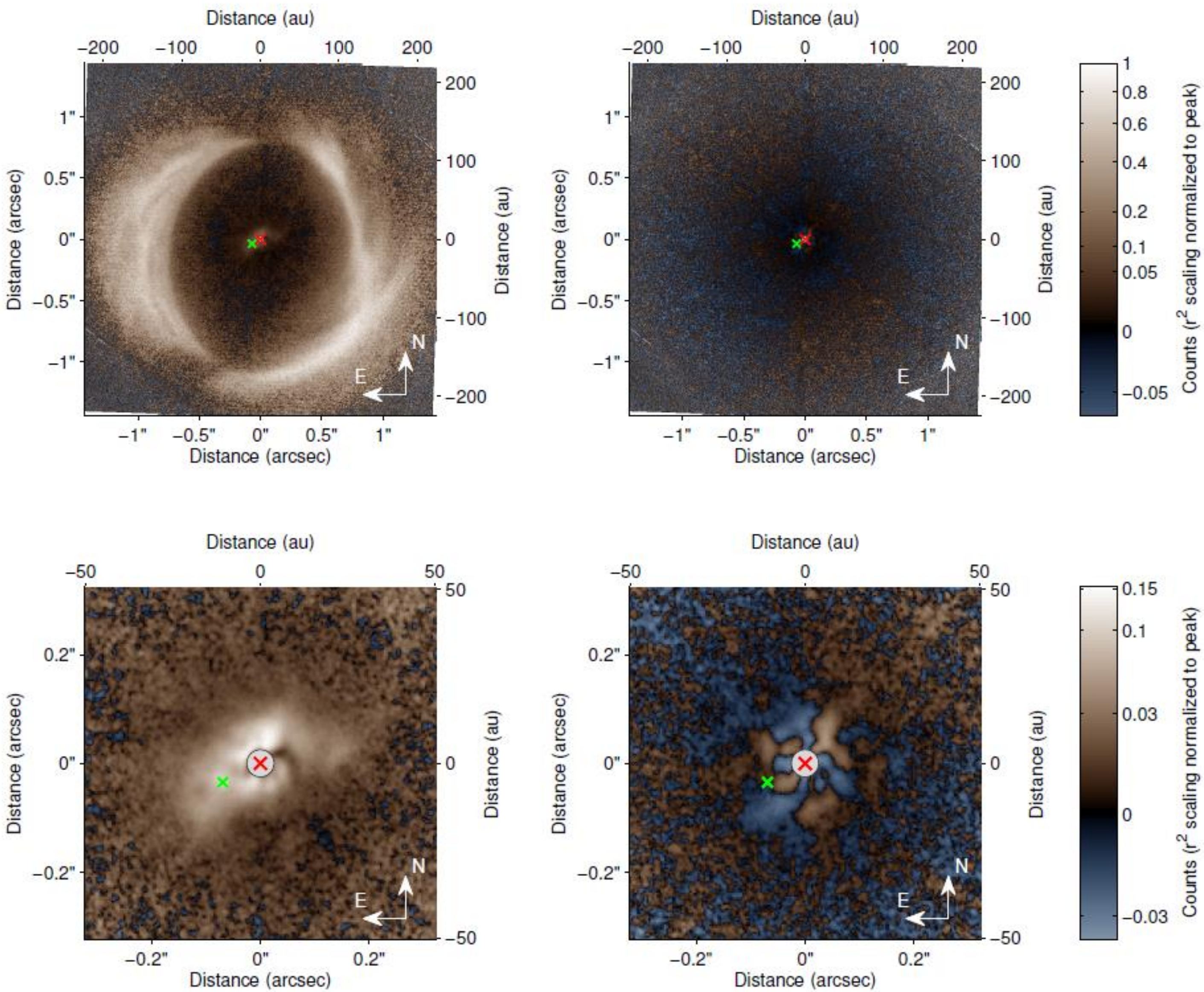
Simulations of how a multiplanet system (3 in this case) can maintain a wide gap in a transitional disk (reproduced from Dodson-Robinson & Salyk 2011).

Hα should be common accretion signature

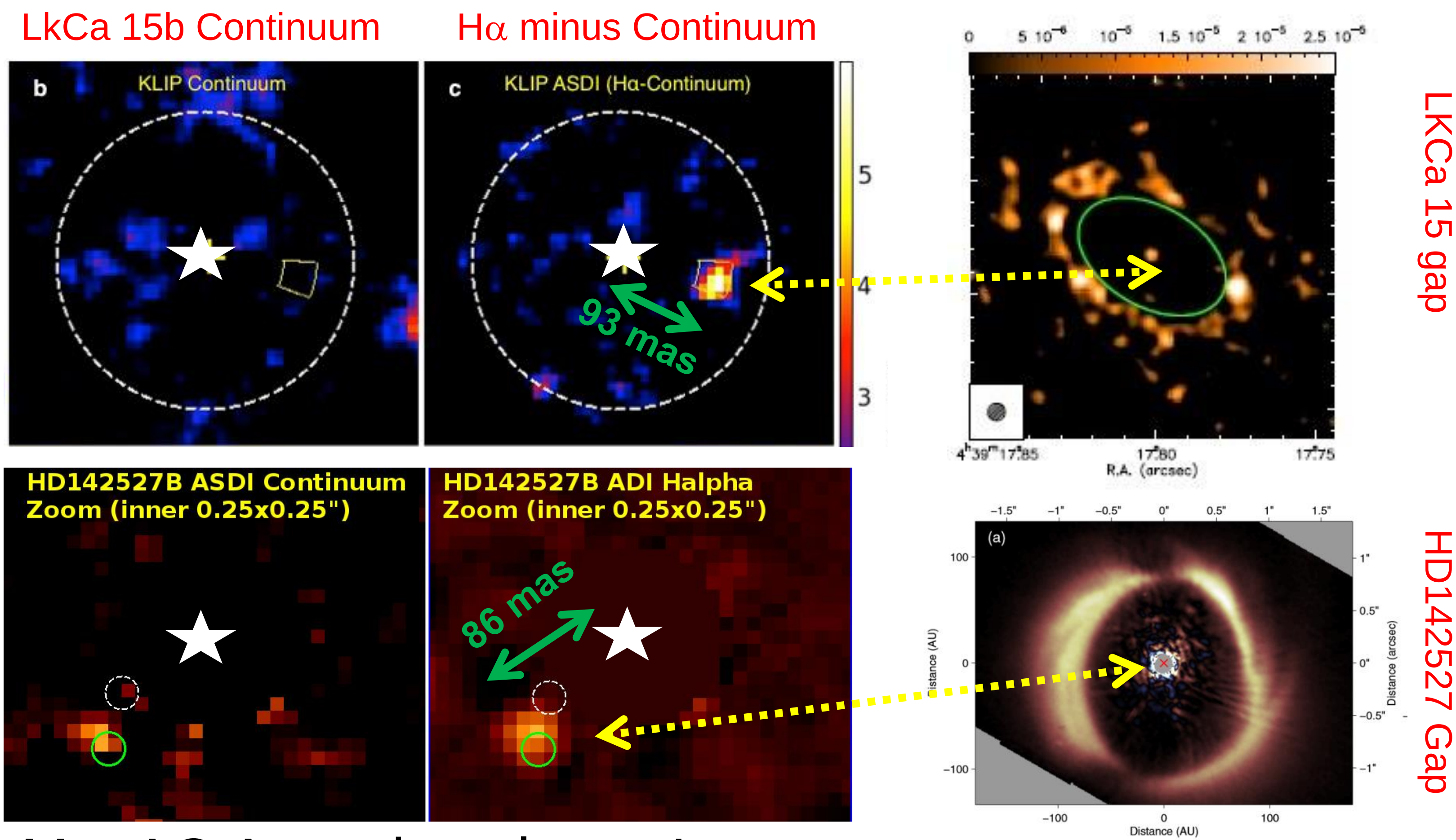
Lets take a look into these disk gaps and see if we can find any GAP Planets by looking at both Halpha and Continuum simultaneously (SDI)

MagAO

Exploring dust around HD142527 down to 0.025″/ 4au using SPHERE/ZIMPOL



Avenhaus et al A&A 2017



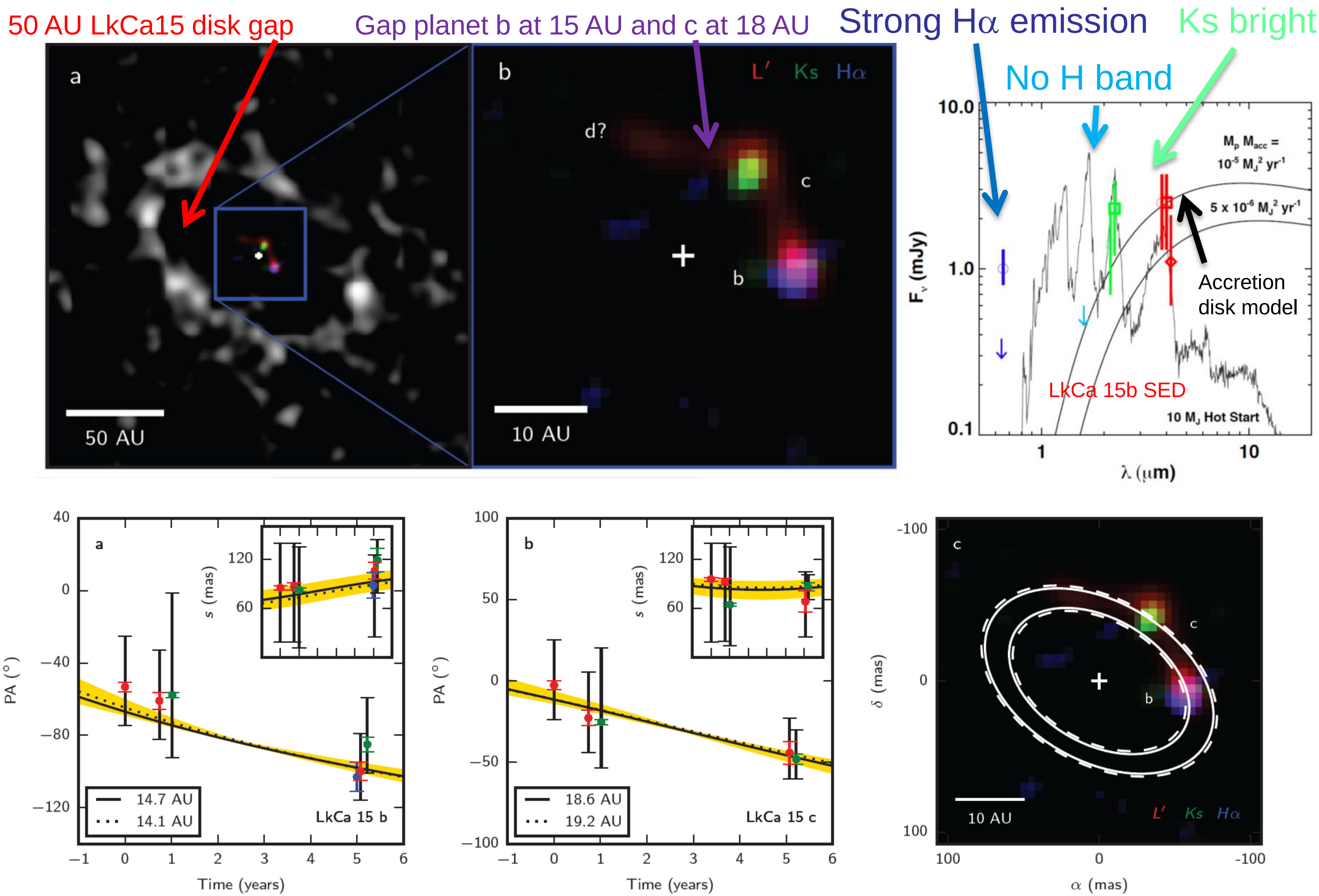
MagAO Accreting planets!

LkCa 15b Sallum et al. Nature 2015

6 sigma detection of accreting planet at just 93 mas!

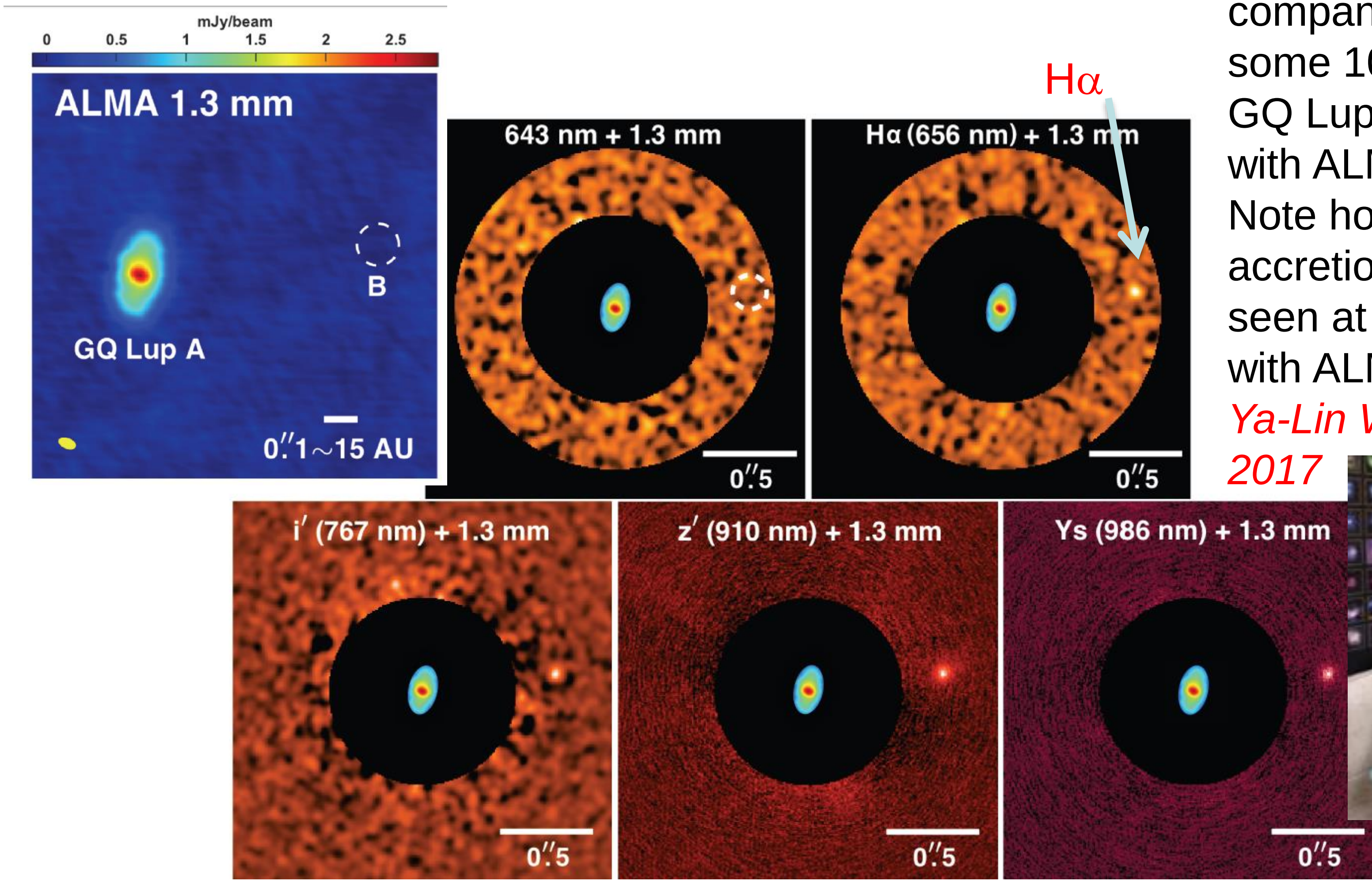
First GapPlanetS result: a faint Hα accreting sources inside T-Tauri Transition disks*– 10 sigma at just 83 mas (14 AU).*

Close et al. 2014 ApJ Lett 781 30

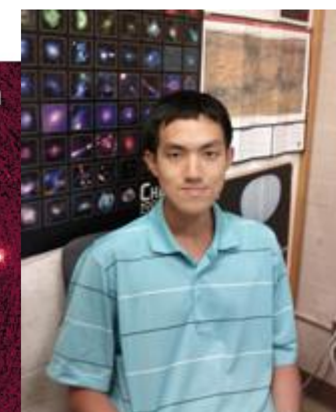


Sallum et al. 2015 Nature

Hα is also a better tracer of low-mass companion accretion disks then Alma?

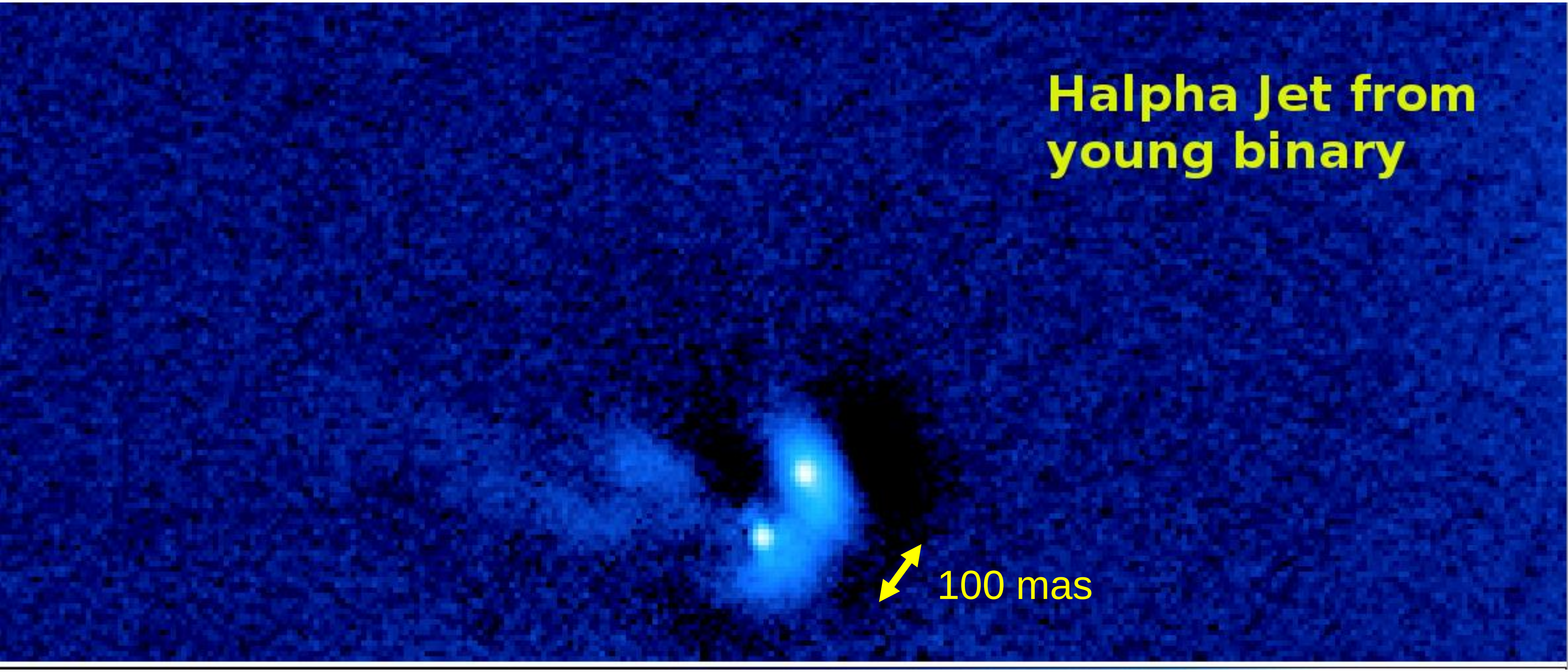


Here we see the low mass (~1myr old) companion GQ Lup B some 100 AU from GQ Lup A (show here with ALMA dust disk). Note how the accretion on B is seen at Ha but not with ALMA in the mm. *Ya-Lin Wu et al. ApJ 2017*



MagAO

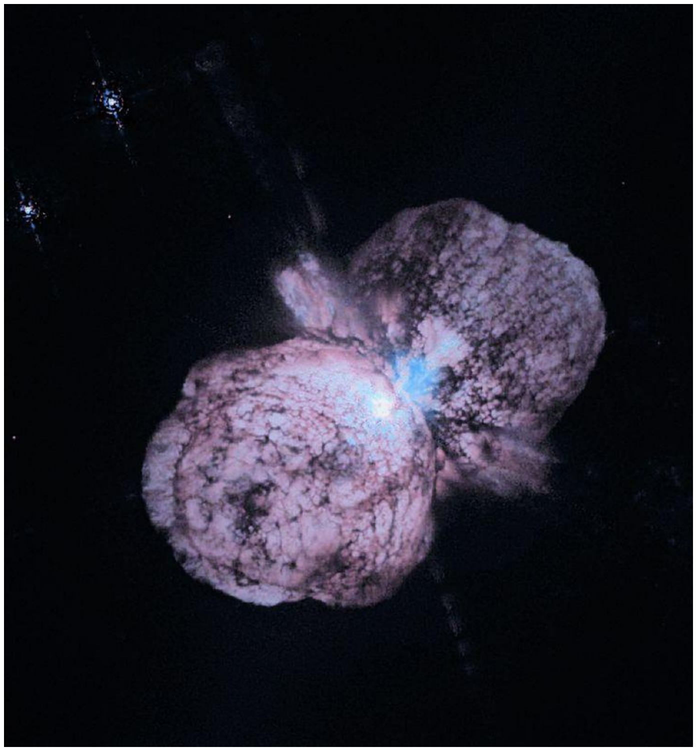
MagAO Halpha Jets



- Halpha Jets in 5 min. on a faint binary

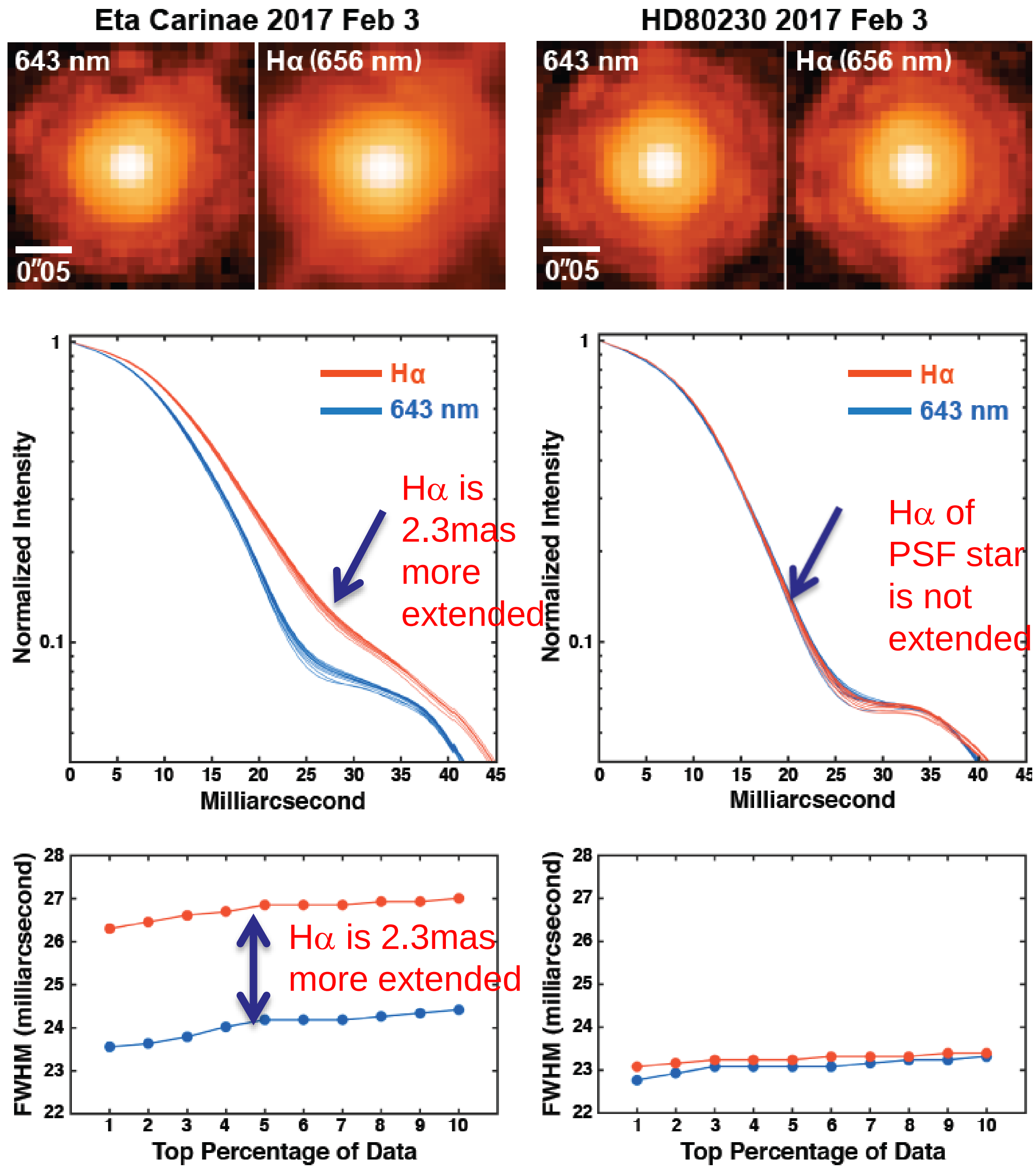
Wu et al. 2017 in prep

MagAO Resolution of 12 mas (30AU) Stellar Wind at Hα

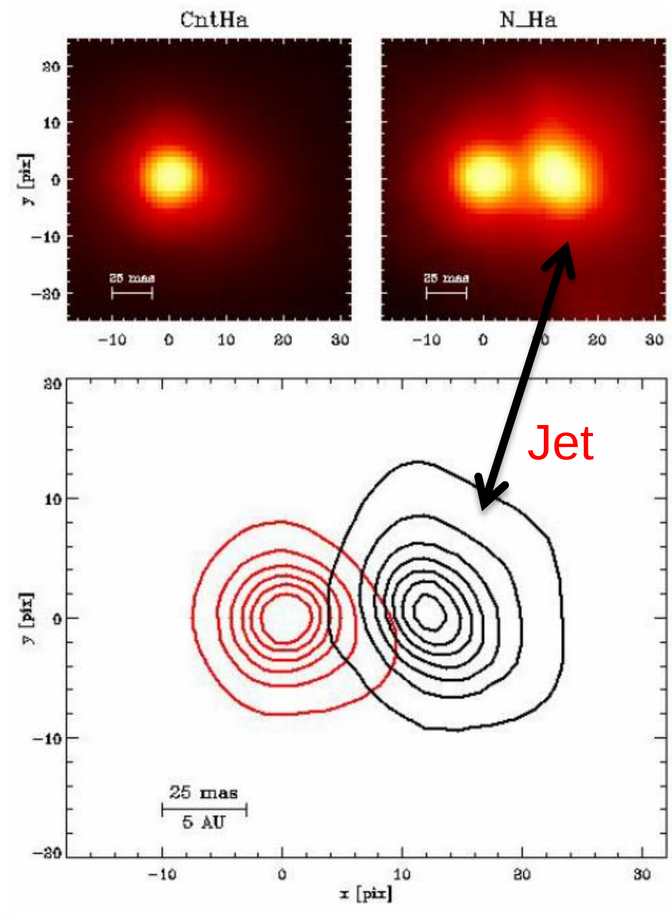


Eta Car by HST

Wu et al. ApJ 2017



Zimpol Can Image at Hα too: R Aqr



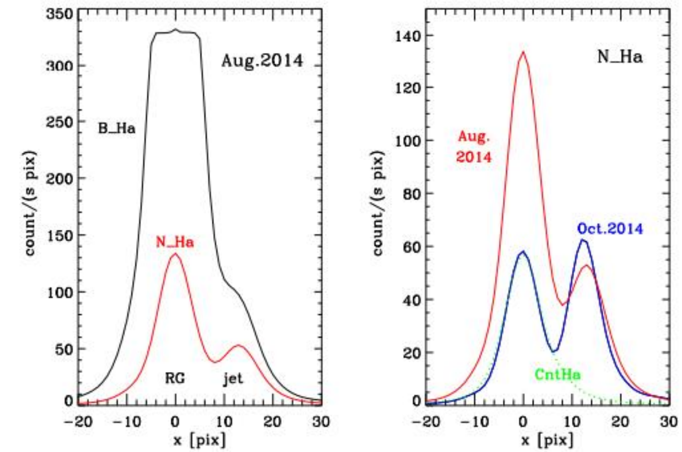


Fig. 5. East-west cuts through the R Aqr binary system for different Hα filter observations taken in imaging mode. *Left*: B_Ha and N_Ha profiles from August 12, 2014, showing the much reduced continuum throughput in N_Ha (the peak of B_Ha is strongly saturated); *right*: N_Ha profiles for August 12, 2014 and October 11, 2014 illustrating the brightness change of the red giant within 60 days. The dotted green curve shows the scaled red giant profile as seen in the CntHa filter (slow pol. mode) from October 11.

mira variable for our ZIMPOL filter observation which are useful for the absolute Hα line fluxes of the jet clouds, the determination of upper flux limits for the hot companion, and for estimates of the flux contribution of the mira star to the HST line filter images. Photometric magnitudes are obtained by summing up all counts "ct_{1M}" registered in the 10^6 pixels area $[x_1{:}x_2, y_1{:}y_2]$ = [13:1012, 13:1012] of the 1024 × 1024 pixel detector. This is

Schmid et al. A&A 2017

ZIMPOL at other optical emission lines: Z Cma

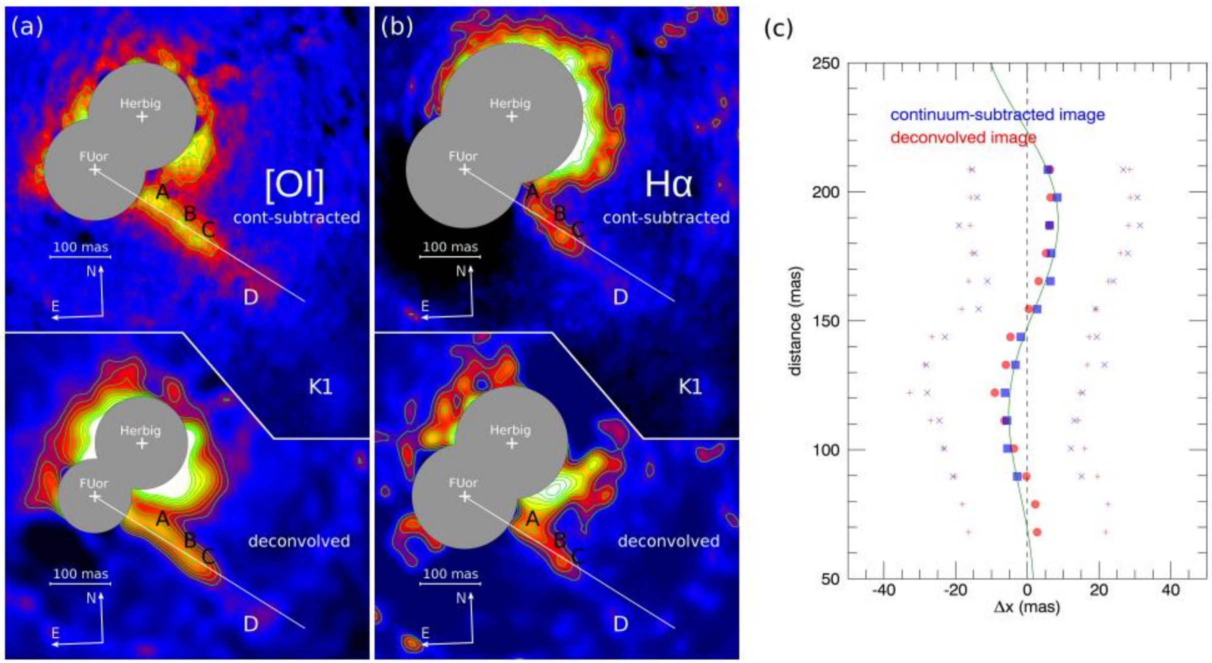


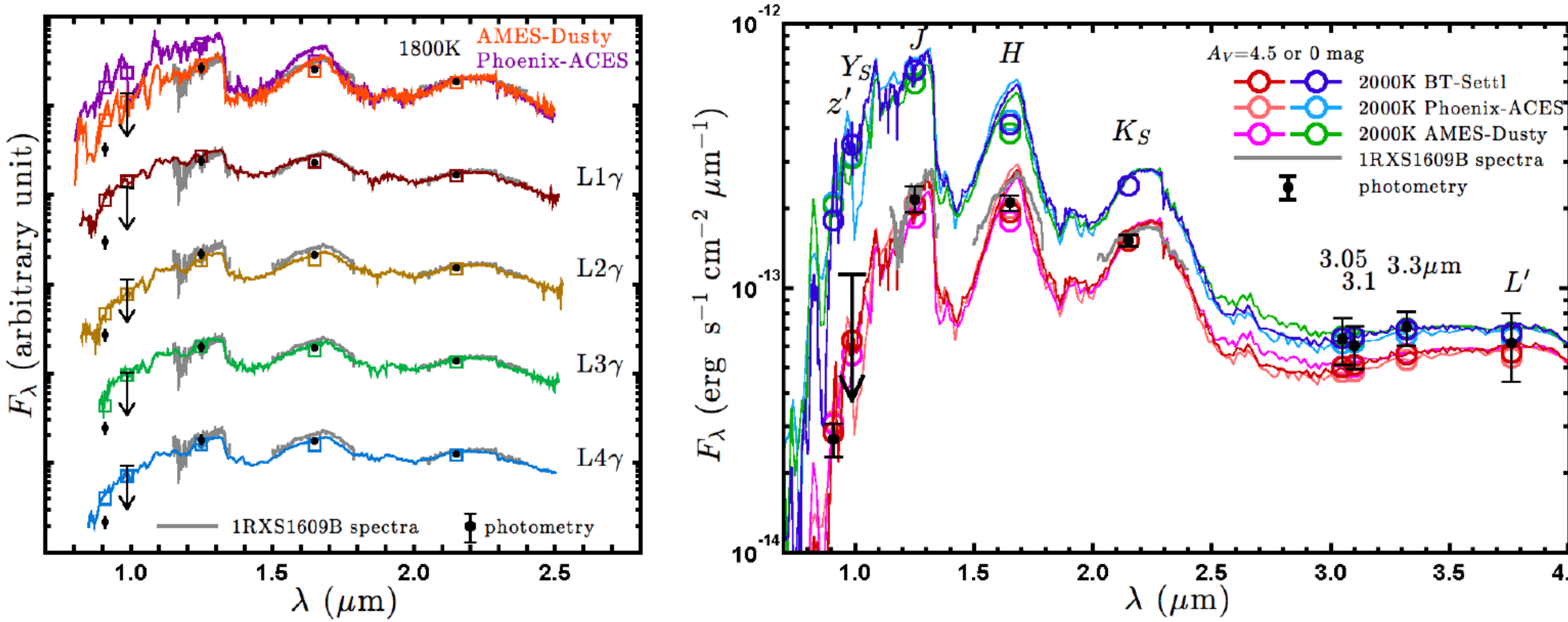
Fig. 1. **(a)**: Continuum-subtracted (top) and deconvolved (bottom) [O I] images of the Z CMa system. The deconvolved image shows only the diffuse emission as reconstructed by the MC-RL algorithm. The centroids of the two stars and the position of the main knots of the FUor jet are indicated. Areas heavily corrupted by artefacts around the star centroids have been masked. **(b)**: Same for the Hα observations. **(c)**: Fitted transverse positions of the peak of the FUor jet spatial profile as a function of the distance from the exciting source for both the [O I] continuum-subtracted (blue squares) and deconvolved images (red circles). Blue crosses and red pluses indicate the measured profile width of the two images. The solid green line is the best fit of the wiggle produced by an orbital motion of the jet source around a companion (Anglada et al. 2007) to the peaks of the continuum-subtracted image.

Antoniucci et al. A&A 2016

Visible Exoplanet Science with MagAO – examples that could also be done with ELTs in the future!

We Can Use Visible AO to probe the extinction towards Planetary Mass Companions: Example 1RXS 1609 b

NEW EXTINCTION AND MASS ESTIMATES OF 1RXS1609 B WITH MAGAO



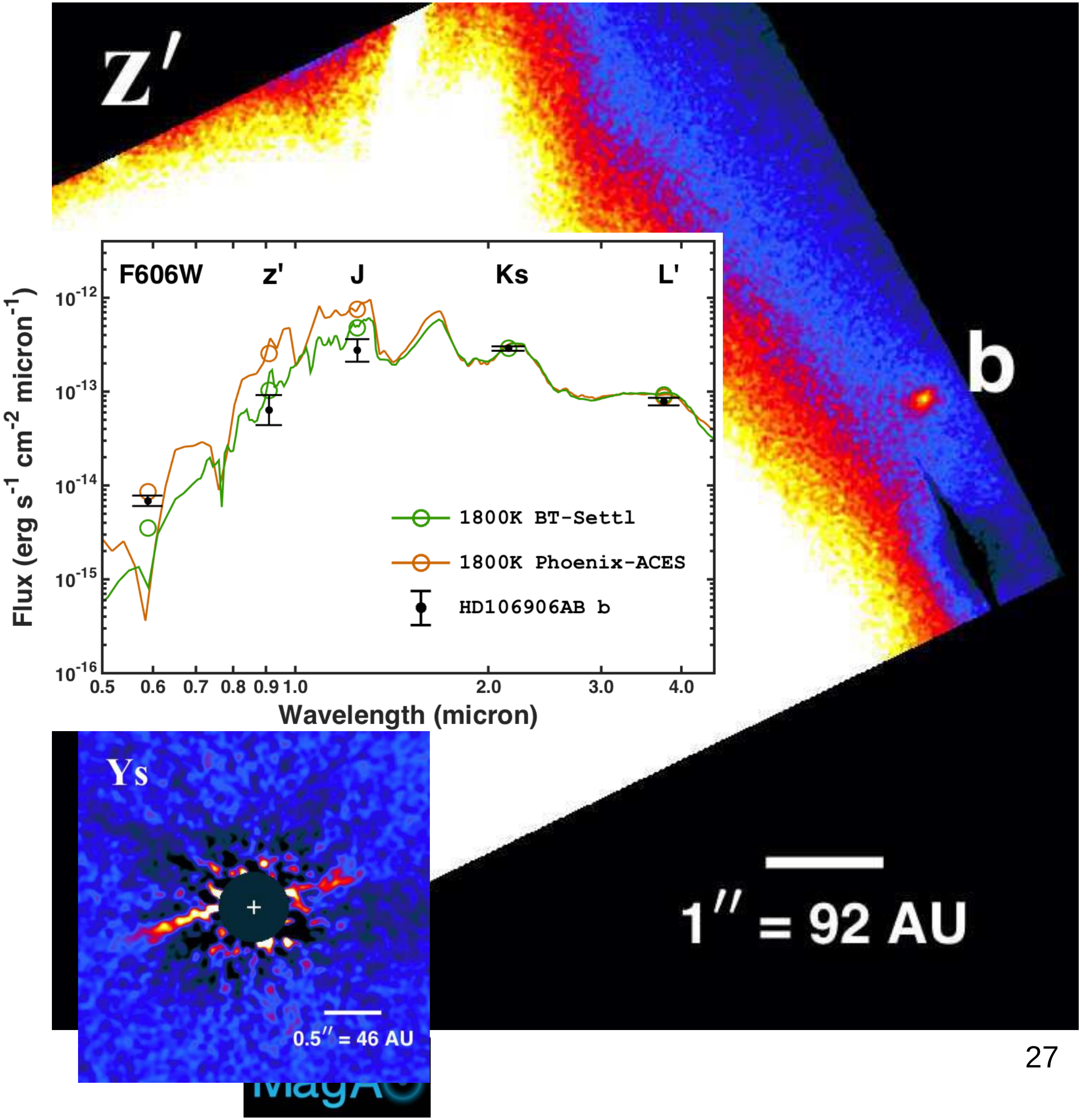
For 1RXS 1609b we find a Av~4.5 mag, Mass 12-15 Jupiters and its own disk, so a BD formed by frag. at ~320 AU proj. sep.

