Direct imaging and spectral characterization of habitable planets with ELTs

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Subaru Coronagraphic Extreme AO (SCExAO) team
(Martinache, Clergeon, Garrel, Blain, Morino, Kudo, Russell, Groff)

Extreme AO myths

Extreme AO myth #1

ExAO = “Extremely complicated AO”, and should be the last thing to think about commissionning on an ELT

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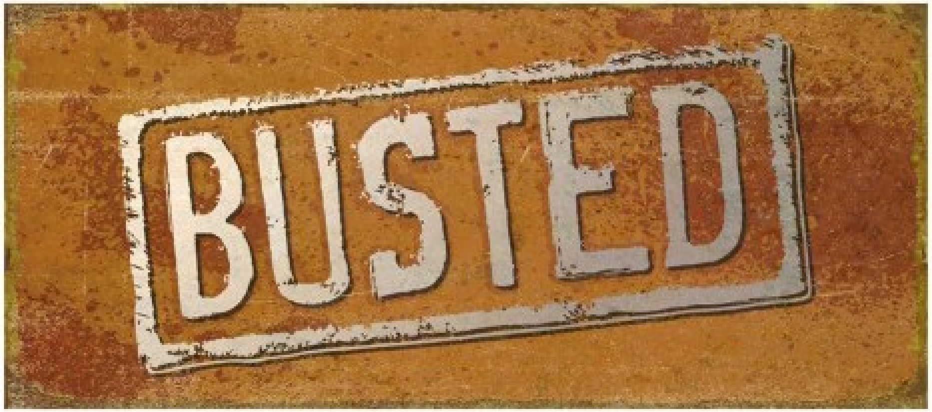
→ ExAO is in many respects simpler than other AO systems:
- bright on-axis natural guide star (no lasers, easiest configuration for cophasing segments)
- zero field of view system (small optics, single DM OK)
- ExAO system on 8-m telescope could be used on ELT



Extreme AO myth #2

ExAO = “Extremely costly AO”

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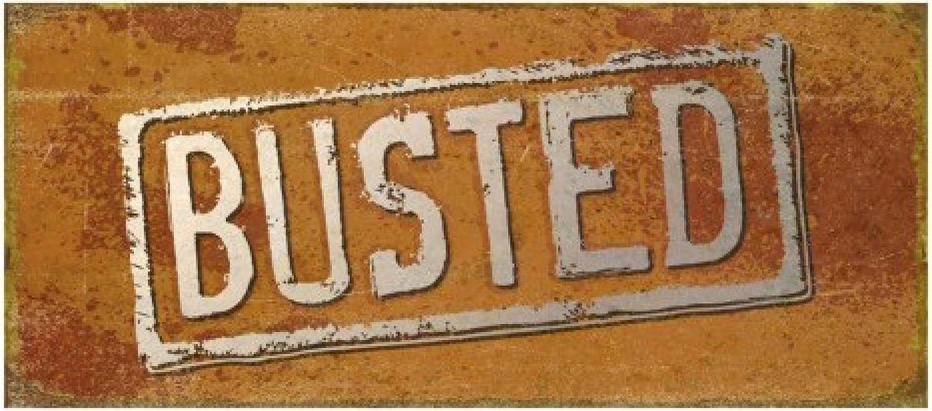
ExAO system can be small, and relatively cheap for ELT
Think of ExAO as small experiment instead of facility instrument



Extreme AO myth #3

ExAO needs DMs with several 1000s of actuators, especially on ELTs

→ needs insane computing power

→ needs development of new DM technologies

Extreme AO myth #3

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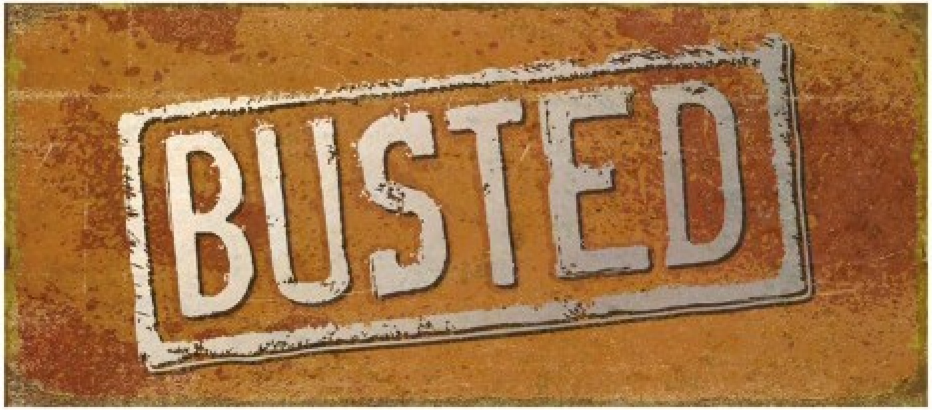
→ **needs insane computing power**

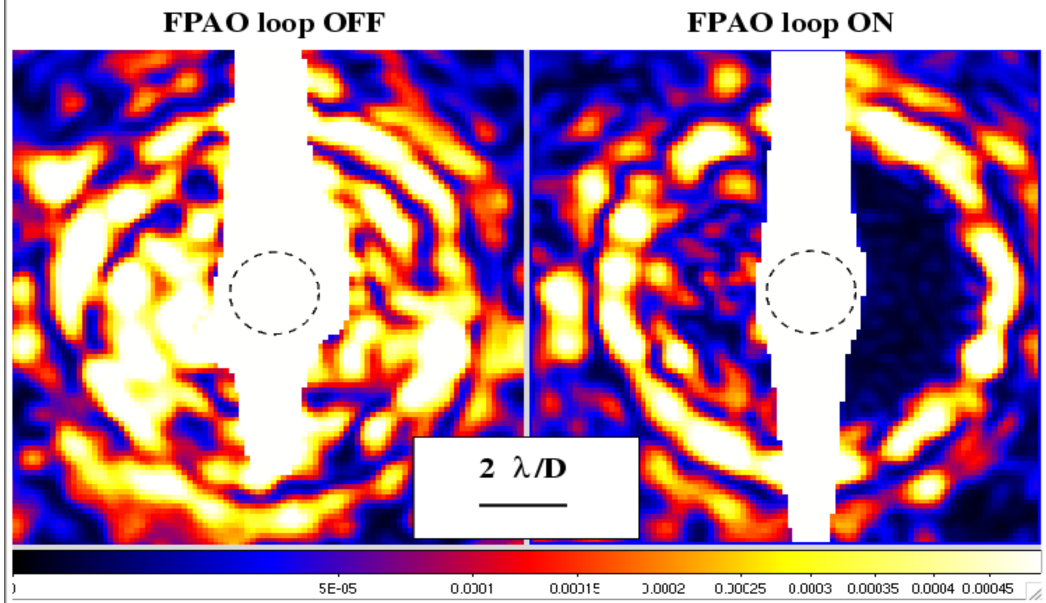
→ **needs development of new DM technologies**

In ExAO, the number of actuators in the DM defines the field of view, not the contrast

→ small field = no need for high number of actuators

→ detection of planets at up to 15 l/D can be done with existing 32x32 actuators DM (fewer actuators than facility AO is OK !!!)





Extreme AO myth #4

ExAO itself is a myth, it doesn't work on sky

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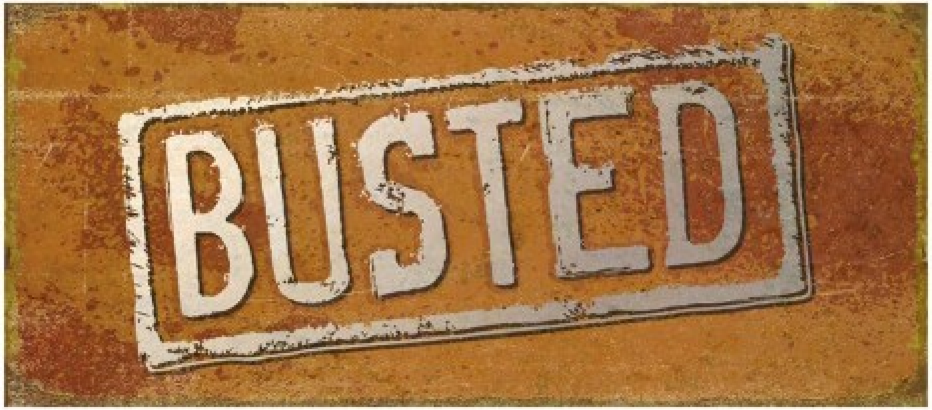
Yesterday: Mostly true

ExAO techniques (coronagraphy, wavefront control) work very well in labs, and are being applied on sky in new instruments (GPI, SPHERE, SCExAO – see also Palm3000/P1640)



Extreme AO myth #5

ExAO people have no clue what they are doing.
They change their mind about what coronagraph or wavefront sensor to use every two years.

