MKIDs @ Subaru

Imaging reflected light exoplanets with high performance coronagraphy and MKIDs at Subaru Telescope

The SCExAO Team:

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NAOJ: Junichi Morino

Observatoire de la cote d'Azur: Frantz Martinache

+ University of Sydney VAMPIRES team

+ Observatoire de Paris FIRST team

+ Princeton University CHARIS group

+ SCExAO coronagraph teams (Univ. of Hokkaido, JPL, Princeton University)

The Optical/UV MKID Team:

UCSB: Ben Mazin, Seth Meeker, Matt Strader, Paul Szypryt, Gerhard Ulbricht, Julian van Eyken, Alex Walter, Clint Bocksteigel

JPL: Bruce Bumble

Oxford: Kieran O'Brien

Fermilab: Chris Stoughton, Juan Estrada, Gustavo Cancelo

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Exoplanets: Contrast ratio, visible vs. infrared, giant vs rocky

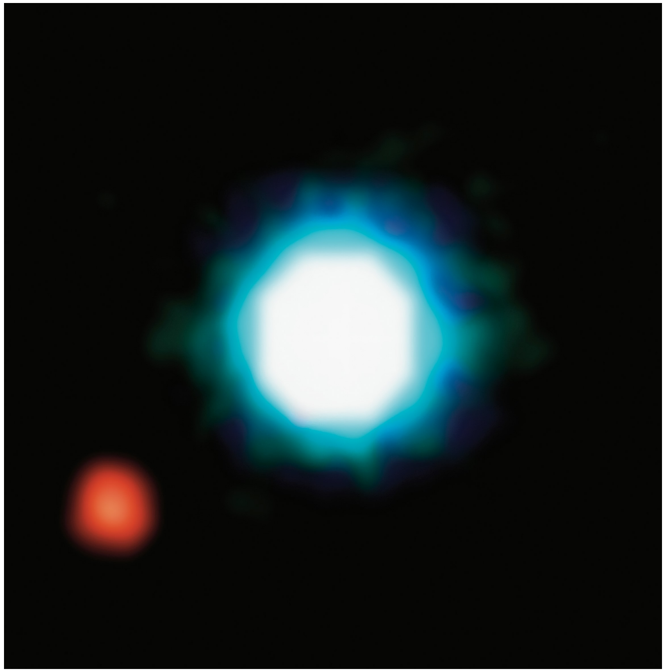
Reflected light: luminosity goes as d^{-2}
High contrast required

In the near-IR (GPI, SPHERE, SCExAO, P1640...), giant and young planets (“young Jupiters”) can be imaged:

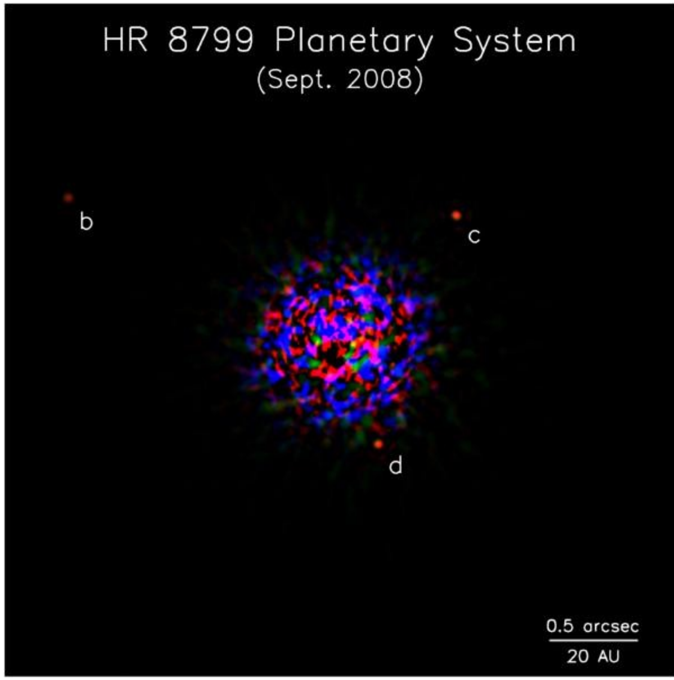
- AO systems work well in the near-IR
- Giant planets emit their own light (thermal emission)

But, habitable planets are not bright in near-IR

In the Thermal IR (~10 um), contrast is more favorable for habitable planets.