MagAO

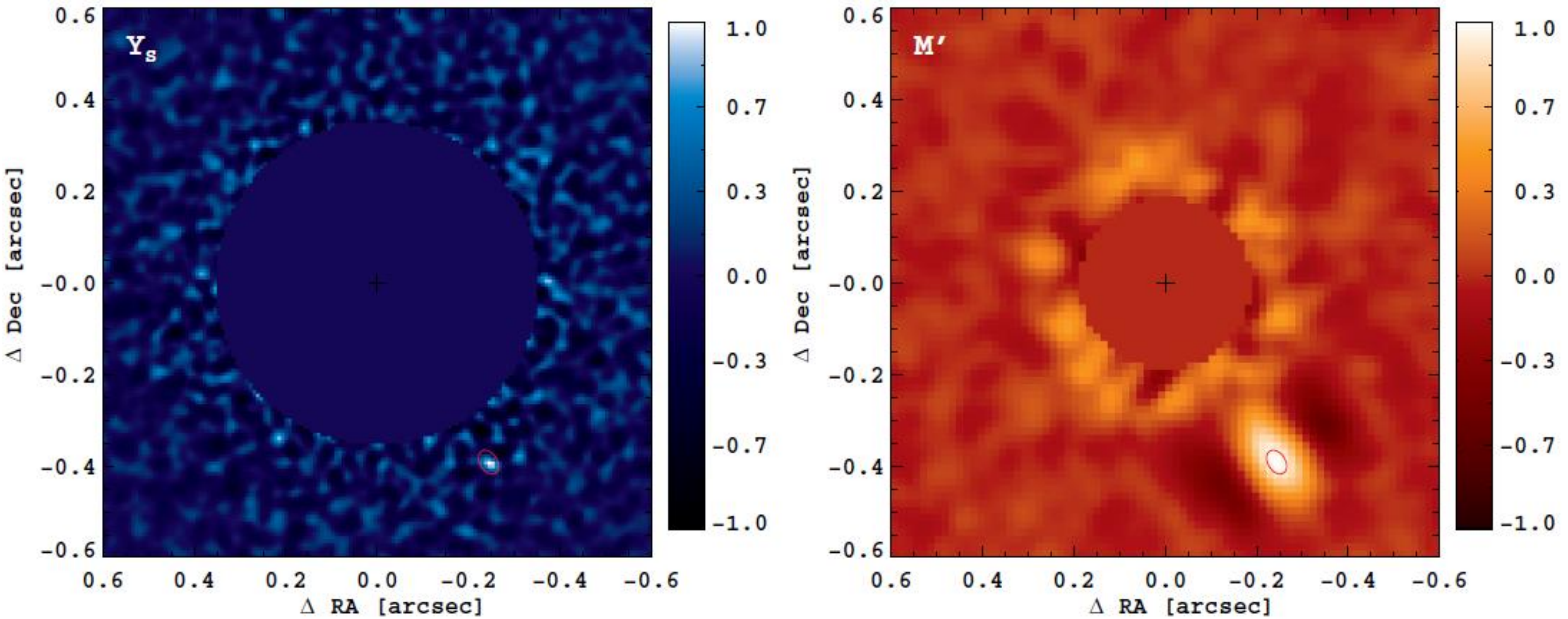
Wu et al. ApJ Lett 2015

We Can Use Visible AO to probe the extinction towards Planetary Mass Companions : Example HD106906b

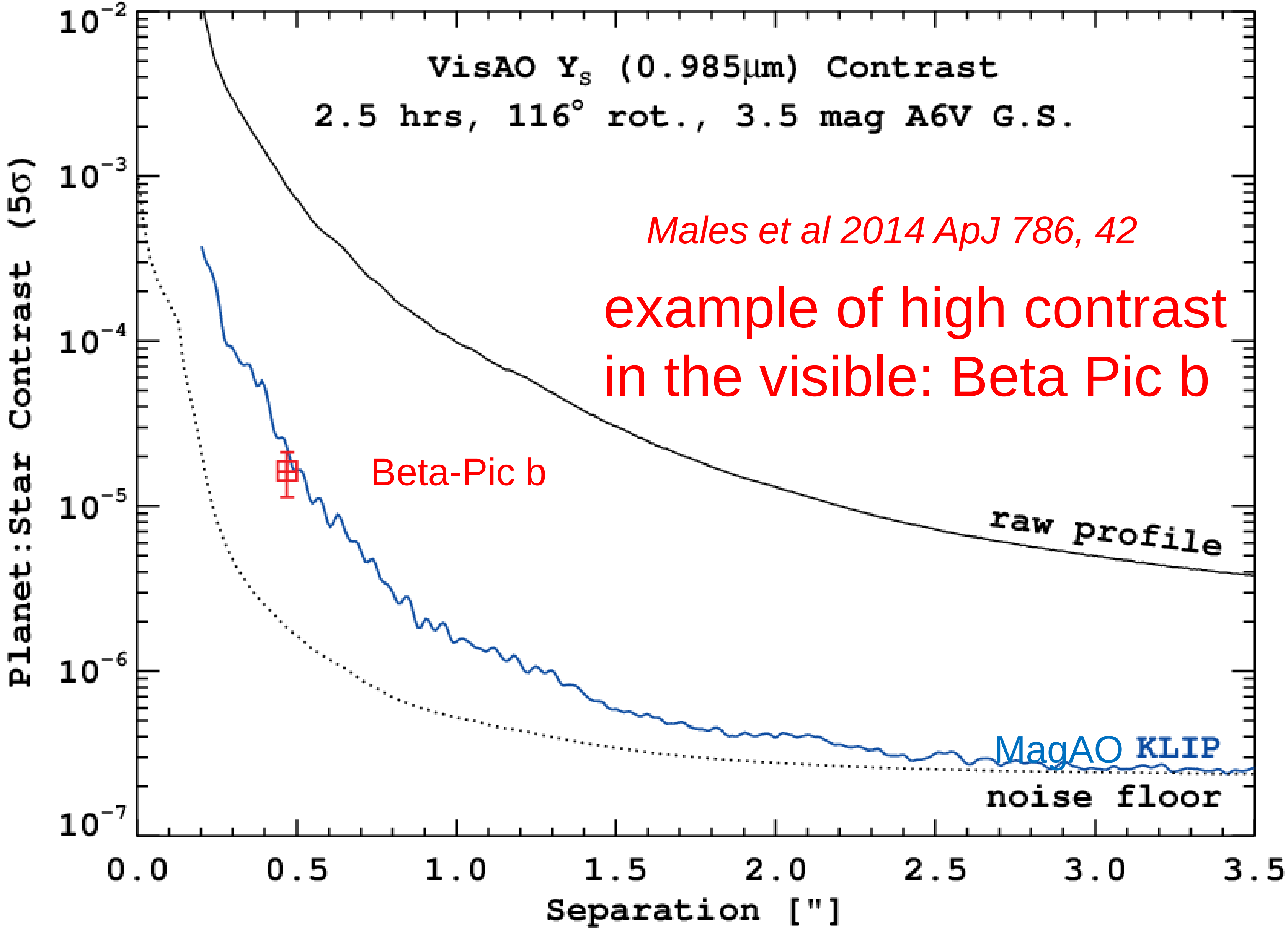
Wu et al ApJ 2016



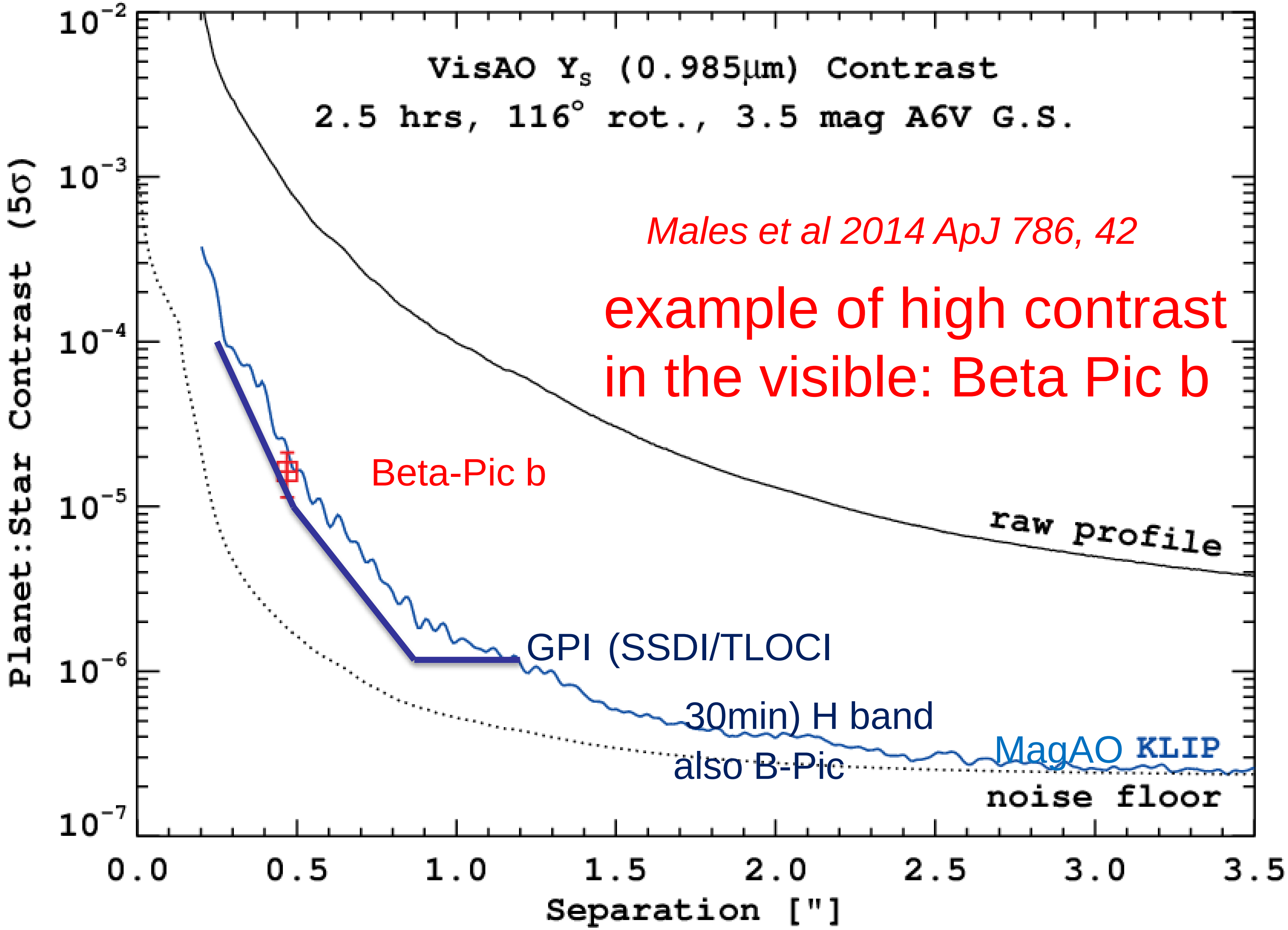
High Contrast in Visible: Beta Pic b (>100,000x fainter at 0.5”) can be seen at 0.98 micron in 2 hours of 6.5m time with PCA/ADI.



Beta Pic b; *Males et al. 2014 ApJ 786, 32; Morzinski et al. 2015 ApJ 815, 108 (See Katie’s talk tomorrow 3:30!)*


VisAO Y_s (0.985μm) Contrast
2.5 hrs, 116° rot., 3.5 mag A6V G.S.
Males et al 2014 ApJ 786, 42
example of high contrast
in the visible: Beta Pic b
Beta-Pic b
raw profile
MagAO KLIP
noise floor
Planet:Star Contrast (5σ)
Separation ["]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

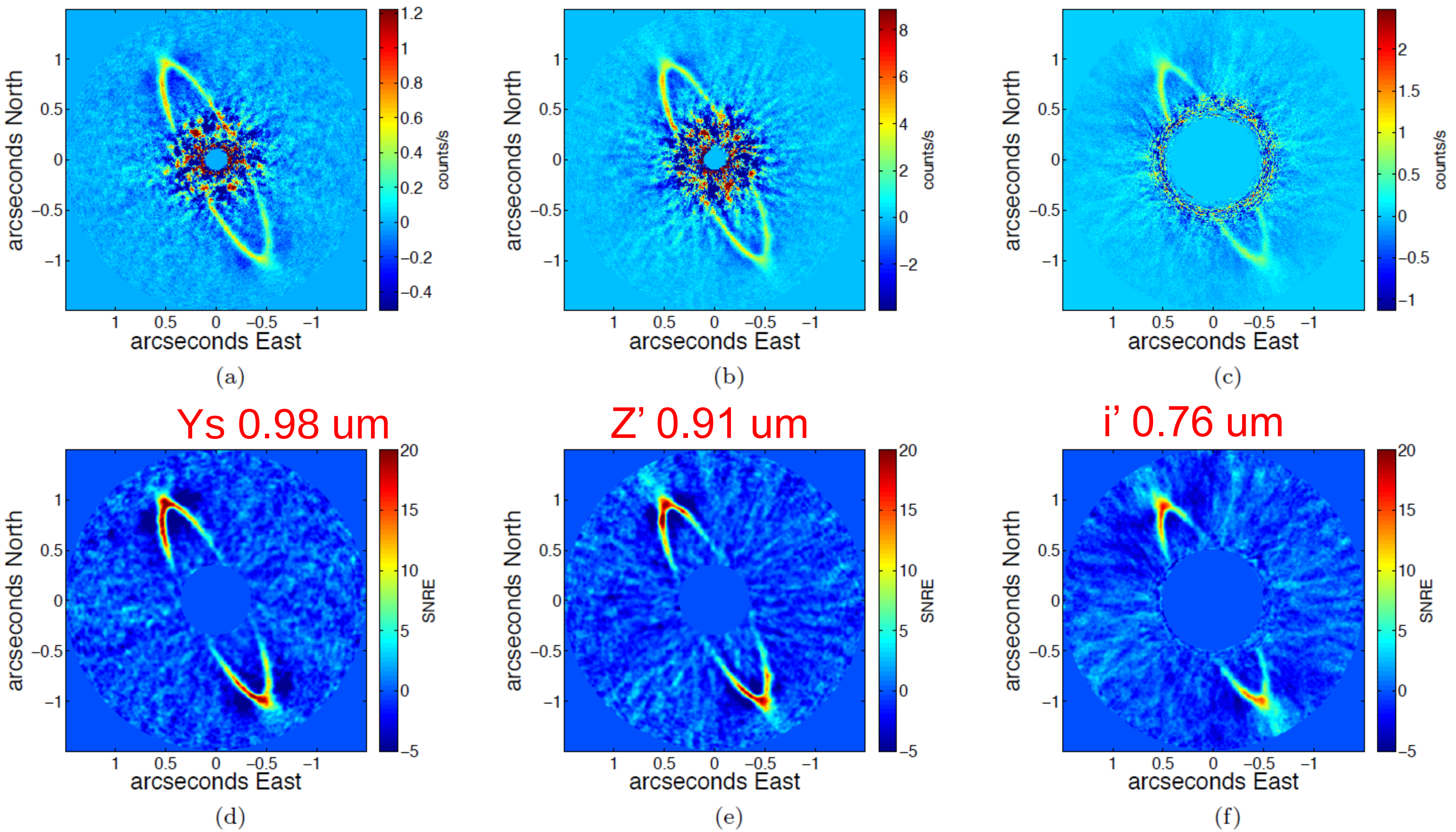
MagAO



So MagAO is Also ExAO too…

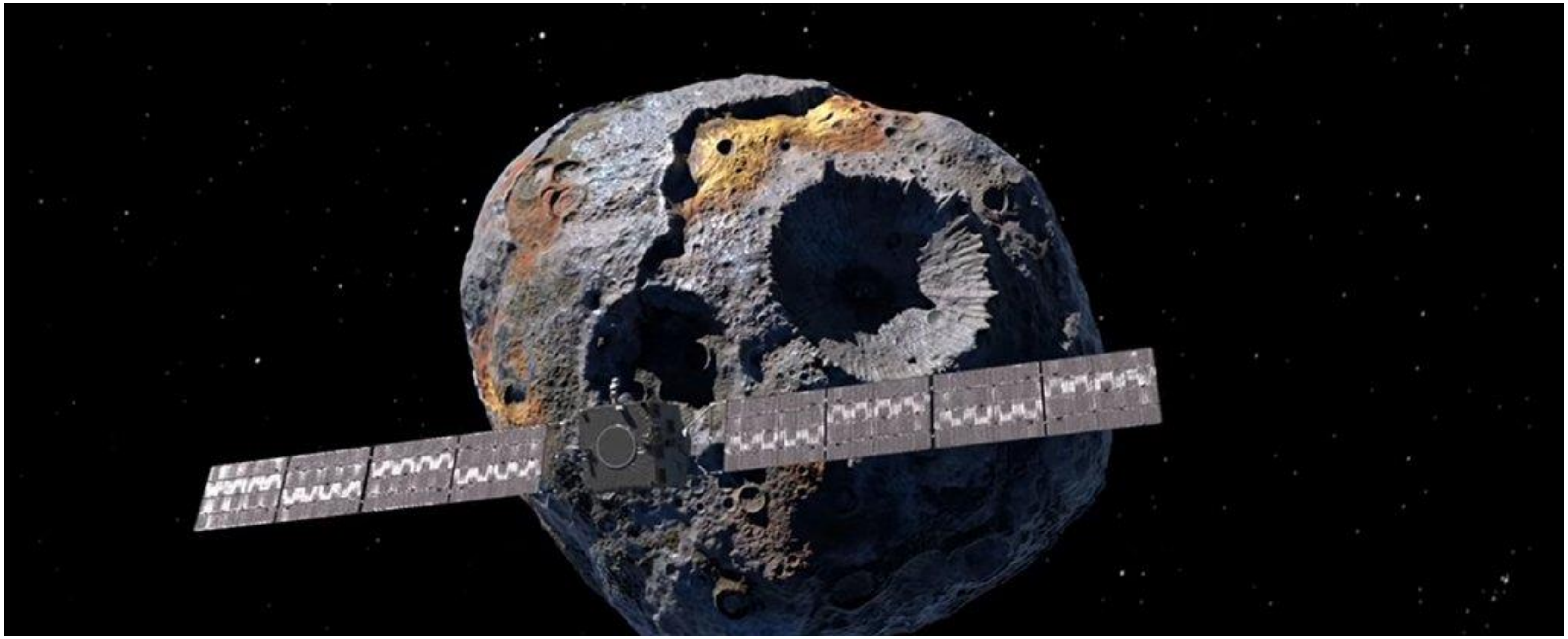
VisAO Can Also Image Debris Disks: HR4796

→ (TJ Rodigas et al. ApJ 2014)



MagAO

Debris disks are generated by grinding of plentismals –which can be imaged today as asteriods in out own solar system 16 Psyche (10 quadrillion dollars ;-)



Visible AO Science Refereed Papers with MagAO

- **Exoplanets** (Males et al. 2014; Bailey et al. 2014; Close et al. 2014; Follette et al. 2014; Biller et al. 2014; Skemer et al. 2014; Wu et al. 2014, Wu et al. 2015a, Sallum et al. 2014, Wu et al. 2015b, Nielsen et al. 2015, Rodigas et al. 2015a, Rodigas et al. 2015b, Morzinski et al. 2015, Sallum et al. 2015, Wu et al. 2016, Wu et al. 2017, Follette et al. 2017, Rameau et al. 2017, Prato et al. 2017

See Katie Morzinski's exoplanet talk tomorrow at 3:30!

- **Star Formation & disks** (Close et al. 2013; 2014, Follette et al. 2013; Wu et al. 2013; Biller et al. 2014; Rodigas et al. 2014; Rodigas et al. 2015),
- **Halpha emission jets and Knots** (Wu et al. in prep),
- **Imaging Stellar surfaces** Wu et al. 2017
- **Imaging the surfaces of asteroids** Shepard et al. 2017

Many more papers are coming out soon…

MagAO Status, June 2017

Both VisAO and Clio have been open to community for science for 3 years (over 100 science nights) → 27 ApJ papers (with more drafts submitted or in prep). Three new directly imaged extrasolar planetary systems discovered.

- **Visible AO focus of ~50% of the MagAO nights (simultaneous NIR and Visible ~70%)**
- Past funding from NSF's MRI,TSIP, ATI
- MagAO^{2K} provided 2kHz speed. Jared Males PI

Near Future: Fully funded extreme AO on Magellan: **MagAO-X** (NSF MRI, Jared Males PI) has just passed PDR technical first light 2018.

Farther Future: Adapting lessons learned from MagAO and MagAO-X to **GMagAO-X on GMT**

MagAO

For ELTs visible AO will be quite complex (particularly w.r.t. servo lag vs. sky coverage) – but big payoff if ~7mas (GMT) to ~3 mas (EELT) can be reached at ~0.7 μm.

- But total wavefront requirements no harder than NIR ExAO System requirements…
- Would enable very exciting science…

However, the visible isoplanatic patch will always be small… and the prospect of LGS VisAO on an ELT would be very challenging! So the visible science will remain "niche", yet very important, science.

For ELTs VisAO is Possible

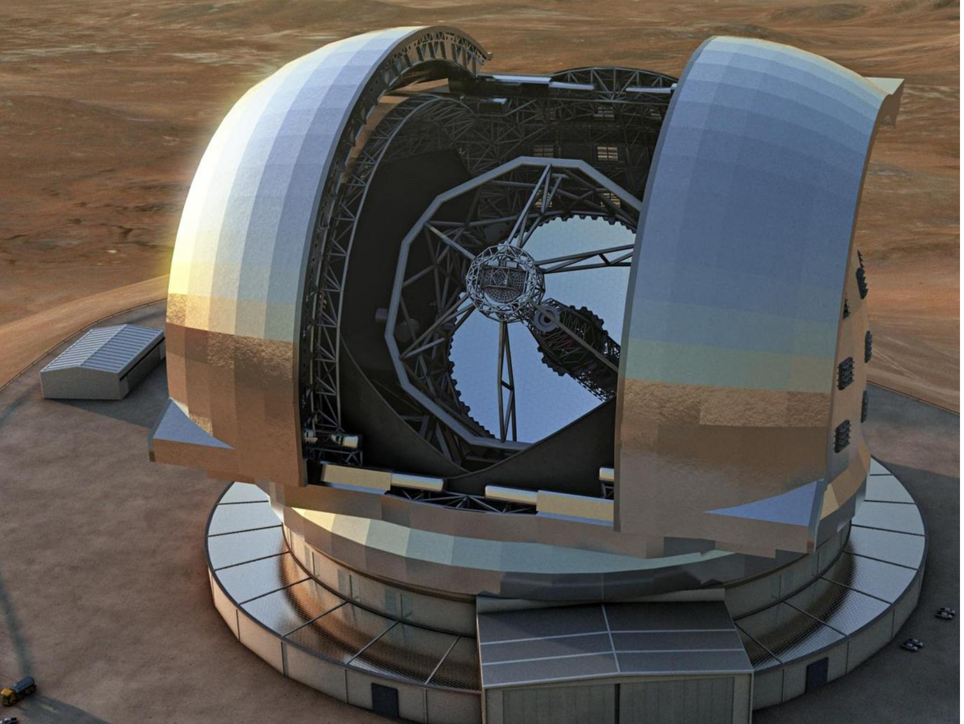
It is worth remembering that as long as D/r_o is the same then any NIR AO system designed for a 10 cm r_o can be also a VisAO system on the very best nights where r_o doubles. So if the system can produce 25% SR at J band (1.25μm) on an average 1” night --then it will work at Hα (0.65 μm) if r_o gets ~2x better on a 0.5” night.

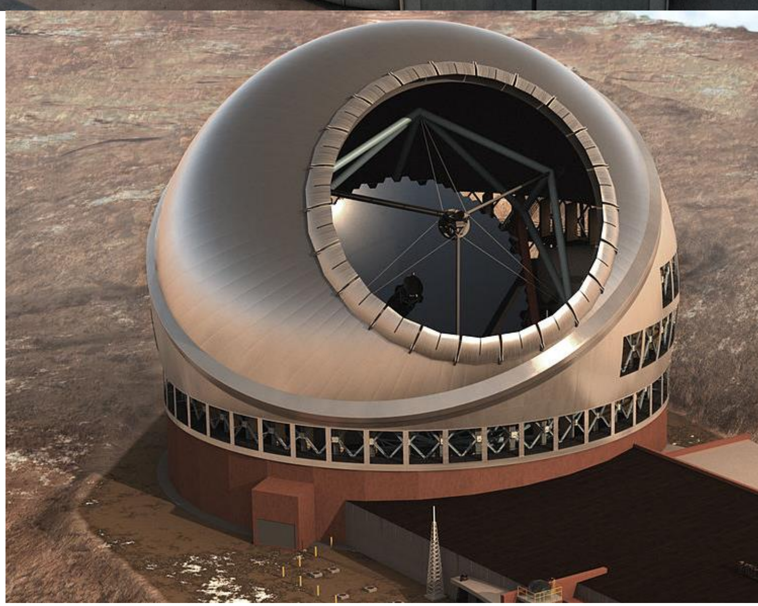
VisAO is a niche mode achievable with current ELT designs on nights where there is really good (20 cm r_o) seeing. We just have allow the possibility…

MagAO

SO HOW MANY ELTS HAVE VISIBLE AO IN A PLANED FIRST LIGHT INSTRUMENT?

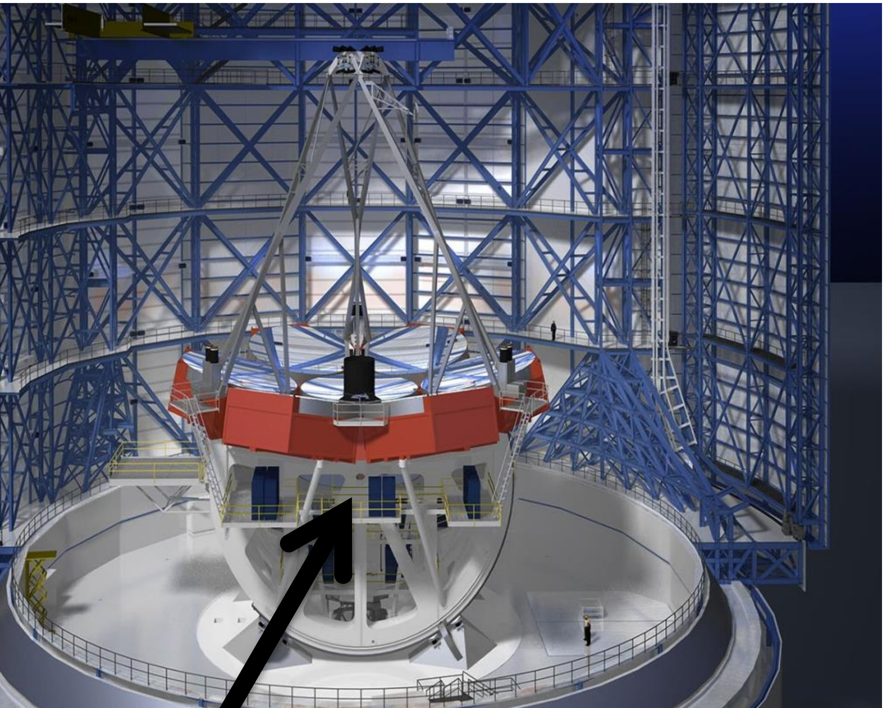
Well None, at least not yet…





For the **EELT** the 2nd gen. EPICS ExAO instrument could do certainly visible light AO if a new visible light science camera is added.

For **TMT** is possible to add a visible light science camera right at the corrected beam fed into the NGS Pyramid WFS. But it must be after the modulator and that adds some optomech complexity (a selectable beamsplitter upstream of the modulator).



GMT Elevation axis → Auxiliary Port

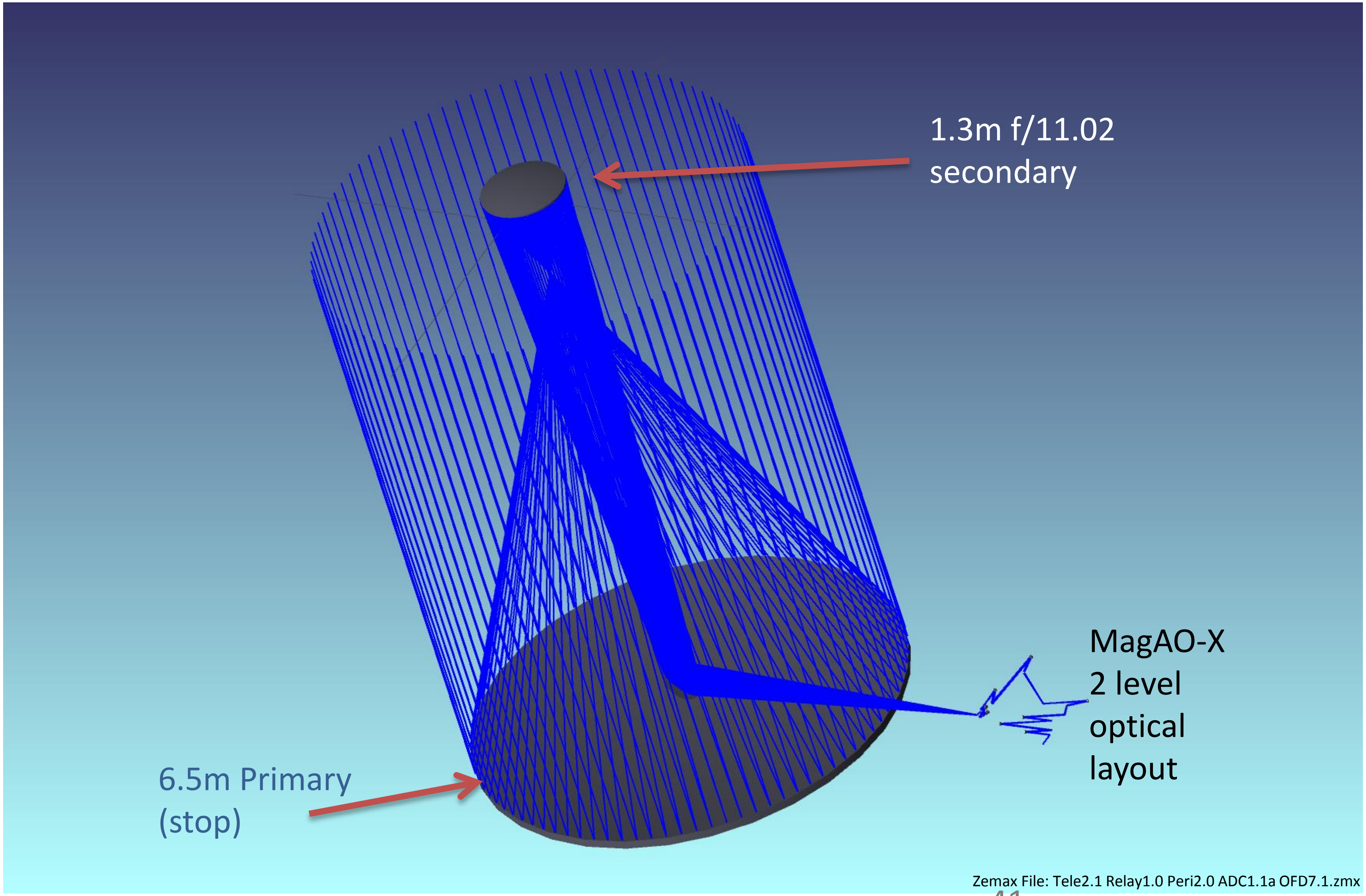
For the **GMT** it is possible to use an auxiliary port for a gravity invariant visible AO system and coronagraph. It is possible to build an ExAO coronagraph on GMT with all available DM parts (7x3000 actuators) today.

But before we can build a massive woofer tweeter XAO system on GMT we need an ExAO pathfinder! → MagAO-X !

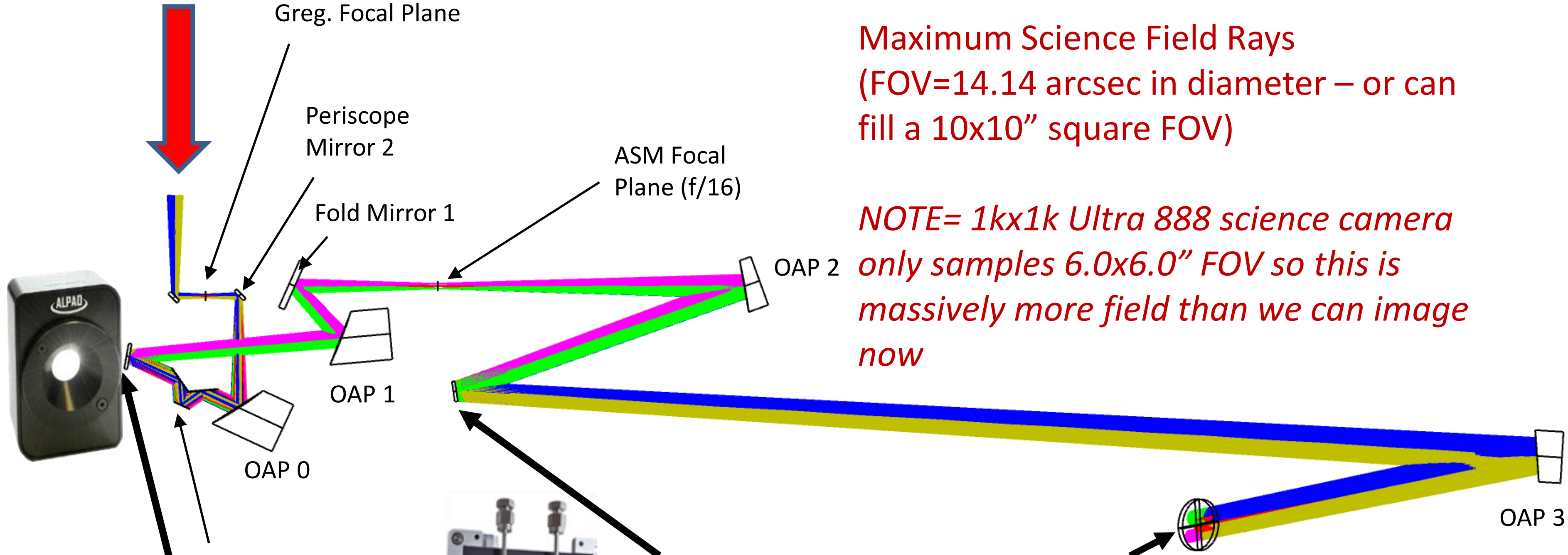
MagAO-X an extreme coronagraph for Magellan (Pathfinder for GMT visible AO)

1. Funded by NSF MRI program. **PI Jared Males, See Jared's MagAOX Poster today!**
2. 97 actuator woofer and 2000 actuator Tweeter
3. 3.3 kHz sample, PyWFS (OCAM2)
4. Targeted for 0.5-1.7 micron science
5. 80% Strehl at Halpha
6. **Contrasts of 10^{-5} @50 mas and 10^{-6}@150 mas on 5th mag star in 1 hr. median seeing**
7. Will feed SDI H-alpha science cameras
8. Can feed: MKID (PI Ben Mazin) or RHEA IFS @R=60,000 resolution (PI Mike Ireland)
9. On-sky 2018, complete by 2019-2020.

MagAO-X


1.3m f/11.02
secondary
MagAO-X
2 level
optical
layout
6.5m Primary
(stop)
Zemax File: Tele2.1 Relay1.0 Peri2.0 ADC1.1a OFD7.1.zmx

MagAO-X Optical Design (10” FOV)



Maximum Science Field Rays (FOV=14.14 arcsec in diameter – or can fill a 10x10” square FOV)

NOTE= 1kx1k Ultra 888 science camera only samples 6.0x6.0” FOV so this is massively more field than we can image now

Woofer (ALPAO DM-97 at telescope Pupil Plane (97 actuators)

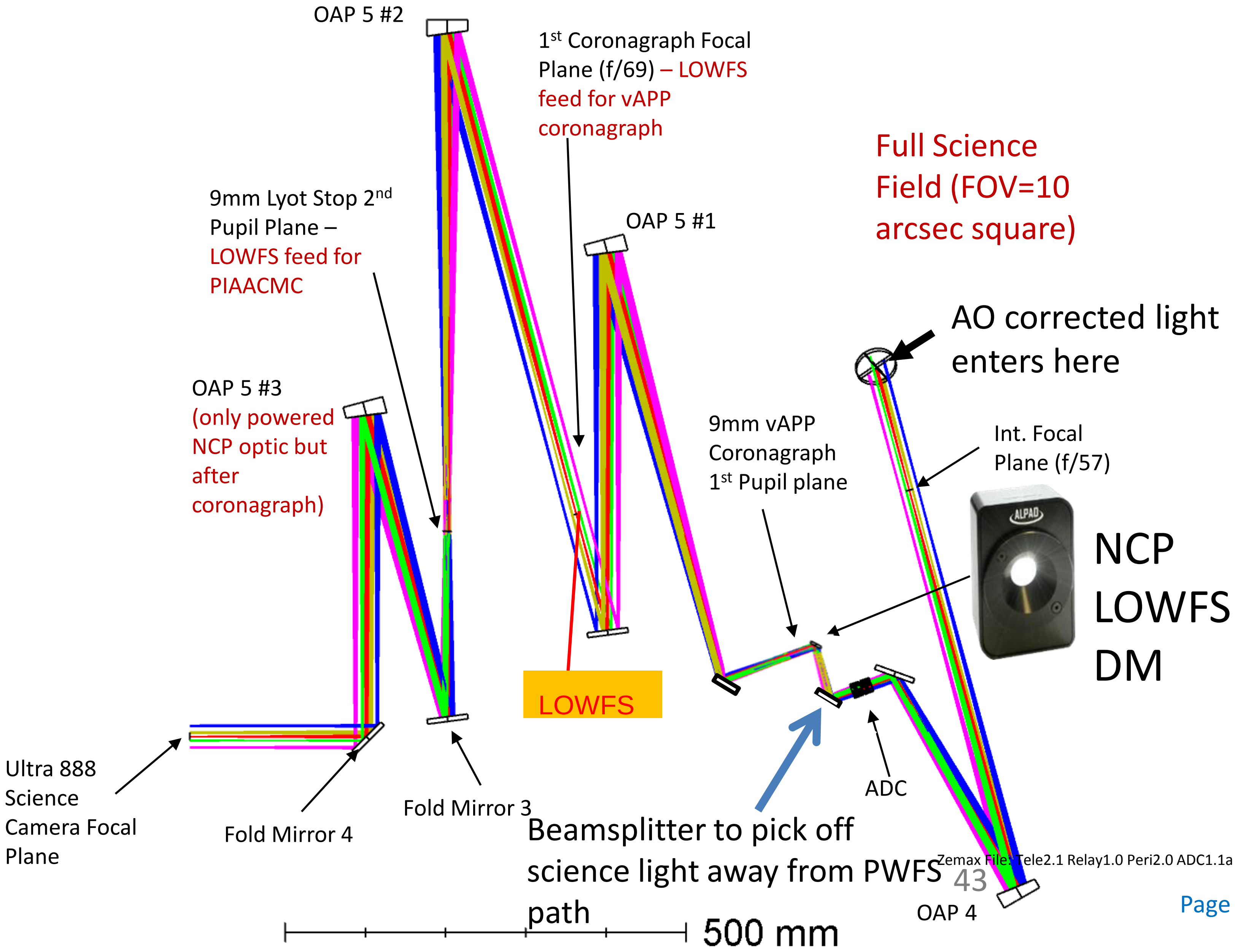
Tweeter DM Pupil Plane (BMC MEMS 2000 actuators)

Fold Mirror through breadboard to the lower table and coronagraph and PyWFS

Zemax File: Tele2.1 Relay1.0 Peri2.0 ADC1.1a OFD7.1.zmx

Doc MagAOX-001
Date: 6/9/2017
Status:Draft v. 24

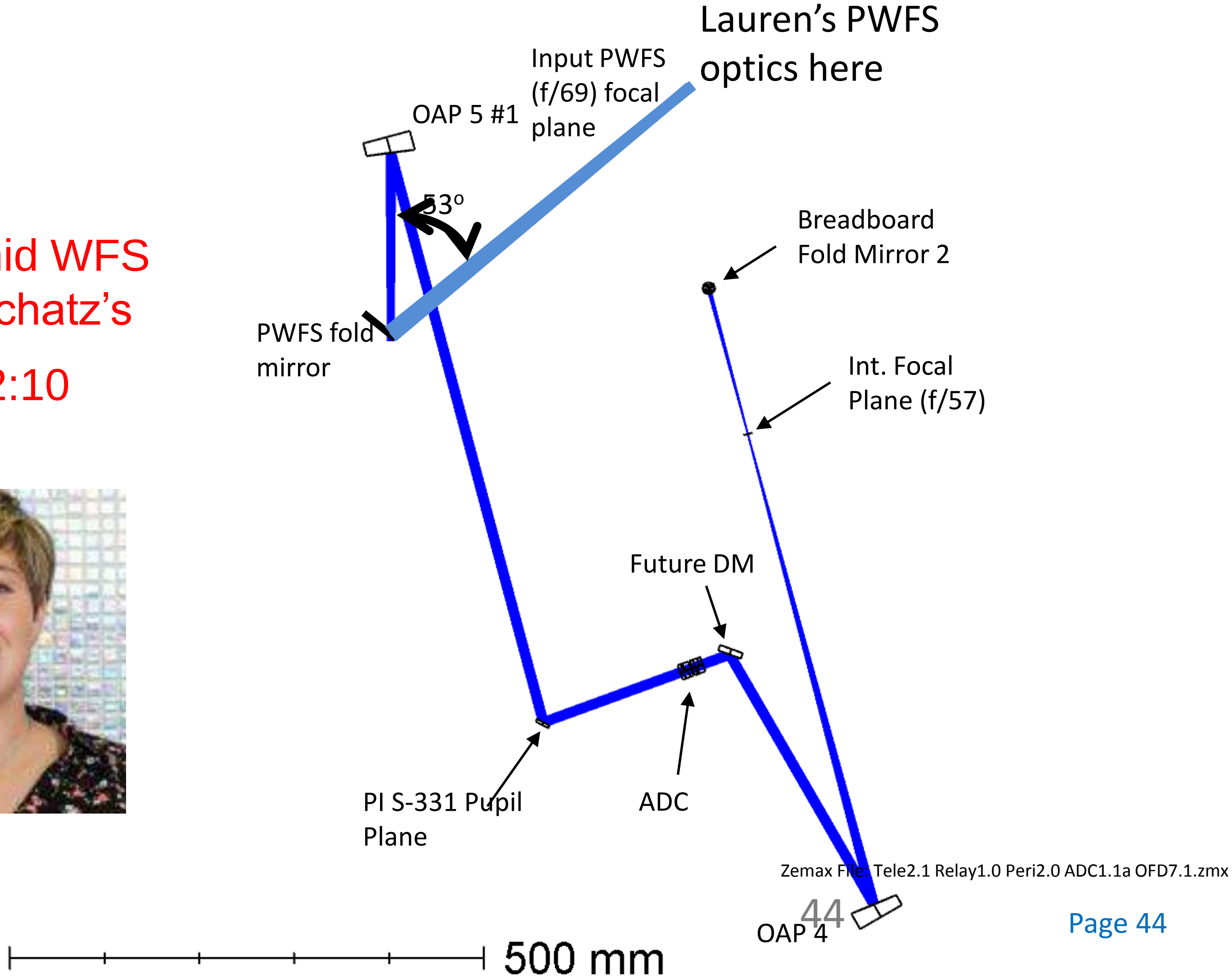
MagAO-X Science Full FOV



Zemax File: Tele2.1 Relay1.0 Peri2.0 ADC1.1a OFD7.1.zmx

MagAO-X PyWFS Feed (Very little NCP<30nm)

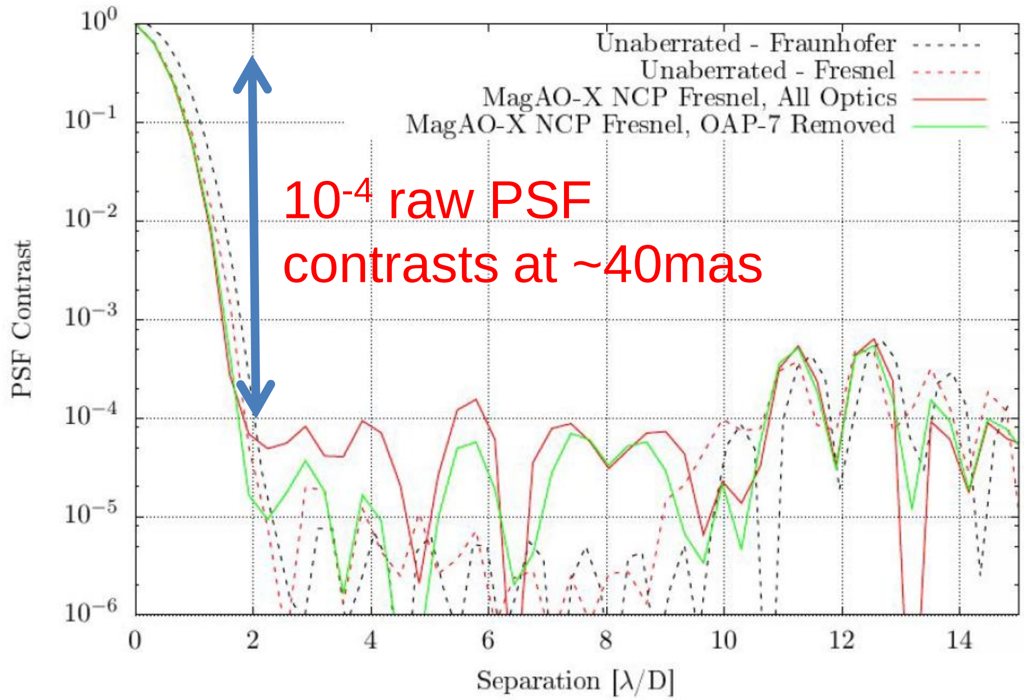
More on this pyramid WFS design in Lauren Schatz's talk on Friday at 12:10

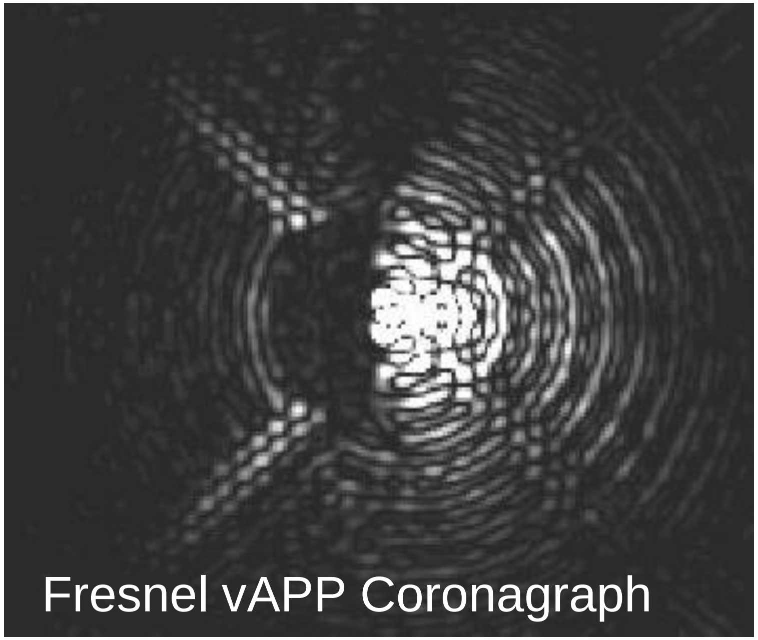


Check of the MagAO-X Optical design (no turbulence)

100% SR on-axis and 99.3% Strehl 1.4” off-axis with ADC at 40^o elevation For λ=0.6 – 0.9 μm.