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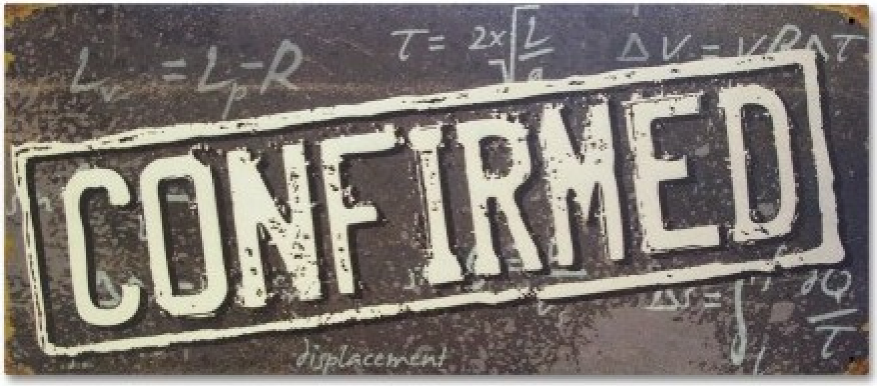

→ ExAO instrument with flexible evolutionary path has a lot of value (SCExAO)
→ don't design ExAO system details now

Develop & prototype on 8-m, telescopes → quickly move to ELT when ELT is ready

Extreme AO myth #6

Coronagraphs don't work on segmented apertures

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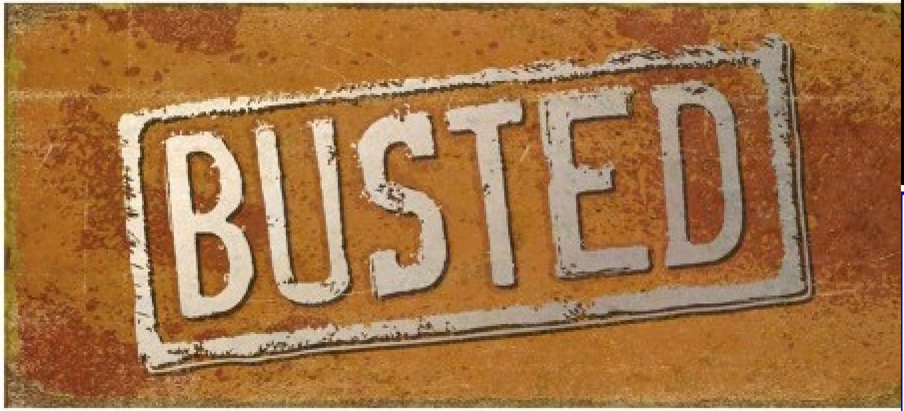
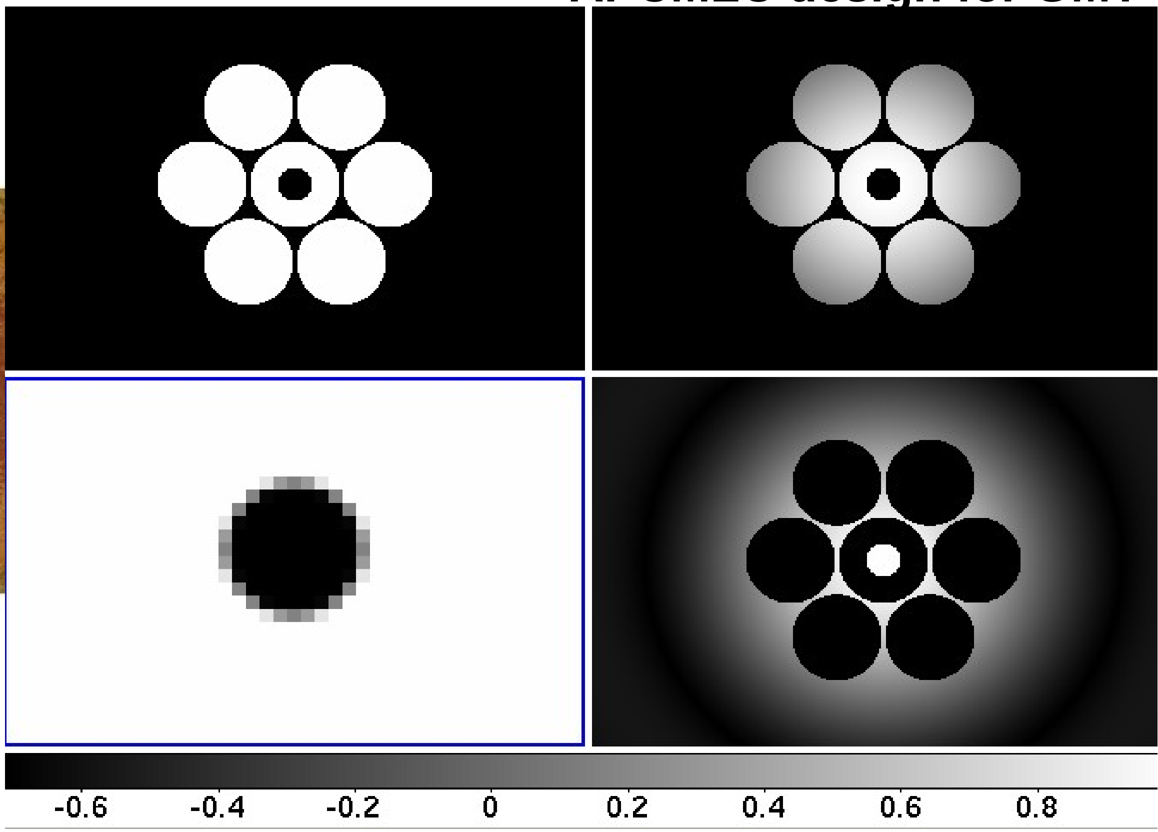


APCMLC design for GMT



→ The highest performance coronagraphs for high contrast at 1 l/D don't care about pupil segmentation

Phase Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC):
IWA = 0.64 l/D, 100% throughput, contrast limited only by wavefront errors
(Guyon, Martinache, Belikov & Soumer 2010)

APCMLC designs

Guyon PhD thesis, 2003

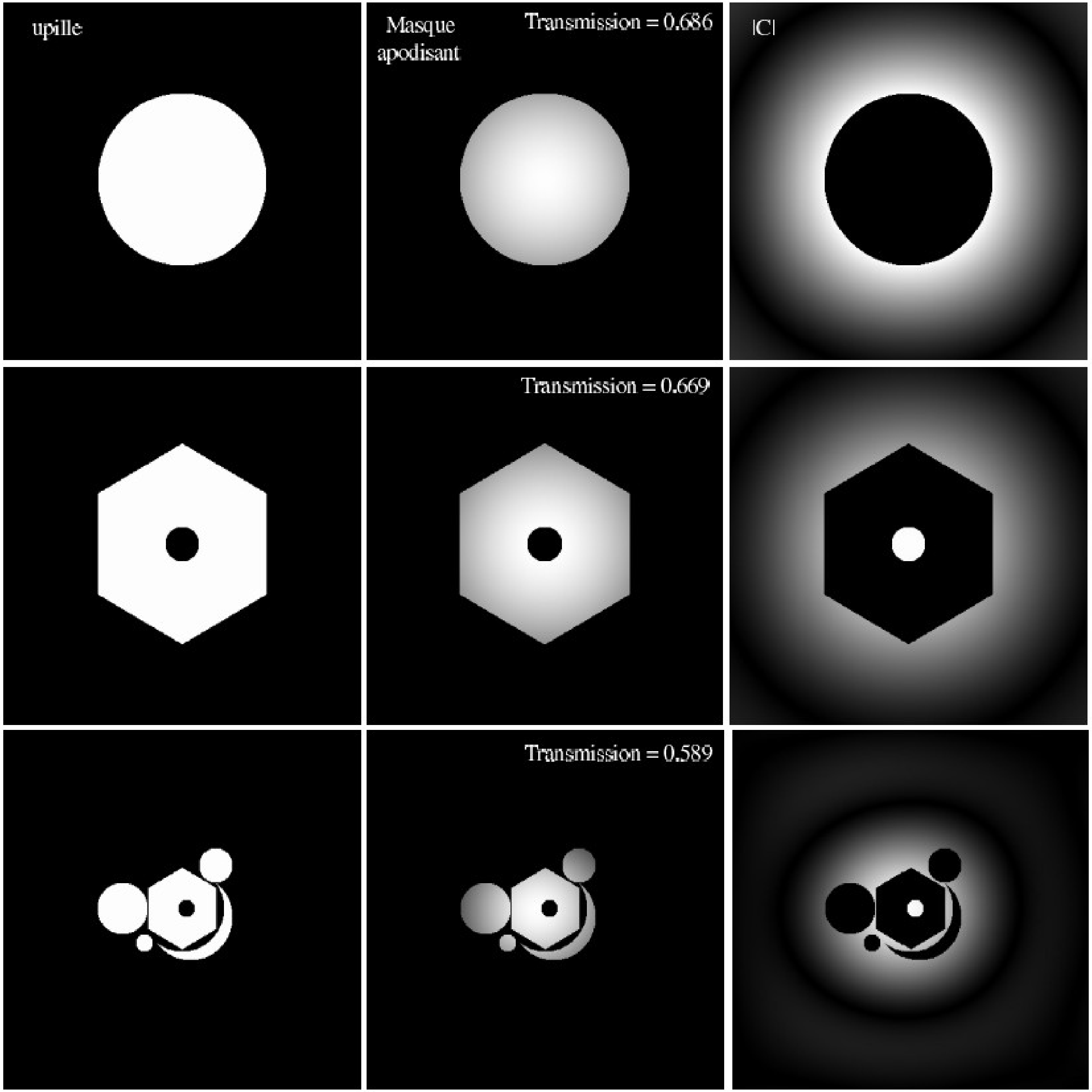


FIG. 3.7 – Masque apodisant (seconde colonne) et distribution de l'intensité lumineuse dans le plan C, plan pupille après le masque de phase, pour une source ponctuelle (troisième colonne) pour différentes formes de pupilles (première colonne).

Exciting exoplanet science with ExAO on ELTs
NearIR spectroscopy of rocky planets in habitable zones

Direct imaging of reflected light in near-IR around low-mass stars has fundamental SNR advantages:

ELT → smaller IWA → brighter reflected light planets, more planets

(1) **Light from planet physically separated from starlight** → D^4 advantage (as opposed to D^2 for transit spectroscopy) → high SNR spectroscopy becomes possible

(2) **Closest system** would be targeted (no need to have a transit, or young system) → planets are bright (planet absolute brightness is constant !)