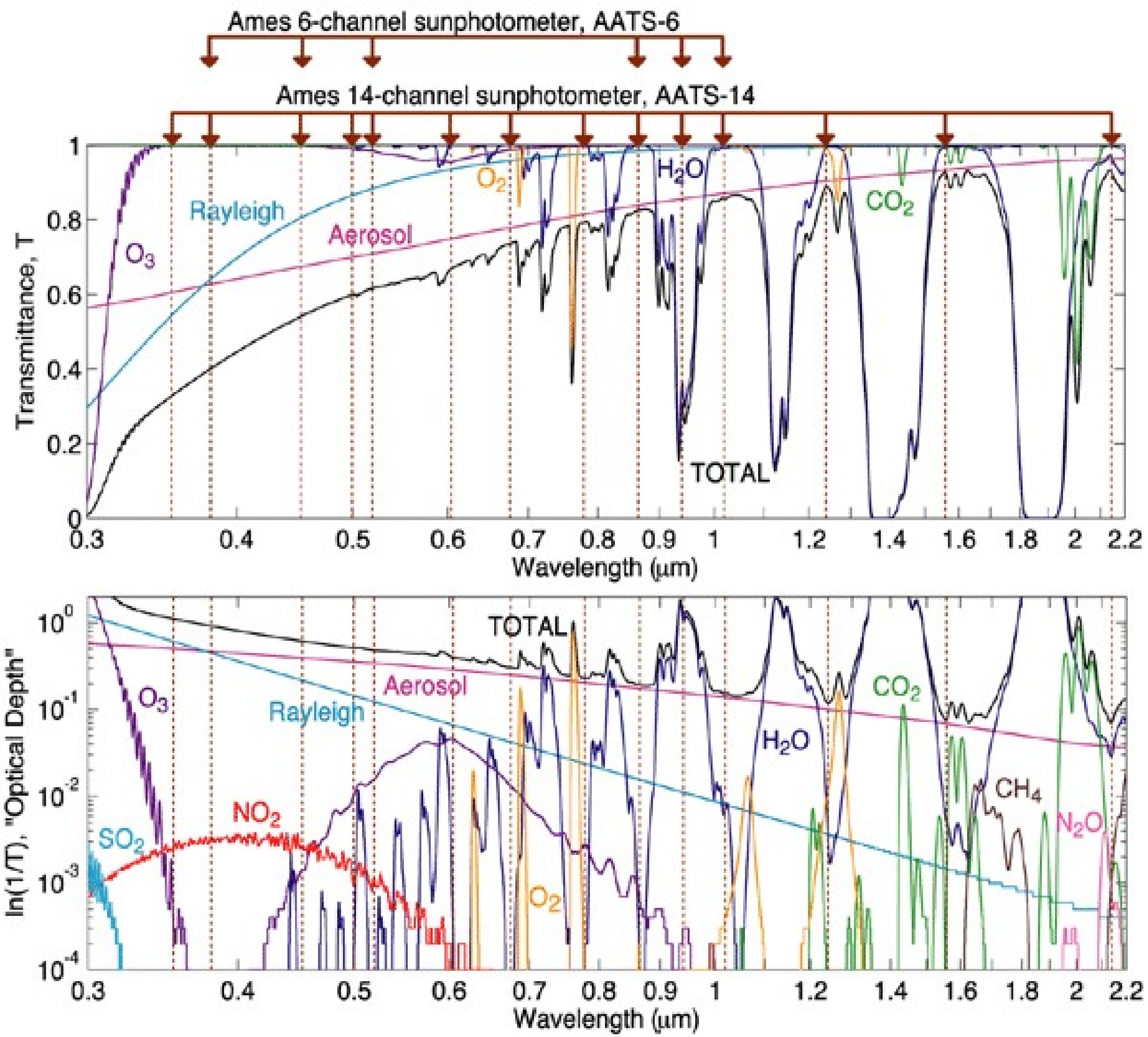


2M1207 exoplanet (Chauvin et al., ESO, 2004)
Probably the first direct image of an exoplanet



HR8799: first image of exoplanetary sytem with multiple planets (Marois et al. 2009)

Habitable Planets Spectroscopy in near-IR



Atmosphere transmission:
O_2 (see Kawara et al. 2012)
H_2O
CO_2
CH_4

Polarimetry

Cloud cover, variability
Rotation period

Reflectivity from ground in atmosphere transparency bands
(Ice cap, desert, ocean etc...)