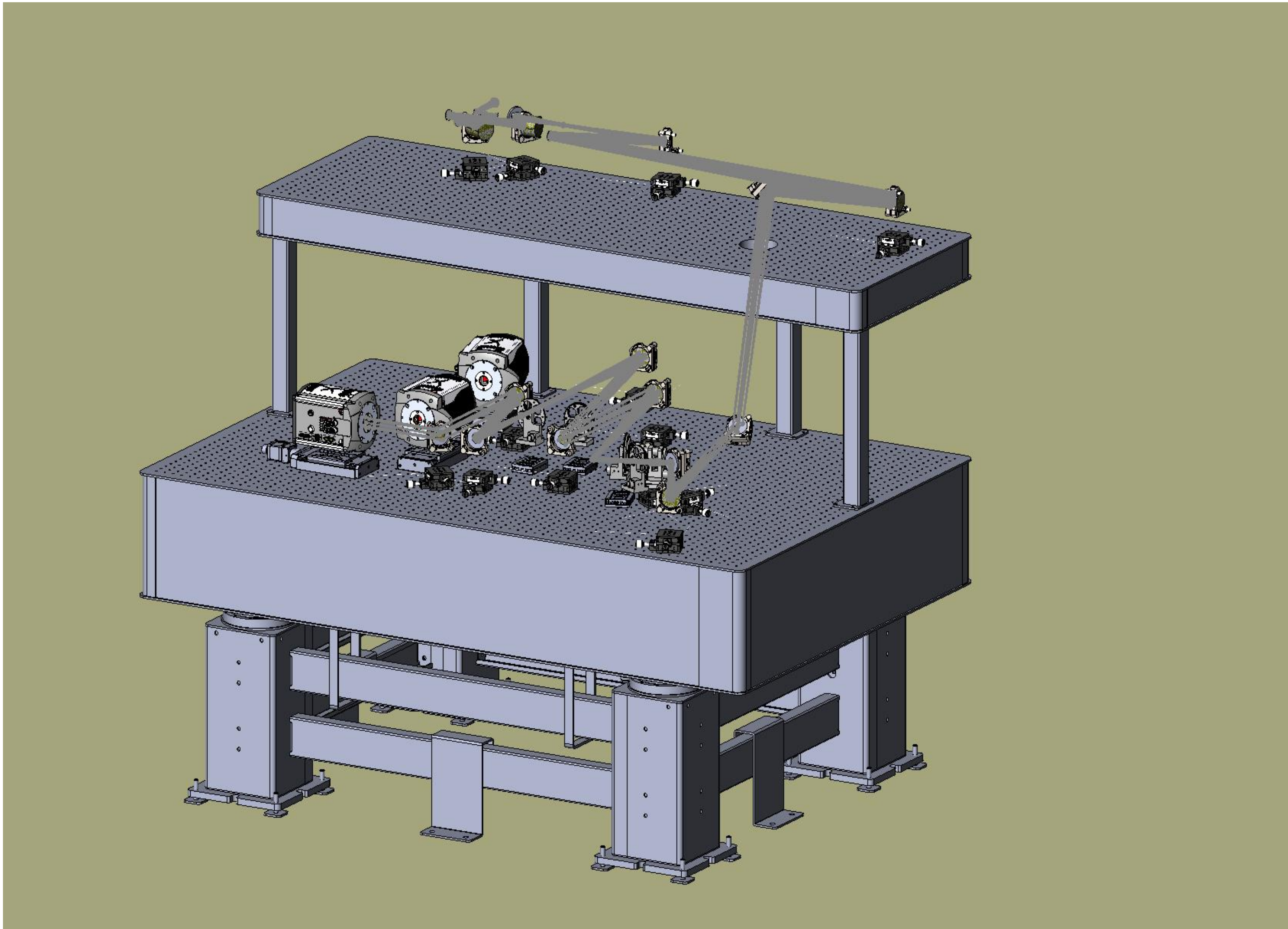
vAPP Performance for v9.5





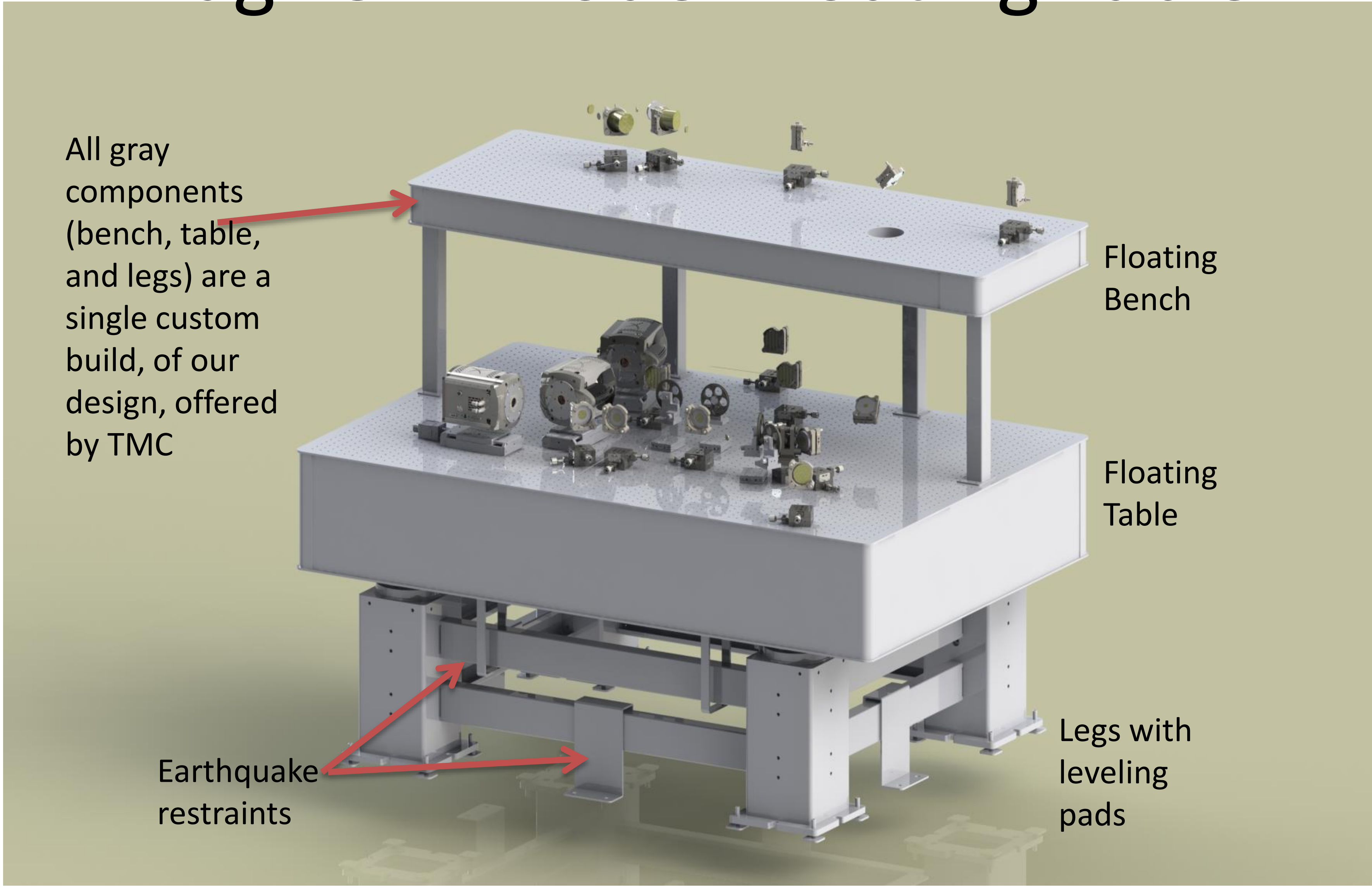
Fresnel propagation by Jennifier (Jhen) Lumbres

MagAO-X OptoMech Layout

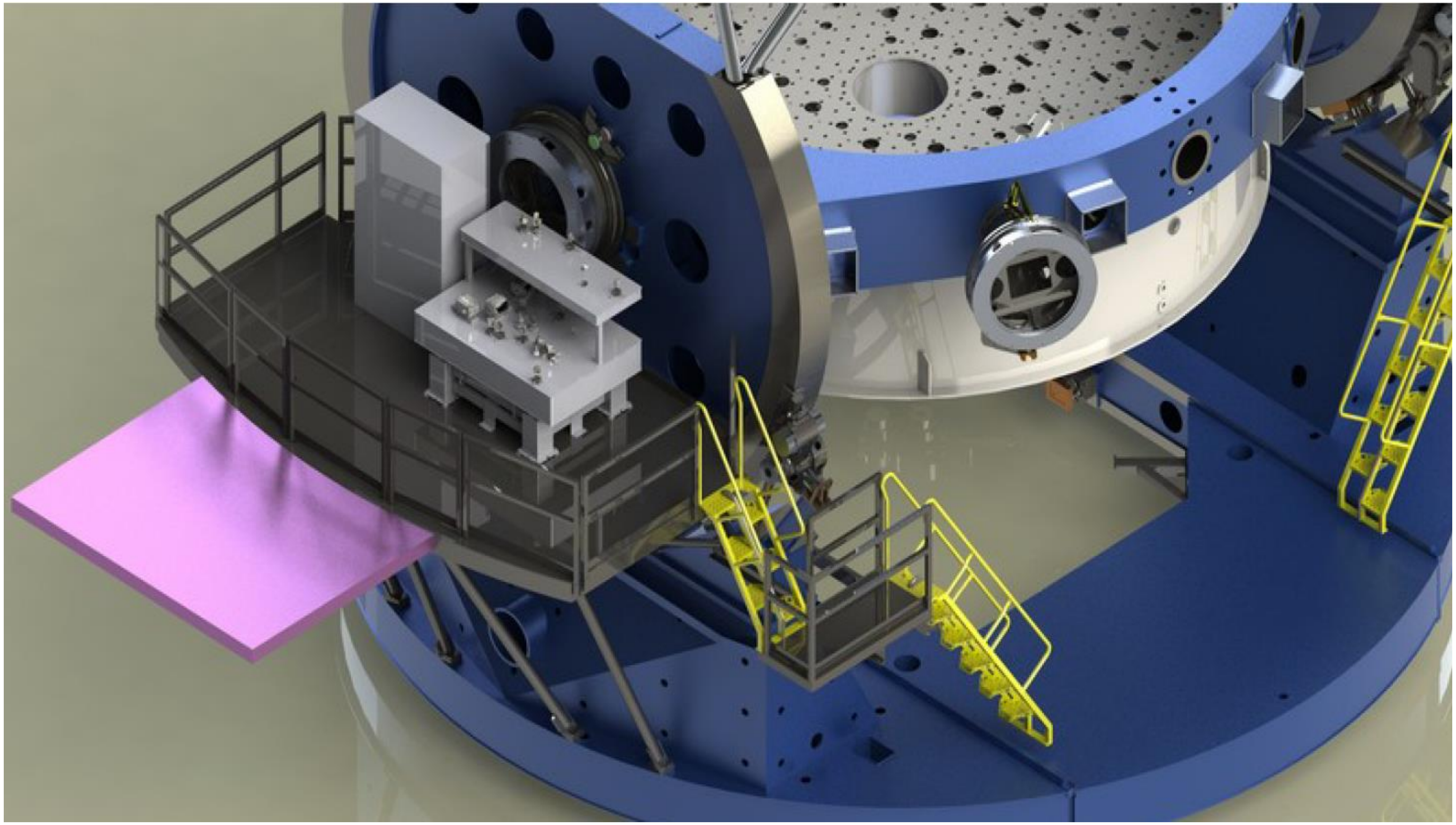


Doc MagAOX-001
Date: 6/9/2017
Status:Draft v. 24

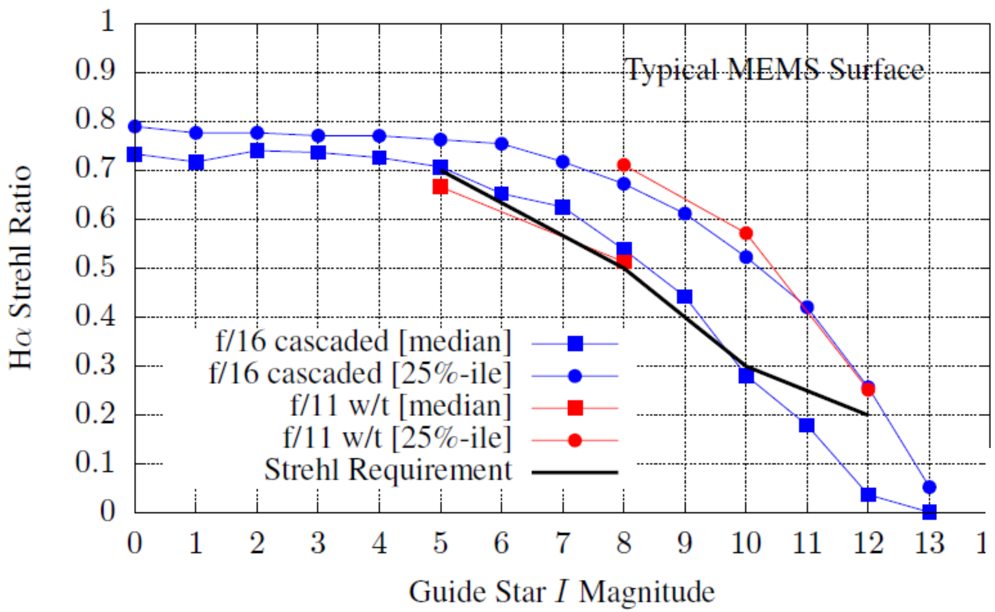
MagAO-X Model Floating Table



MagAO-X Model at Magellan

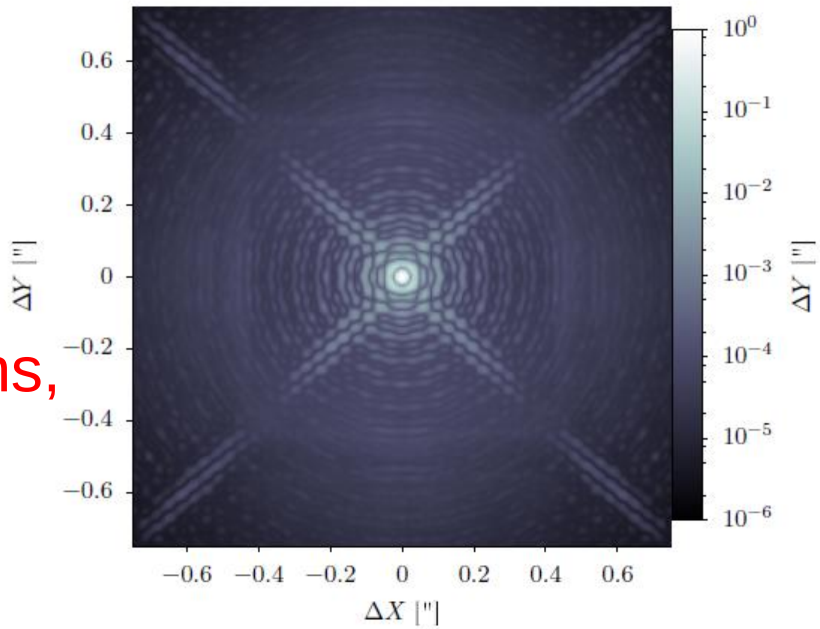


How Well Will MagAO-X's AO Work On Sky?



End to end 80 element **woofer** 1700 actuators **tweeter** at up to 3.5 kHz update (with OCAM2 as **Pyramid WFS**) closed loop AO simulations by Jared Males *(see his poster for more info)*

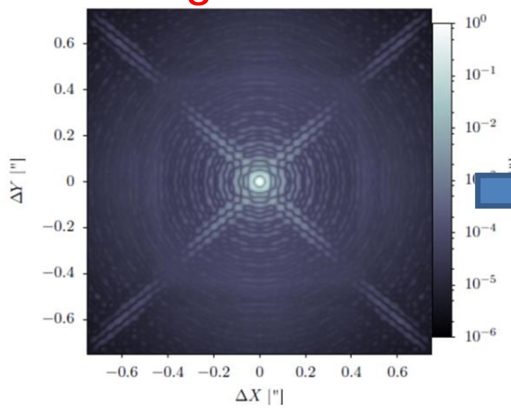
70% Strehl at Hα
8th mag guide star with turbulence (25%-ile conditions, 0.5" seeing)



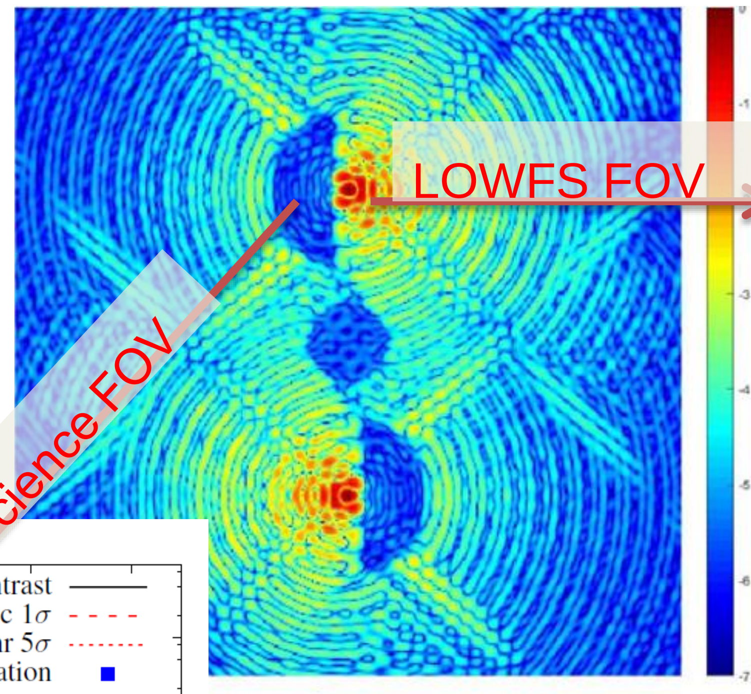
Doc MagAOX-001
Date: 6/9/2017
Status:Draft v. 24

MagAO-X vAPP Coronagraph on-sky Contrasts

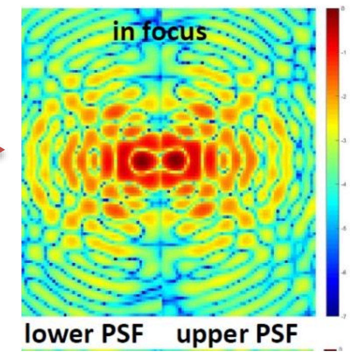
MagAO PSF



Simulated MagAO vAPP PSF

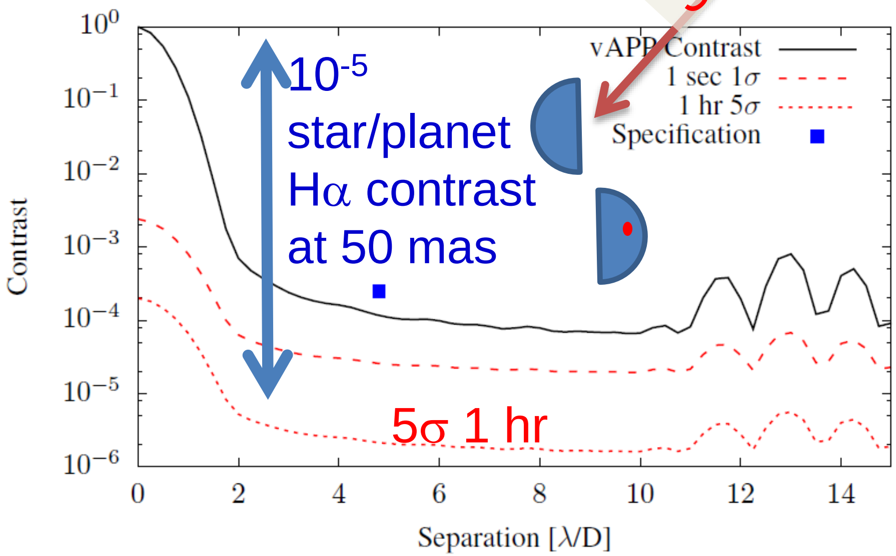


LOWFS limits Non Common Path errors to 38nm rms



LOWFS simulations Kelsey Miller

End to end closed loop simulations by Jared Males



This is a >1000x improvement in contrast over MagAO today

vAPP design by David Doelman, Frans Snik, Cristoph Keller, and Matt Kenworthy; U. Leiden)

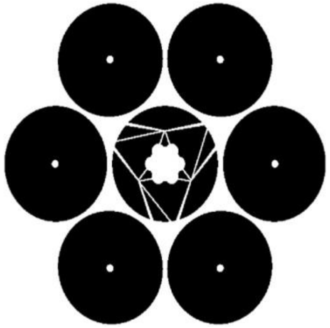
Introducing GMagAO-X

(a MagAO-X like instrument on GMT)

- A draft design of a GMT ExAO instrument "GMagAO-X" at the gravity invariant auxiliary (AP) port. See Jared Males' Poster today
- Concept Based on talks given by Jared Males, Olivier Guyon and Laird Close at:

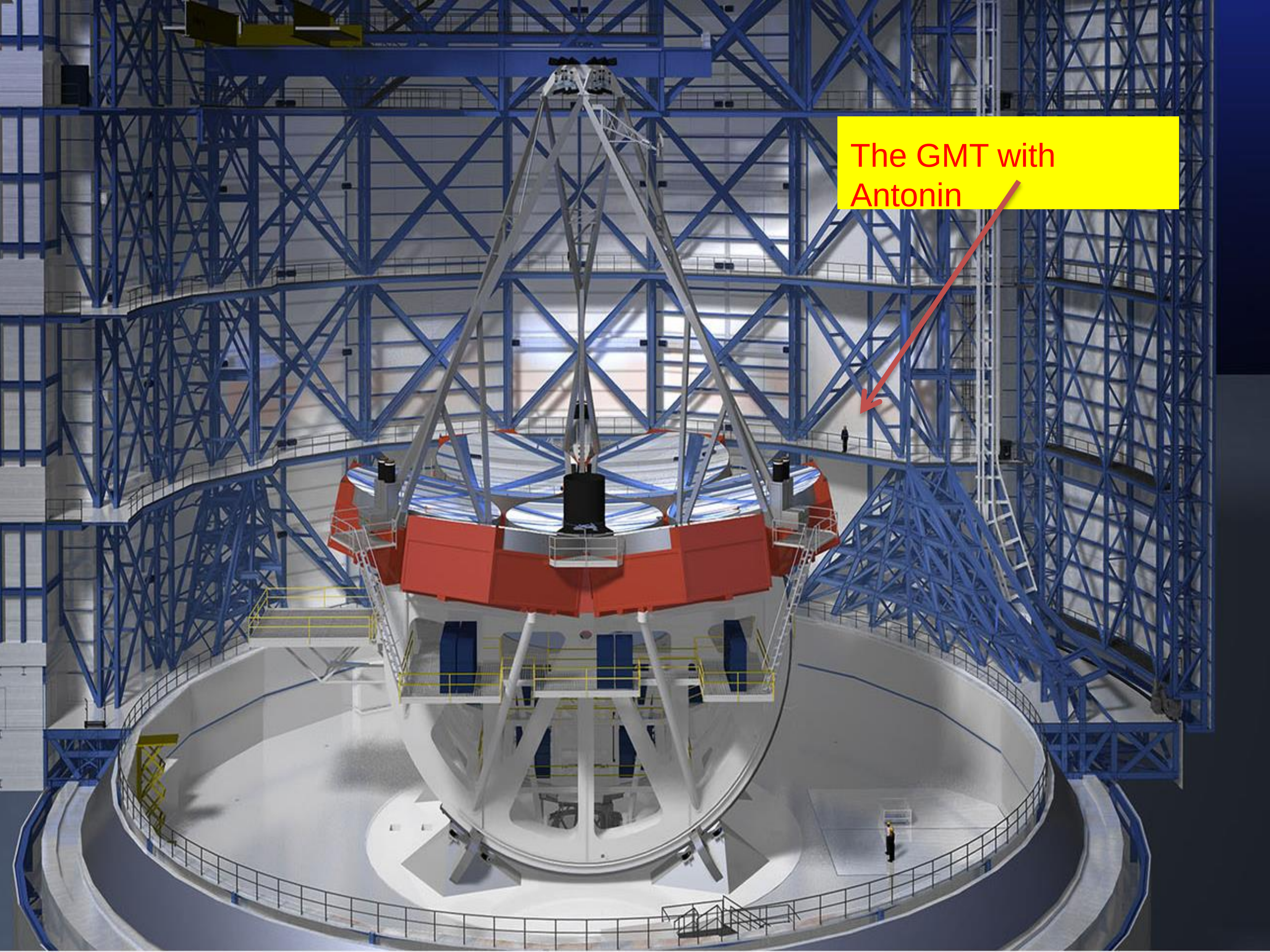
"**Exoplanets in the Era of ELTs**" in Sept 2016.

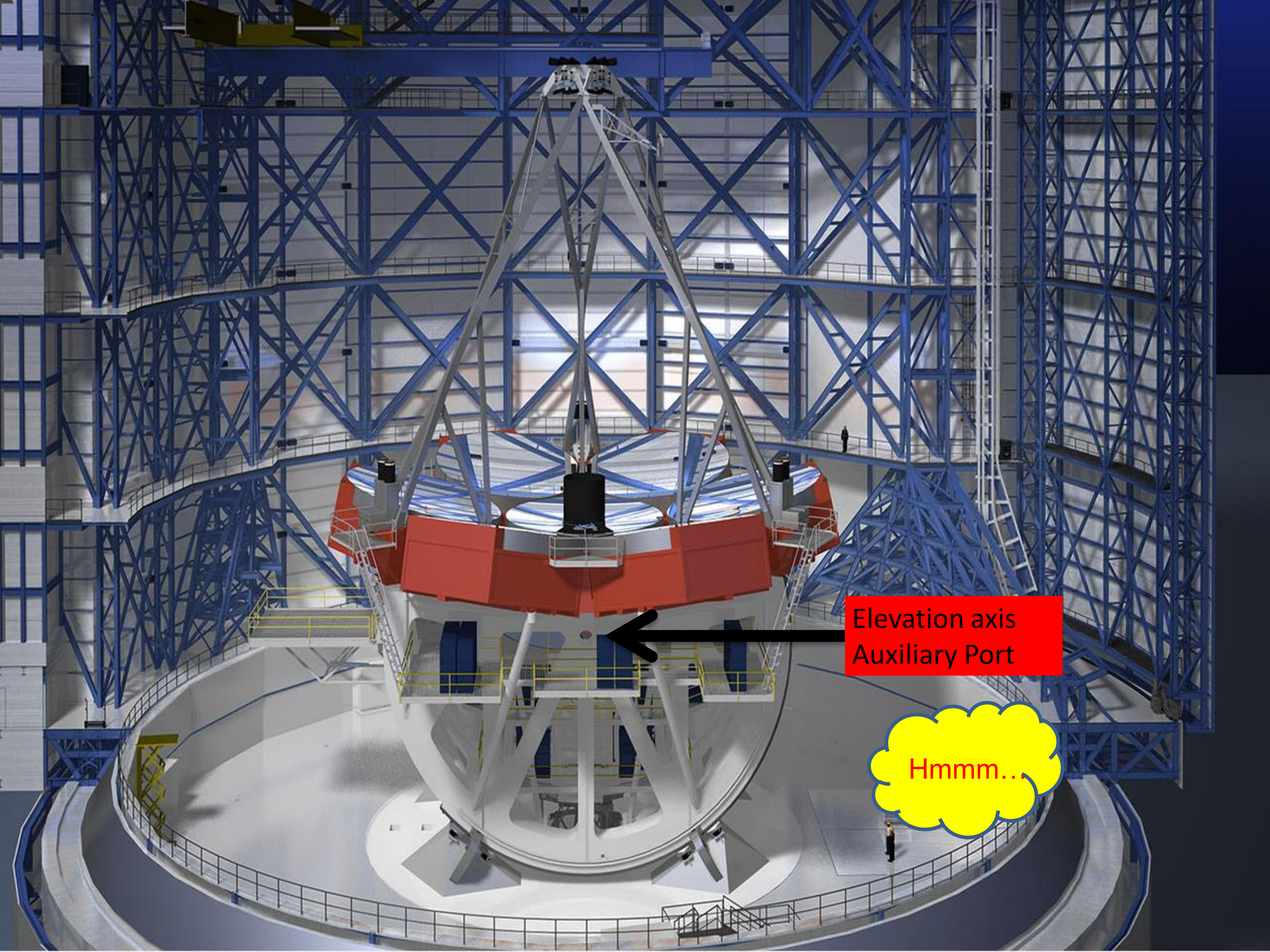
Auxiliary port details based on discussions with the GMT engineering group, in particular Brain Walls (GMTO), and NAU's Nick Herrald (ANU, Australia)



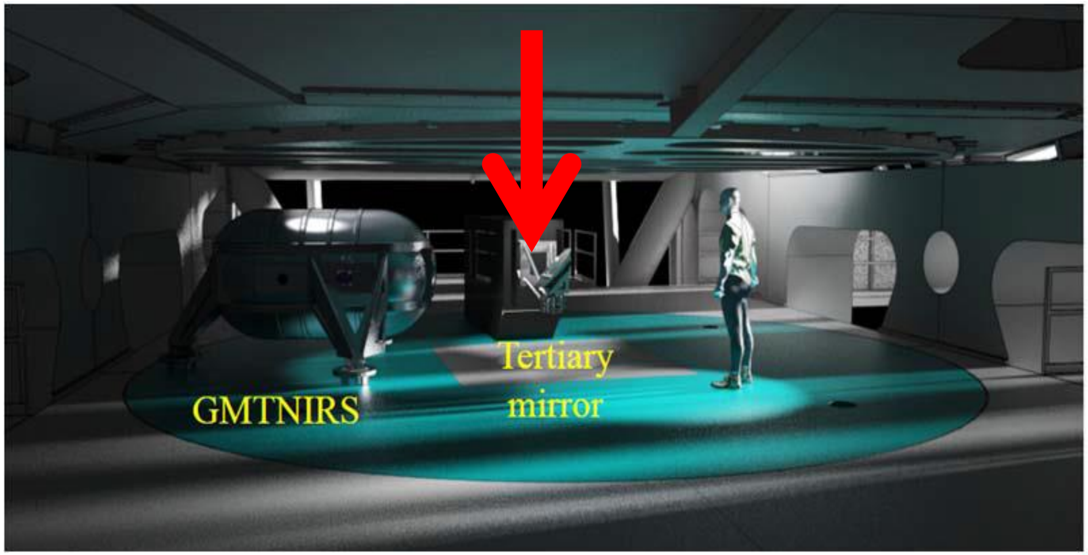
Proof of concept Design of an GMT ExAO Coronagraph (GMagAO-X)

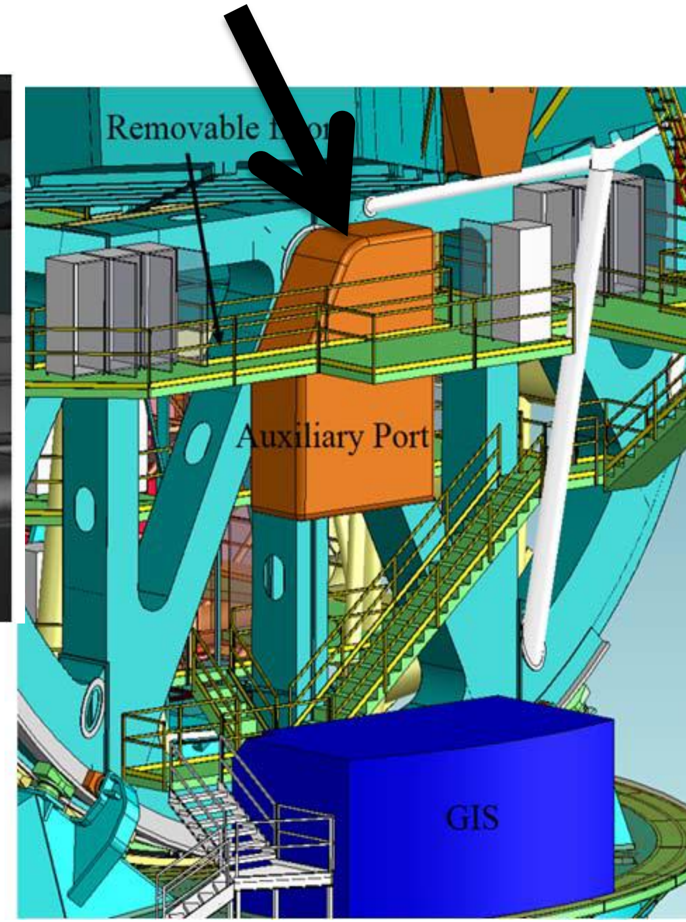
- We believe (based on the six-sided pupil segmentor optic) that the GMT is the only ELT that has the ability to do ExAO coronagraphy with today's "COTS" DMs and WFS detectors. This is unlikely to change in the future, **the GMT is *the* ELT that can do first light ExAO**.
- Moore's law doesn't seem to apply to DMs.
- Here we show a proof-of concept optomech design using today's COTS DMs (Seven BMC 3Ks) and WFS detectors (4 OCAM2ks) combined with the stage 1 GMT could be the most powerful ExAO system ever.
- **See Jared Males' Poster Today on GMagAO-X and how it could image Proxima Cen b**


The GMT with
Antonin

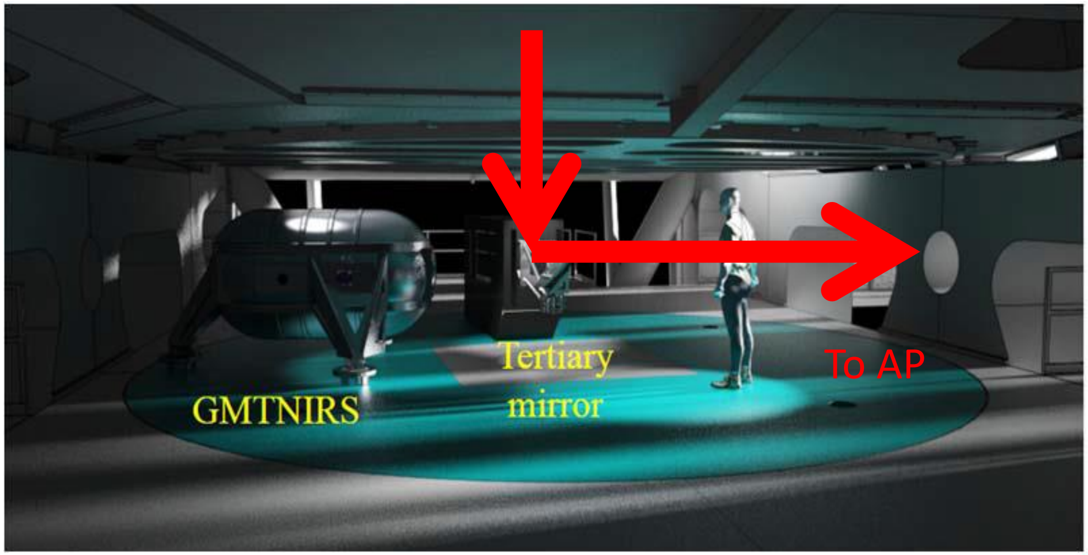

Elevation axis
Auxiliary Port
Hmmm…

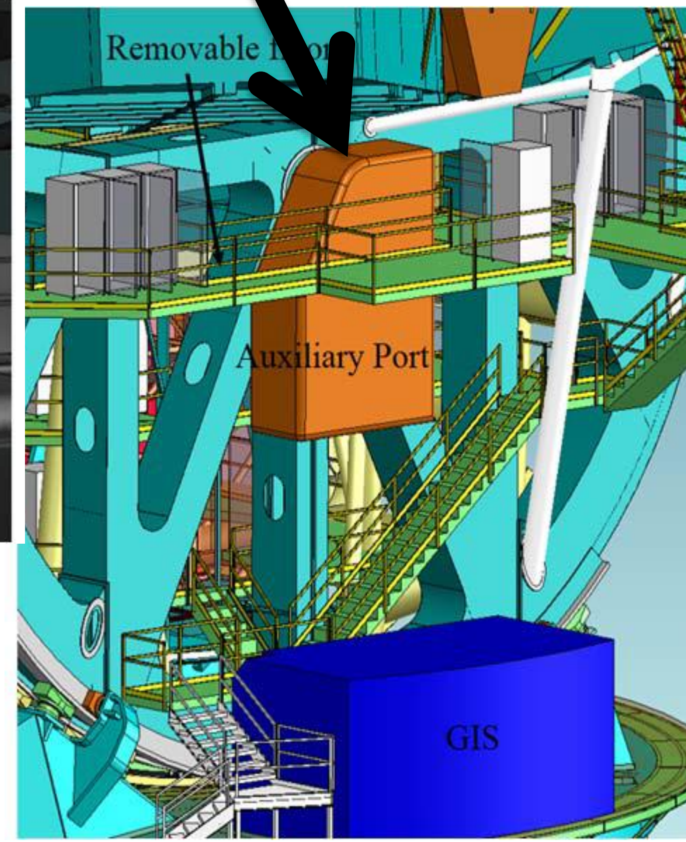
Auxiliary Port (AP)



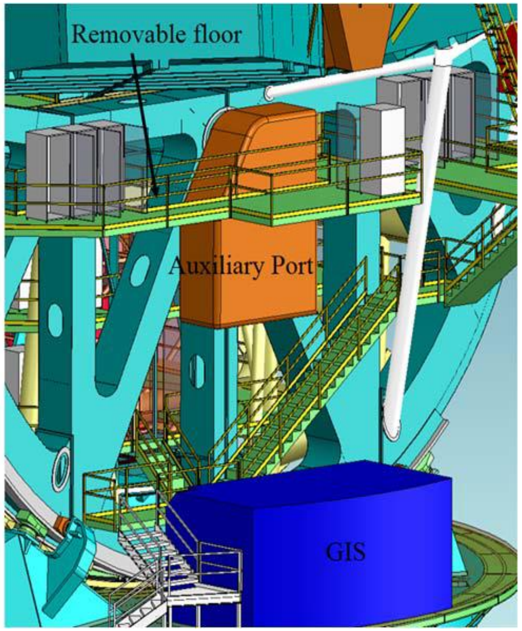


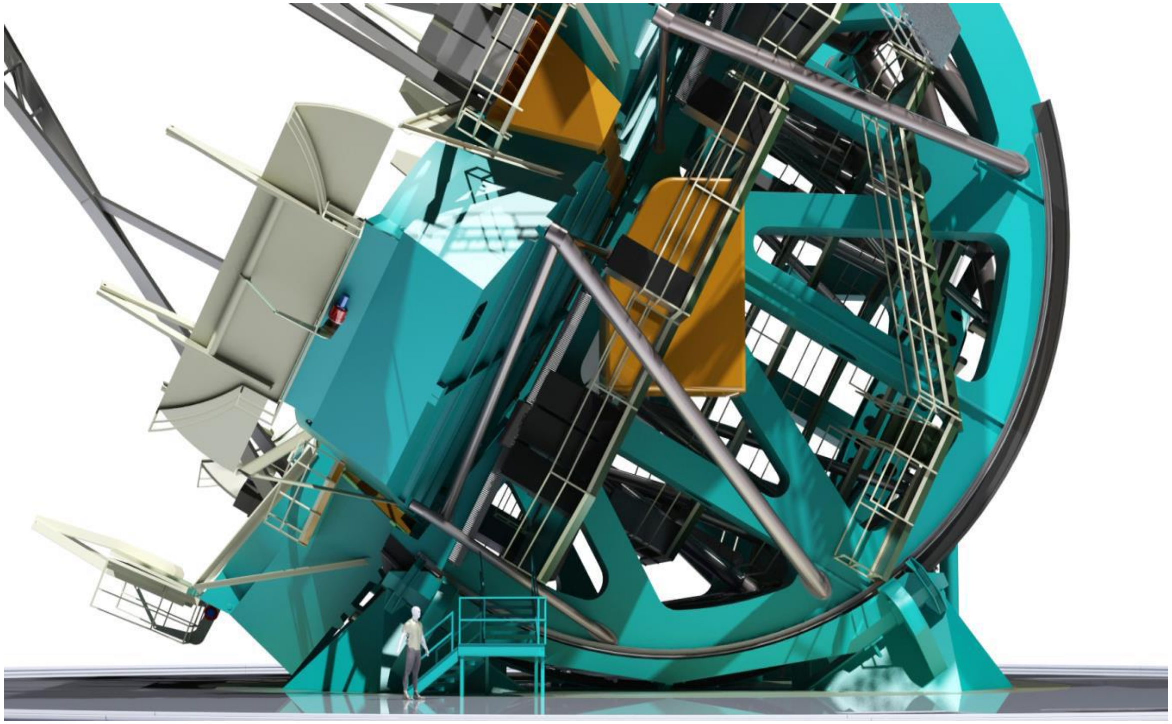
Auxiliary Port (AP)