(3) **Contrast is not too challenging** around low-mass stars

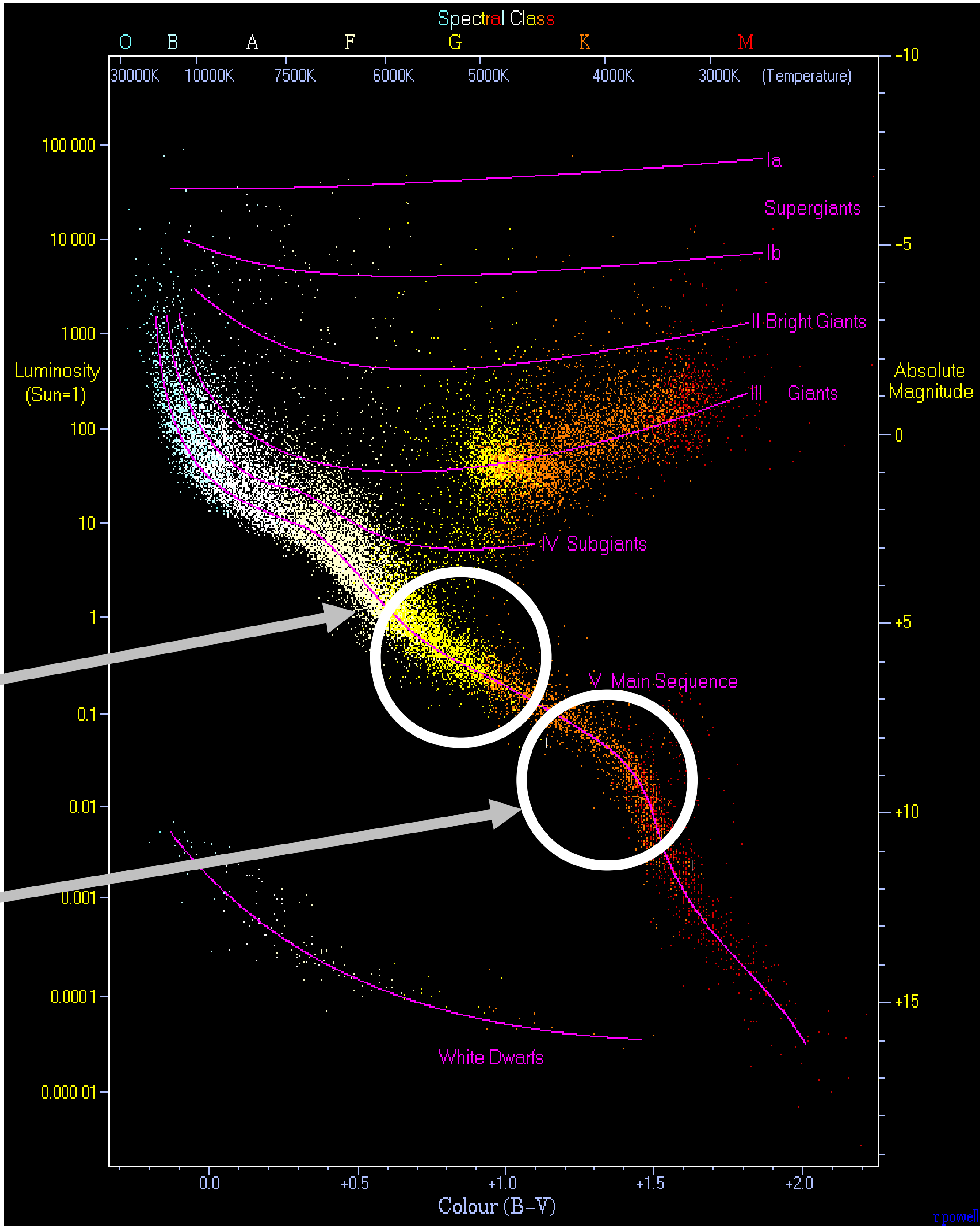
(4) **near-IR is optimal wavelength**, combining angular resolution, contrast sensitivity and technological readiness

Habitable planets spectroscopy

Unique to ELTs for low-mass stars
May also be first opportunity to image habitable planets (timing of space mission ?)

Space (~4m telescope):
F-G-K type stars, visible light

Ground (ELT):
M type stars, nearIR



Science goals, targets
Key assumptions, absolute limits

Assumed performance of ExAO system:

(1) Raw contrast

- Expected to be 14x better than on 8-m telescope
- 1e-5 on 8-m telescope → 7e-7 on ~30-m telescope

(2) Detection contrast

- Expected to be 14x better than on 8-m telescope
- 1e-7 on 8-m telescope → 7e-9 on ~30-m telescope

(3) IWA ~ 1 l/D

- l/D: 40mas on 8-m, 10mas on ELT

(4) Background-limited sensitivity (1hr, SNR=5)

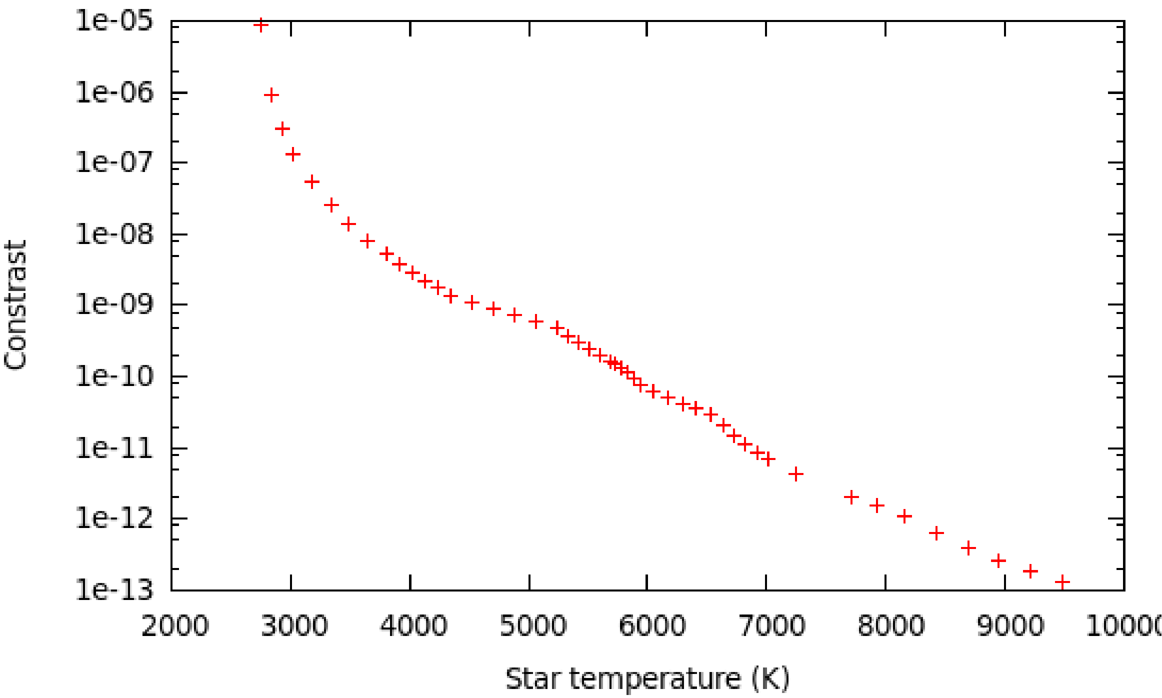
- mH: 23.5 on 8-m telescope → mH = 26.5 on ~30-m

Assuming Super-Earths (~2x Earth diameter)

- Still potentially habitable
- Easier than Earths: 1e9 contrast at 1 AU separation (Earth ~ 2e10)
- Probably abundant (Kepler, RV HARPS results: ~30% occurrence)

Detection, colors: mH = 26.5 limit on planet
Spectroscopy (R=200, SNR = 5): mH = 21.5 limit on planet
→ ability to analyze atmosphere composition, biological activity