Microwave Kinetic Inductance Detectors (MKIDs)

(slides provided by B. Mazin, UCSB)

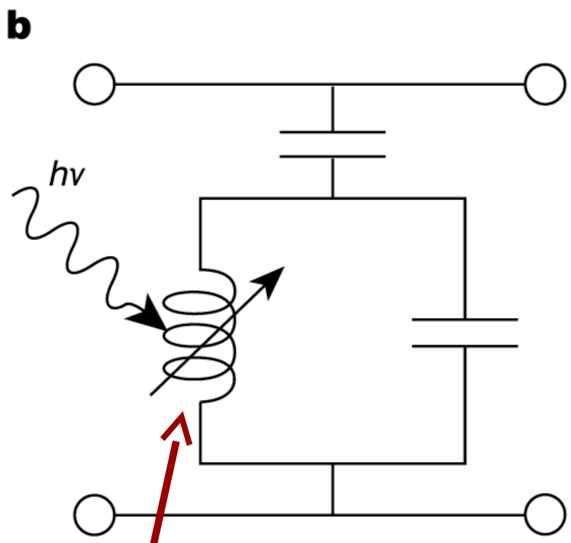
Superconductors

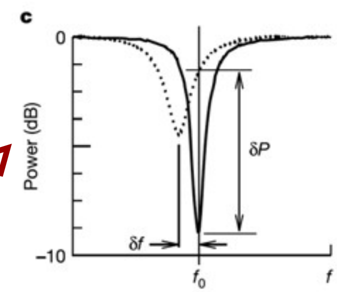
- A superconductor is a material where all DC resistance disappears at a "critical temperature". 9 K for Nb, 1.2 K for Al, 0.8 for our TiN
- This is caused by electrons pairing up to form "Cooper Pairs"
  - Nobel Prize to BCS in 1972

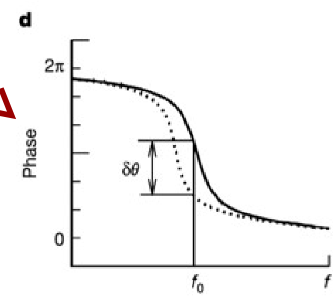
- Like a semiconductor, there is a "gap" in a superconductor, but it is 1000-10000x lower than in Si
- So instead of one electron per photon in a semiconductor, you get ~5000 electrons per photon in a superconductor – much easier to measure (no noise and energy determination)! We call these excitations quasiparticles
- However, superconductors don't support electric fields (perfect conductors!) so CCD tricks of shuffling charge around don't work
- Excitations are short lived, life times of ~50 microseconds