The AP is gravity invariant





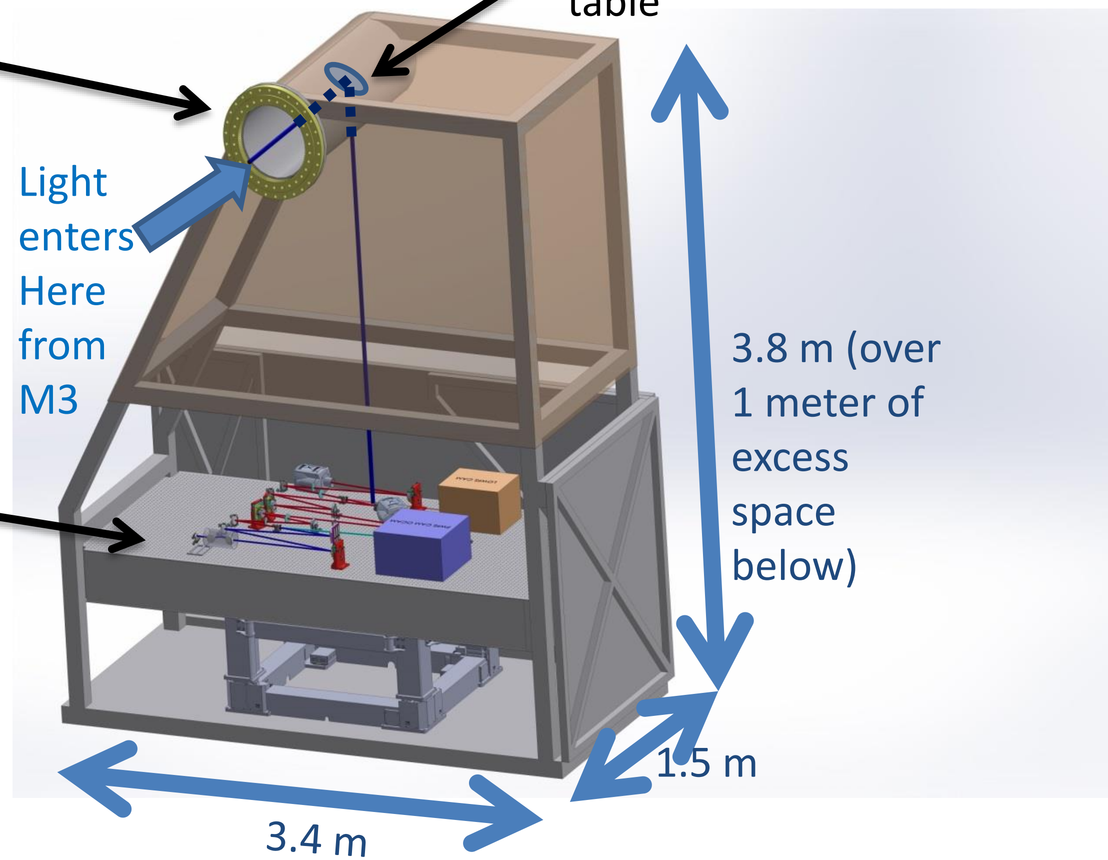
At Zenith

At low elevation – Still at same orientation w.r.t. gravity

A Proof of Concept Design for GMagAO-X

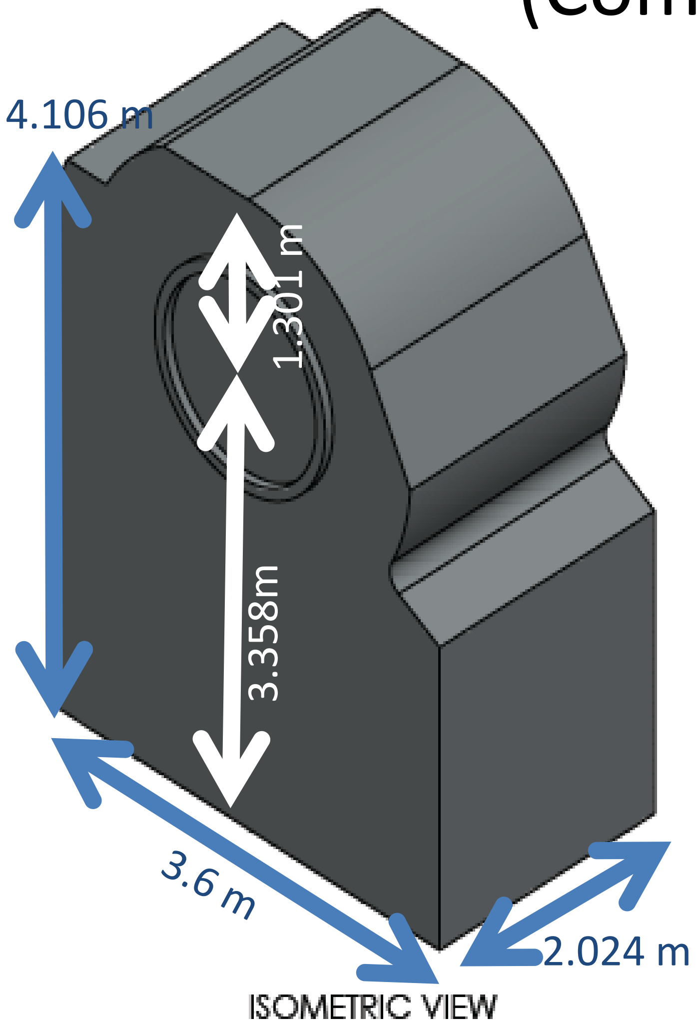
High load/moment bearing

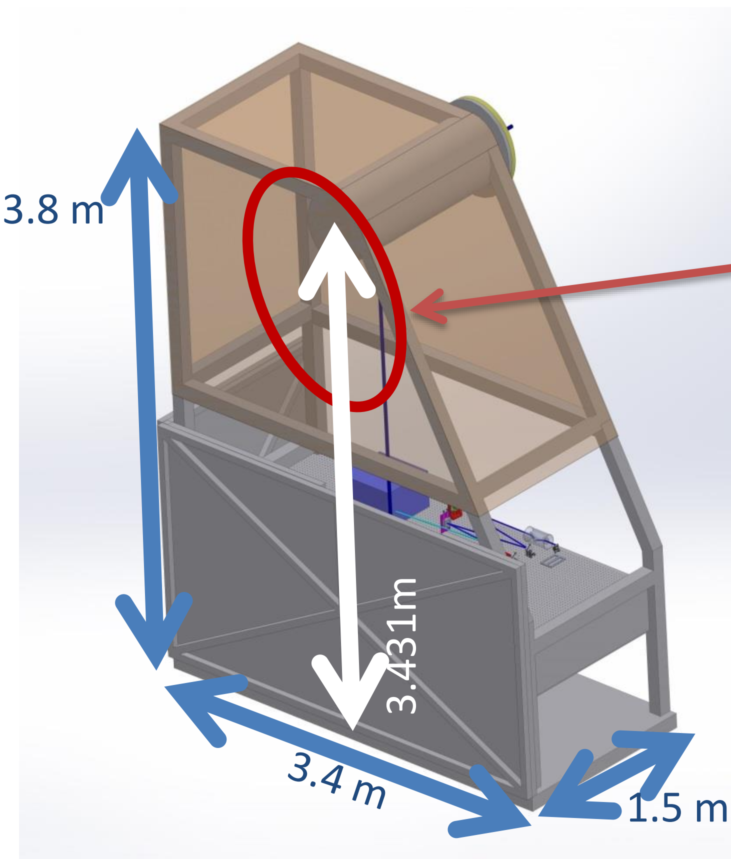
45° mirror folds beam onto floating table



4½ x 10½ foot (1.37x3.2m) (12” thick), 600kg floating (vibration isolated) optical table. This is all that is needed for GMagAO-X.

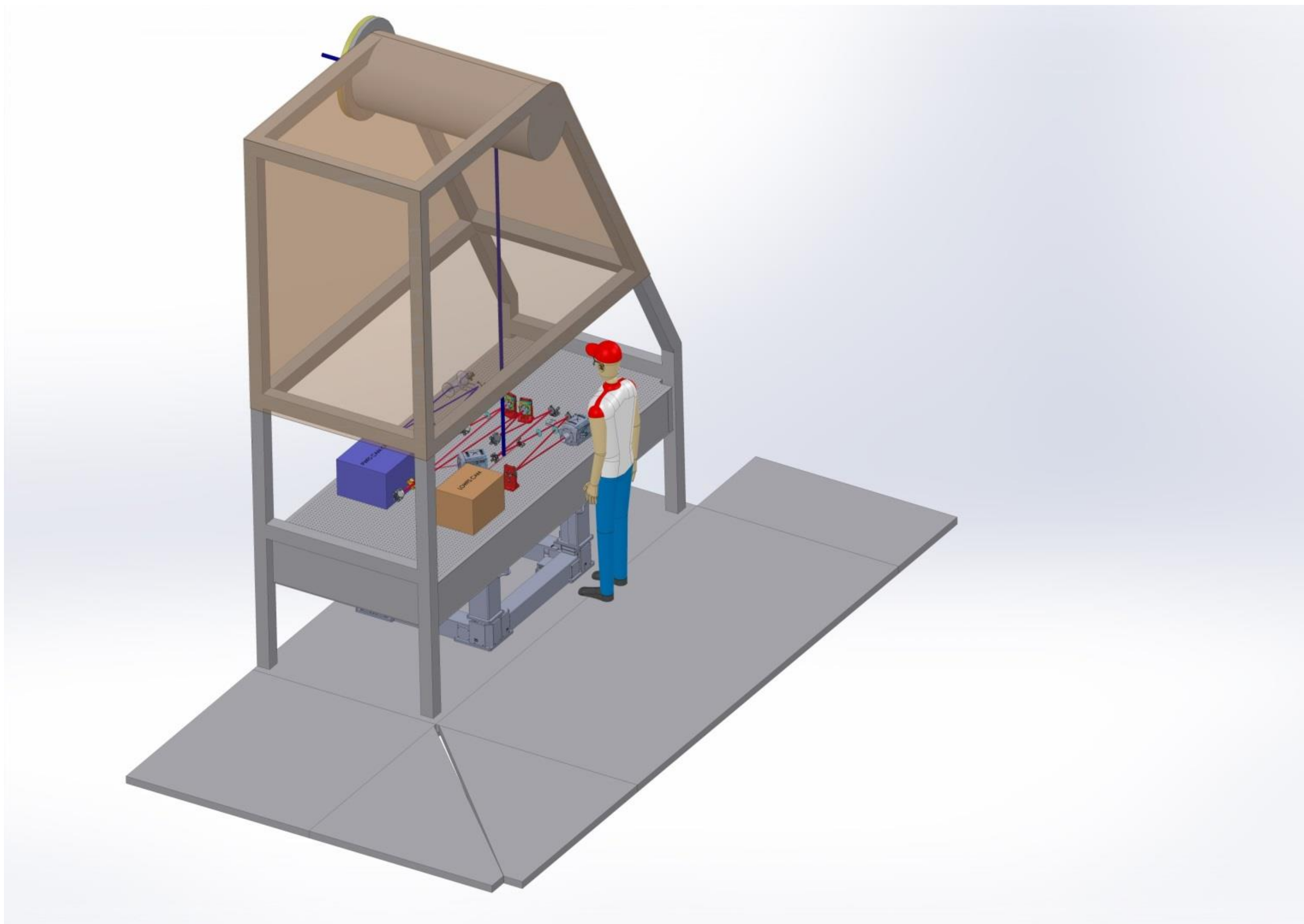
A Proof of Concept Design for GMagAO-X
(Compared to the *NEW* AP volume)



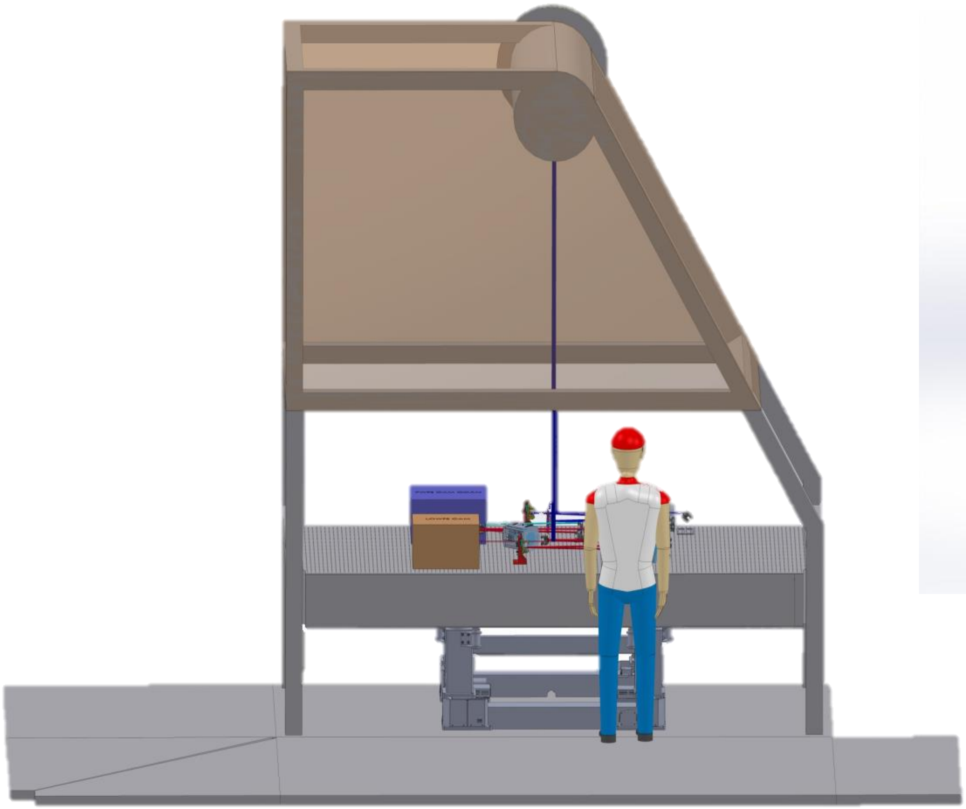


Bearing needs to be increased in size (and lowered down to table by >150mm) to fit the new 1.43m IR and 1.60m OR for the new design: Somewhat (TBD) shorter pathlength required

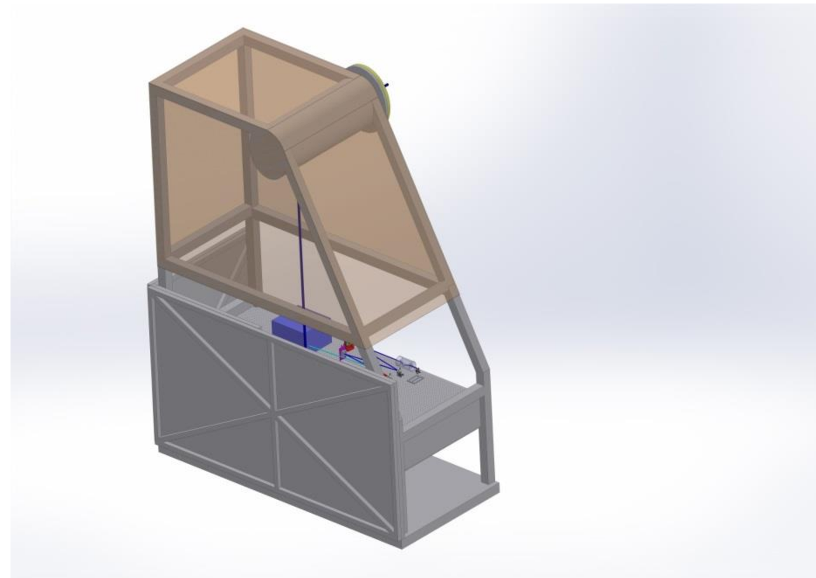
Extendable platform for maintenance (walls fold out onto the catwalk)



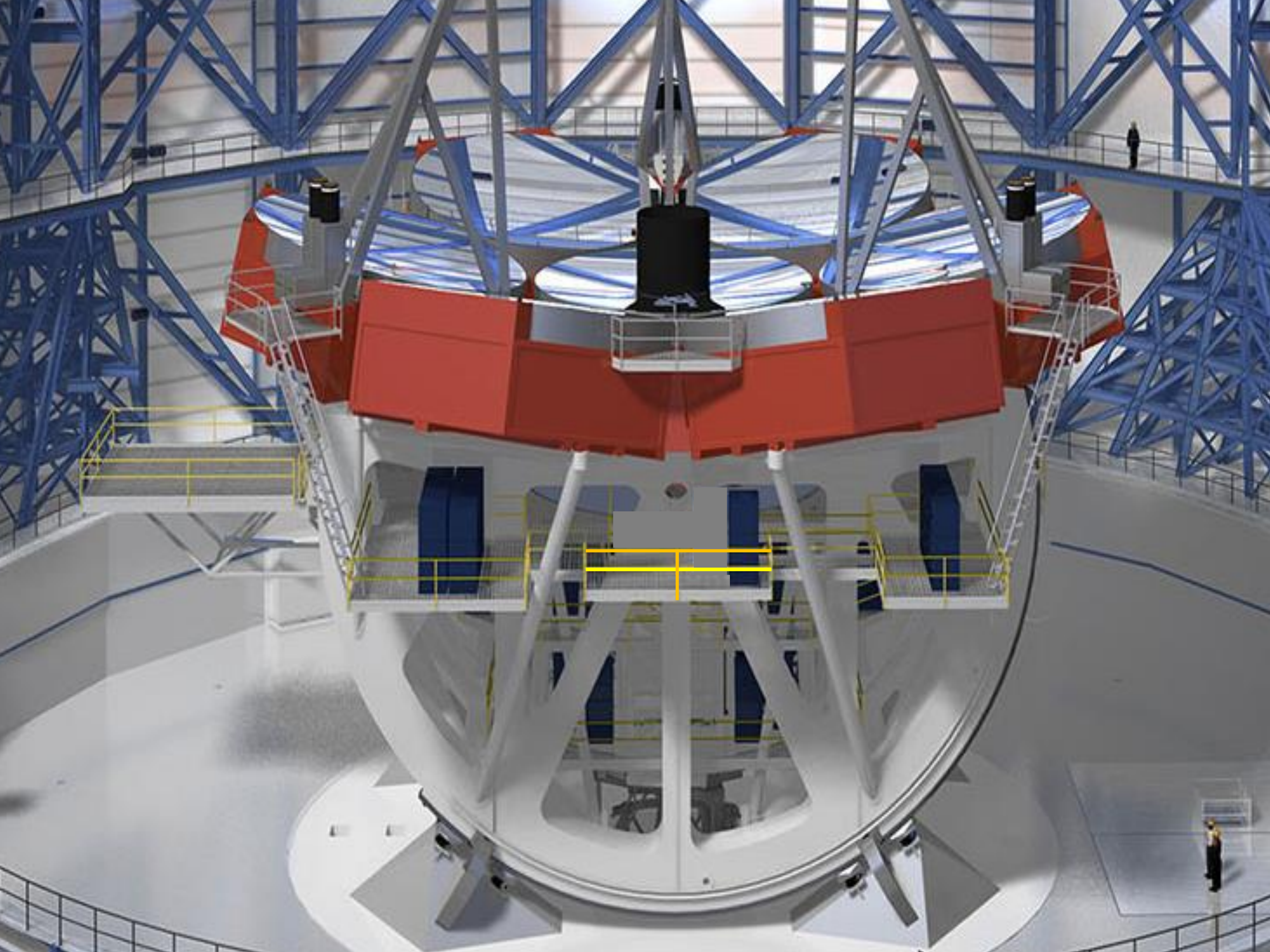
Front view

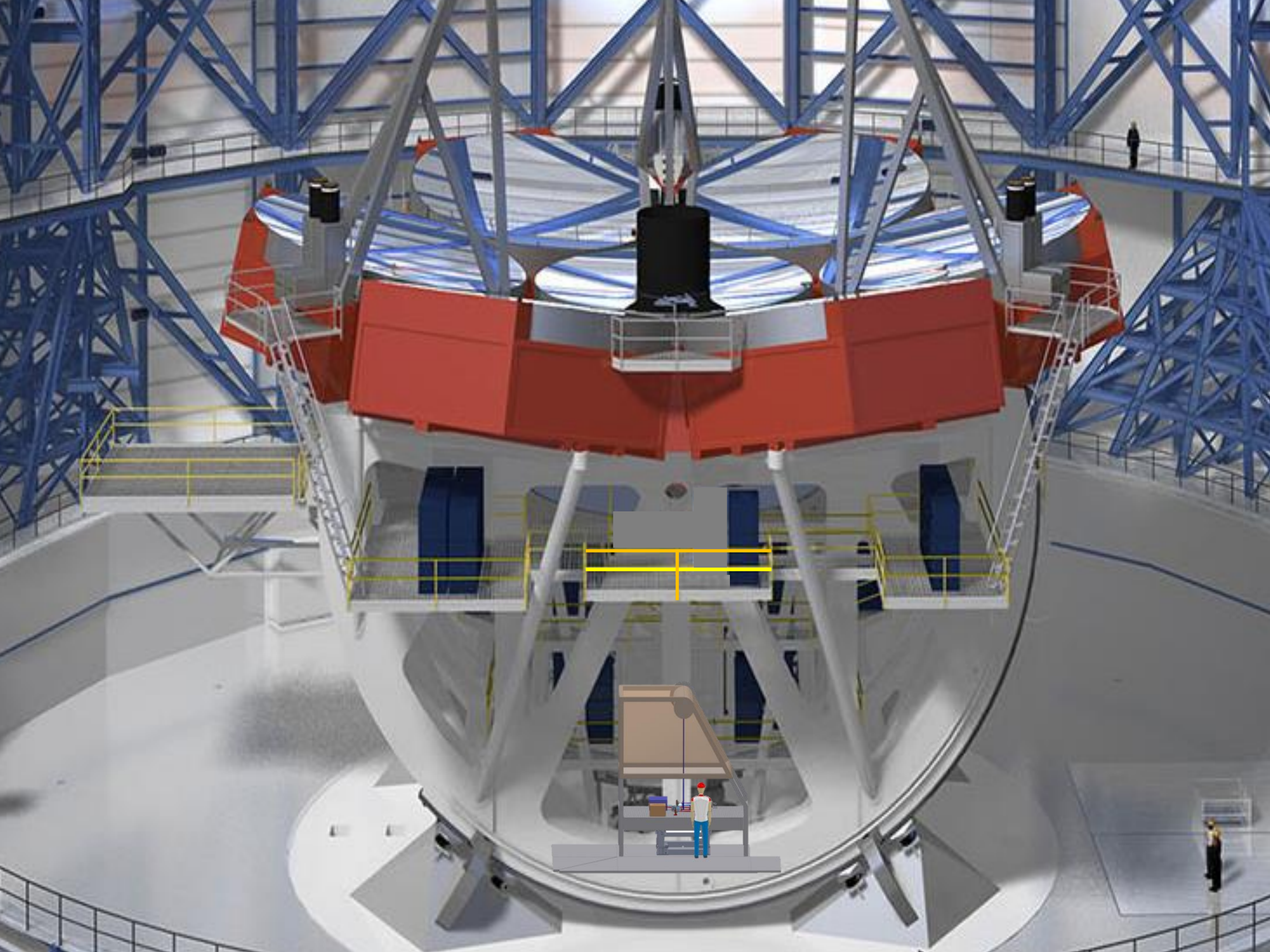


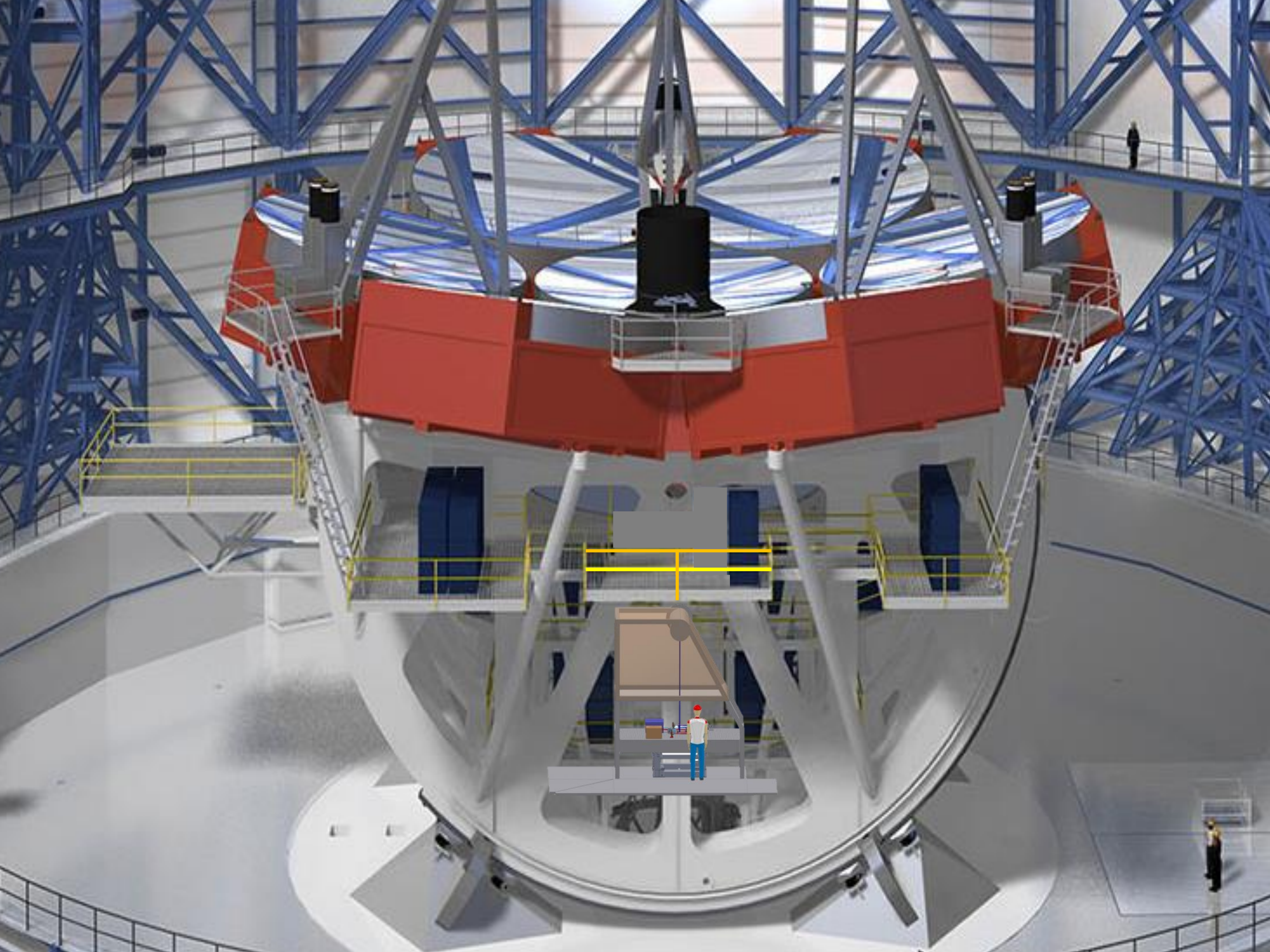
Maintenance mode

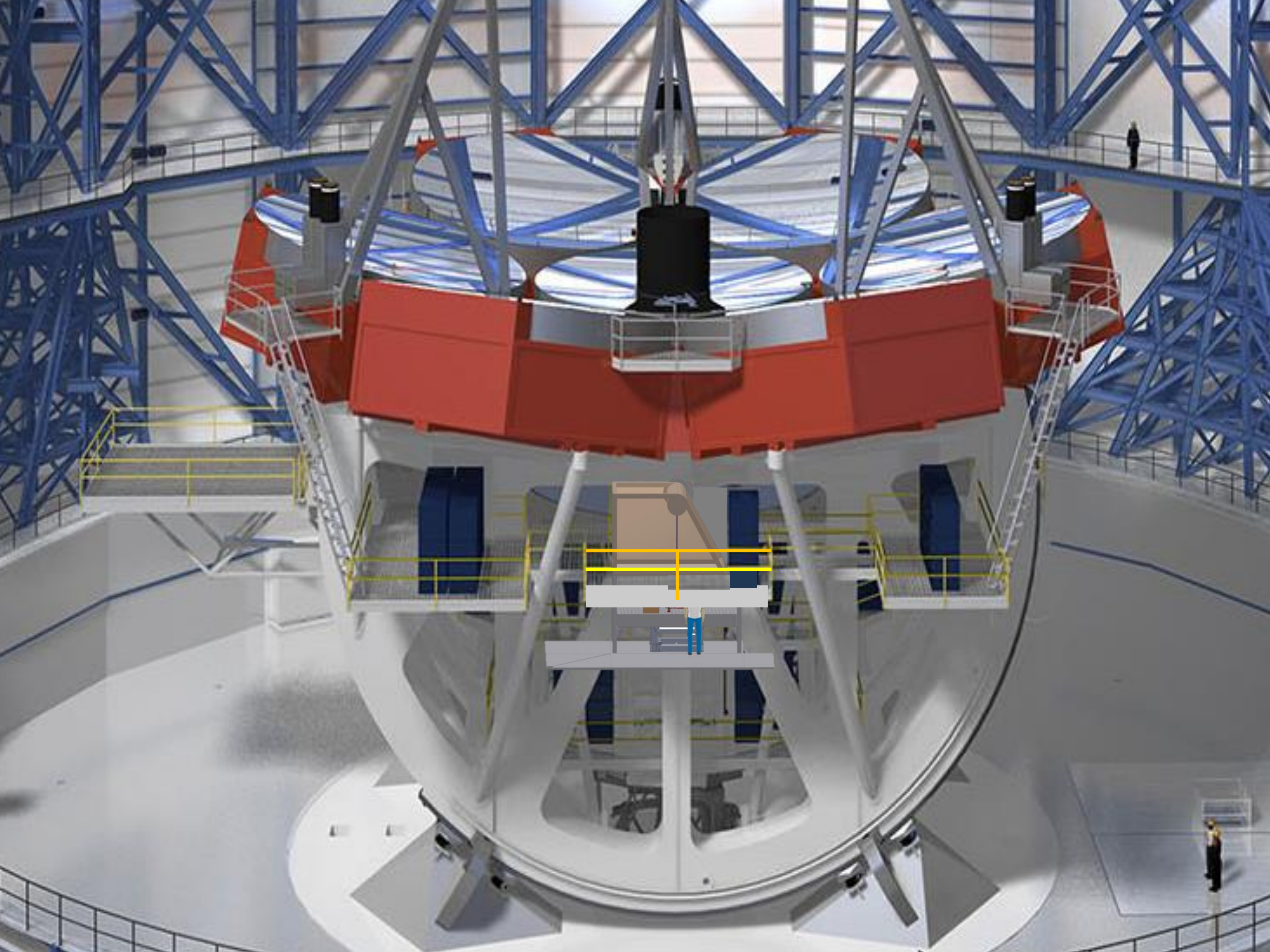


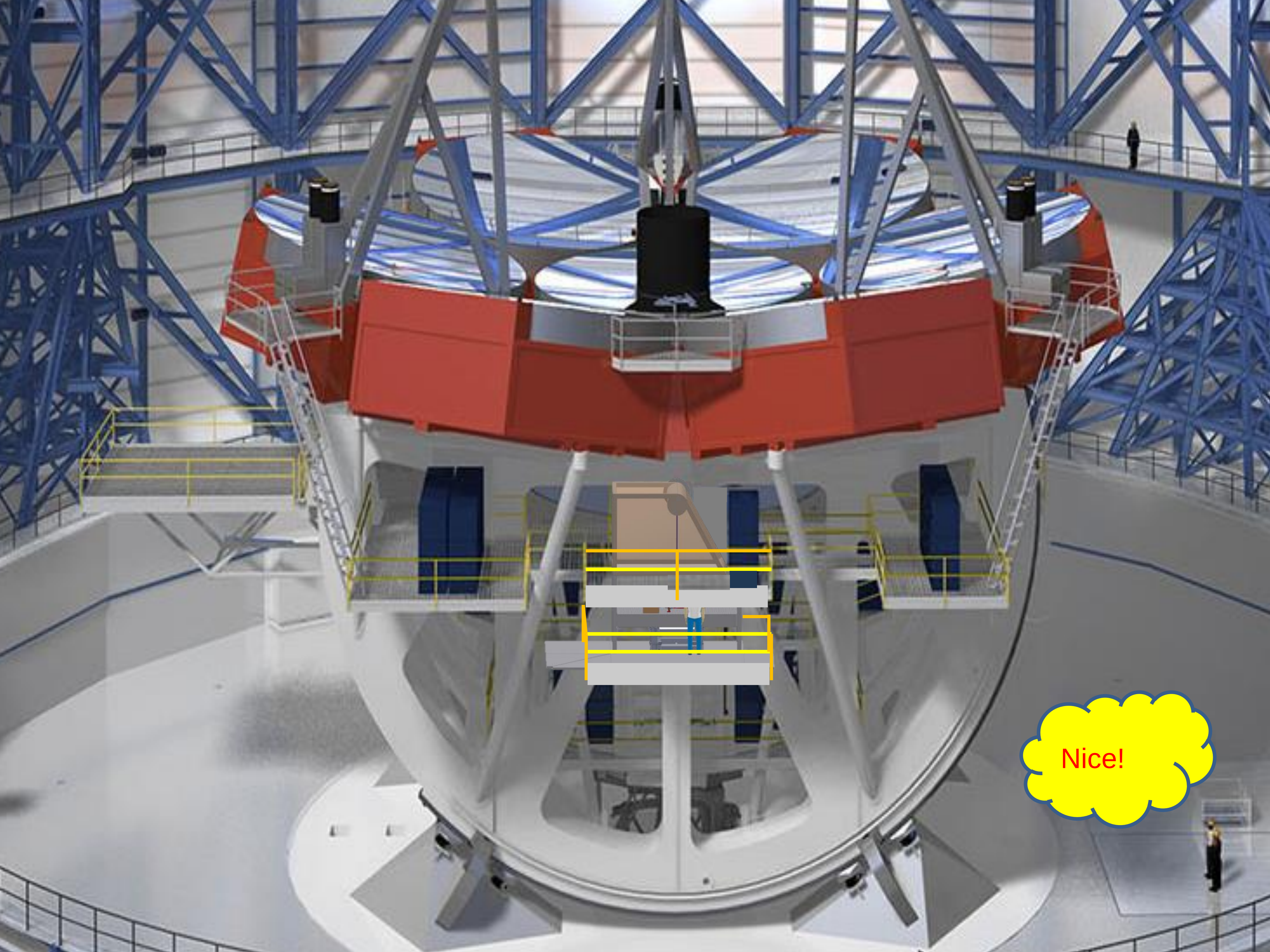
Observing mode



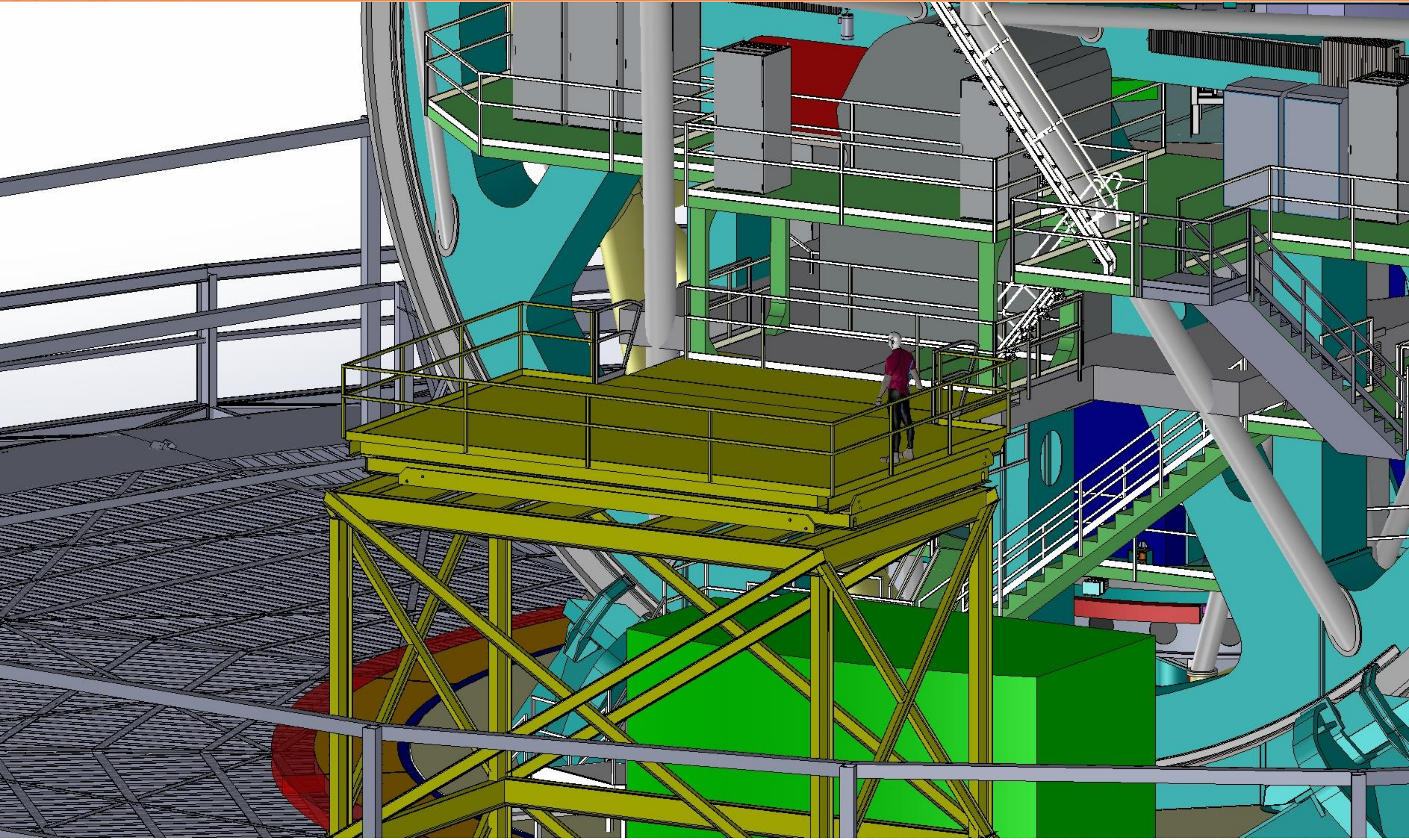




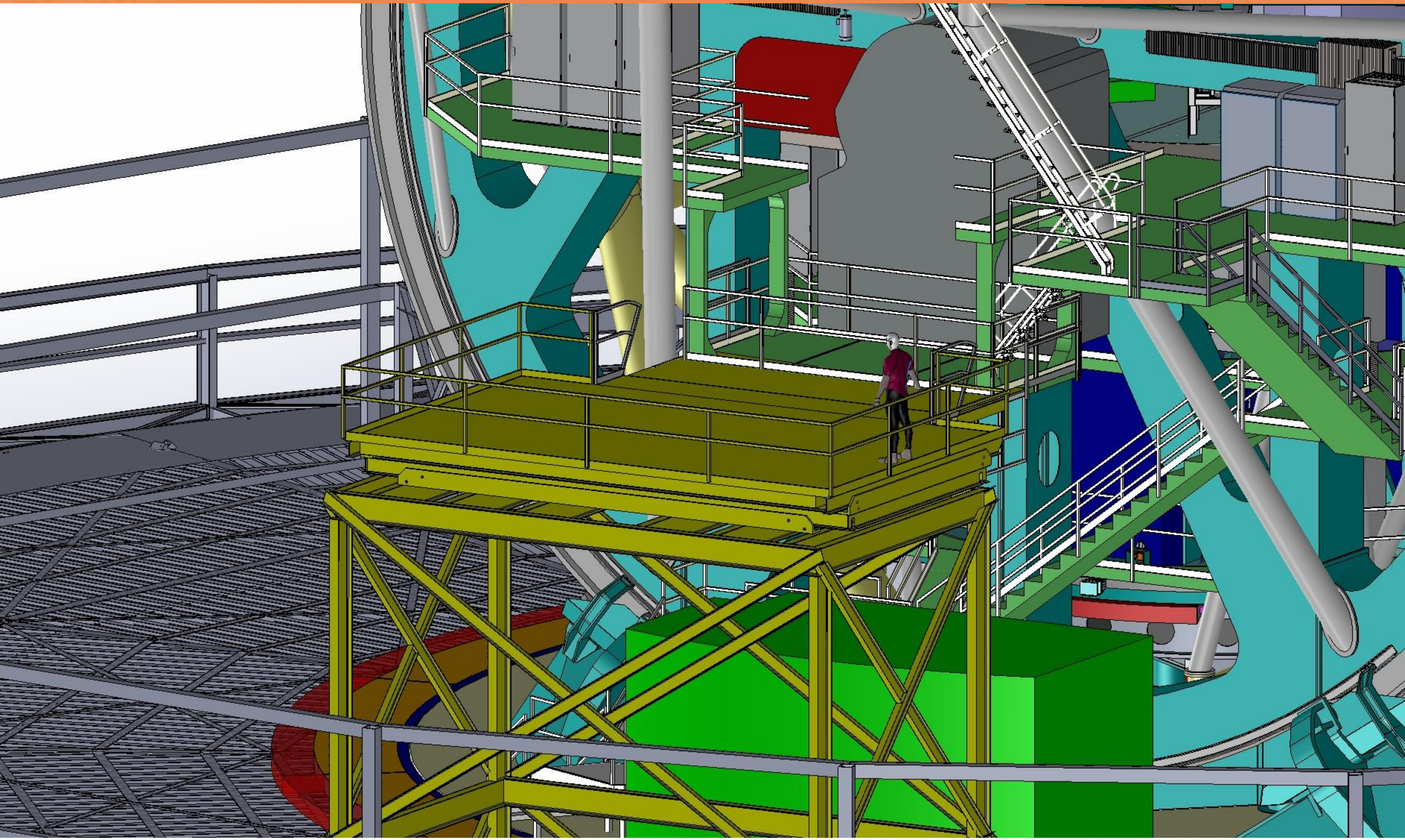



Nice!