Reflected light imaging: Contrast vs separation

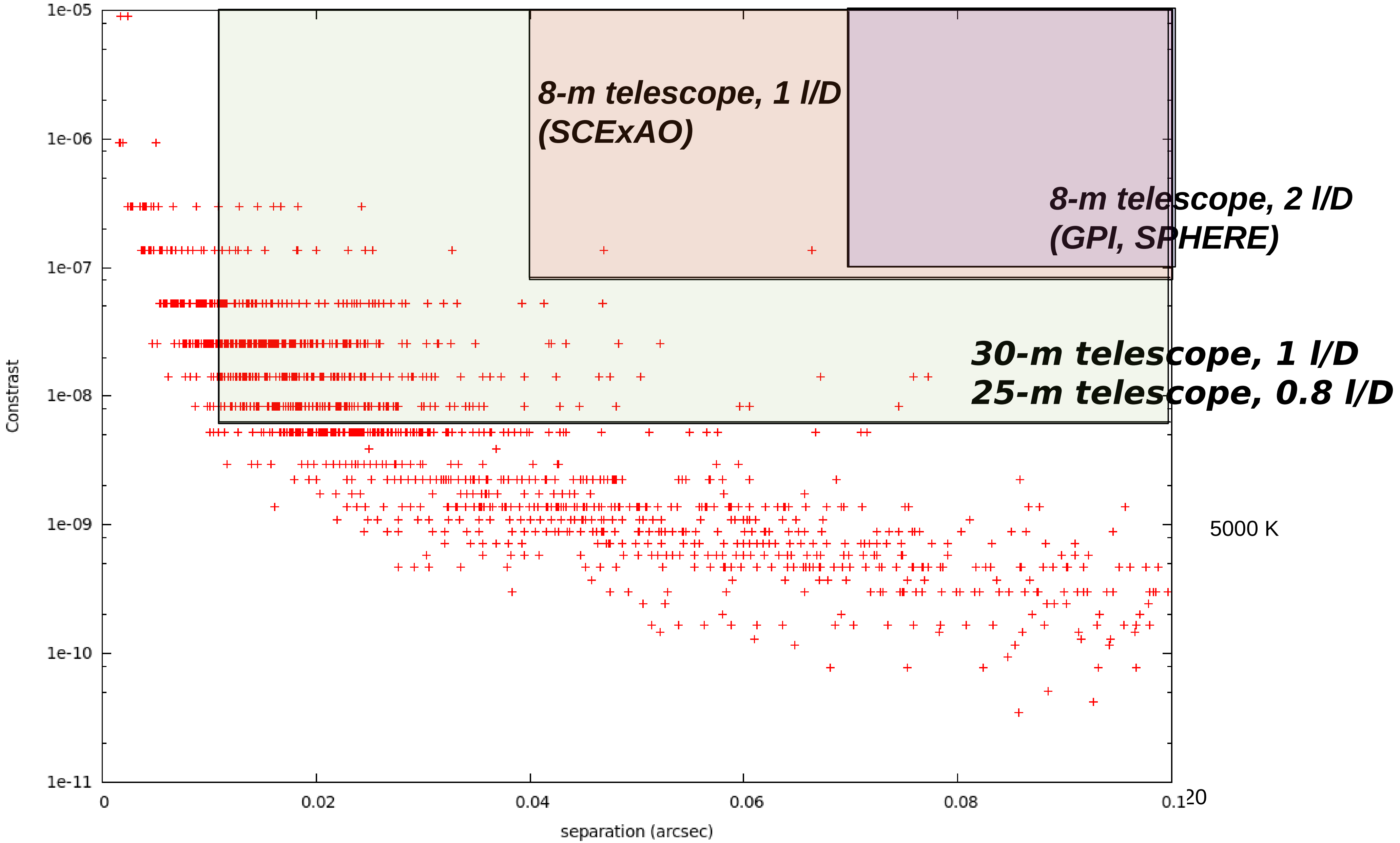


Gliese catalog of nearby stars
Kept only main sequence
→ 2347 stars within 25 pc

Each star characterized by :
- Distance (pc)
- Temperature (K)
- Absolute V magnitude

→ computed bolometric luminosity
→ computed location of habitable zone (1 AU equivalent)
→ placed a 2x Earth size planet, Earth albedo, at max elongation
→ Used main sequence colors (V-H) to compute apparent luminosity of star and planet at H band

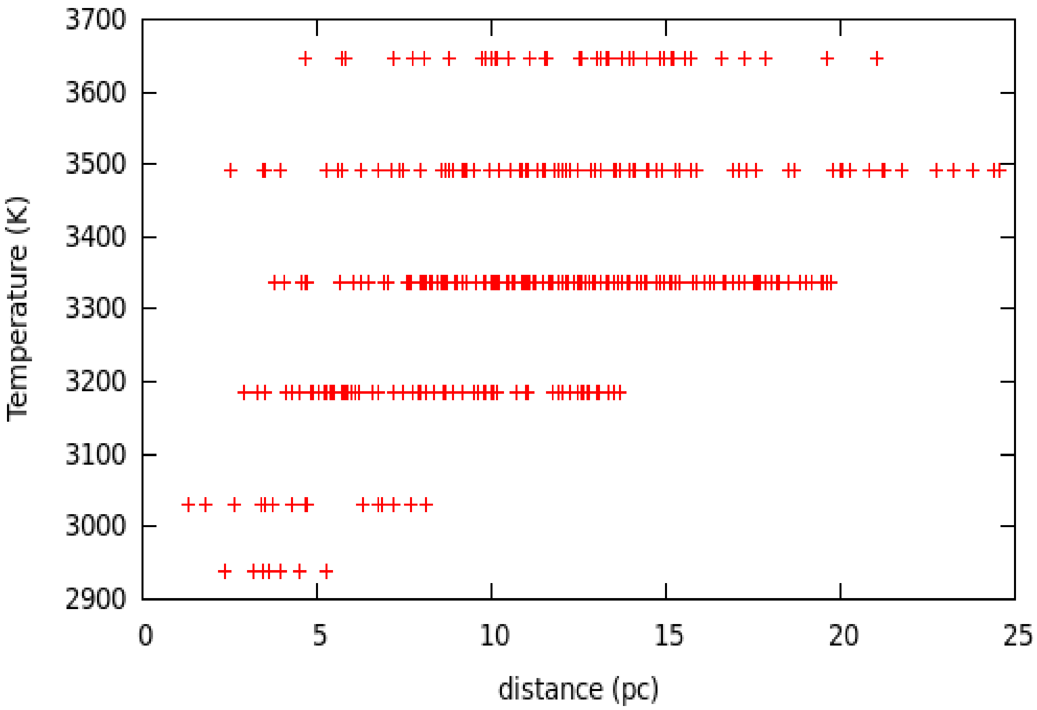
Reflected light imaging: Contrast vs separation (2x Earth diameter)

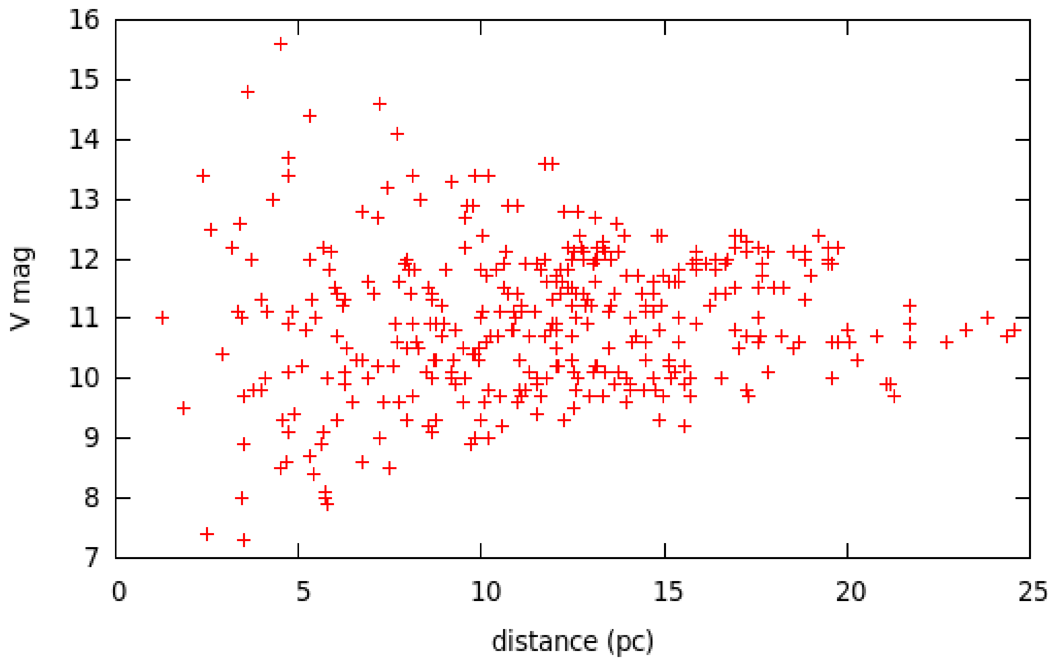


Reflected light imaging: ELT targets

25-m telescope, 0.8 l/D: 365 targets within IWA and detection contrast limits
All are M-type stars, (T~3400K), nearby (d~10pc)

Fainter than conventional ExAO targets (mV ~ 10 to 11)





What kind of ExAO system is required ?

GPI-like system on ELT

Detection contrast: 7e-9 (equivalent to 1e-7 on 8-m)

Wavefront sensing: mV = 8 limit

Coronagraphy: 4 l/D

Sensitivity: mH = 26.5

→ 3 targets (0 for R=200 spectroscopy)

Increased WFS sensitivity

Same as above, but with mV = 12 limit for WFS

→ 23 targets (0 for R=200 spectroscopy)

Improved Inner Working Angle (IWA)

Same as above, but with 0.8 l/D coronagraph on GMT

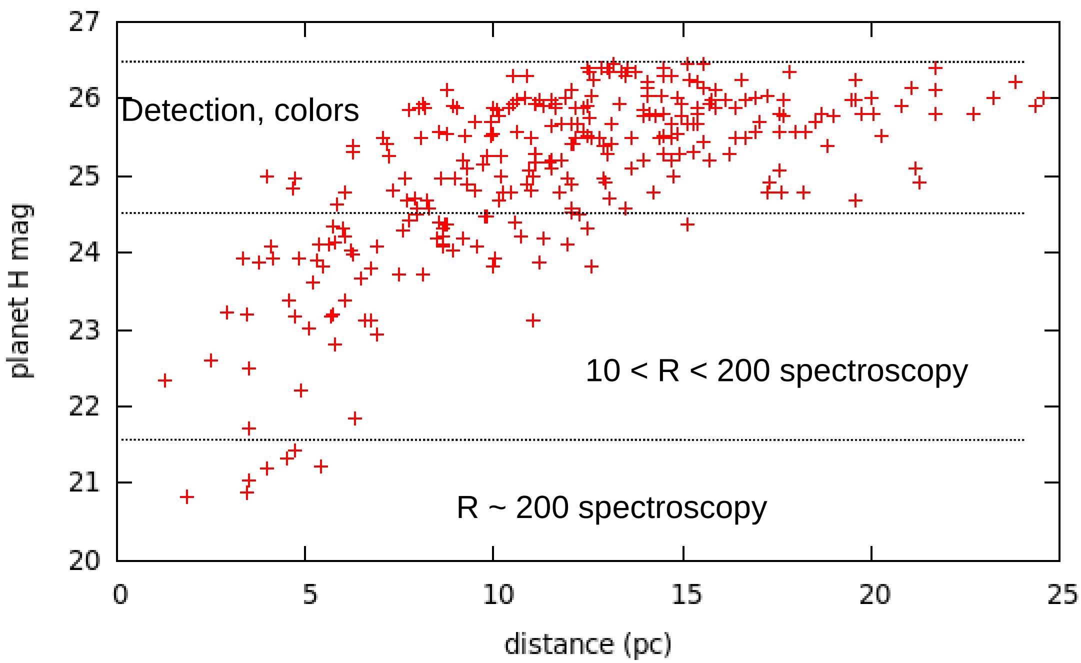
→ 287 targets (7 for R=200 spectroscopy)