MKIDs

MKID Equivalent Circuit

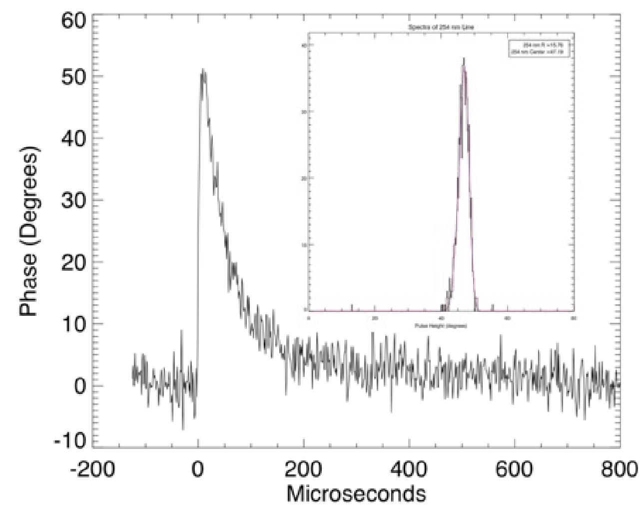


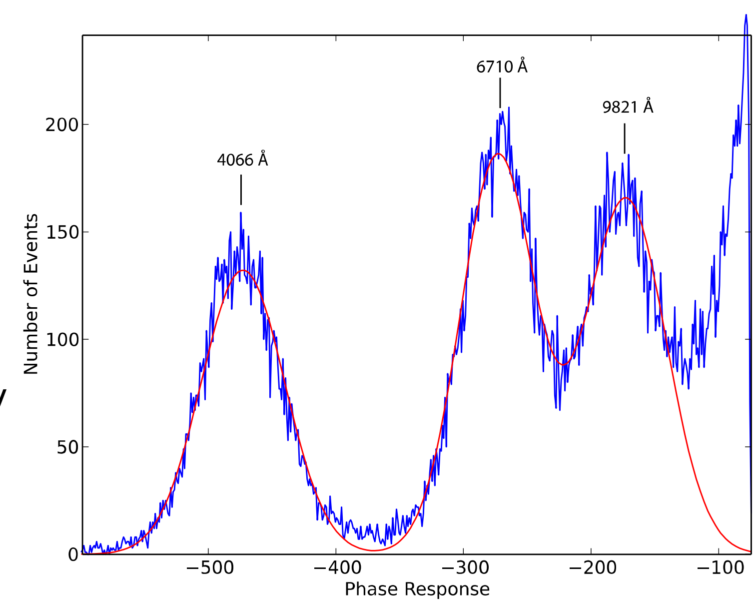


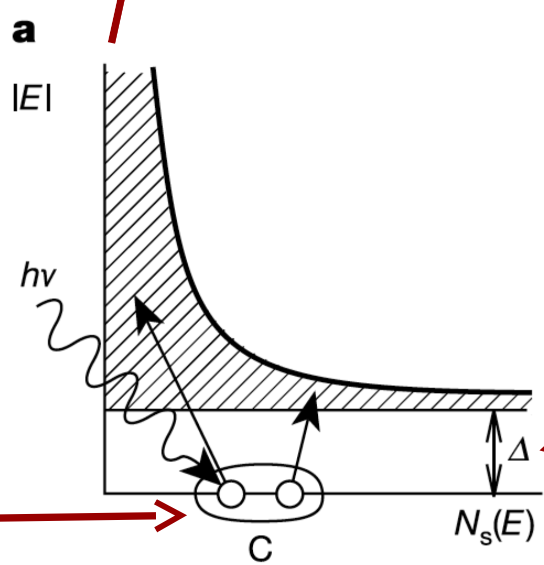


Inductor is a Superconductor!