REMOVAL OF AUX PORT INSTRUMENT

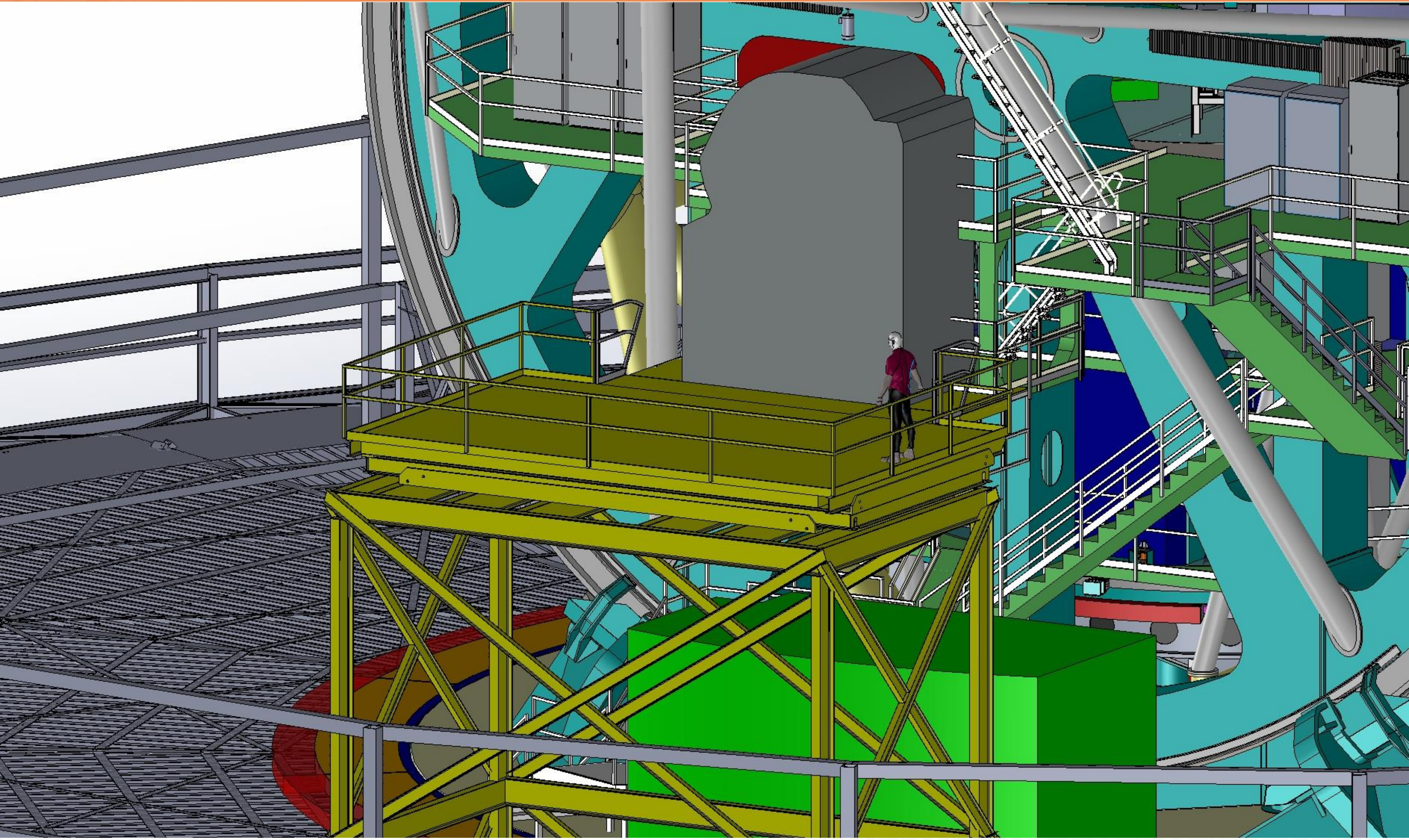


Remove platform section

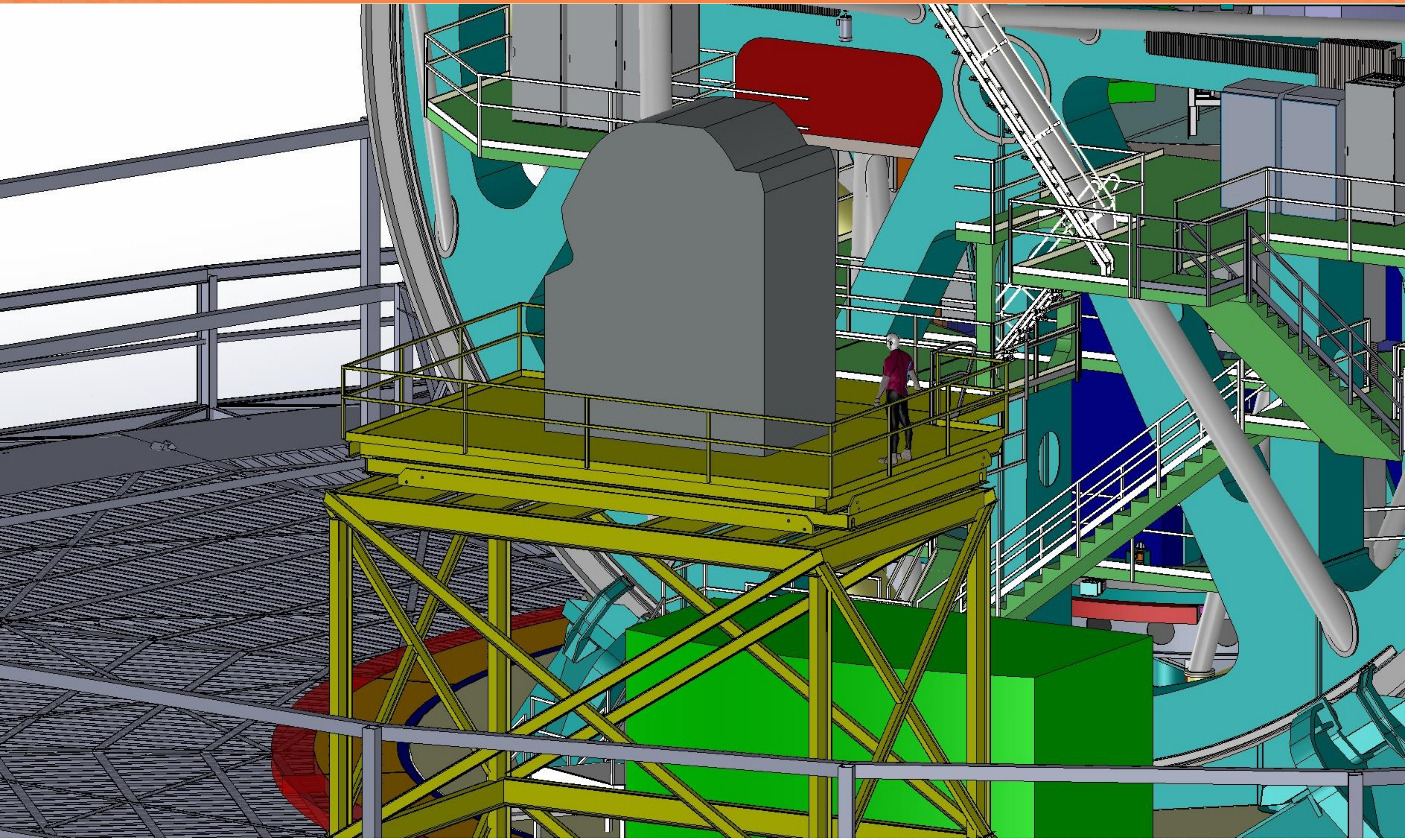


From Nick Herrald (ANU, Australia)

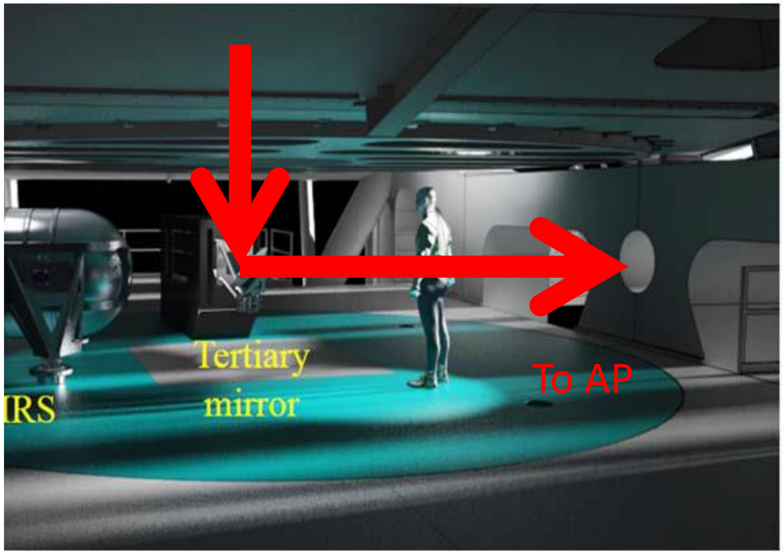
GMT

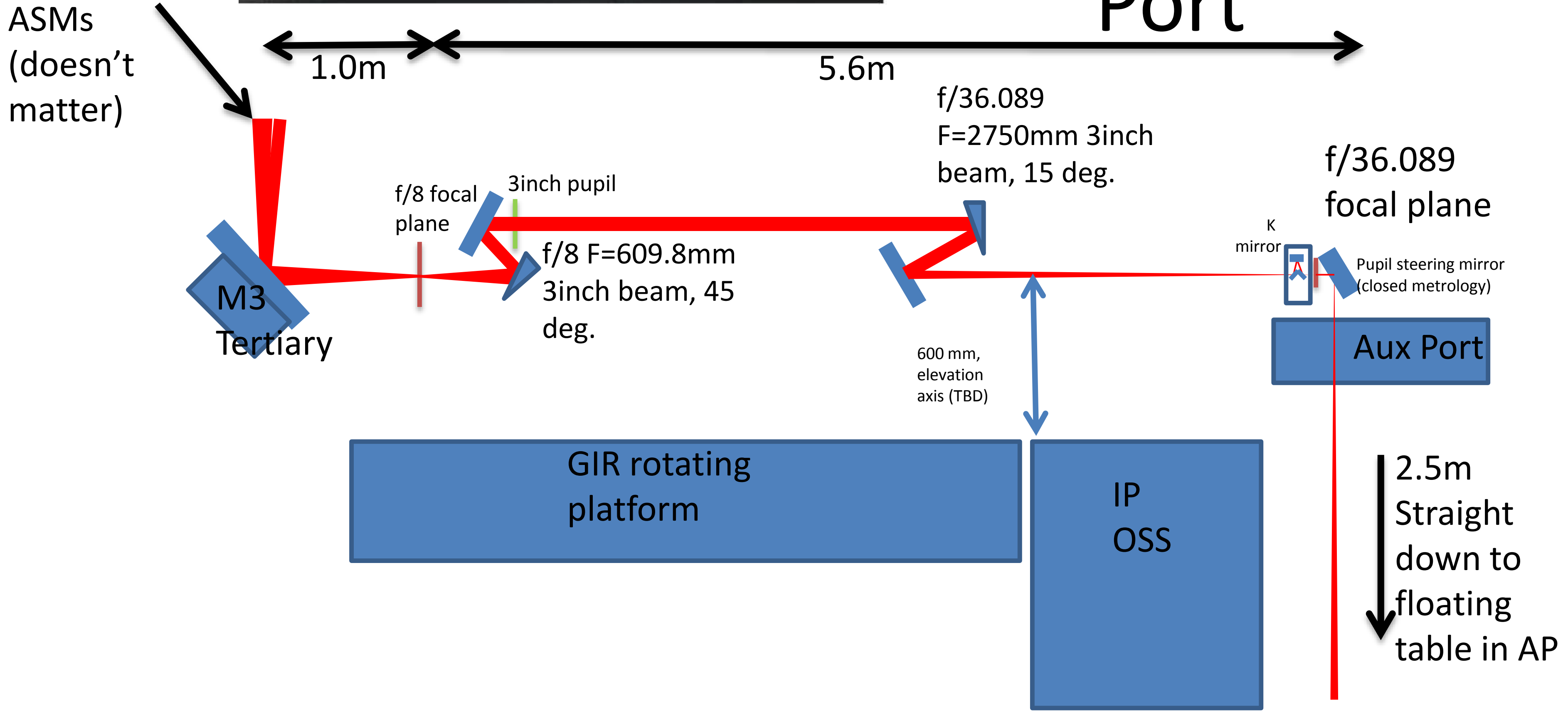


From Nick Herrald (ANU, Australia)

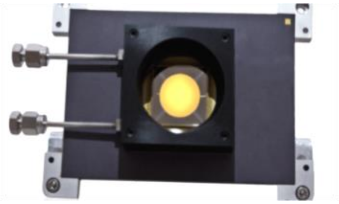


GMagAO-X Relay: M3 to Floating Table in Aux Port





The GMT Tweeter: How Can we have 21,000 actuators when that is not currently possible to fabricate in one DM?

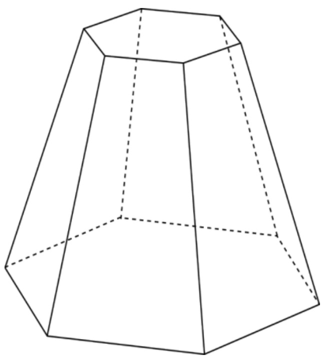


21,000 ????

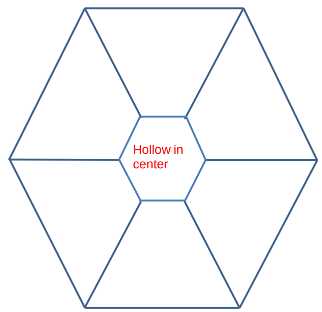
A Boston Micro Machines 3000 actuator DM with 20mm dia. – Today's COTS

How can you split up the GMT pupil to enable ExAO ?

Hollow in center

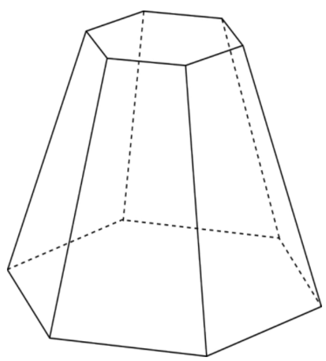


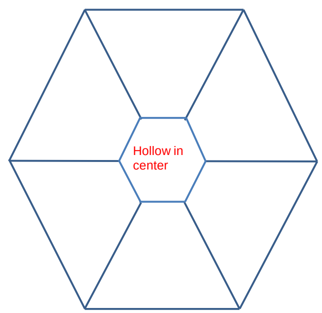
Top view



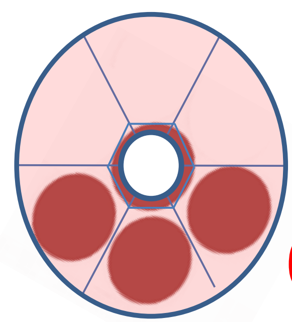
6 sided reflective pyramid

How can you split up the GMT pupil to enable ExAO ?



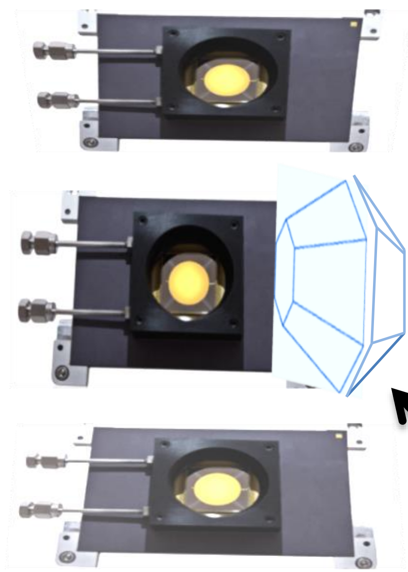


6 sided reflective pyramid



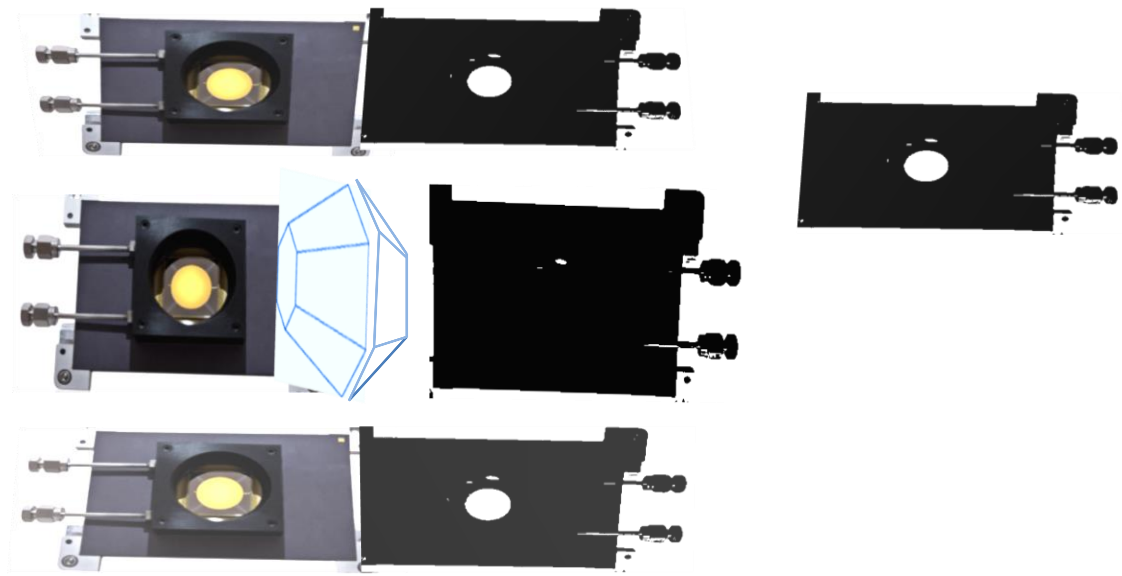
6 sided reflective pyramid slicing GMT pupil inside Magellan pupil

The GMT stage 1 Tweeter:12,000 Actuators

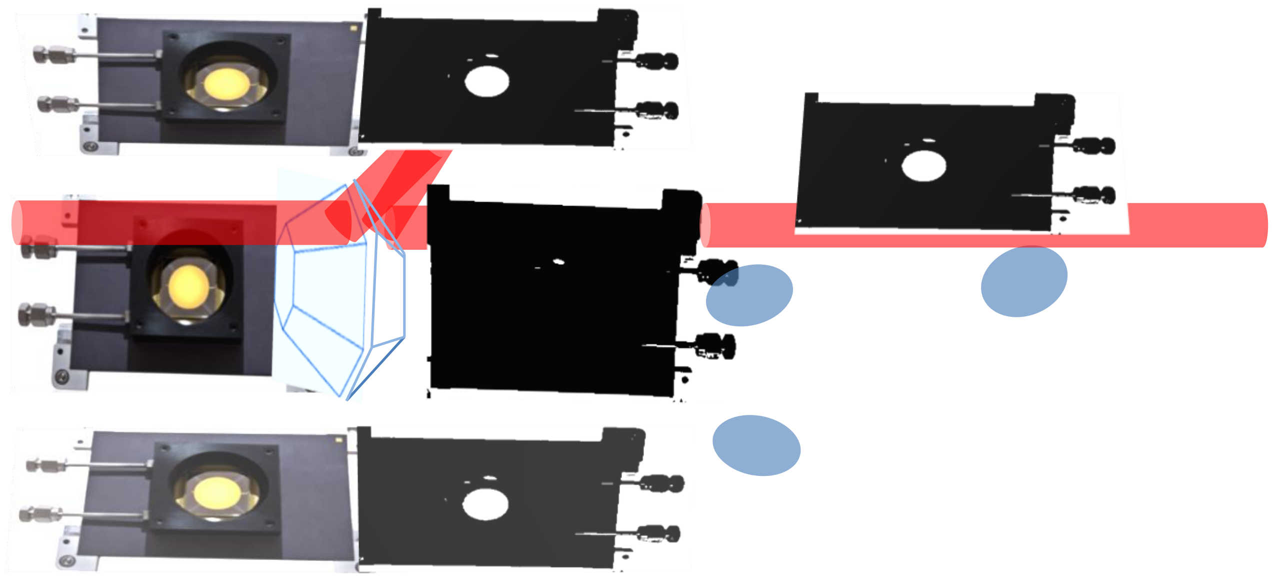


6-sided reflective hollow pyramid optic for pupil segmentation

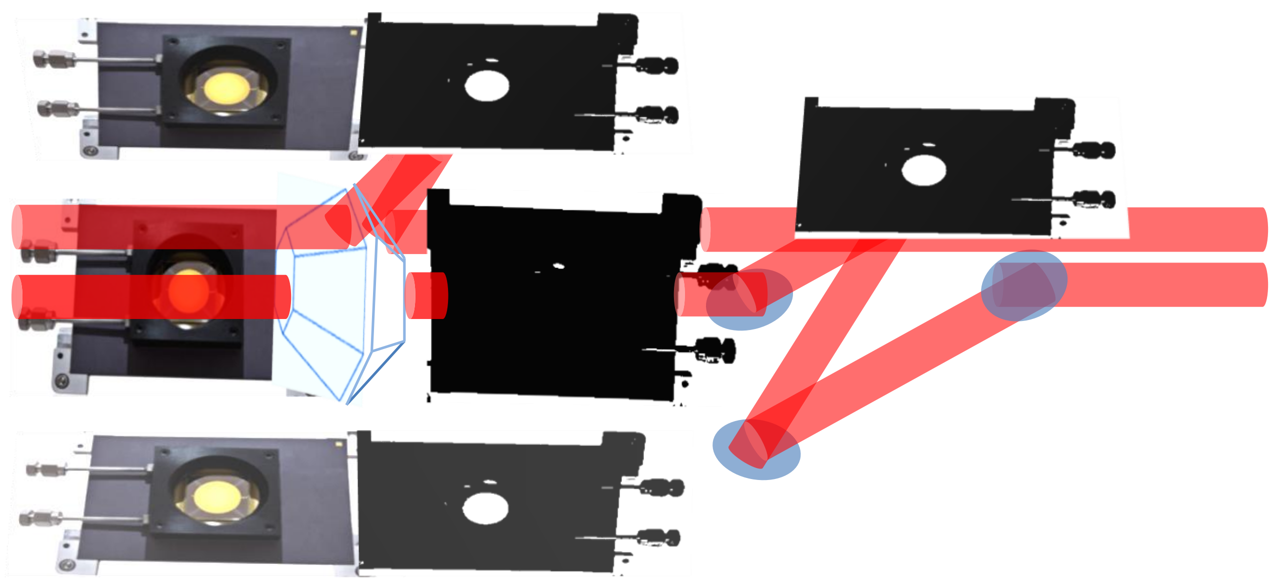
The GMT Tweeter:21,000 Actuators



The GMT Tweeter: Off Axis primary Mirror Optical path

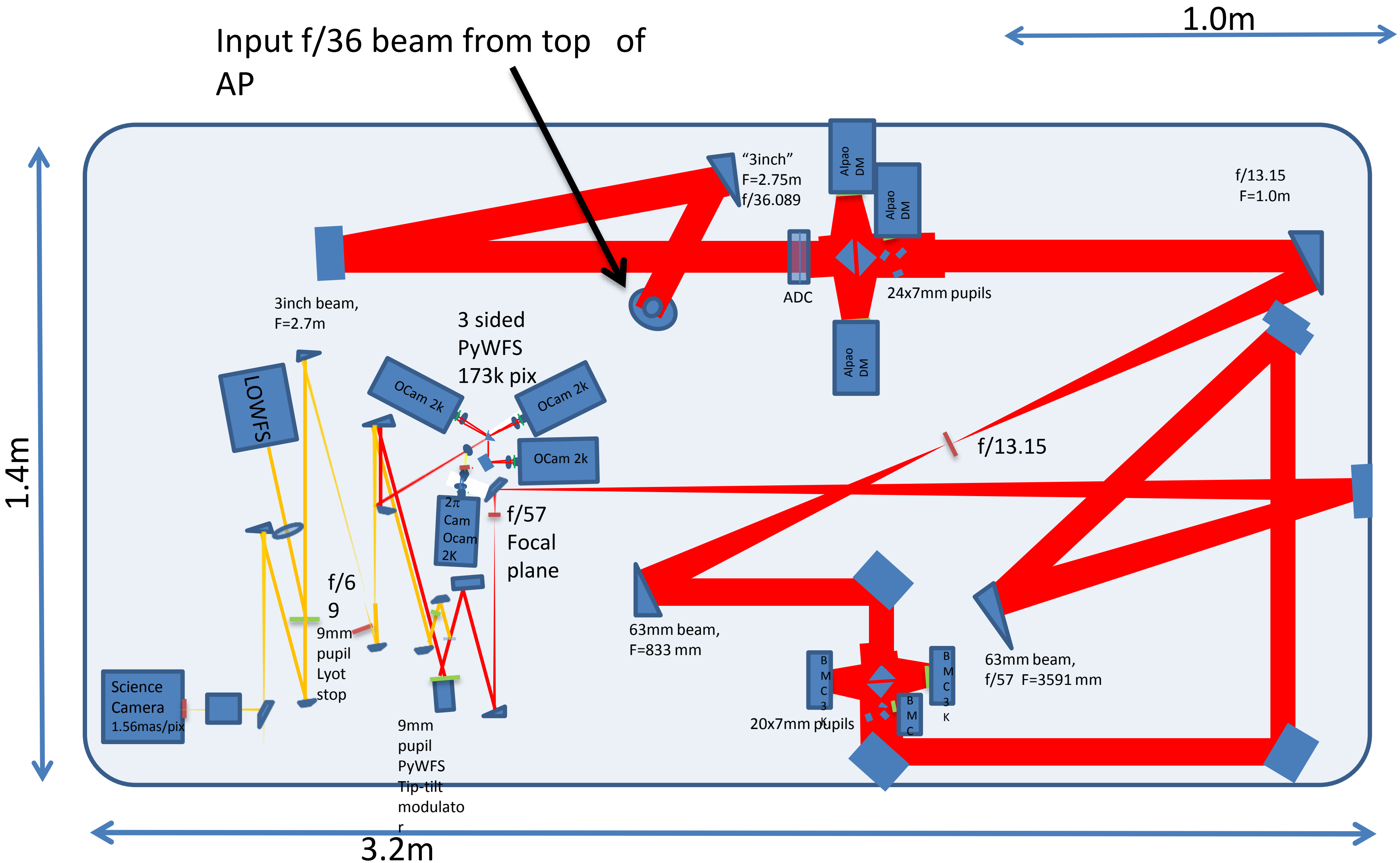


The GMT Tweeter: Off-axis and On-axis

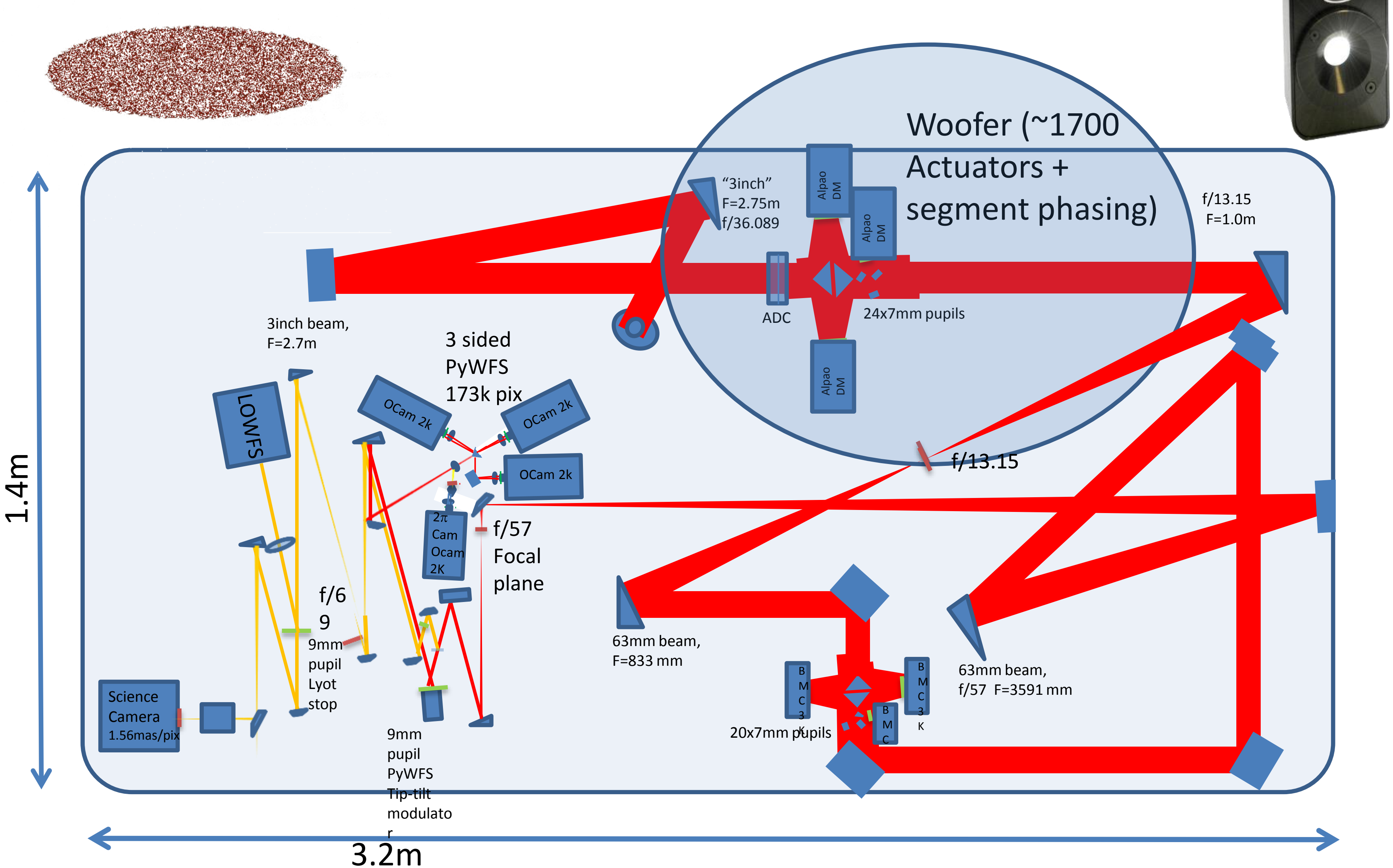


NOTE: On GMT each pupil would be a 20mm dia. 3000 actuator MEMS DM (300um pitch, 1.5um stroke surface) which would be illuminated by 6^{o} beam 97 mm above the 6-sided pyramid with 42^{o} slope angles to allow a total unvignetted 25m FOV of 2” (really 2.6” with zero misalignments --except for the slightly undersized mirrors (8.25m, 3.6% light loss).

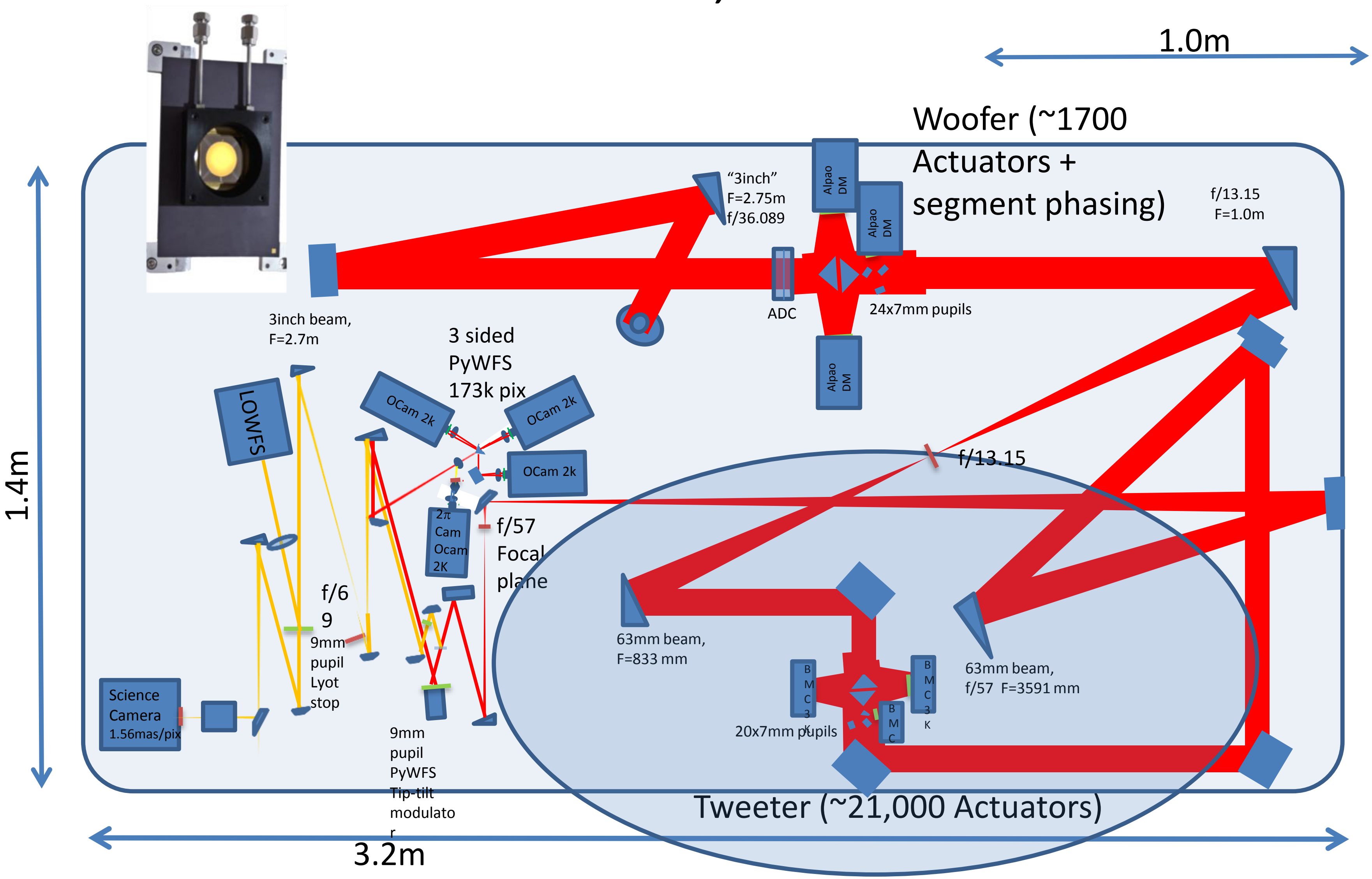
GMagAO-X 1.4x3.2m floating Table



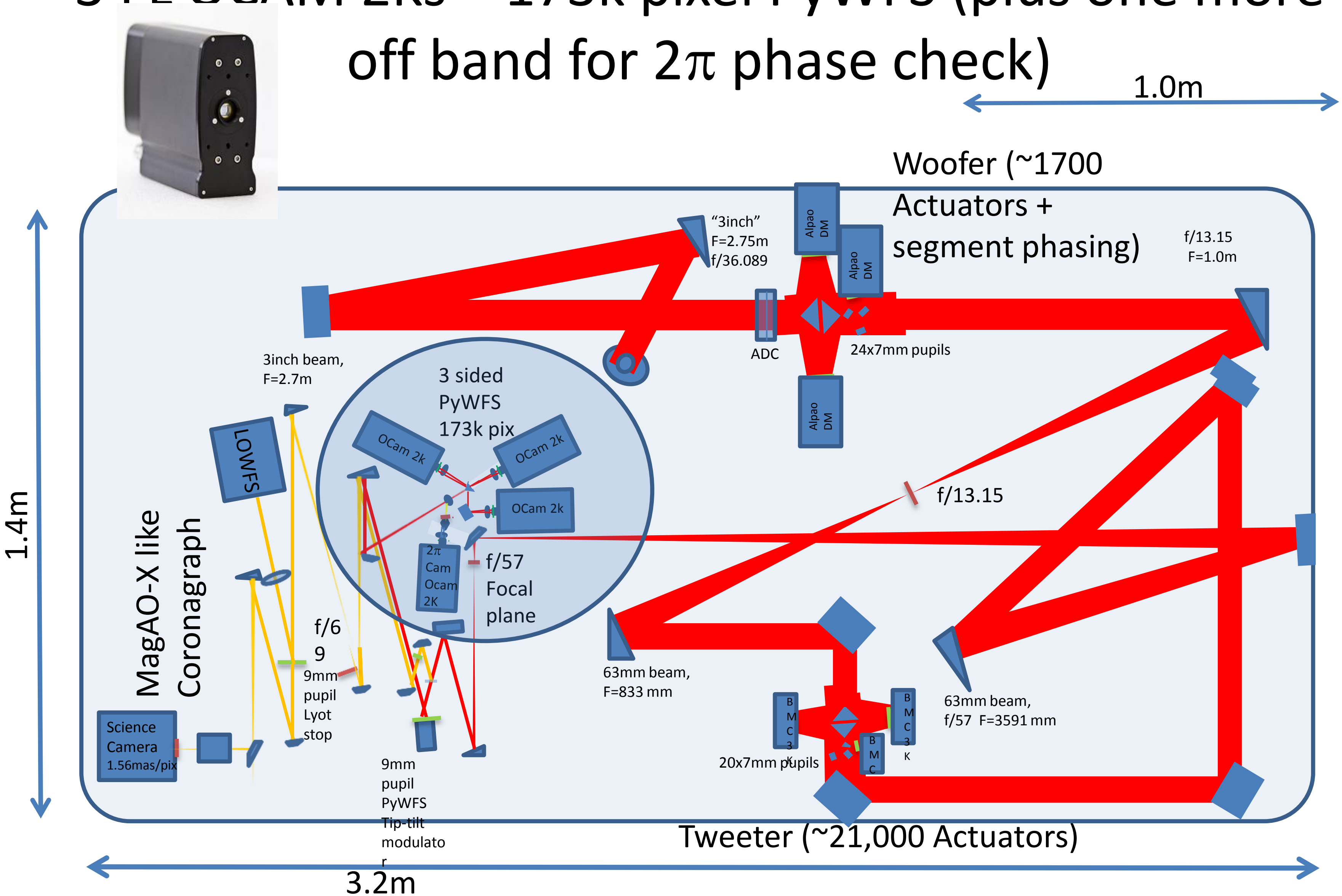
7x277 Alpao DMs= 1939 actuator Woofer



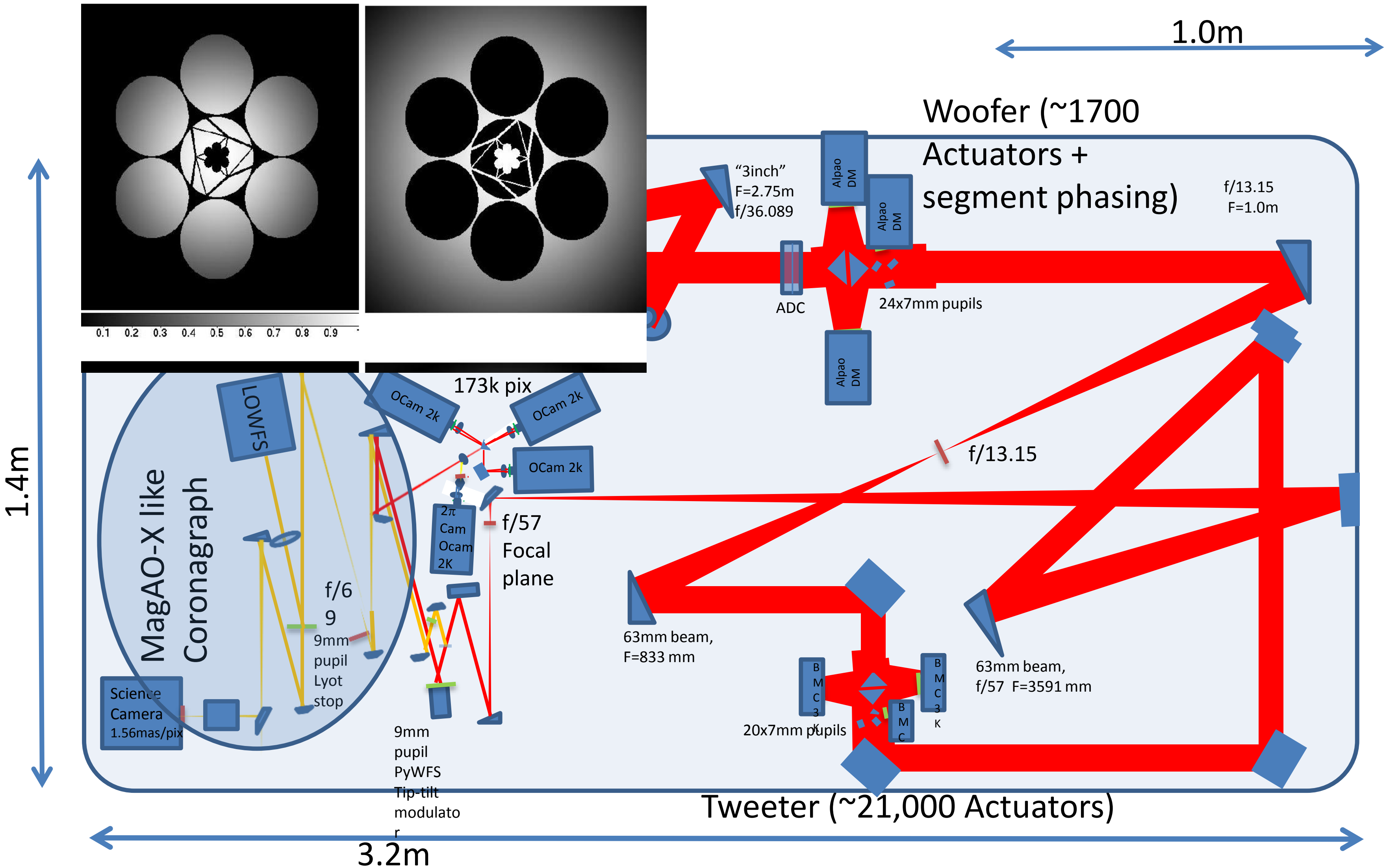
7x3000 BMC DMs= 21,000 actuator Tweeter



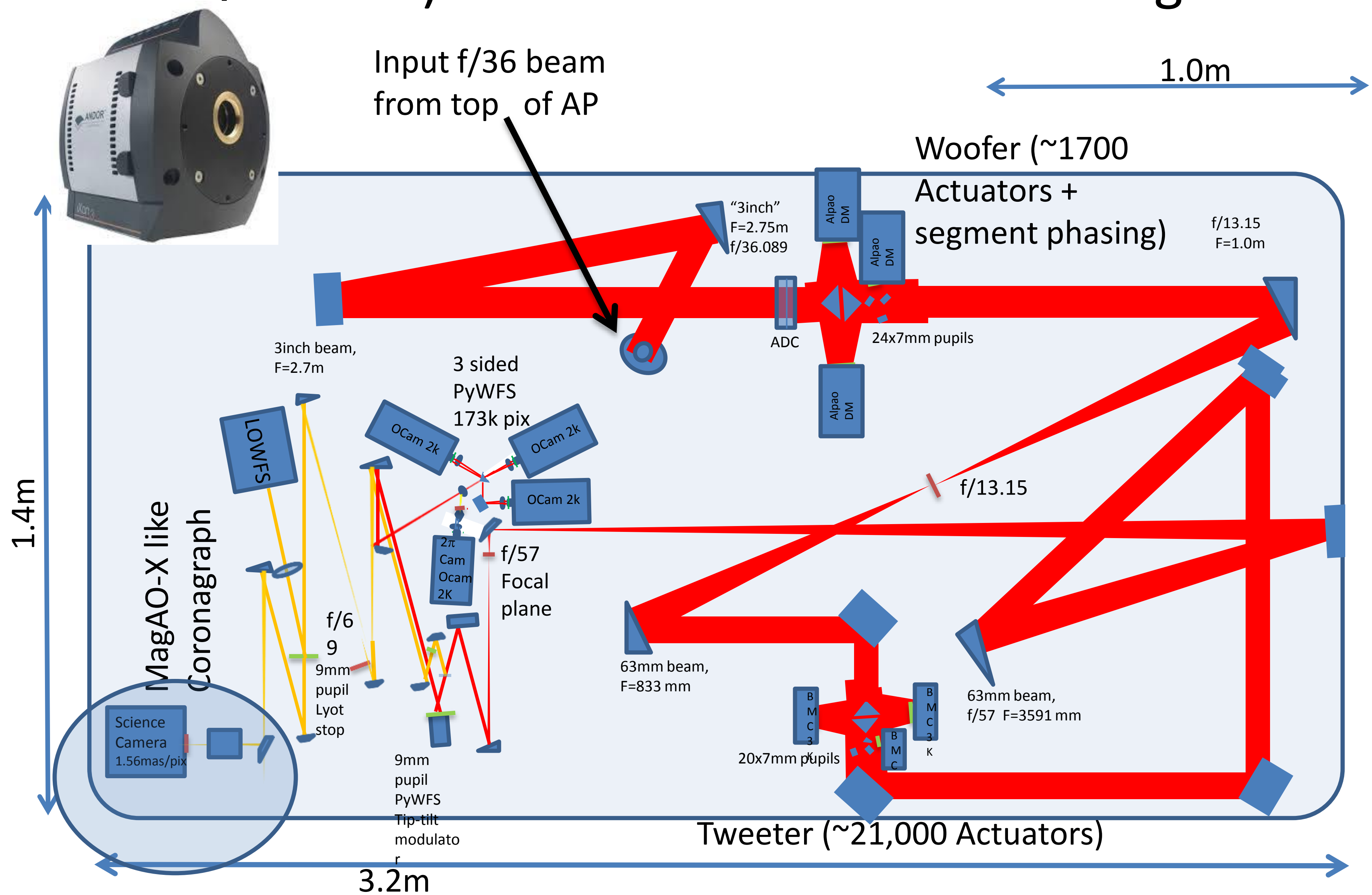
3 FL OCAM 2Ks = 173k pixel PyWFS (plus one more off band for 2π phase check)



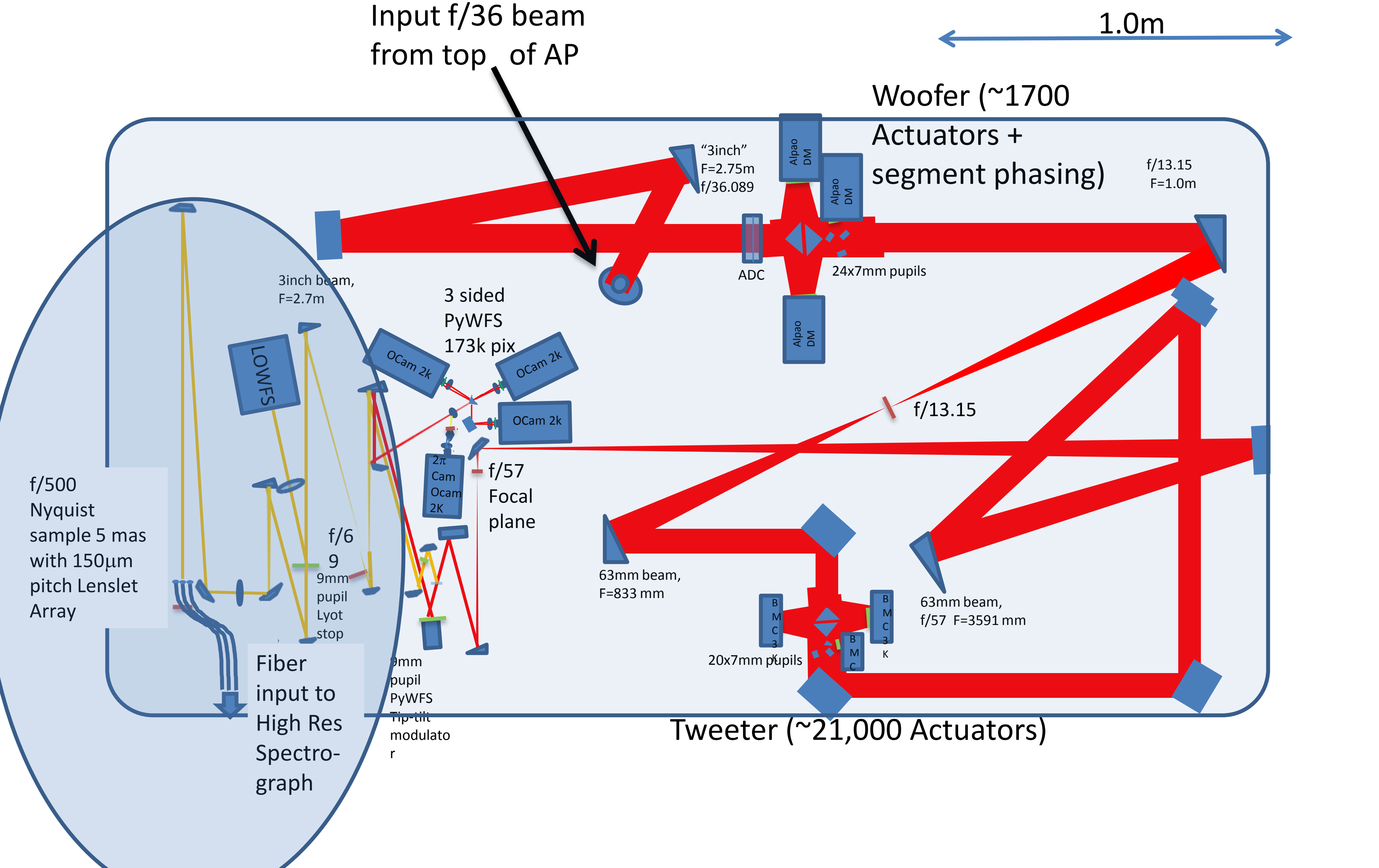
MagAO-X Coronagraph (APP or PIAACMC or others)



(EMCCD) = Science Cameras +SDI imager



f/500 Lenslet/fiber bundle Feed = High Res. Spectrograph (HCI + HRS mode)



Thank-you!