R=200 spectroscopy targets

287 targets suitable for detection

7 prime targets on ELT, for which R=200 spectroscopy in near-IR can be done at SNR=5 in <1hr

Distance:	1.8 – 5.4 pc
Teff :	2900 K – 3200 K
Contrast:	3e-7 - 5e-8
Separation:	14 mas – 30 mas
Star V mag:	9.8 – 11.3
Star H mag:	3.0 – 4.9
Planet H mag:	20.8 – 21.4



→ The targets are challenging because of their angular separation (& star V mag)

Achieving high contrast at 1 l/D
Challenges & Solutions

(1) Coronagraphy at 1 l/D
→ PIAA coronagraph

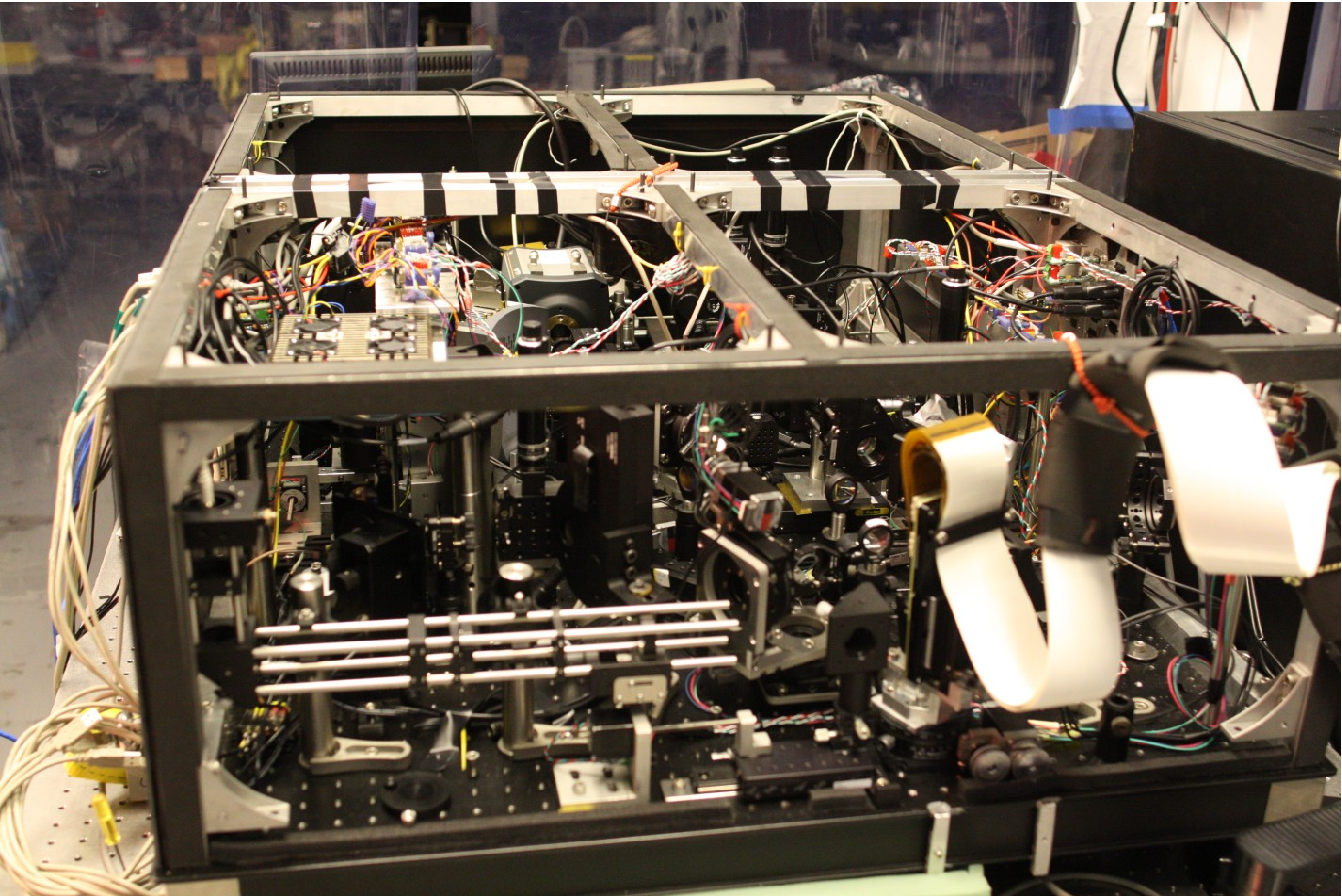
(2) High sensitivity wavefront sensing and control
→ LOWFS for tip-tilt
→ Pyramid or nlCWFS for higher orders
→ focal plane AO for bias-free correction

(3) Speckle calibration (SDI, ADI will not work at 1 l/D)
→ speckle modulation in focal plane

→ Solutions to these problems have been developed in the last ~10 yrs in several labs

These techniques are at the core of the SCExAO instrument on Subaru (optimized for 1 l/D), which is a precursor to an ELT ExAO system able to characterize habitable planets