Typical Single Photon Event







Coope
r Pair

Energy Gap

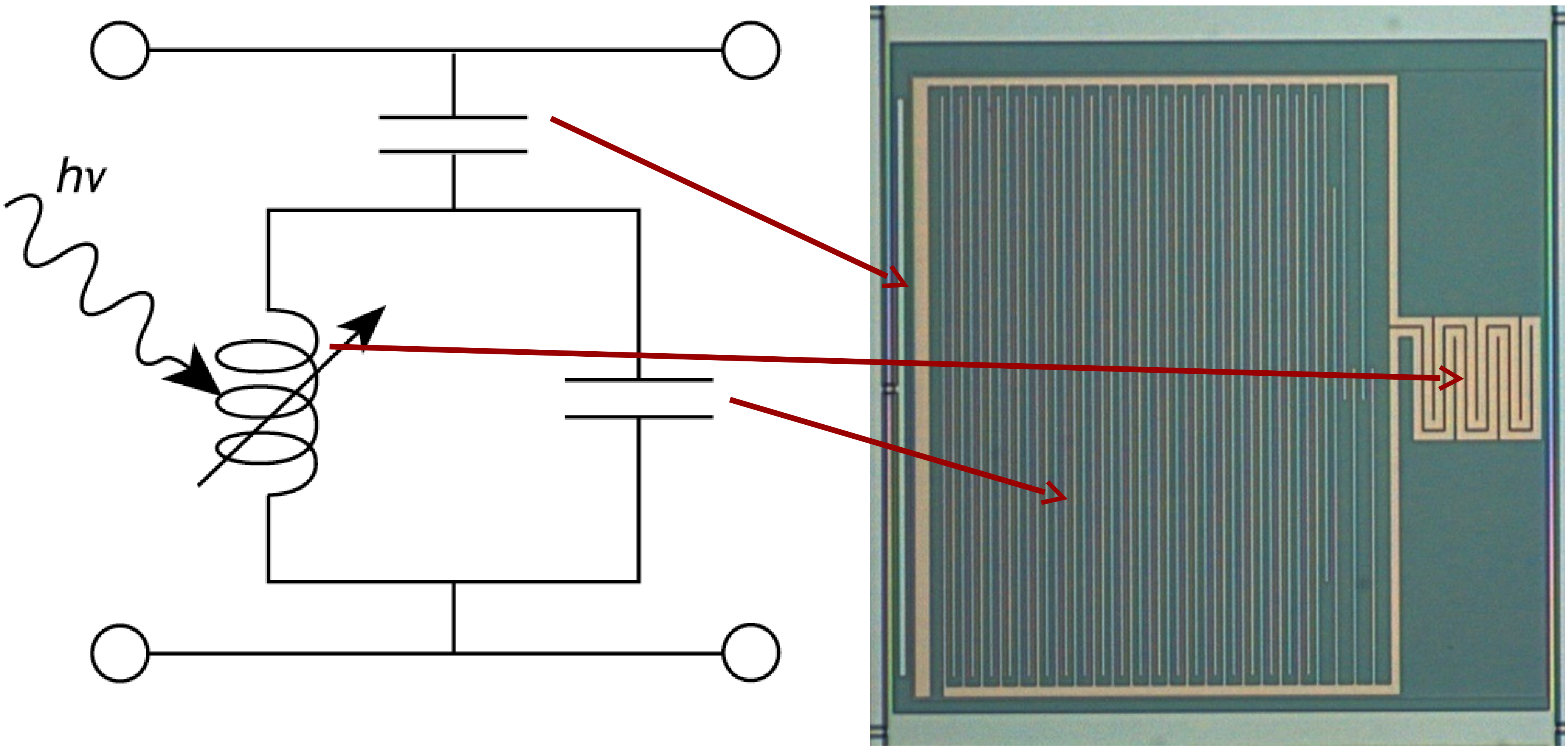
Silicon – 1.10000 eV

Aluminum – 0.00018 eV

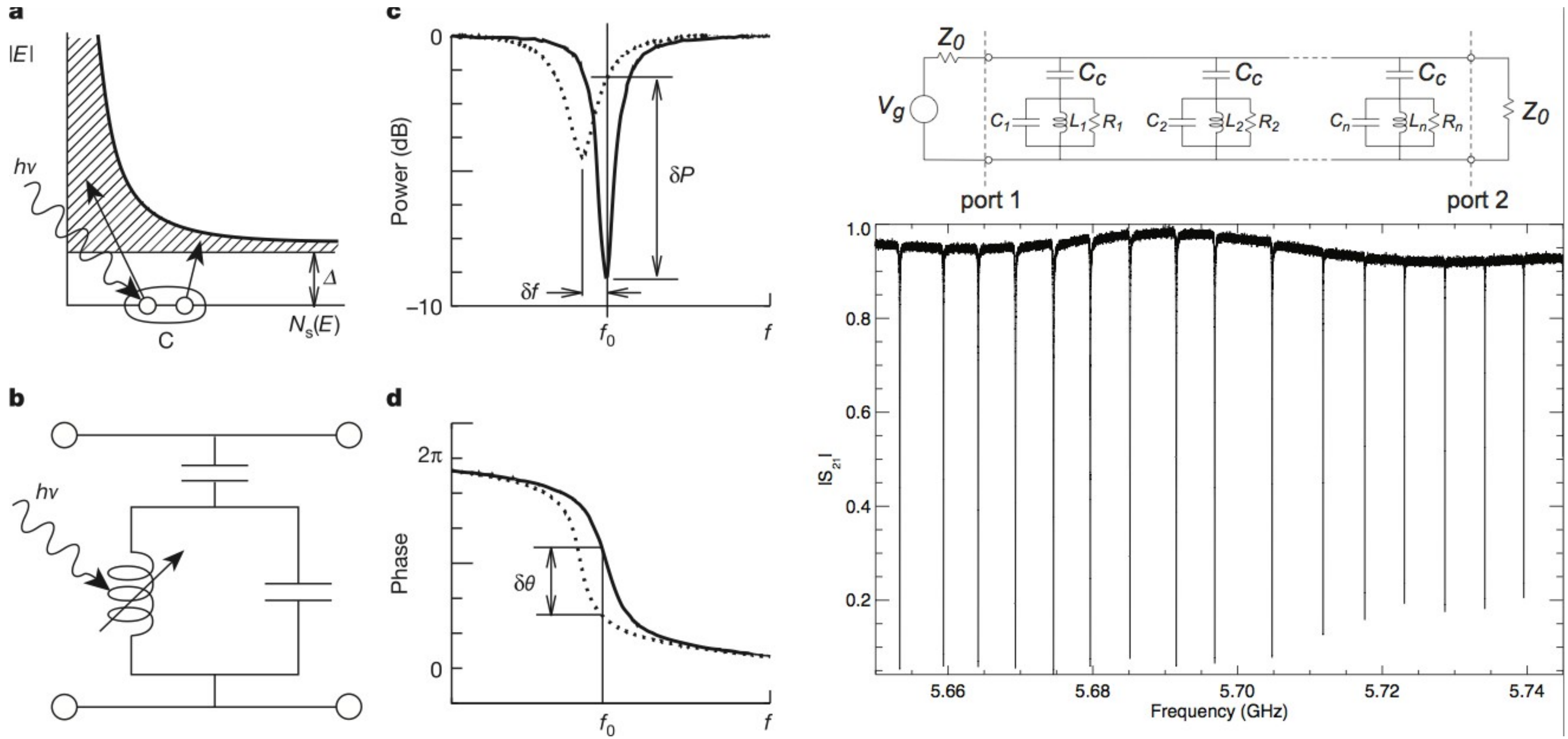
Energy resolution:

$$R = \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{F\Delta}}$$

What is a Kinetic Inductance Detector ?