Clear Skies!

Interested in Using MagAO?:

http://visao.as.arizona.edu/

*and use the "**Information for Observers**" link*

MagAO

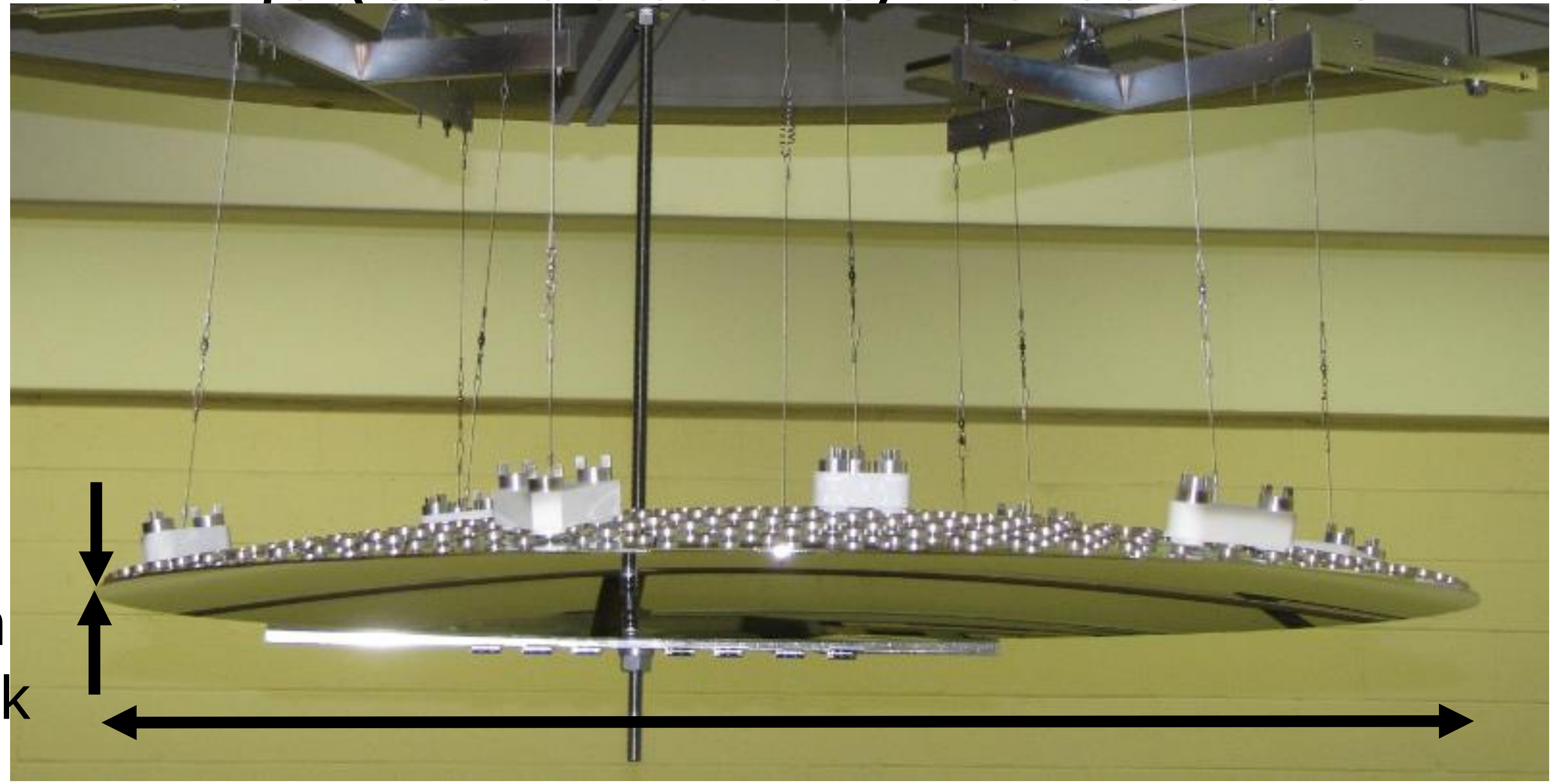
Photo by Yuri Beletsky LCO

BACKUPS

Key #1: GOOD SITE

Located at LCO (near ESO's La Silla) in Chile (beside the Giant Magellan Telescope site). The Magellan site is excellent for seeing **(<0.7" median, 0.5" nights typical**). The MagAO system is on the Clay telescope on the righthand side.

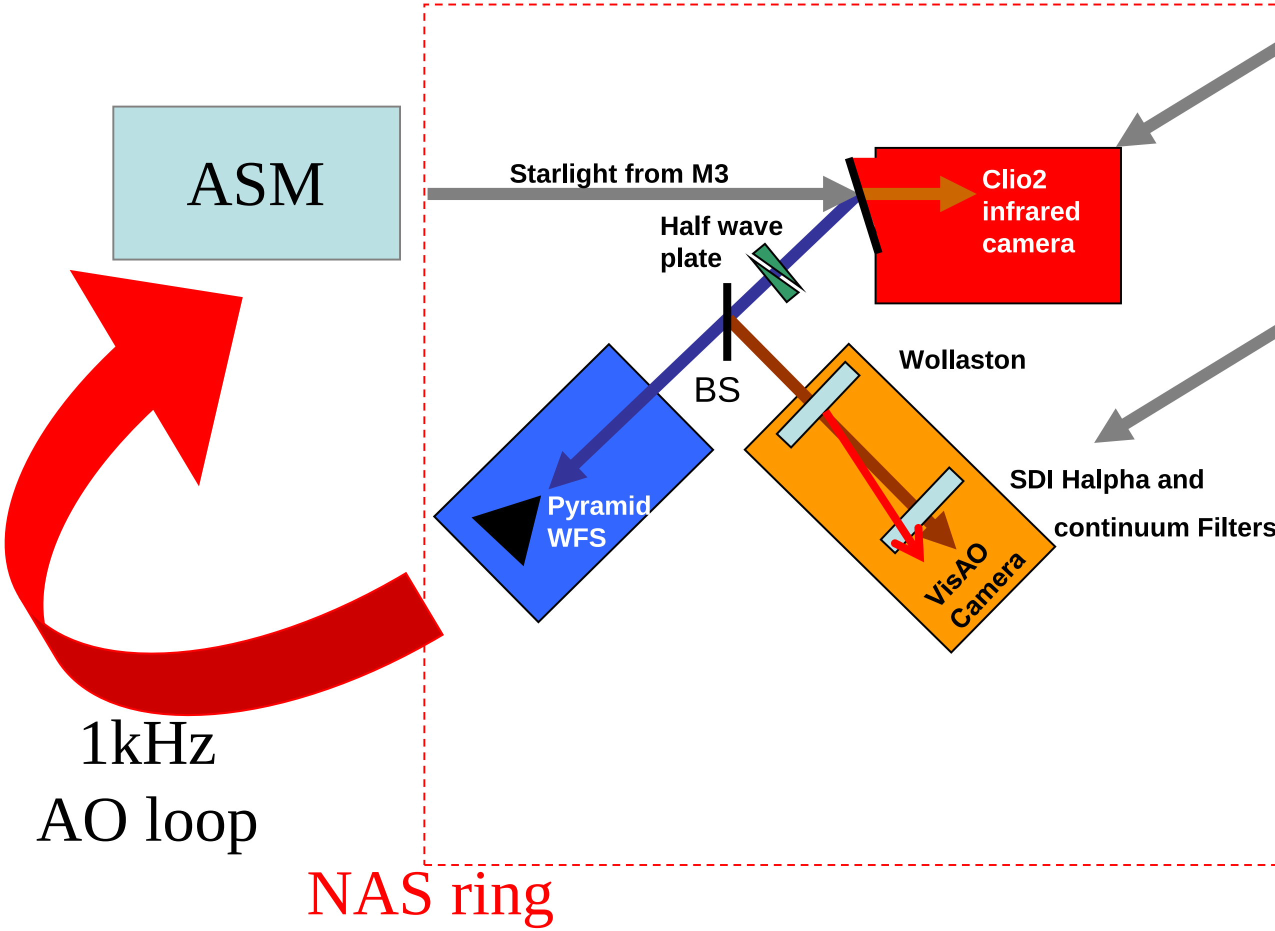
Key #2: GOOD DM adaptive secondary is thin flexible (<1 ms response time all modes) large (585 actuators) Zerodur shell



1.6 mm thick

851 mm

VisAO (SDI+ Hα) & CLIO2 IR (H or Brγ) Simultaneous SCIENCE CAMERAS



Clio2 (1-5.3 μm)

Camera, coronagraph uses all λ>1 μm light

VisAO CCD

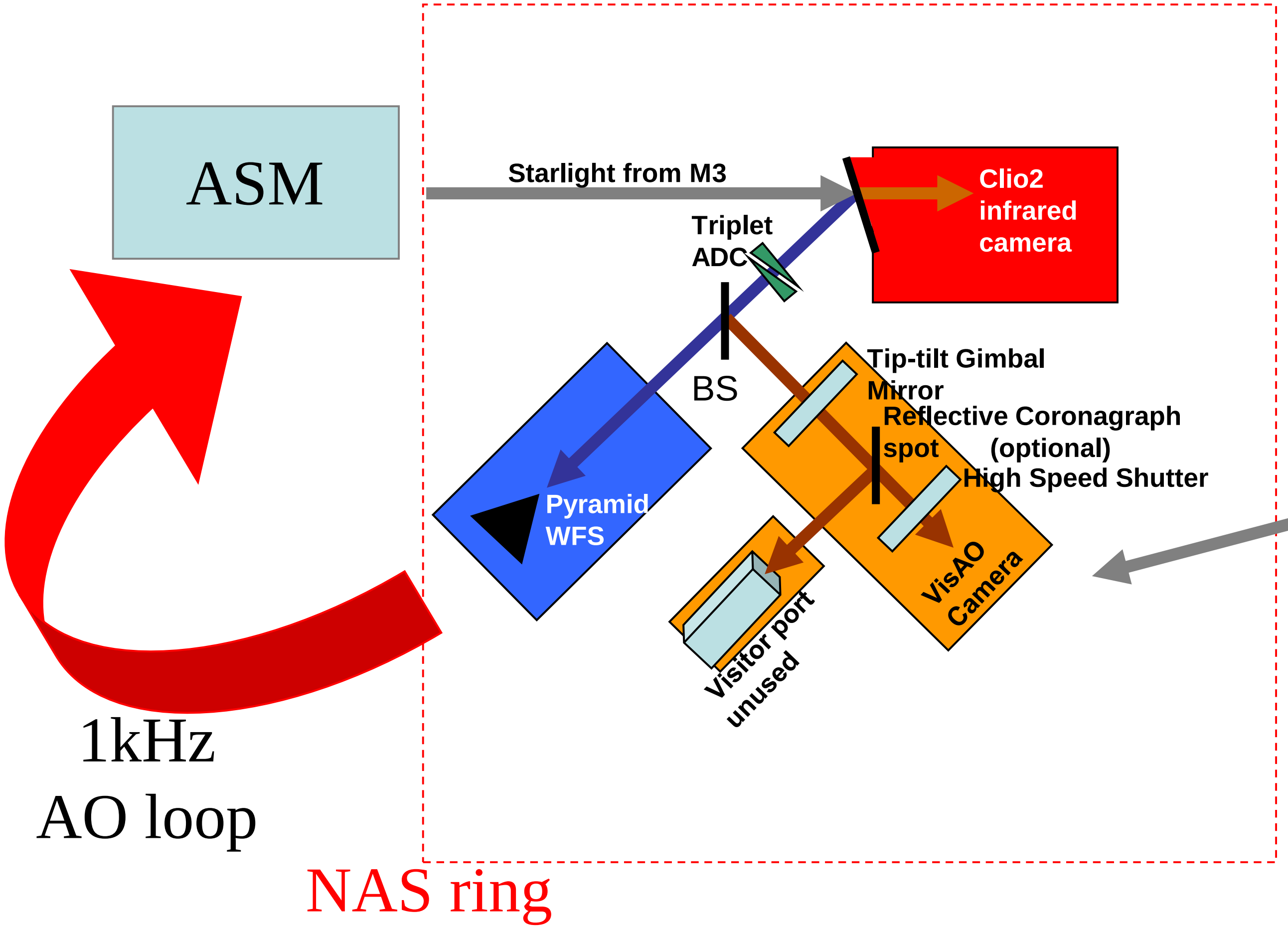
20 mas resolution CCD/coronagraph

AO imaging at Hα or longer

(0.6<λ<1.0 μm)

Clio is installed (Clio PI Phil Hinz)

VisAO Visible Light (0.6-1μm) Science Camera

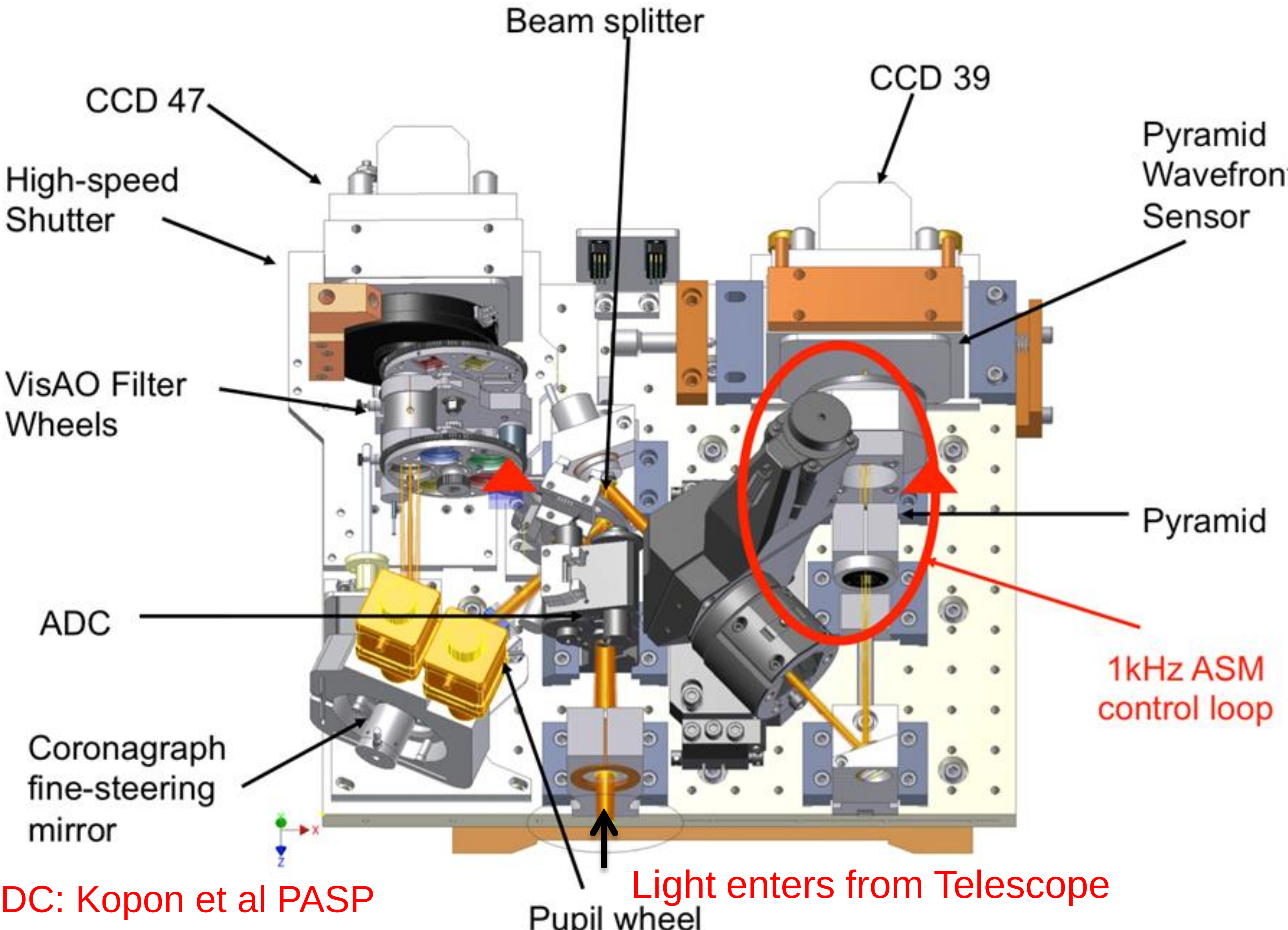


VisAO CCD
20 mas resolution
CCD/coronagraph

AO imaging at Hα and longer

(0.6<λ<1.0 μm)

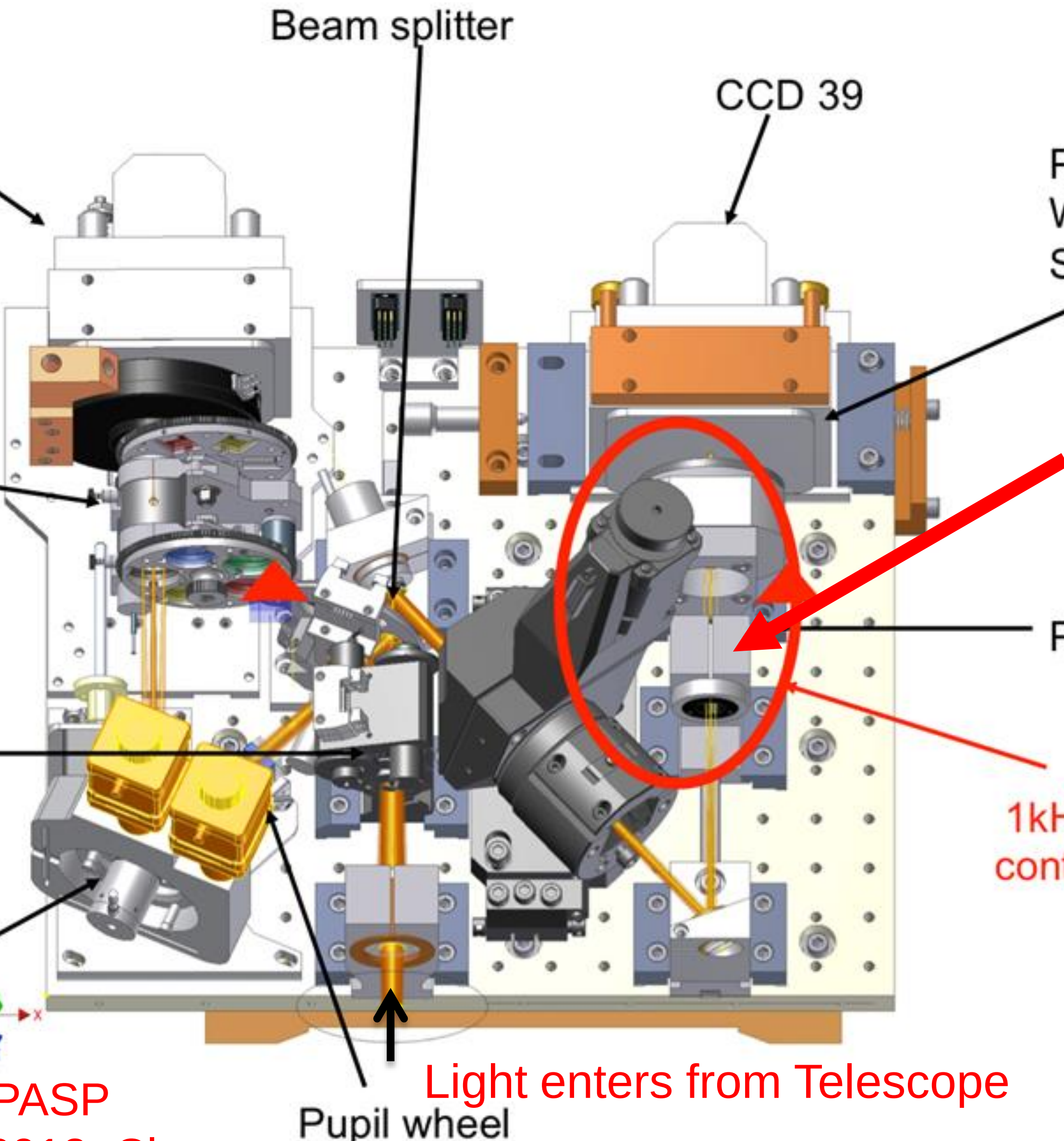
KEY#3: Coupled VisAO Science Camera and Pyramid Wavefront Sensor



ADC: Kopon et al PASP 2013, Males et al 2012, Close et al. 2013 ApJ

MagAO

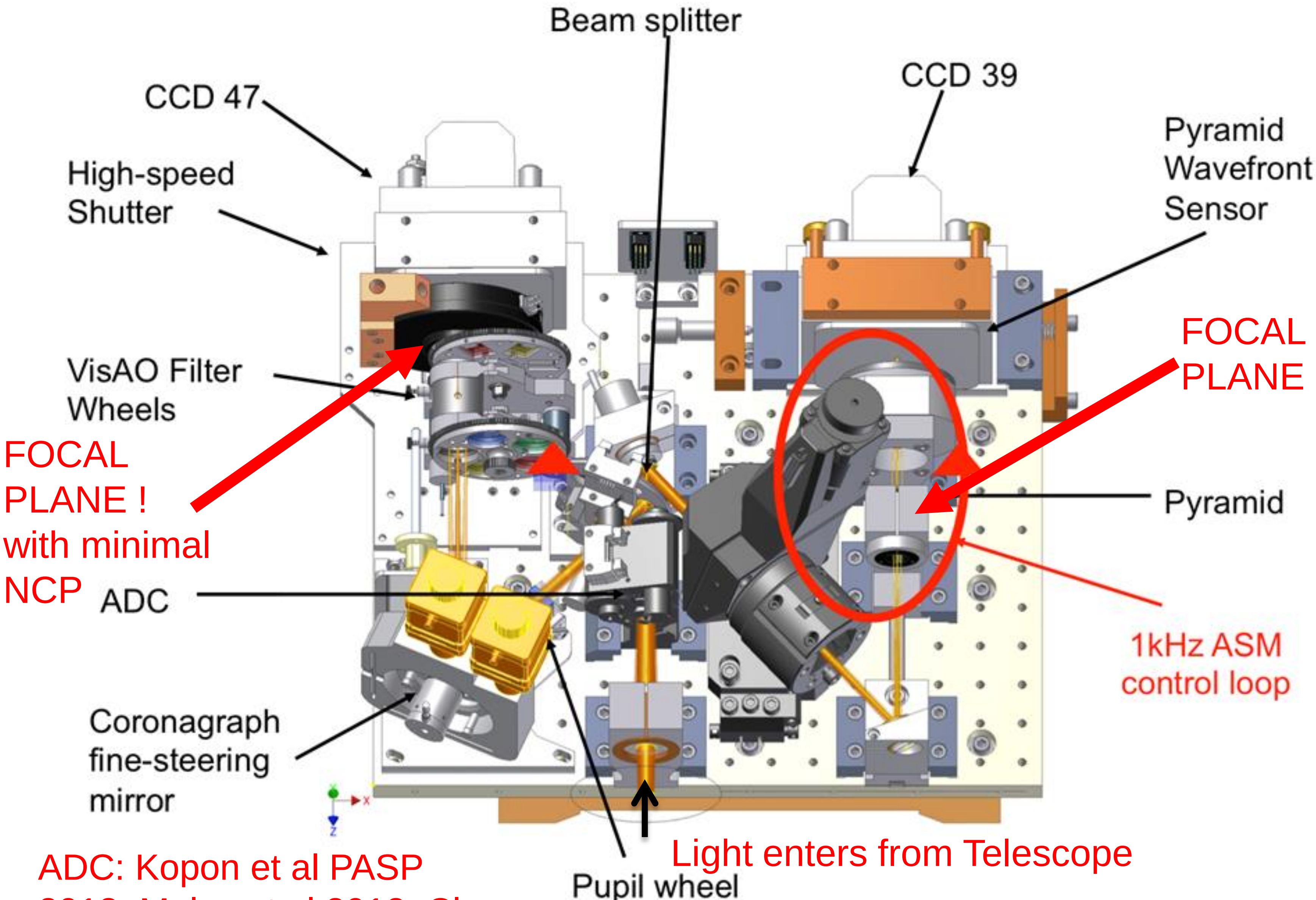
KEY#3: Coupled VisAO Science Camera and Pyramid Wavefront Sensor



ADC: Kopon et al PASP 2013, Males et al 2012, Close et al. 2013 ApJ

MagAO

KEY#3: Coupled VisAO Science Camera and Pyramid Wavefront Sensor



ADC: Kopon et al PASP 2013, Males et al 2012, Close et al. 2013 ApJ

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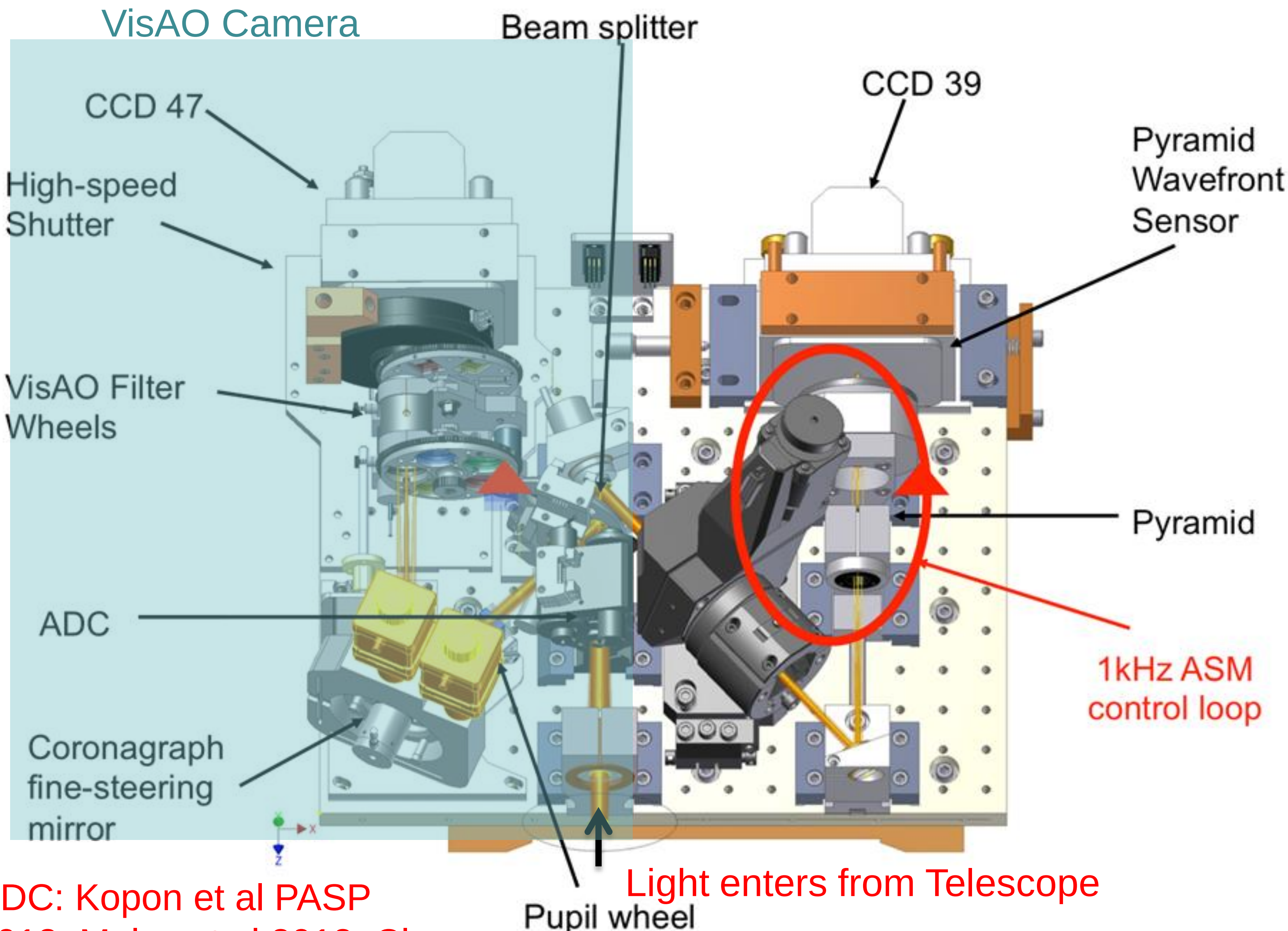

ADC: Kopon et al PASP 2013, Males et al 2012, Close et al. 2013 ApJ

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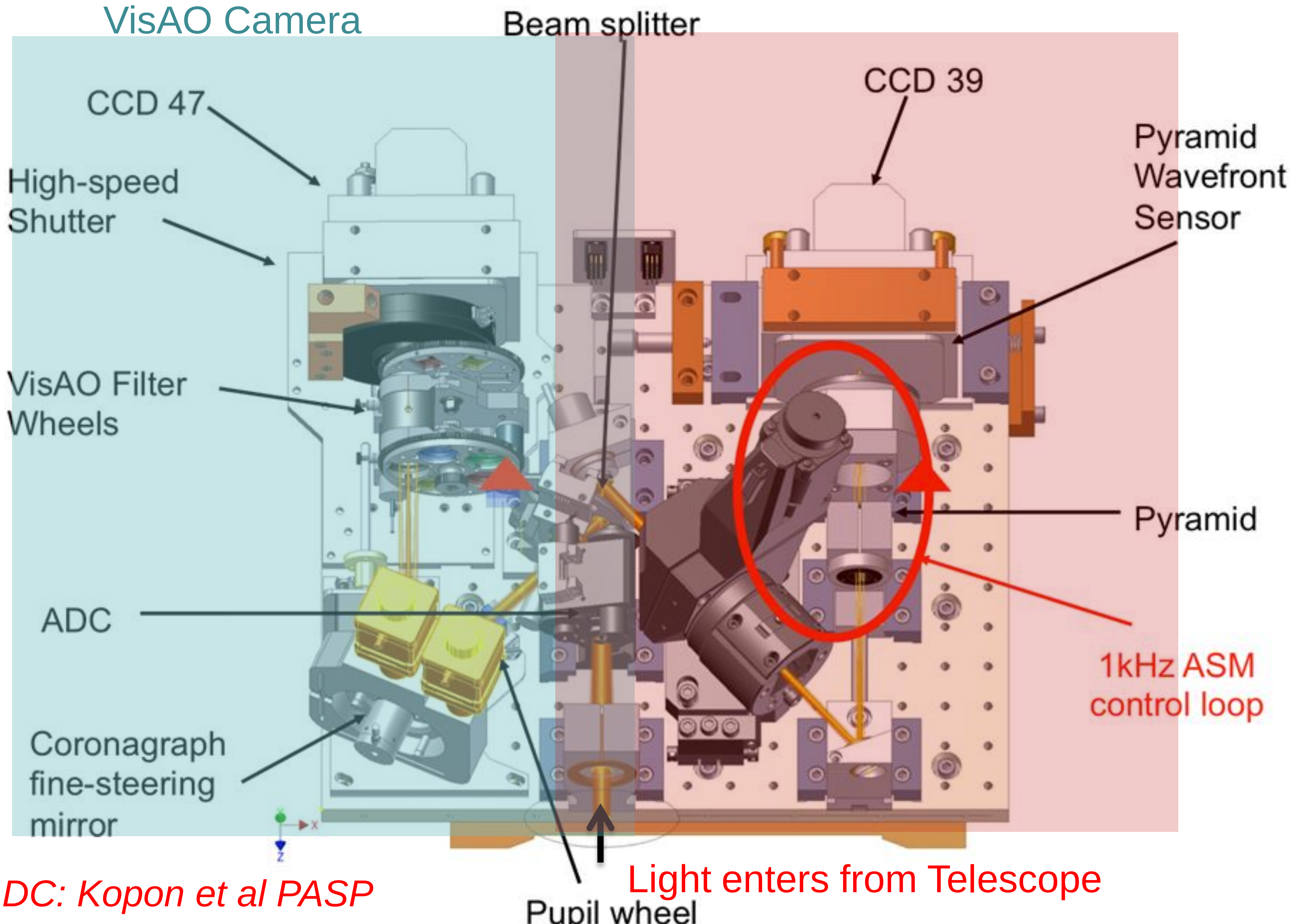
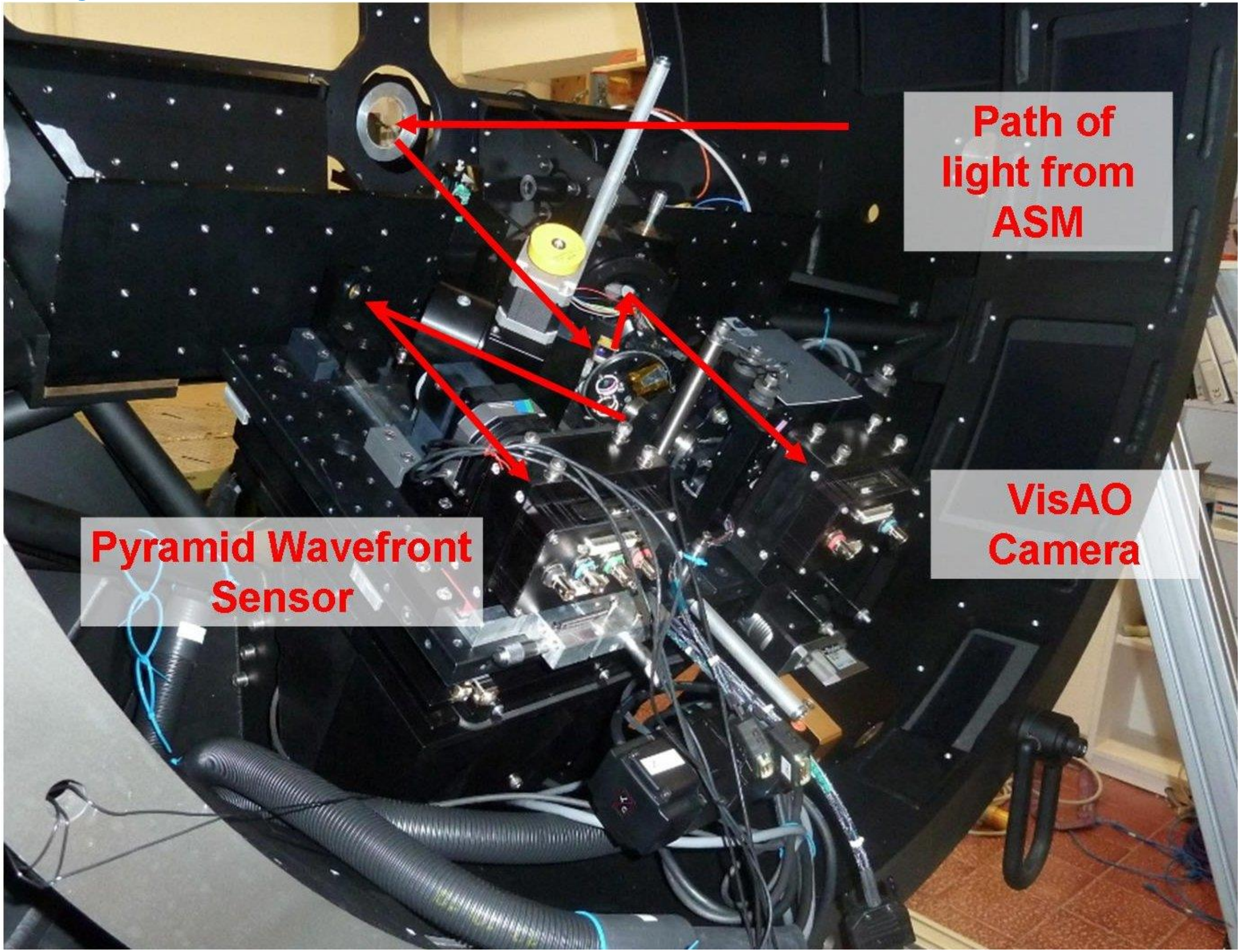
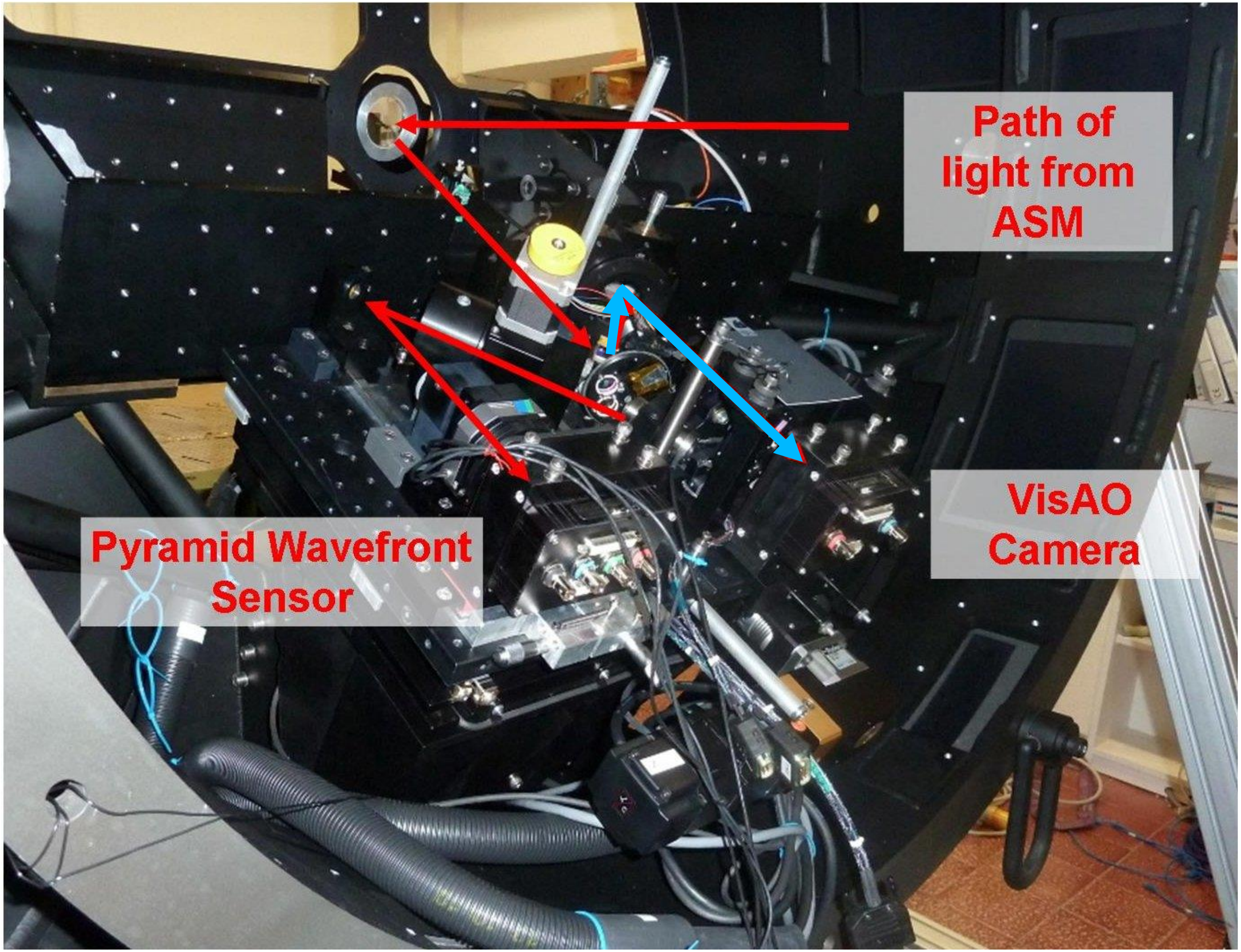


ADC: Kopon et al PASP 2013, Males et al 2012, Close et al. 2013 ApJ

Key #3: CCD Camera and WFS on same table



Close et al. 2012



Close et al. 2012

MagAO ^{2K} upgrade

- Now 1 kHz PWFS speed→ Baseline 1.5 KHz (goal 2 kHz)
- IR camera 512x1024 pixels → Upgrade Clio2 to 2kx2k H2RG MBE 1-5um detector

				Total WFE [nm]			
	Speed	PWFS Sampling	Controlled Modes	25%	50%	75%	Jitter rms
current	1 kHz	27x27	300 modes	102	142	180	8.1 mas
baseline	**1.5 kHz**	**30x30**	**400 modes**	**92**	**121**	**145**	**6.0 mas**
goal	**2.0 kHz**	**34x34**	**450 modes**	**90**	**114**	**137**	**4.0 mas**

MagAO

Better Calibration → 450 modes

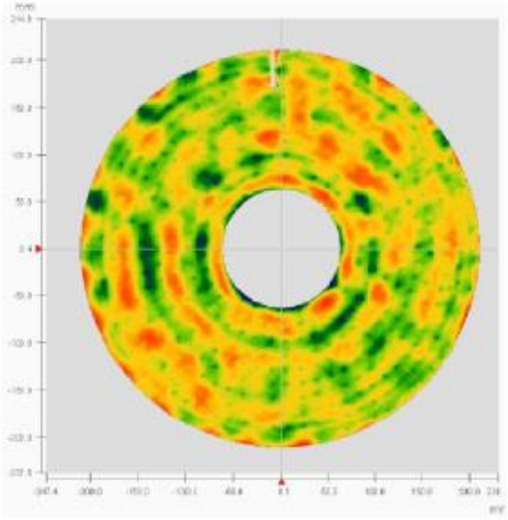


Figure 9: The MagAO ASM flat measured using the 4D in the Arcetri test tower lab, which had a 50 nm r.m.s. phase residual. One important goal of this work is to develop the ability to make this measurement at LCO.