The Subaru Coronagraphic Extreme-AO (SCExAO) system

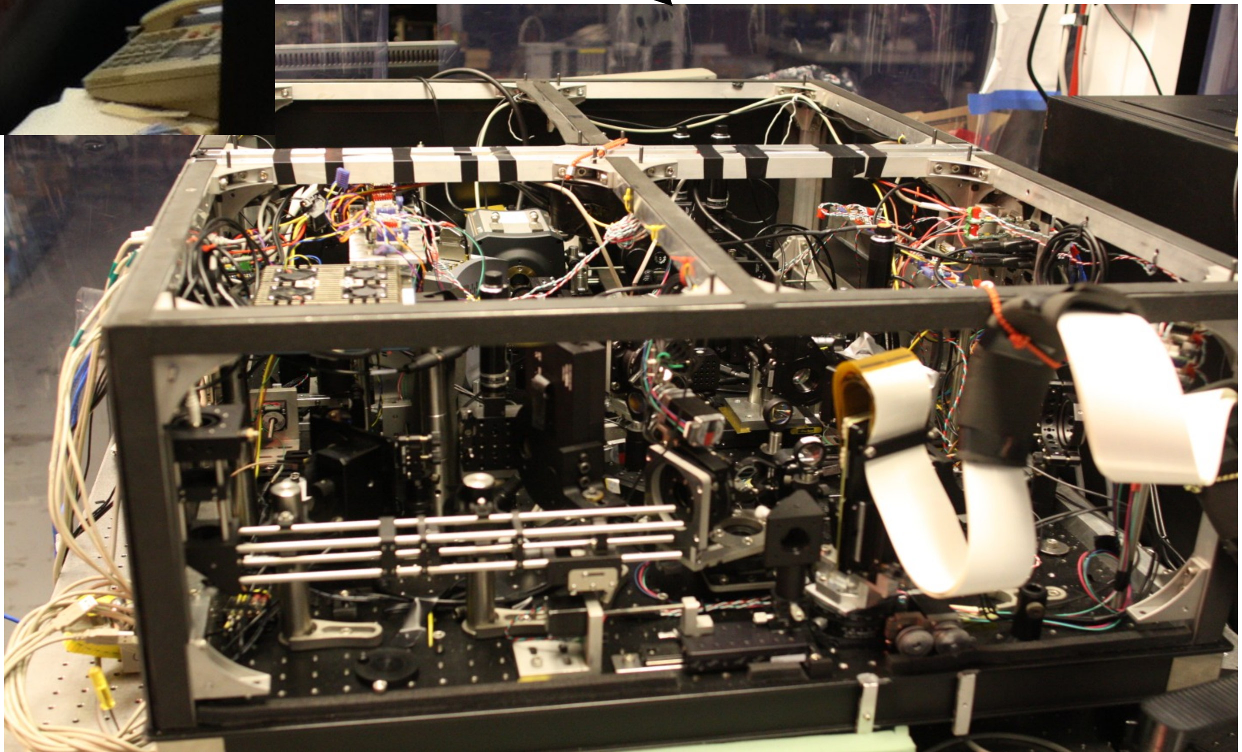


The Subaru Coronagraphic Extreme-AO (SCExAO) system

Olivier's office

About 30 sec walk

SCExAO bench



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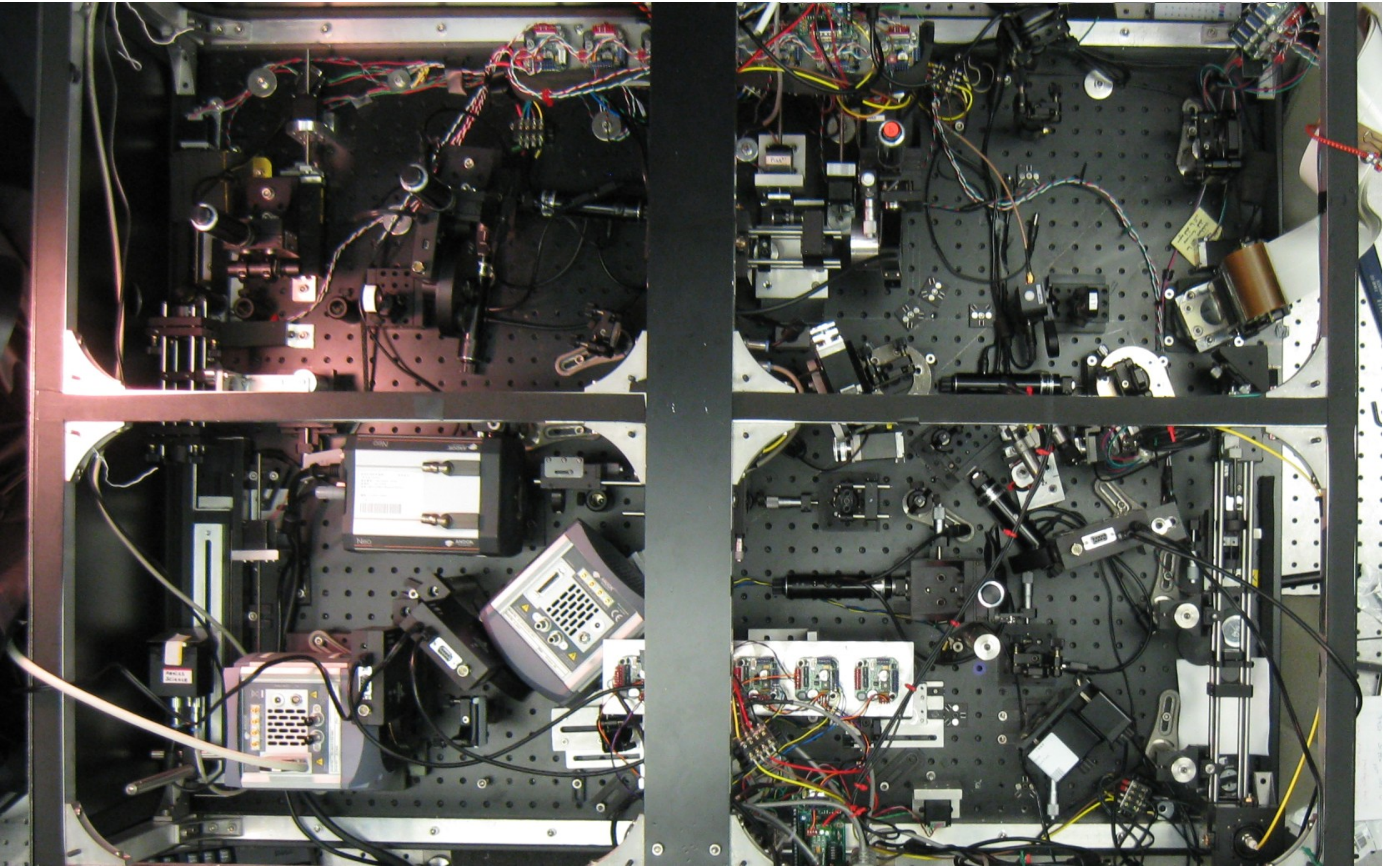
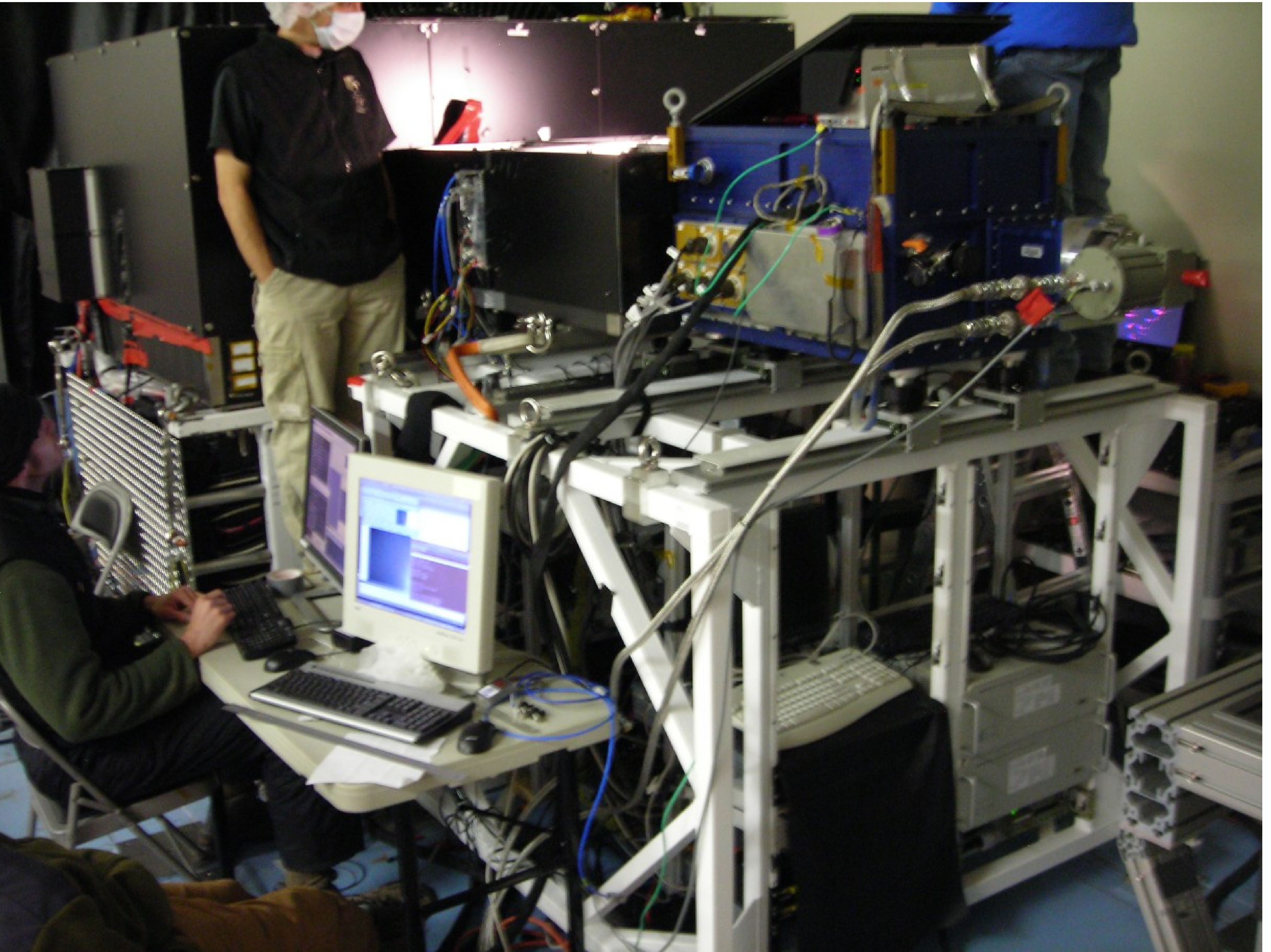
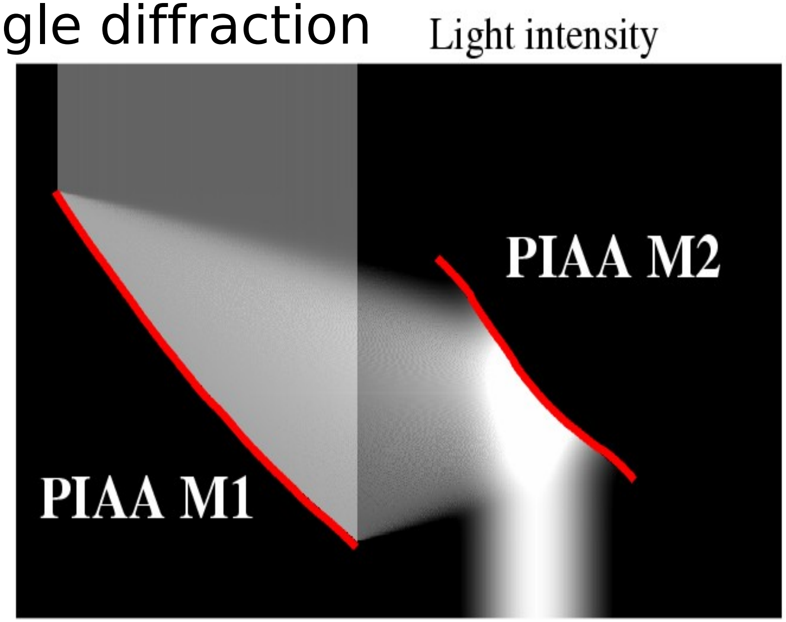



WLL 6,000 LB
EXIT

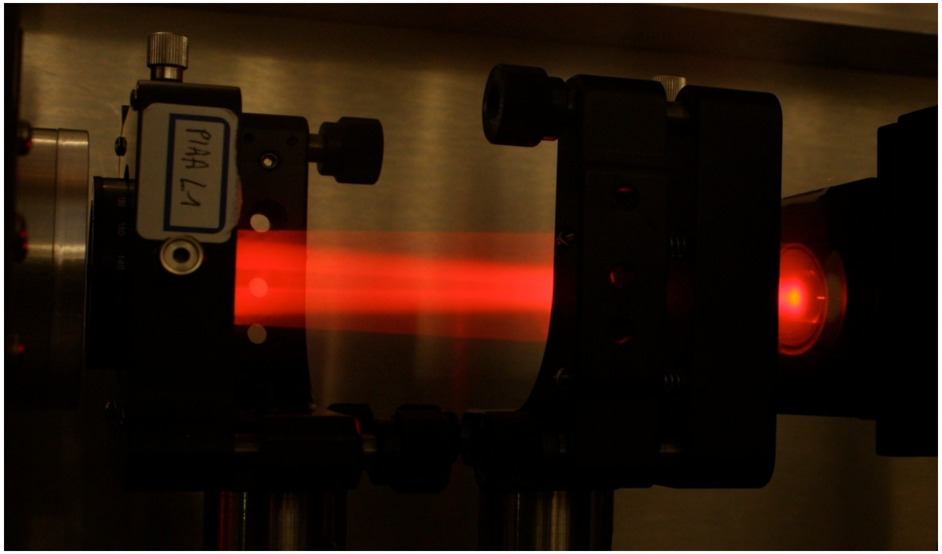


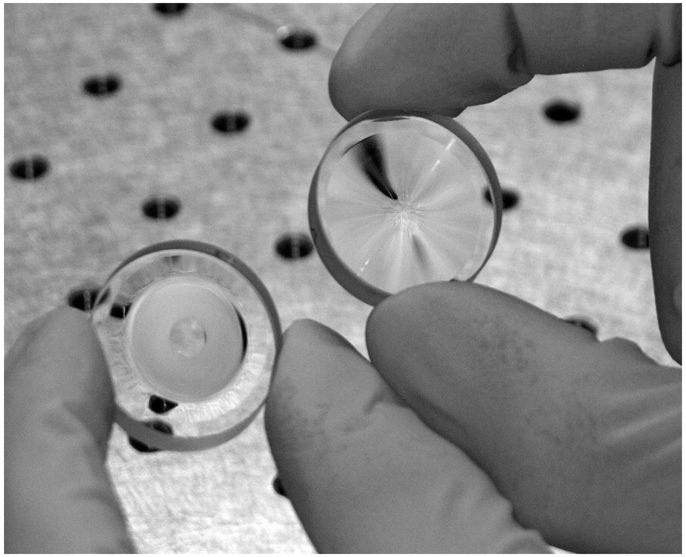
(1) Phase-Induced Amplitude Apodization (PIAA) coronagraph

Utilizes lossless beam apodization with aspheric optics (mirrors or lenses) to concentrate starlight in single diffraction peak (no Airy rings).



- high contrast (limited by WF quality)
- Nearly 100% throughput
- IWA down to 0.64 λ/D (PIAACMC)
- 100% search area
- no loss in angular resol.
- Works on segmented pupils (GMT)
- achromatic (with mirrors)





(2) Wavefront sensing at the sensitivity limit imposed by the telescope diffraction limit

Seeing limited wavefront sensing (what we do now)

Example: SH WFS

Diffraction limited wavefront sensing (what needs to be done for ExAO)

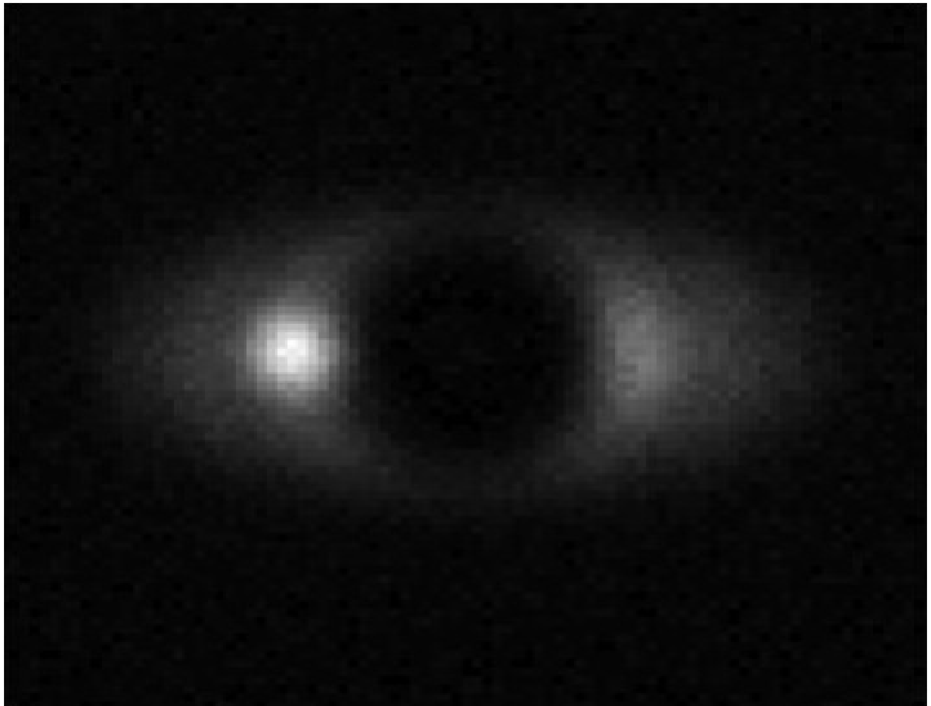
Examples: Pyramid (non-modulated), non-linear curvature

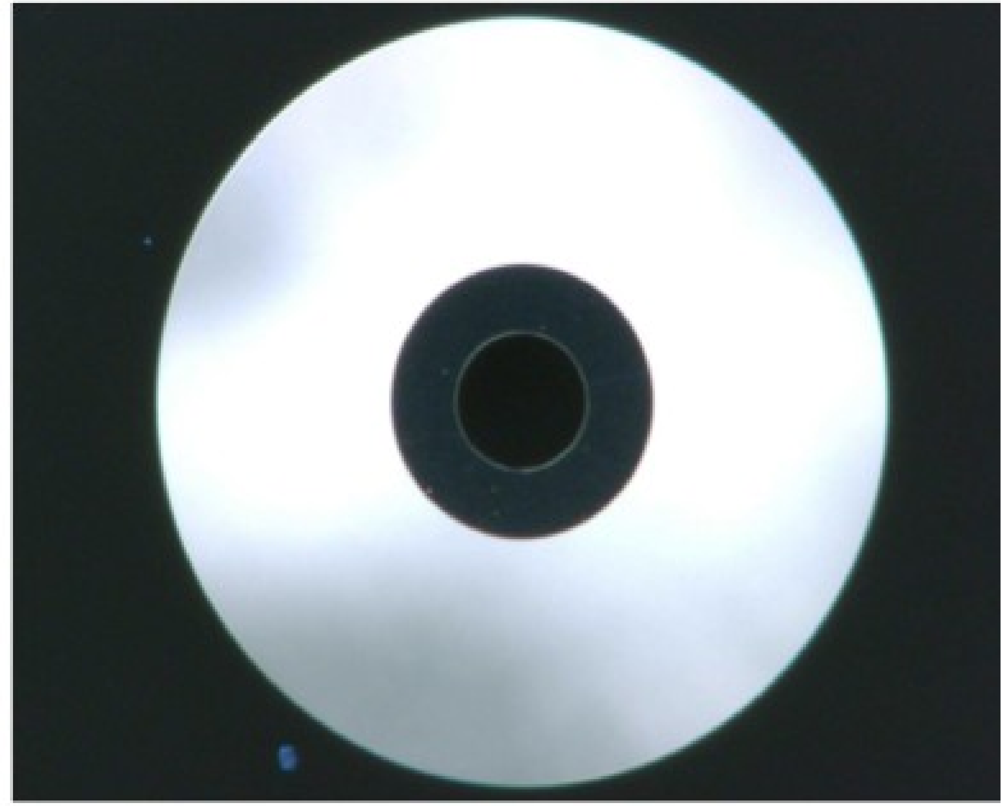
Tip-tilt example (same argument applicable to other modes):
With low coherence seeing-limited WFS, $\sigma^2 \sim 1/D^2$ (more photons)
Ideally, one should be able to achieve: $\sigma^2 \sim 1/D^4$ (more photons + smaller λ/D)

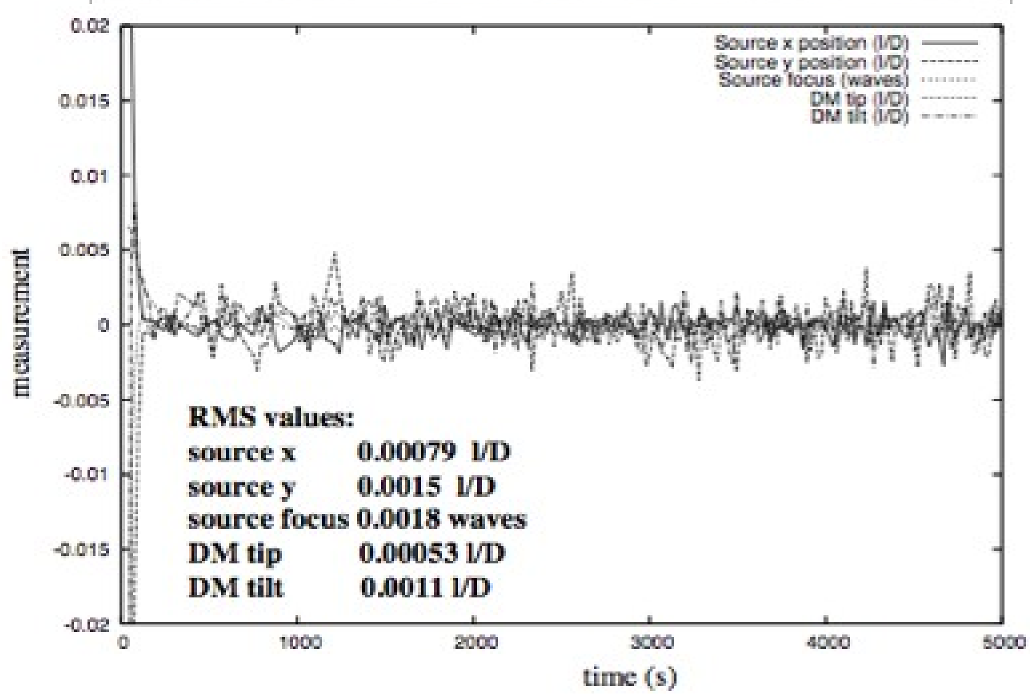
This makes a big difference for Extreme-AO on large telescopes