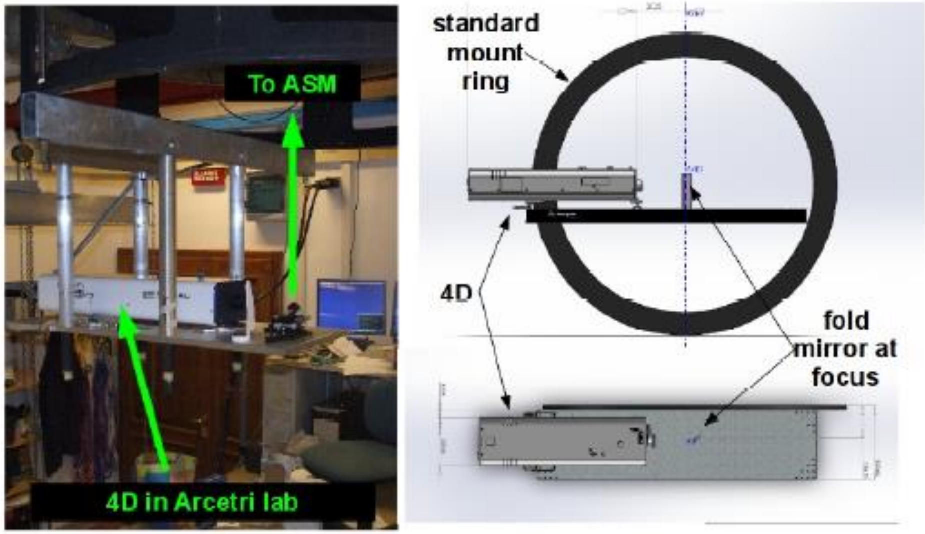


Figure 10: Left: The 4D interferometer in use at the Arcetri test-tower lab. This is the unit that will be shipped to LCO for this work. **Right:** Solid model showing the notional layout of the 4D and the mounting ring. NOTE: the complete specification and design of the ICD compliant mechanical interface is part of this effort. These drawings serve only to establish feasibility.

Current Vibrations ~8mas rms (Goal 4 mas rms)

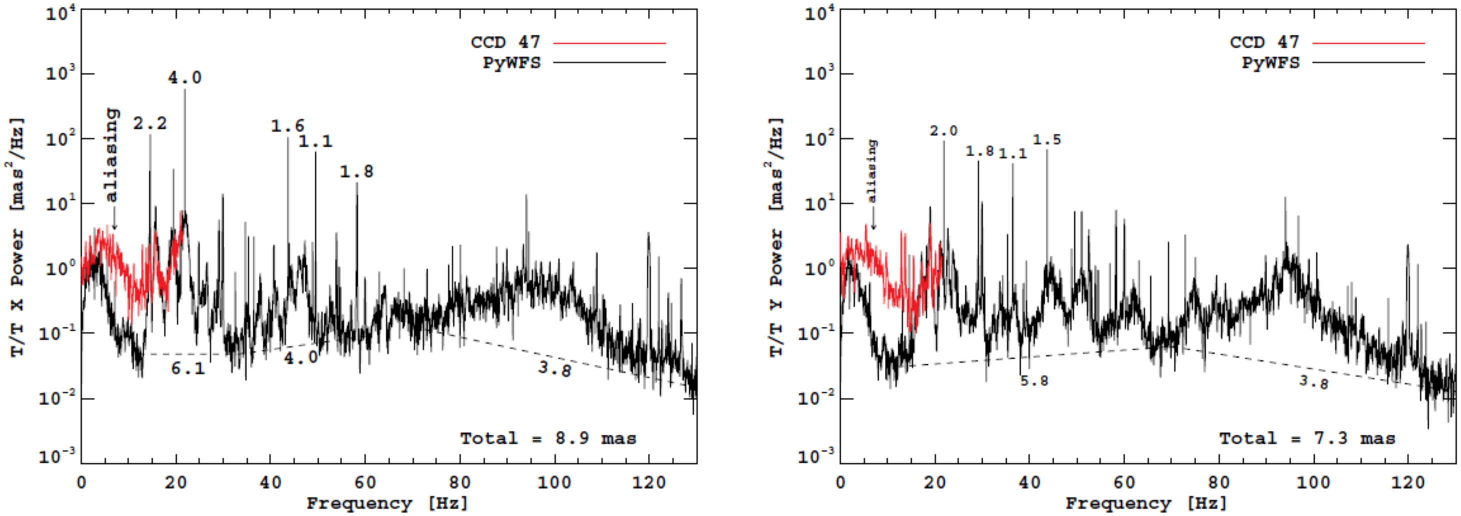
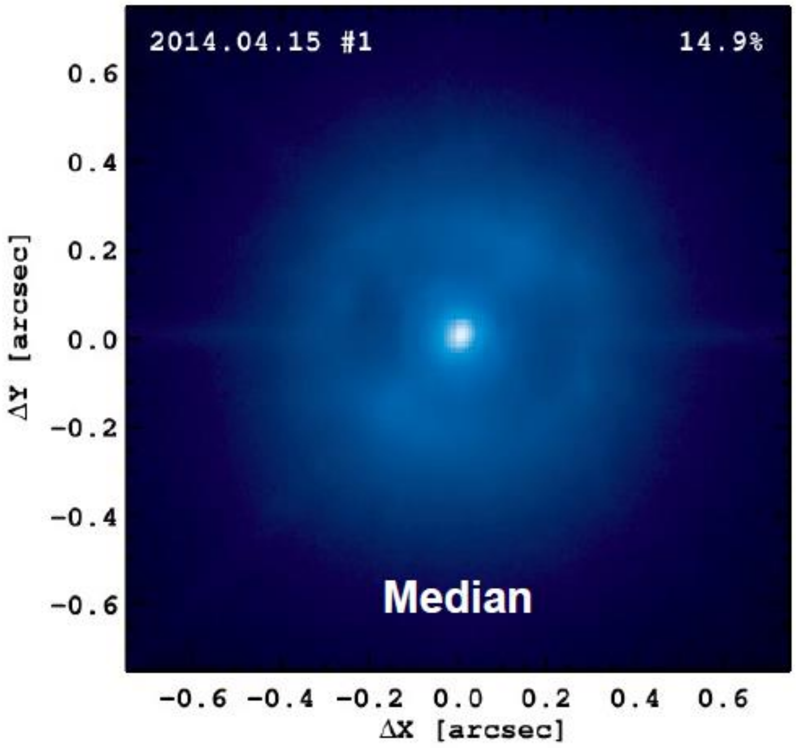
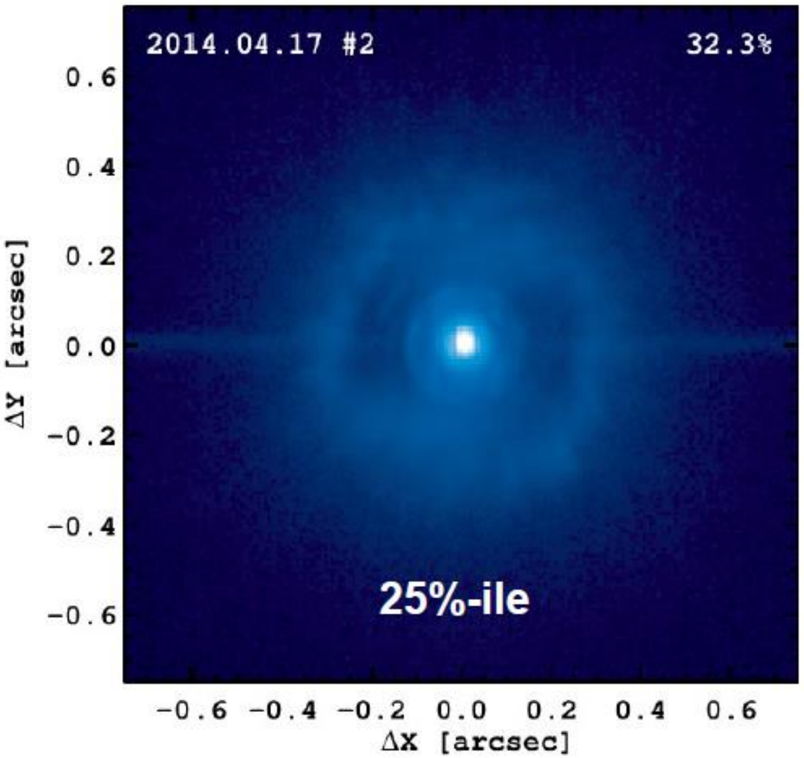


Figure 12: Vibration PSDs measured in 1 kHz closed-loop on-sky. The CCD-47 image position was measured at 42 f.p.s., and the PWFS tip and tilt modal amplitudes were recorded at 333 Hz (1/3 loop speed). The PWFS tip/tilt PSDs (black) were normalized to the CCD-47 PSDs (red) from 15 to 21 Hz (lower frequencies are subject to aliasing). Peaks are labeled with root-integrated-power in mas. The area between the PSD and a simple estimated continuum is also indicated. The bandwidth is obvious at ~95 Hz.

I band Strehls 32% → 50%

- The following plots are based on the preceding analysis.
- Comparisons to on-sky data are for alpha Cen A observations of 2014A.





<100nm rms wavefront error (50% Strehl at I-band)

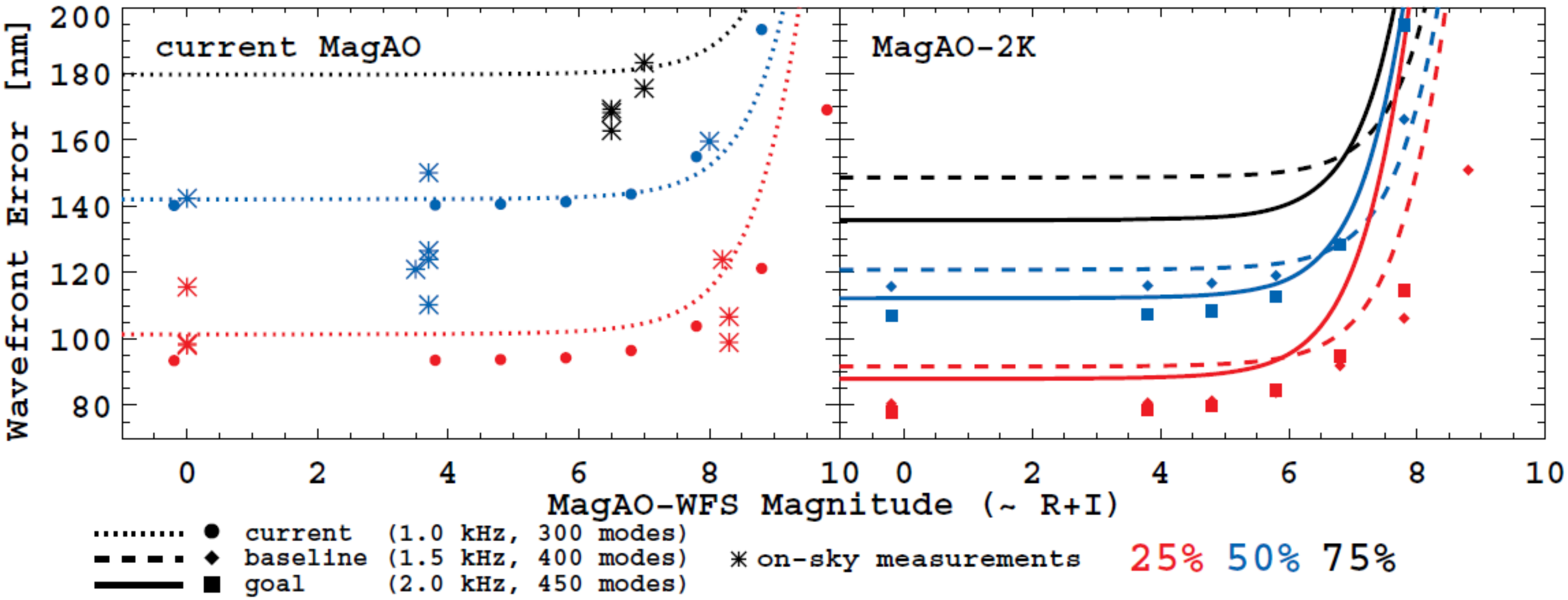
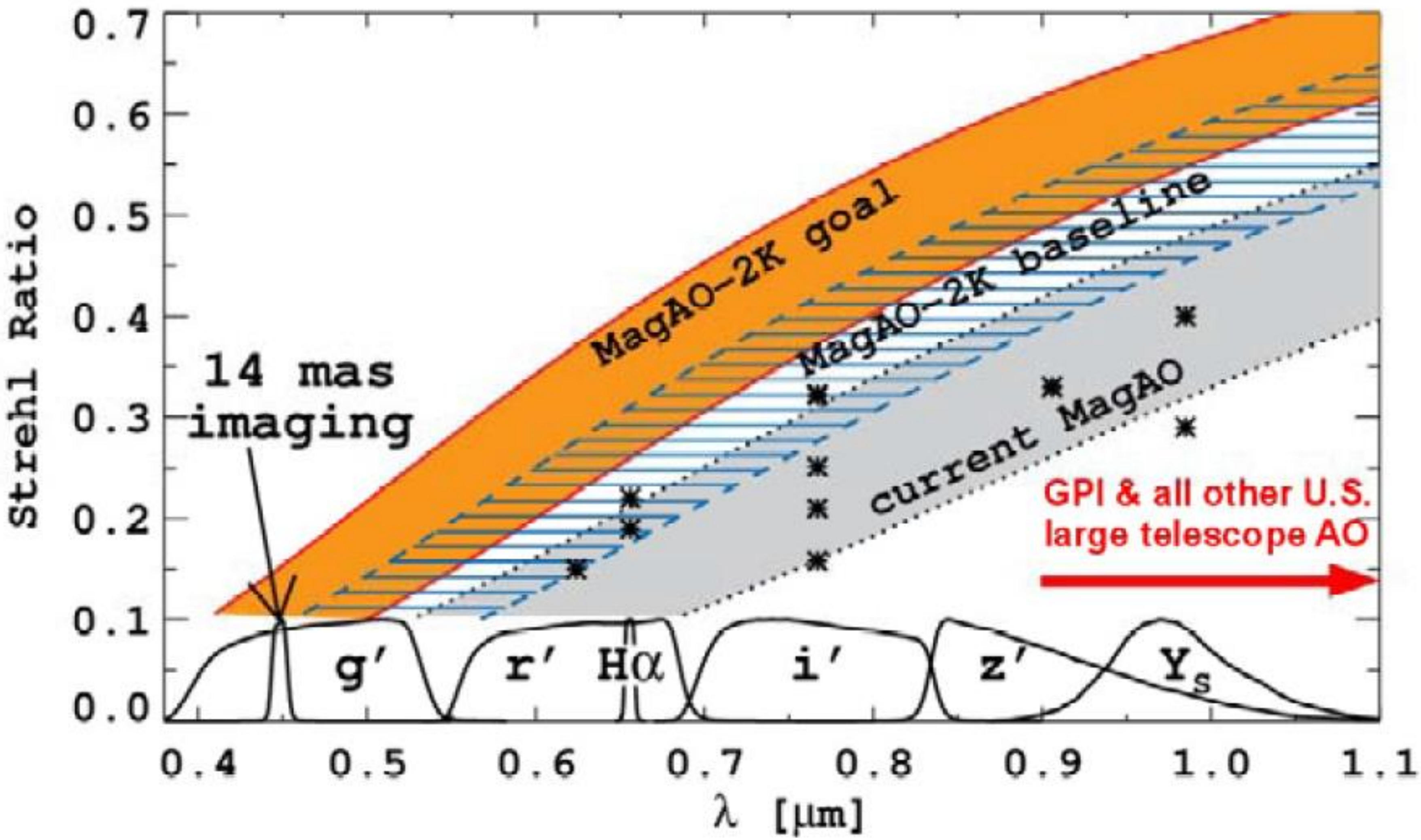
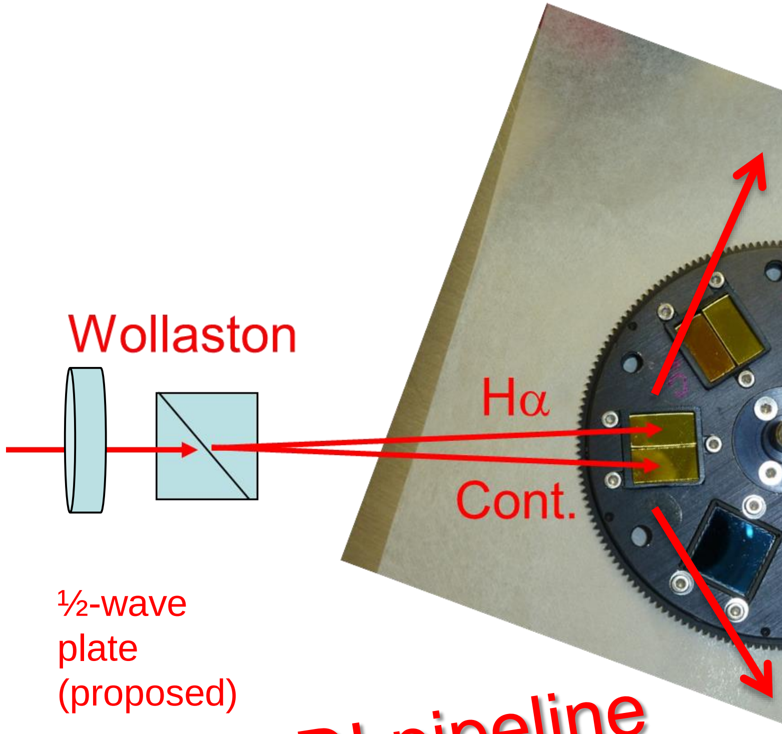


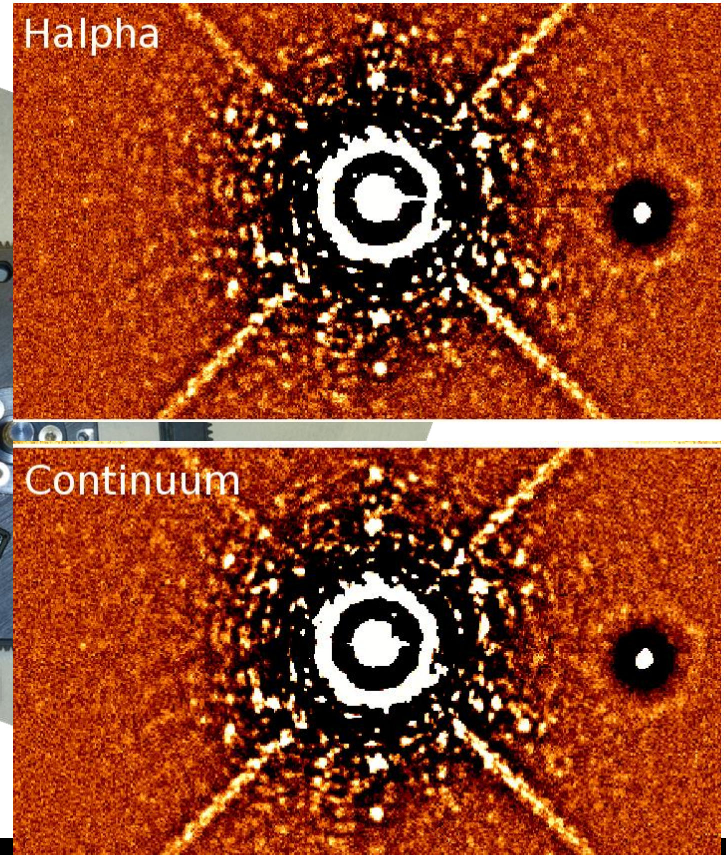
Figure 13: MagAO wavefront error (WFE). **Left panel:** current WFE, in 25%-ile (red), 50%-ile (blue), and 75%-ile (black) conditions without jitter. Lines are the analytic error budget, filled symbols are end-to-end simulations (for 25% and 50%), and asterisks are on-sky measurements from VisAO, corrected for 8.1 mas jitter. Our models of MagAO performance at LCO are validated by the on-sky data. **Right panel:** predicted performance of MagAO-2K under the same conditions. The baseline upgrade will produce performance in 75% conditions equal to current-system performance in 50% conditions.

Overview of Upgrade



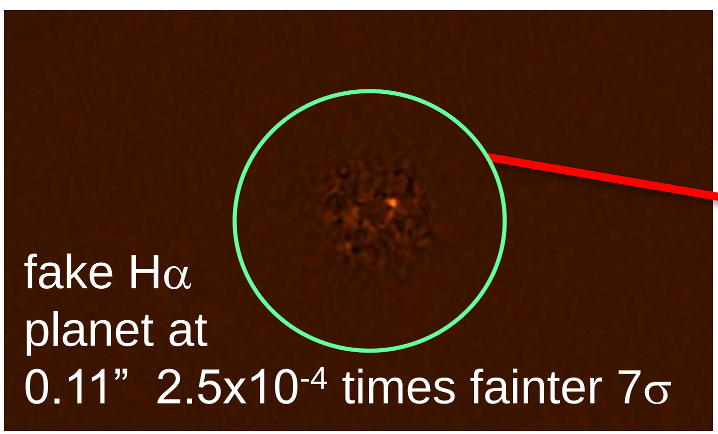
MagAO

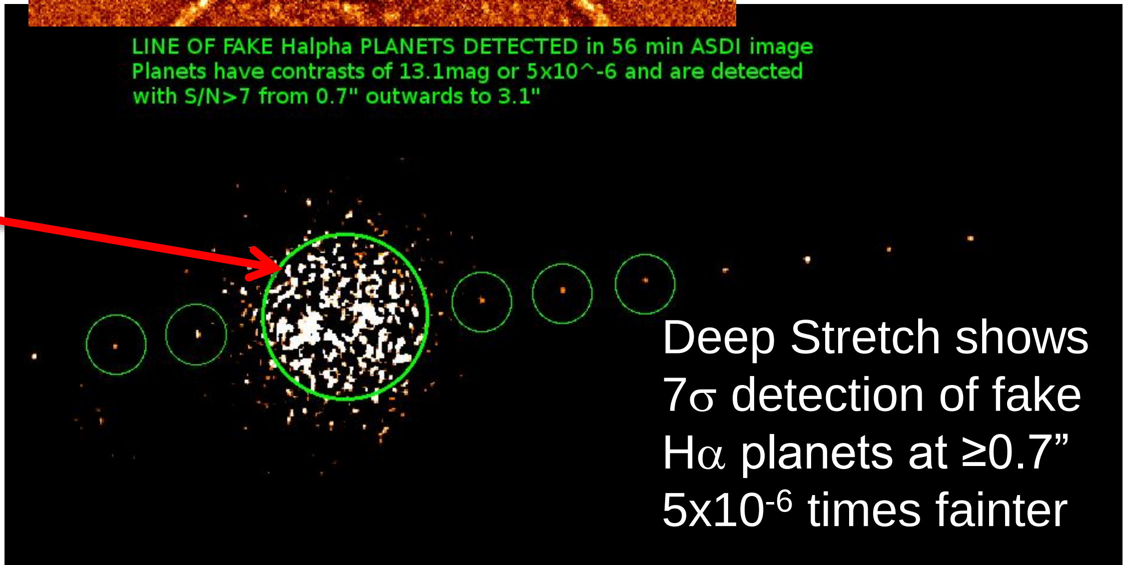




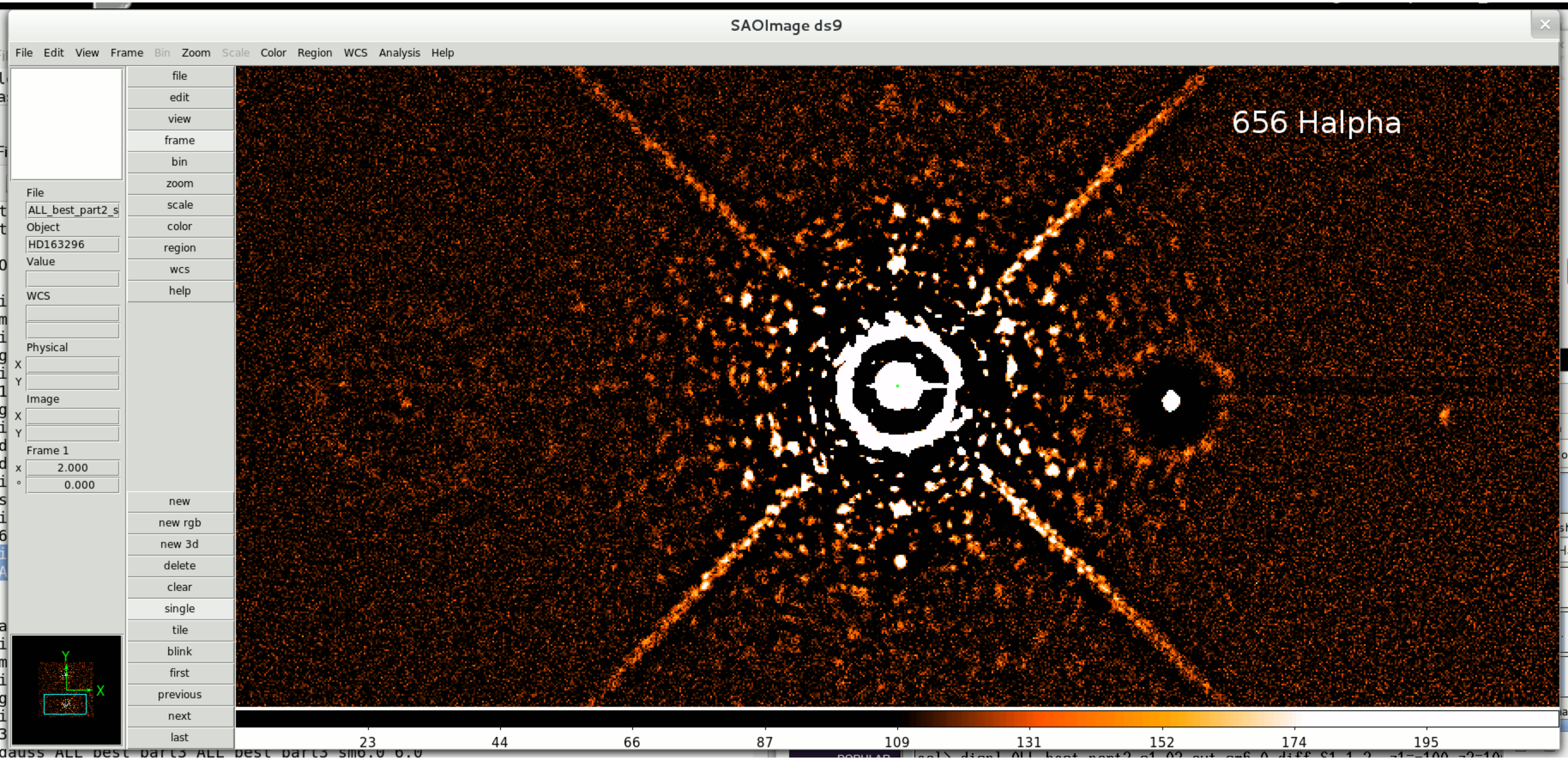
Optical Break through: SDI images are identical to the <0.1% level (best speckle calibration ever)

ASDI pipeline

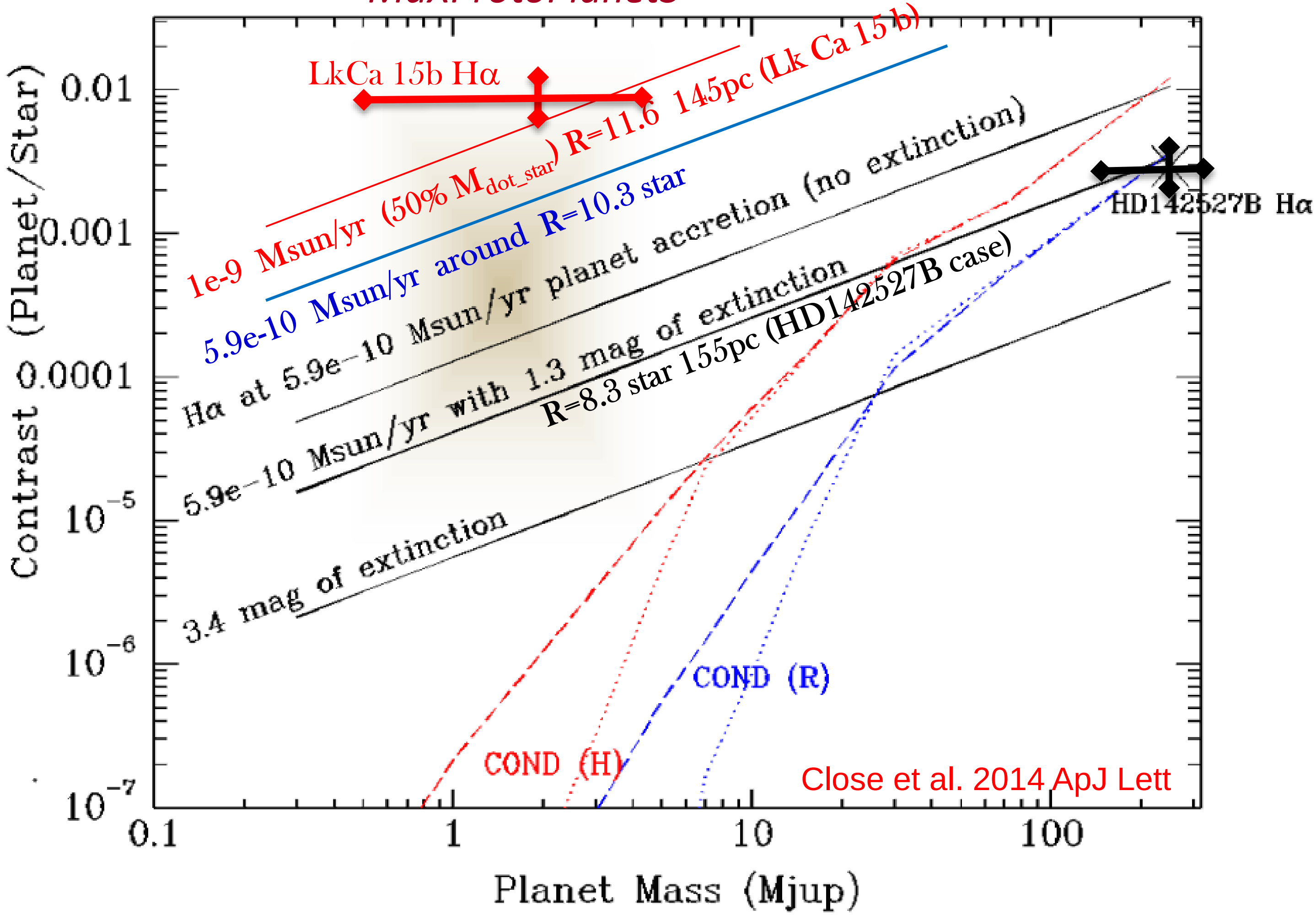




SDI Optics are very good now

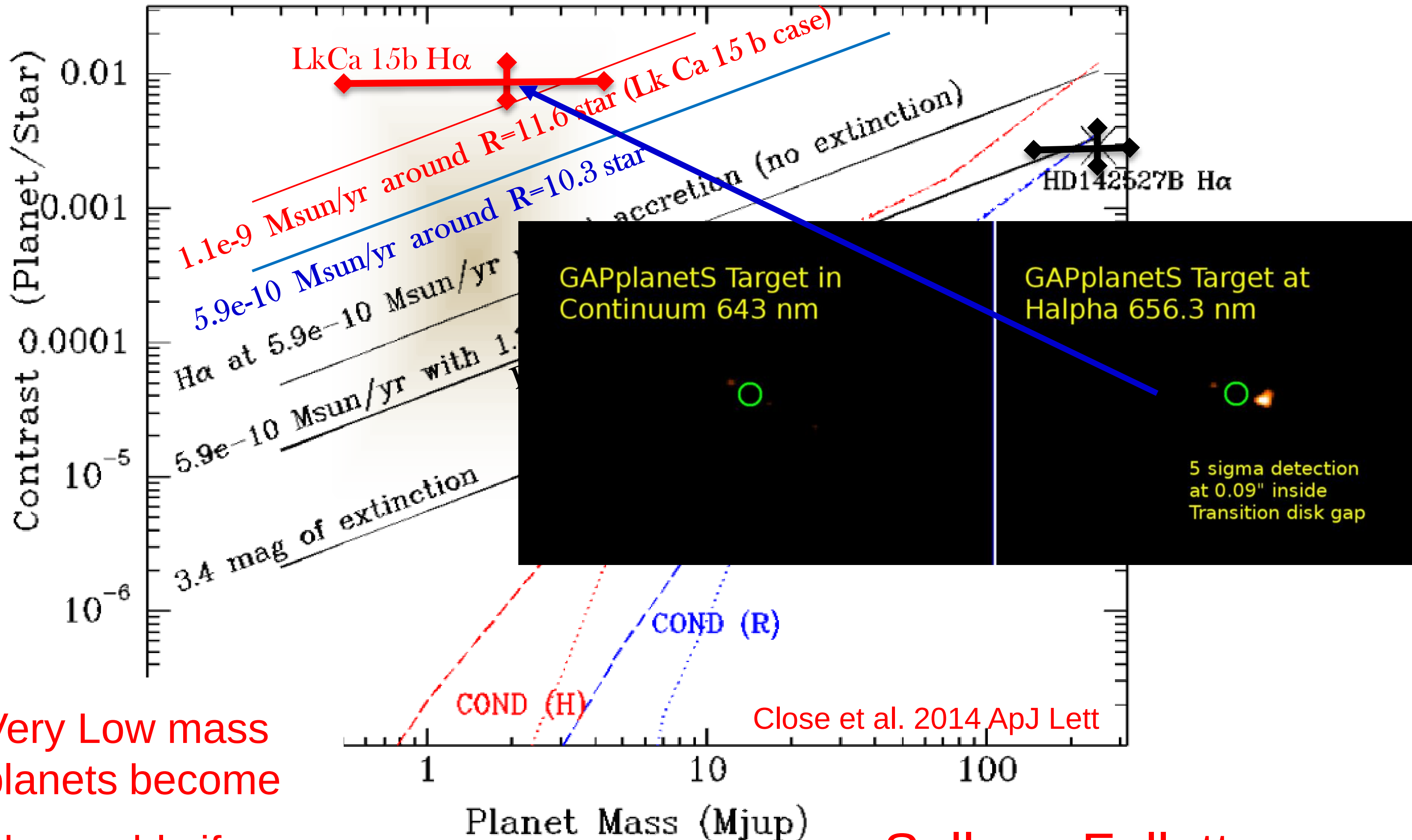


Likely distribution of MaXProtoPlanetS



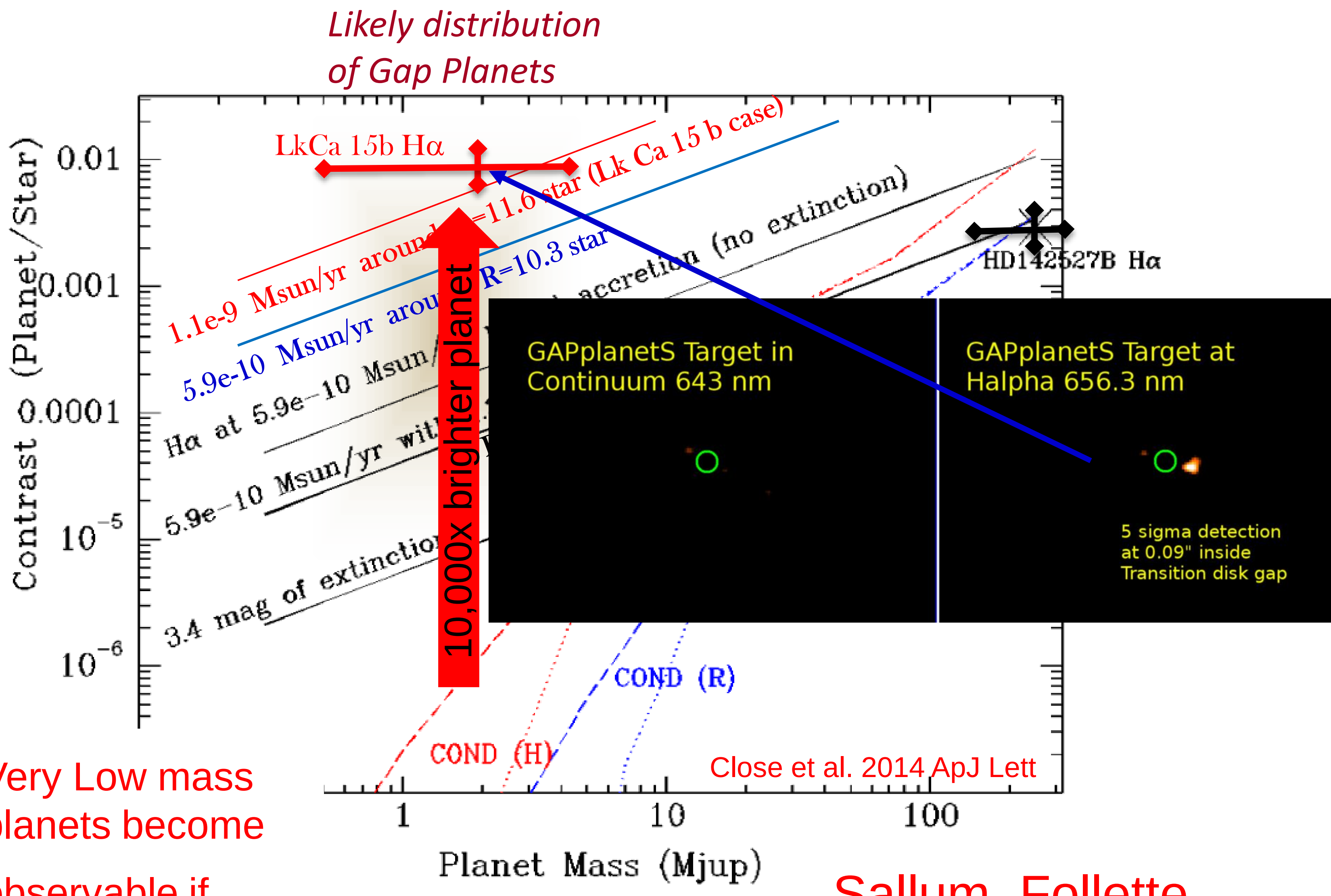
MagAO

Likely distribution of Gap Planets



Very Low mass planets become observable if accreting at Halpha !

Sallum, Follette, Eisner, Close et al. Nature in press



Very Low mass planets become observable if accreting at Halpha !