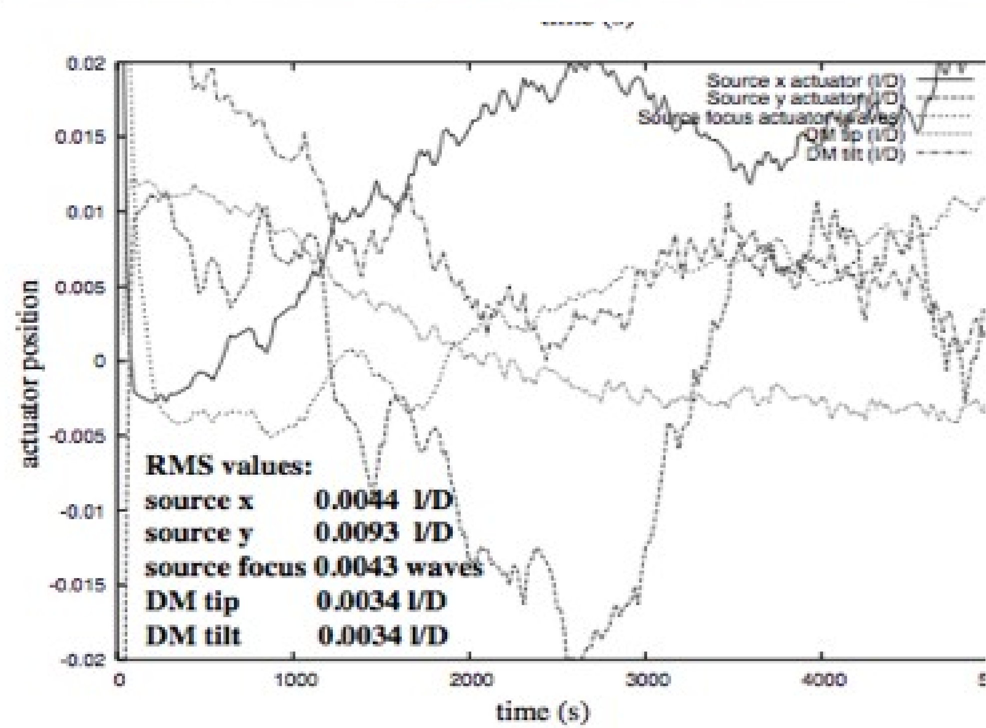
For Tip-Tilt, SHWFS on ELT is 40000x less sensitive than diffraction-limited WFS (11.5 mag)
Similar gain on other low order modes

(2) Coronagraphic LOWFS

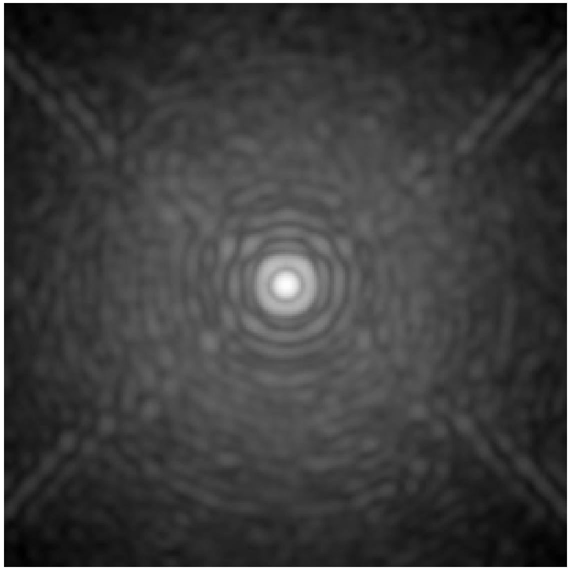








(2) and (3): Focal plane WFS based correction and speckle calibration



Use Deformable Mirror (DM) to add speckles

<u>SENSING</u>: Put “test speckles” to measure speckles in the image,
watch how they interfere

<u>CORRECTION</u>: Put “anti speckles” on top of “speckles” to have destructive interference between the two (Electric Field Conjugation, Give’on et al 2007)

<u>CALIBRATION</u>: If there is a real planet (and not a speckle) it will not interfere with the test speckles

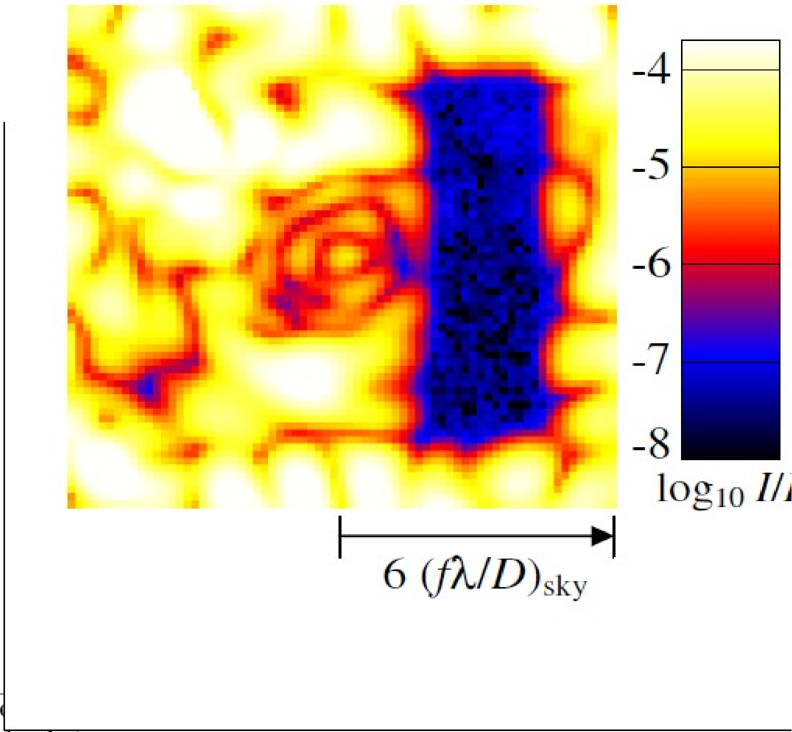
Fundamental advantage:
Uses science detector for wavefront sensing:
“What you see is EXACTLY what needs to be removed / calibrated”

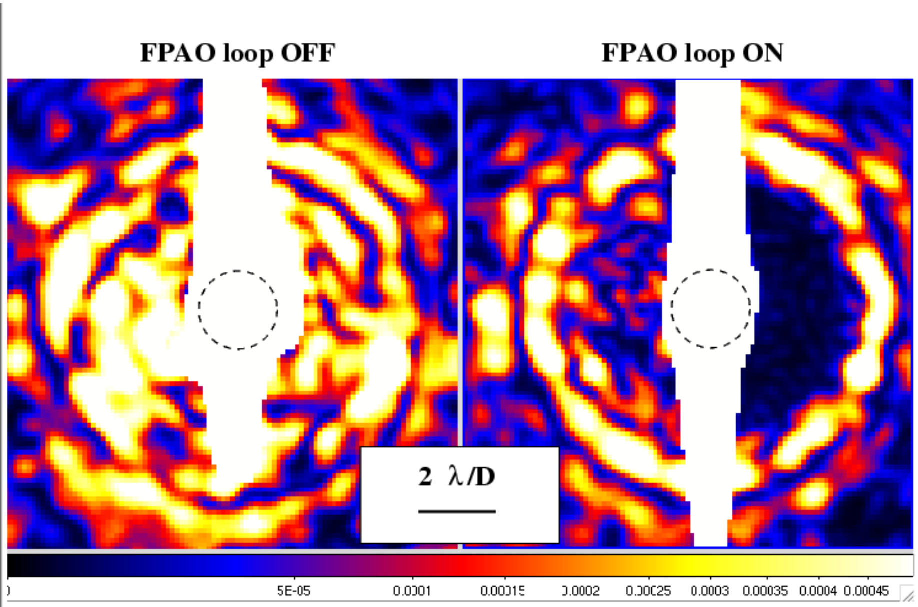
(2) and (3): Focal plane WFS based correction and speckle calibration

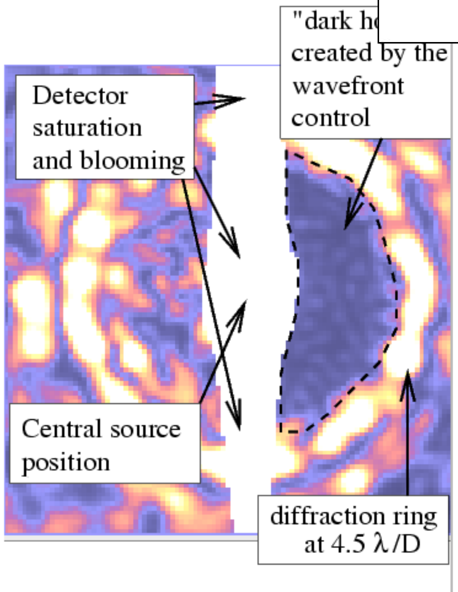
<1e-8 raw contrast obtained at 2 λ/D with PIAA
Coherent bias <3.5e-9

Tests demonstrates:
- ability to separate light into coherent/incoherent fast/slow components
- ability to slow and static remove speckles well below the dynamic speckle halo

Guyon et al. 2010







Conclusions

Habitable planets may be imaged with ELTs around low-mass stars. Spectroscopy of several targets can be done at R~200.

This requires aggressive IWA system able to work at 1 l/D and high sensitivity WFS, but:

- Contrast by itself not too challenging
- Technology to do this exists (benefits from several M$ of NASA funding per yr)

SCExAO is a precursor to such a system (designed for 1 l/D).

A SCExAO-like system could be placed on an ELT in a short time, as optical interfaces for narrow FOV system are relatively easy

8-m class telescopes should be used to develop ExAO at 1 l/D → goal is to be ready when ELT come online

Note:

SCExAO is hiring a postdoc for development (integrate IfU to system) and science observations