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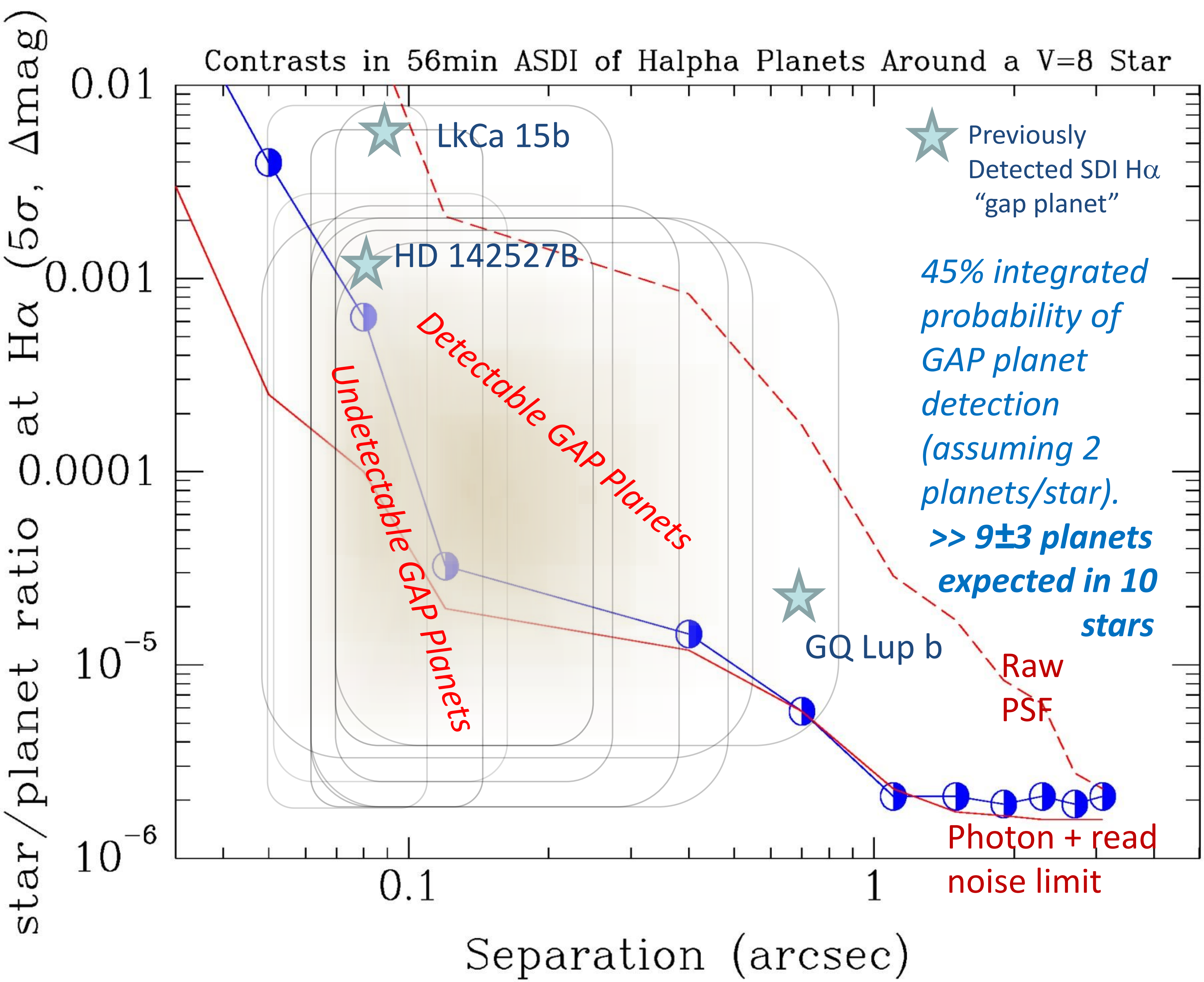
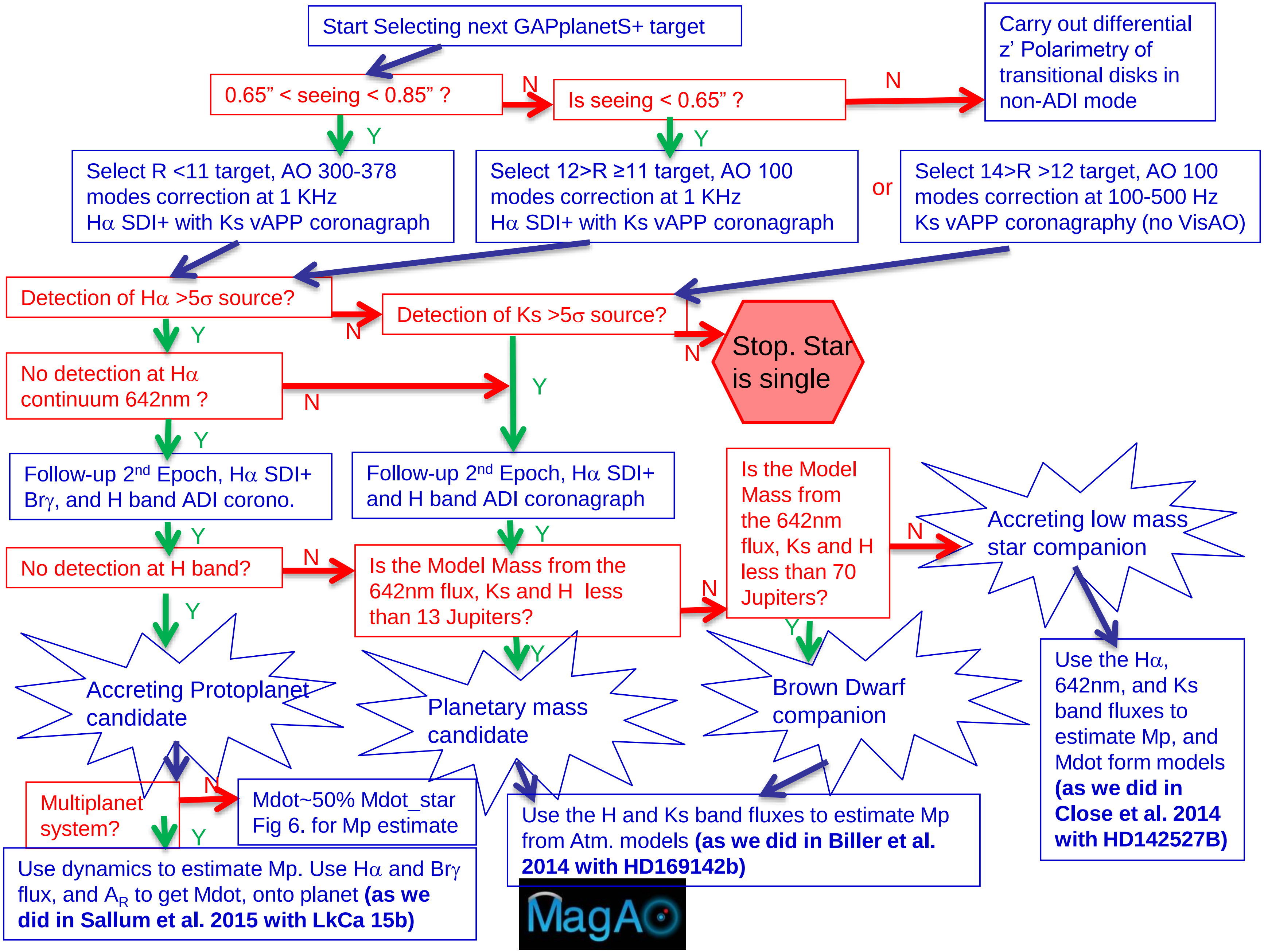
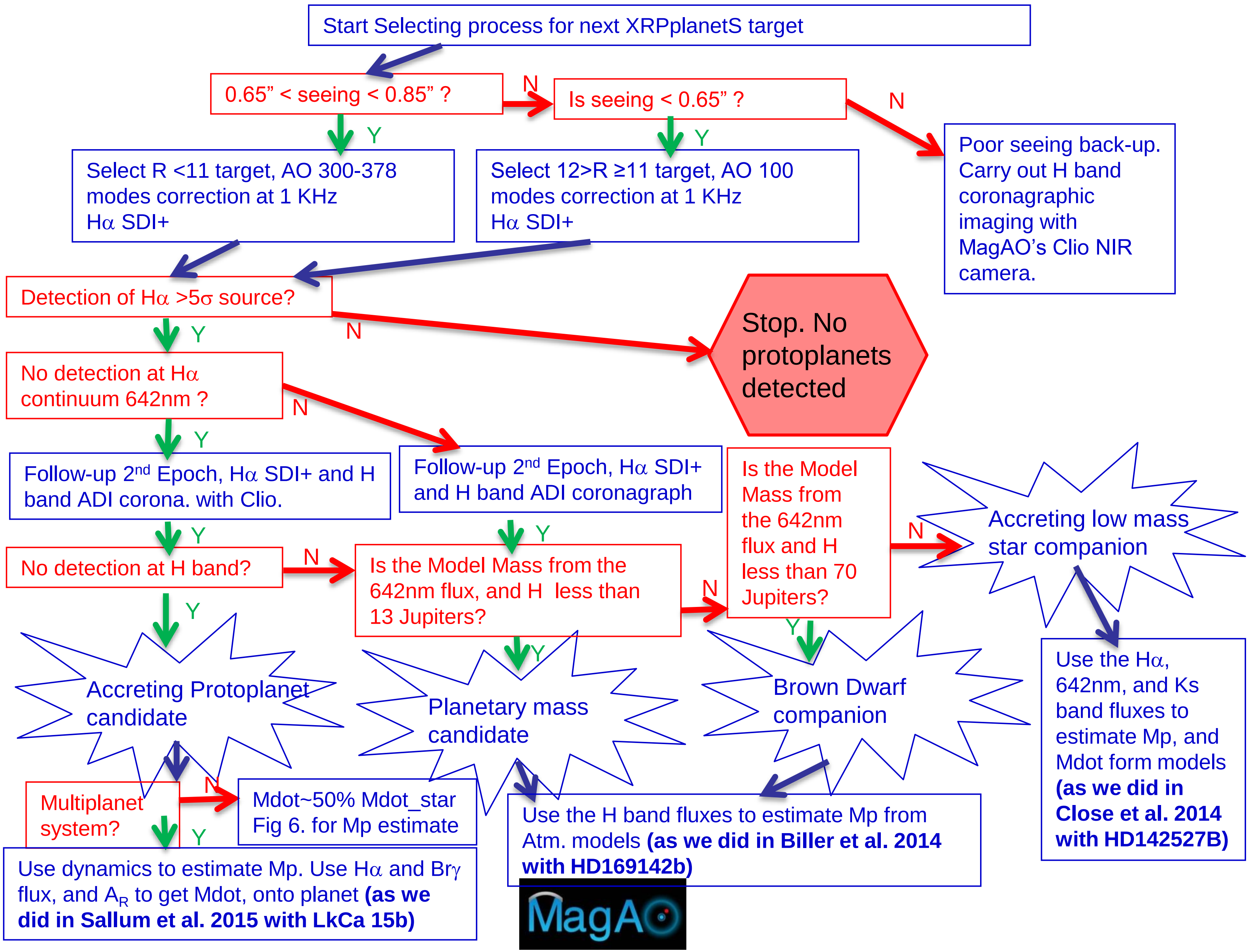
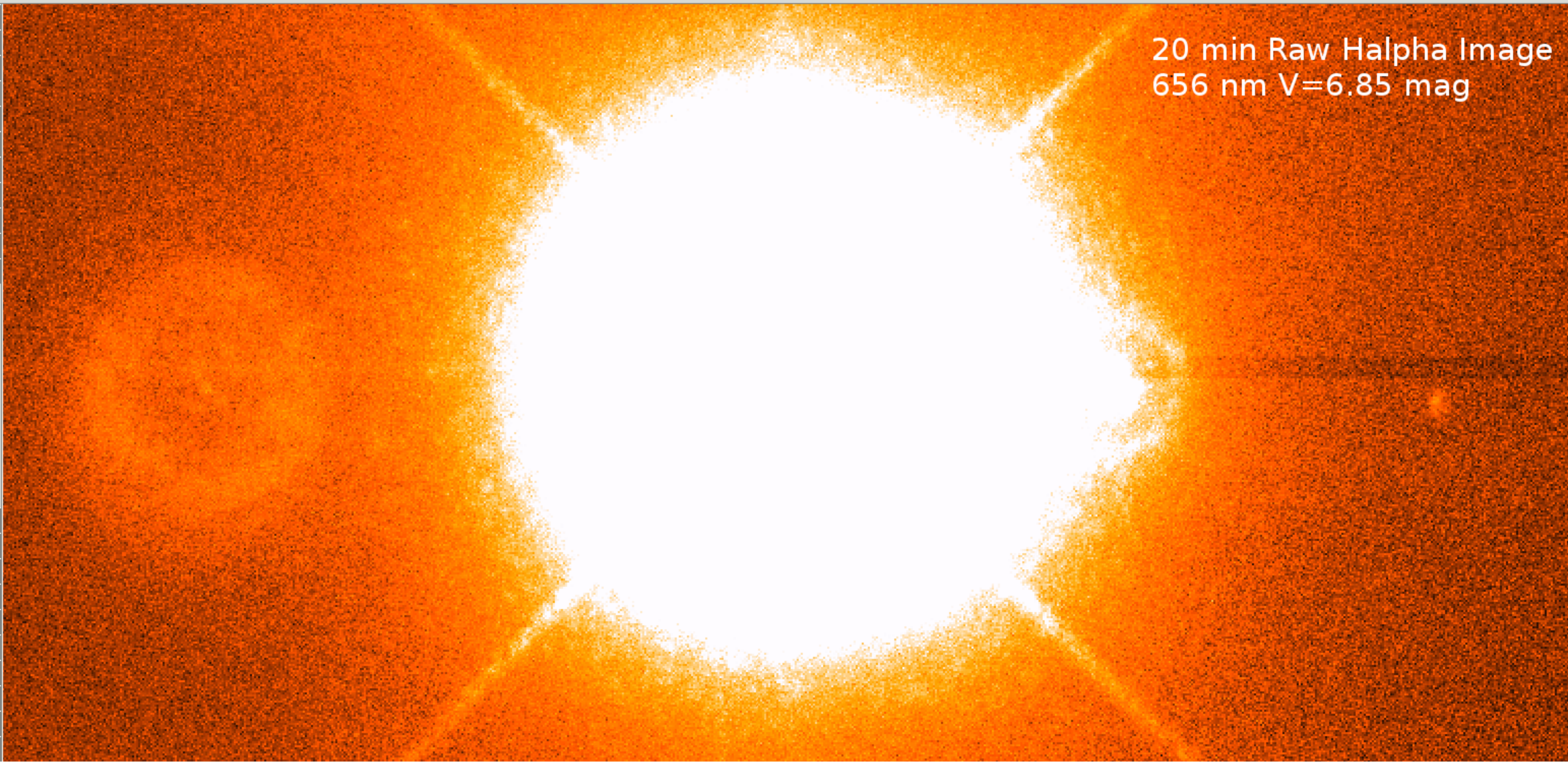

Contrasts in 56min ASDI of Halpha Planets Around a V=8 Star
star/planet ratio at Hα (5σ, Δmag)
0.01
0.001
0.0001
10^{-5}
10^{-6}
0.1
1
Separation (arcsec)
LkCa 15b
HD 142527B
GQ Lup b
Previously Detected SDI Hα "gap planet"
Detectable GAP Planets
Undetectable GAP Planets
45% integrated probability of GAP planet detection (assuming 2 planets/star).
>> 9±3 planets expected in 10 stars
Raw PSF
Photon + read noise limit


Start Selecting next GAPplanetS+ target
0.65" < seeing < 0.85" ?
N
Is seeing < 0.65" ?
N
Carry out differential z' Polarimetry of transitional disks in non-ADI mode
Y
Y
Select R <11 target, AO 300-378 modes correction at 1 KHz Hα SDI+ with Ks vAPP coronagraph
Select 12>R ≥11 target, AO 100 modes correction at 1 KHz Hα SDI+ with Ks vAPP coronagraph
or
Select 14>R >12 target, AO 100 modes correction at 100-500 Hz Ks vAPP coronagraphy (no VisAO)
Detection of Hα >5σ source?
N
Detection of Ks >5σ source?
N
Stop. Star is single
Y
No detection at Hα continuum 642nm ?
N
Y
Y
Follow-up 2nd Epoch, Hα SDI+ Brγ, and H band ADI corono.
Follow-up 2nd Epoch, Hα SDI+ and H band ADI coronagraph
Is the Model Mass from the 642nm flux, Ks and H less than 70 Jupiters?
N
Accreting low mass star companion
Y
Y
No detection at H band?
N
Is the Model Mass from the 642nm flux, Ks and H less than 13 Jupiters?
N
Y
Y
Y
Accreting Protoplanet candidate
Planetary mass candidate
Brown Dwarf companion
Use the Hα, 642nm, and Ks band fluxes to estimate Mp, and Mdot form models (as we did in Close et al. 2014 with HD142527B)
Multiplanet system?
N
Mdot~50% Mdot_star Fig 6. for Mp estimate
Y
Use the H and Ks band fluxes to estimate Mp from Atm. models (as we did in Biller et al. 2014 with HD169142b)
Use dynamics to estimate Mp. Use Hα and Brγ flux, and A_R to get Mdot, onto planet (as we did in Sallum et al. 2015 with LkCa 15b)
MagAO


Start Selecting process for next XRPplanetS target
0.65” < seeing < 0.85” ?
N
Is seeing < 0.65” ?
N
Y
Y
Select R <11 target, AO 300-378 modes correction at 1 KHz Hα SDI+
Select 12>R ≥11 target, AO 100 modes correction at 1 KHz Hα SDI+
Poor seeing back-up. Carry out H band coronagraphic imaging with MagAO’s Clio NIR camera.
Detection of Hα >5σ source?
N
Stop. No protoplanets detected
Y
No detection at Hα continuum 642nm ?
N
Y
Follow-up 2nd Epoch, Hα SDI+ and H band ADI corona. with Clio.
Follow-up 2nd Epoch, Hα SDI+ and H band ADI coronagraph
Is the Model Mass from the 642nm flux and H less than 70 Jupiters?
N
Accreting low mass star companion
Y
Y
No detection at H band?
N
Is the Model Mass from the 642nm flux, and H less than 13 Jupiters?
N
Y
Y
Y
Accreting Protoplanet candidate
Planetary mass candidate
Brown Dwarf companion
Use the Hα, 642nm, and Ks band fluxes to estimate Mp, and Mdot form models (as we did in Close et al. 2014 with HD142527B)
Multiplanet system?
N
Mdot~50% Mdot_star Fig 6. for Mp estimate
Y
Use the H band fluxes to estimate Mp from Atm. models (as we did in Biller et al. 2014 with HD169142b)
Use dynamics to estimate Mp. Use Hα and Brγ flux, and A_R to get Mdot, onto planet (as we did in Sallum et al. 2015 with LkCa 15b)
MagAO

Movie of ASDI data reduction



Preliminary SCExAO/VAMPIRES science – in preparation

Circumstellar dust around Red Supergiant μ Cephei

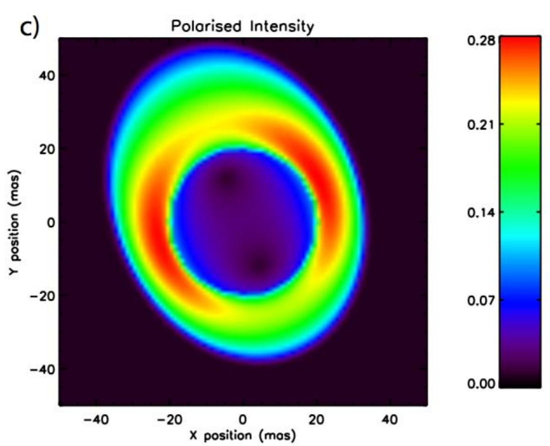
Model-fitting reveals extended, asymmetric dust shell, originating within the outer stellar atmosphere, without a visible cavity. Such low-altitude dust (likely Al_2O_3) important for unexplained extension of RSG atmospheres.

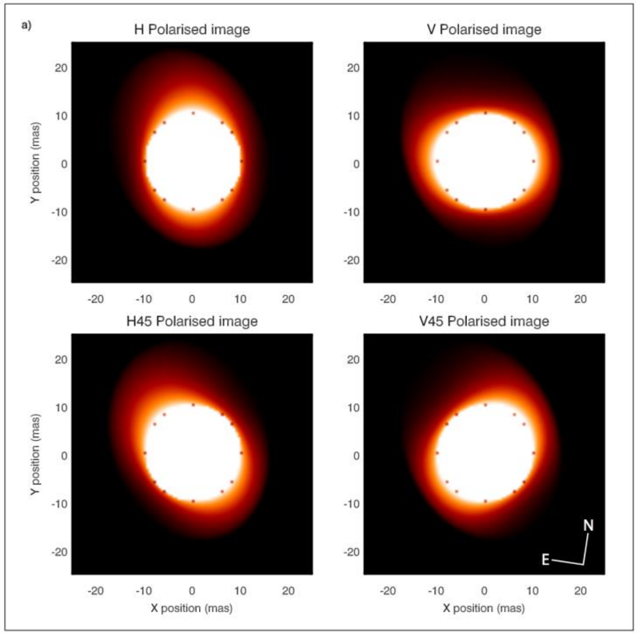
Inner radius: 9.3 ± 0.2 mas (which is roughly R_{star})

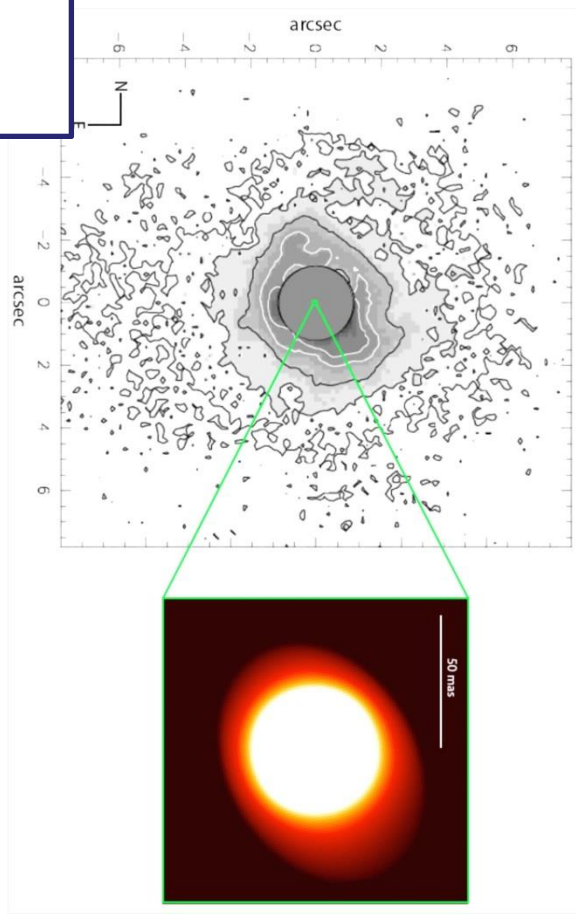
Scattered-light fraction: 0.081 ± 0.002

PA of major axis: 28 ± 3.7 ° • Aspect ratio: 1.24 ± 0.03

Left: model image, shown in polarized intensity. **Middle:** model image show in four polarisations. **Right:** Model image (intensity), shown with wide field MIR image (from de Wit et al. 2008 – green box shows relative scales. Axis of extension in MIR image aligns with the close-in VAMPIRES image.







KEY #6 Good interaction Matrixes with the CRO

Taking the IMATS with the Loop Closed in an iterative fashion is a great innovation of the LBTAO/Arcetri group

	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
Maximum number of controlled KL modes	378 300 250 200	120 100	66	28	21 10
Maximum Guide Star V magnitude	8.4	12.7	14.2	15.6	16.0 17

Key #5 well designed ERROR BUDGET

Simulated system end-to-end in CAOS

Males et al. 2010,2012

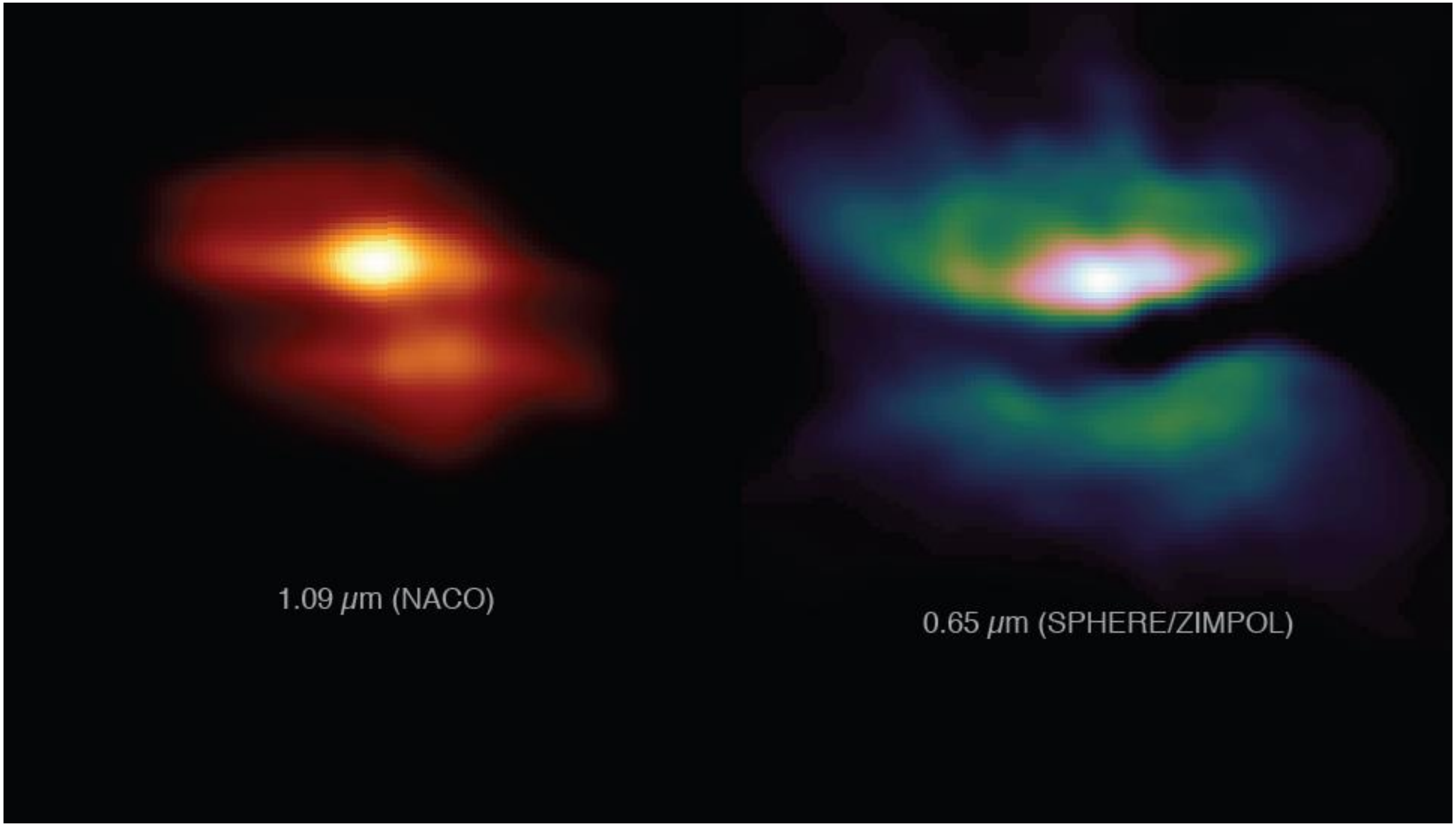
Table 3: Error Budget (nm rms) for Mag AO system for a R=8 mag NGS. λ=0.76μm		
Term	**CAOS value**	**Notes (red terms have been independently measured in lab.)**
Fitting	91	r_o=14 cm @V "poor" (75%-ile) 0.8" seeing
Servo	55.4	800 Hz framerate
Recon.	47.0	11e RON (9e in lab)
Static	30	Verified by 4D int.
Noncom	29.0	estimated by 4D in lab.
tilt	52.6	5 mas –Assuming Vibration Control if windy
Total (rms) wavefront	**135 nm**	96 nm obs. in Tower. Corrected to 122 nm for all modes > 500 as well.
Strehl 0.76μm	**30%**	**37% expected "on sky" correcting from lab.**
Strehl at 3.4 μm	**93%**	**95% "on-sky"**

Fit: 561 illuminated act. controlling 400 modes
Servo: Cn^2 weighted <V> = 15 m/s , 1 ms delay added.

102-140 nm rms observed on-Sky in these conditions

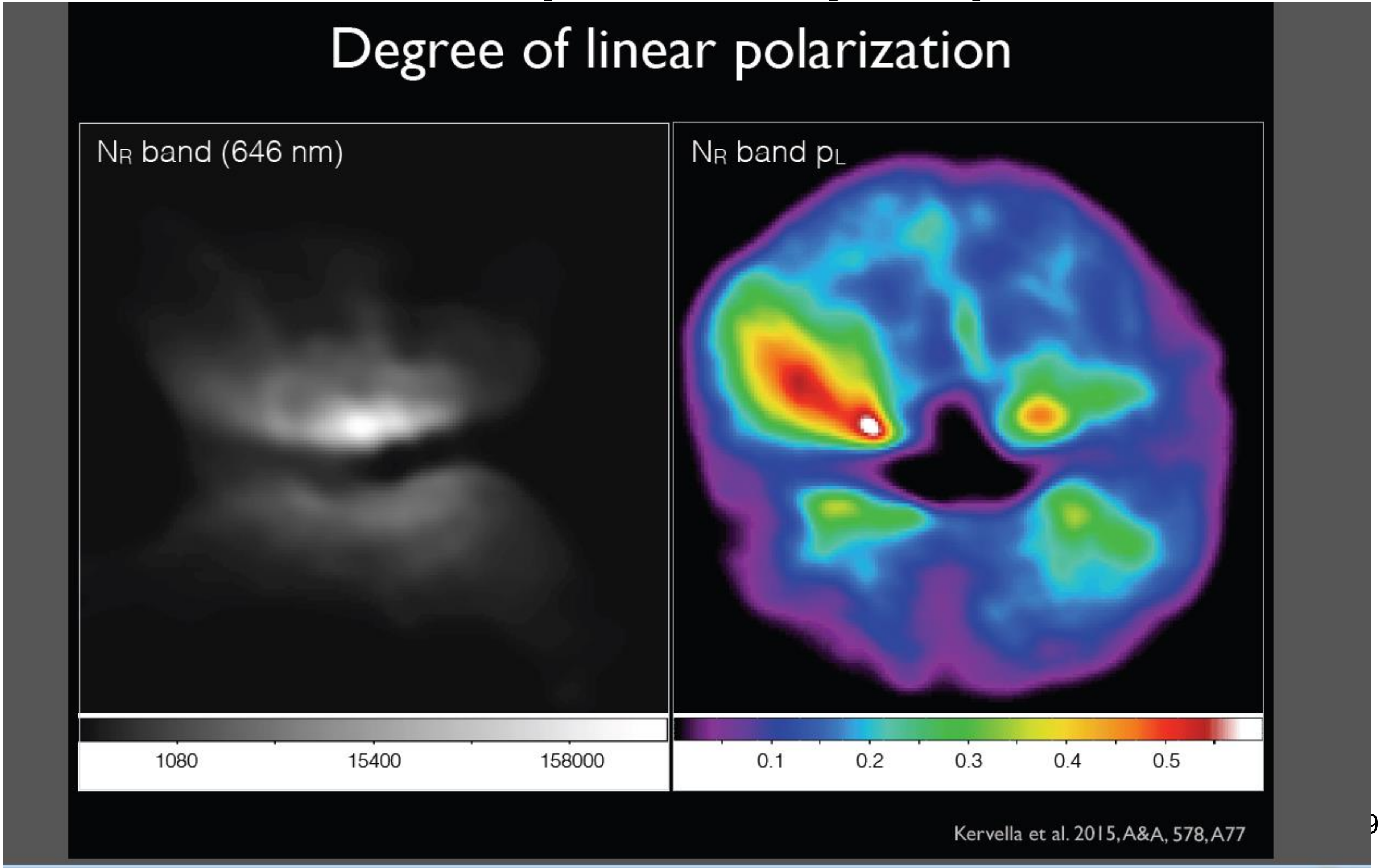
MagAO

SPHERE/ZIMPOL



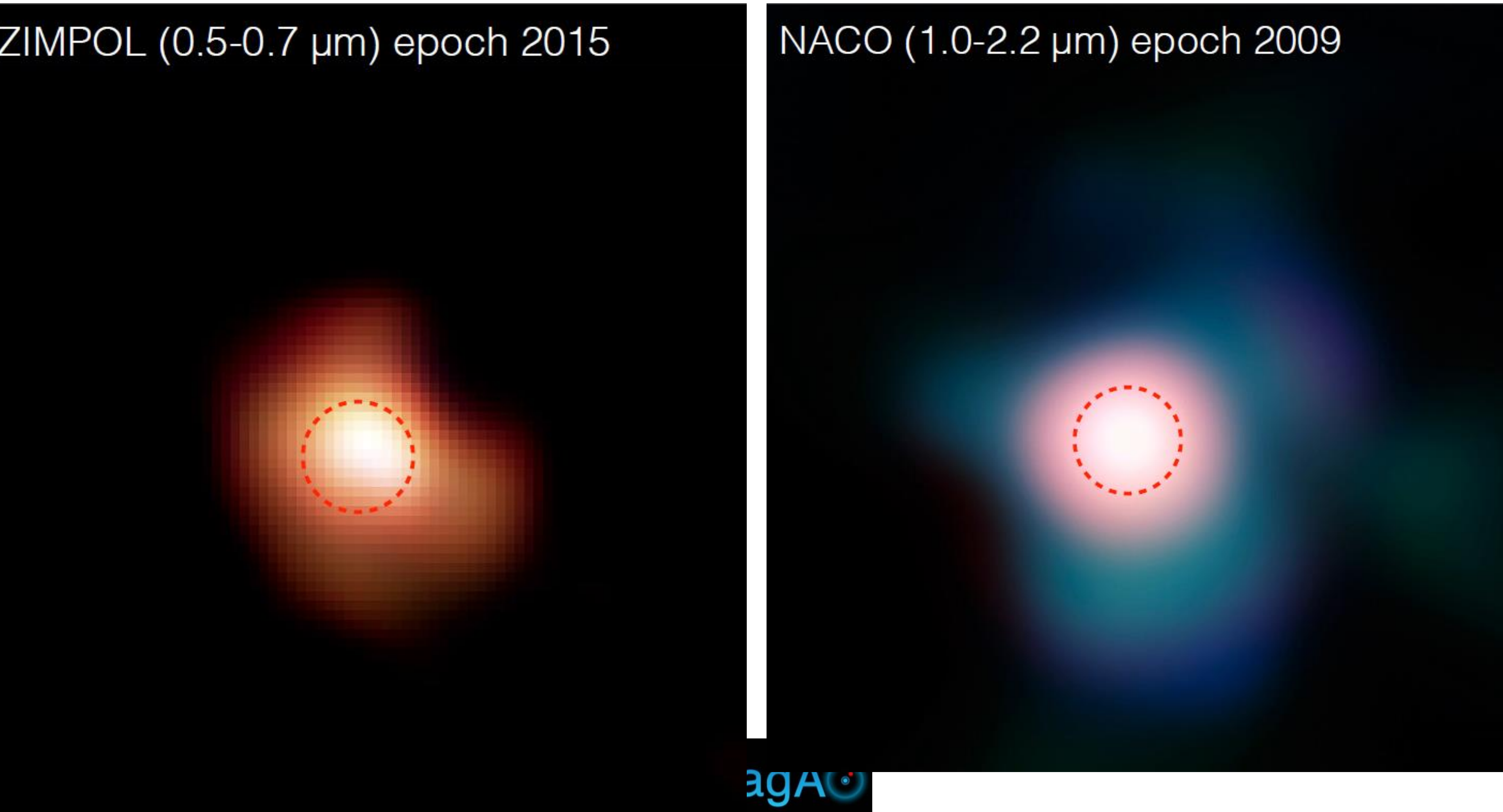
- The Nearest AGB star: L2 Pup (Kervella et al 2015)

ZIMPOL is primarily a polarimeter

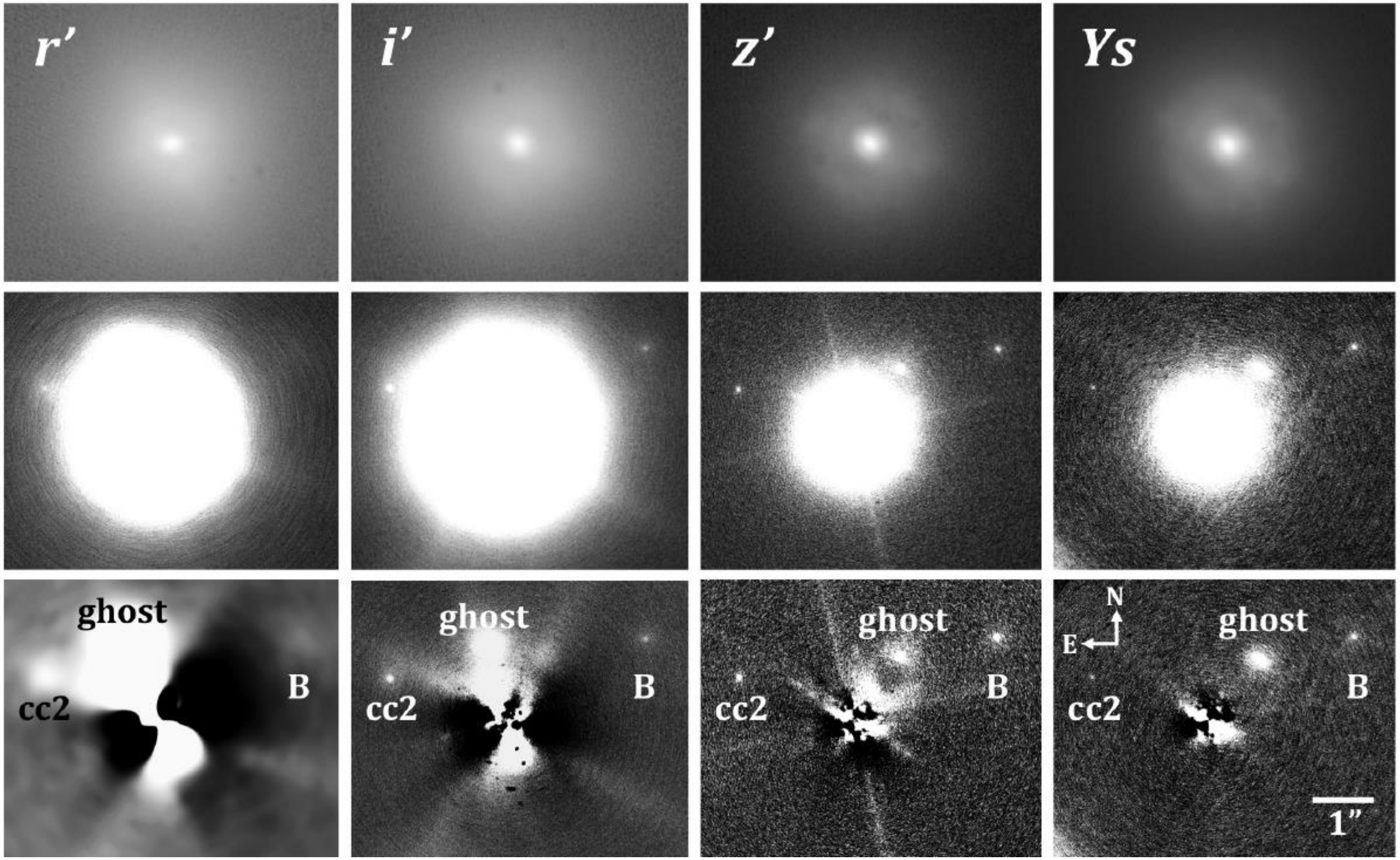


Star Surfaces: ~50 mas surface of Betelgeuse, giant convective cells

(Kervella et al. A&A 2016)

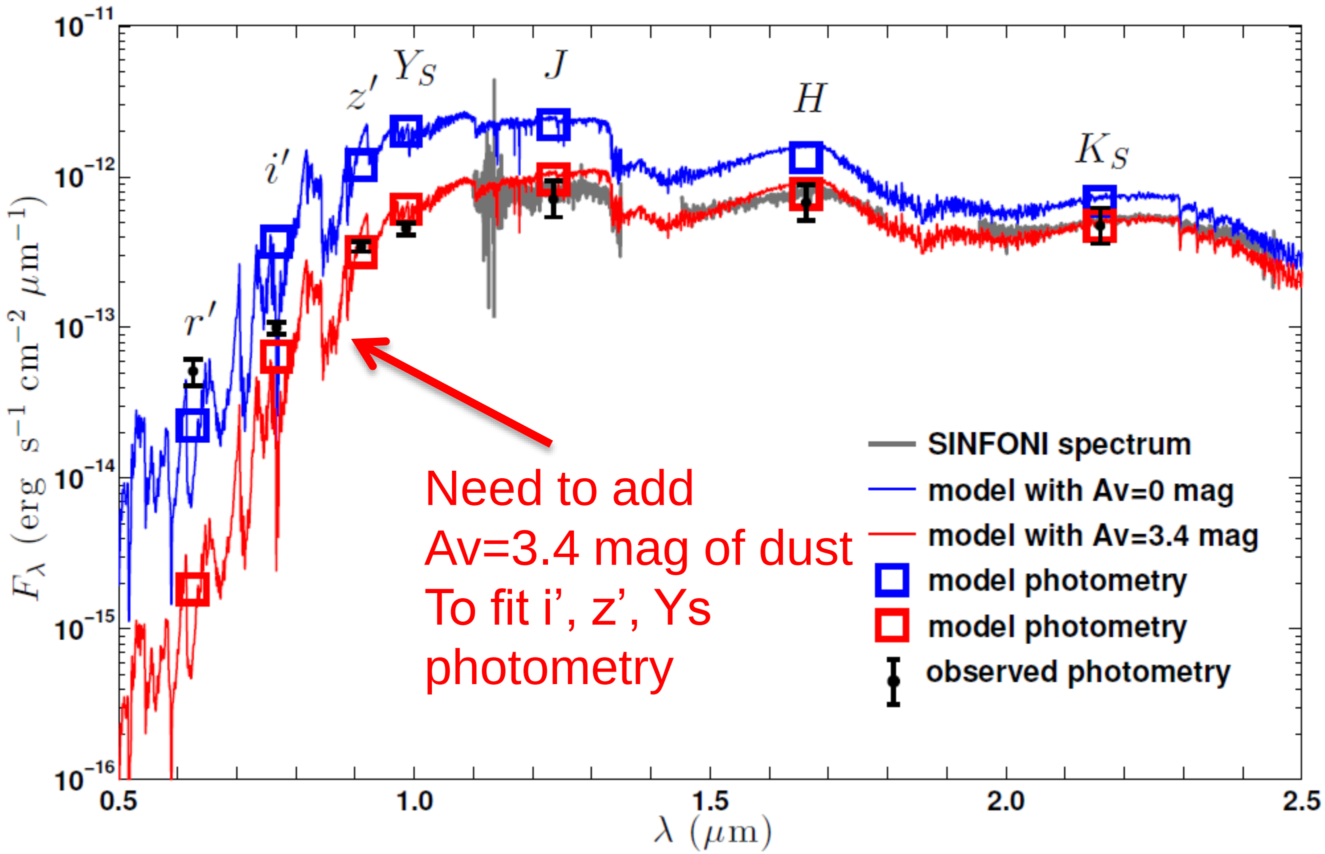


We Can Use Visible AO to probe the extinction towards Planetary Mass Companions: Example CT Cha B



Wu et al. ApJ 2015

We Can Use Visible AO to probe the extinction towards Planetary Mass Companions: Example CT Cha B



we find a Av=3.4+/-1.1 mag and accretion, hence CT Cha B has its own disk and is a BD formed by core fragmentation at 430 AU

Wu et al. ApJ 2015