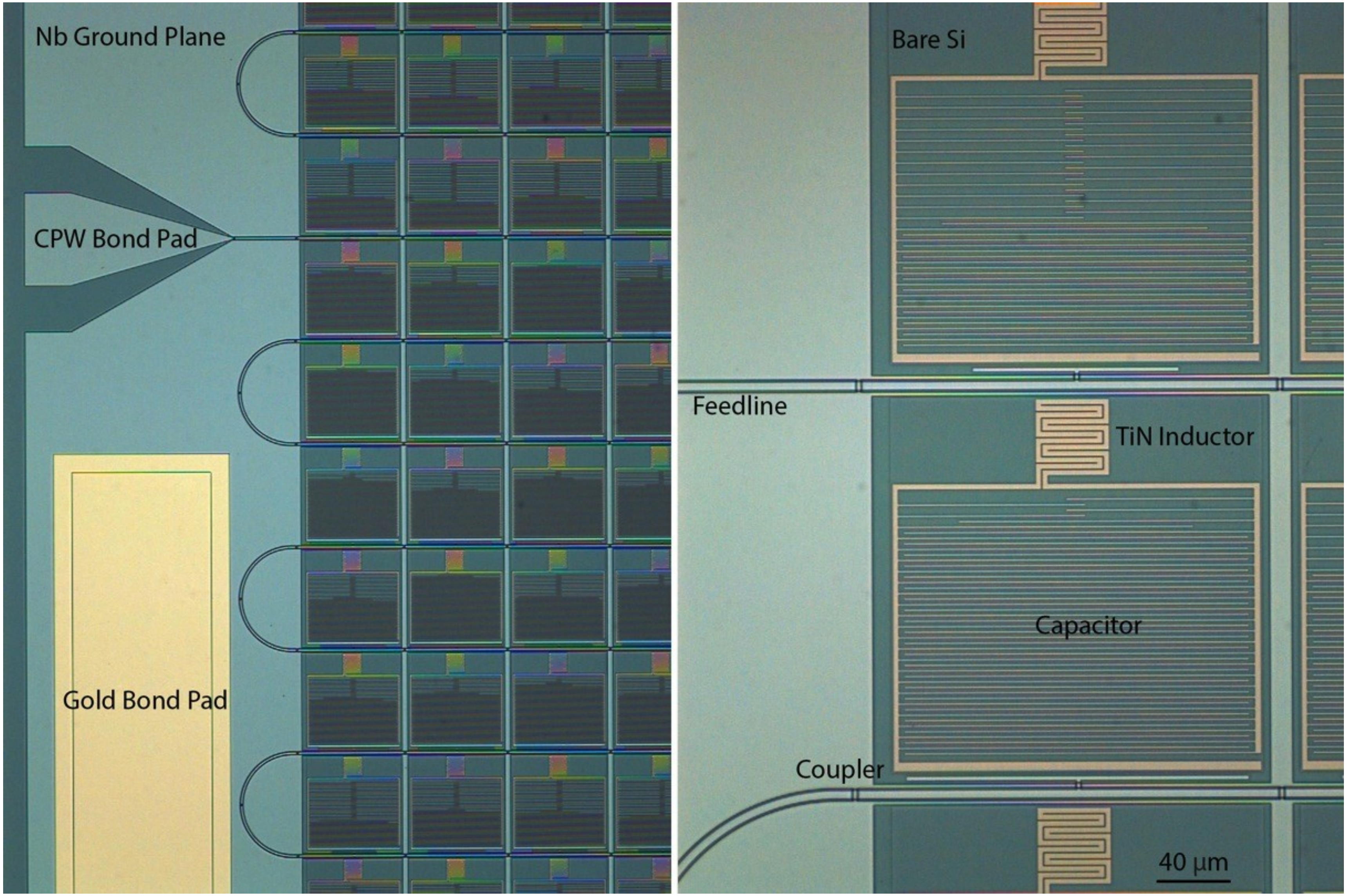
Frequency Domain Multiplexing



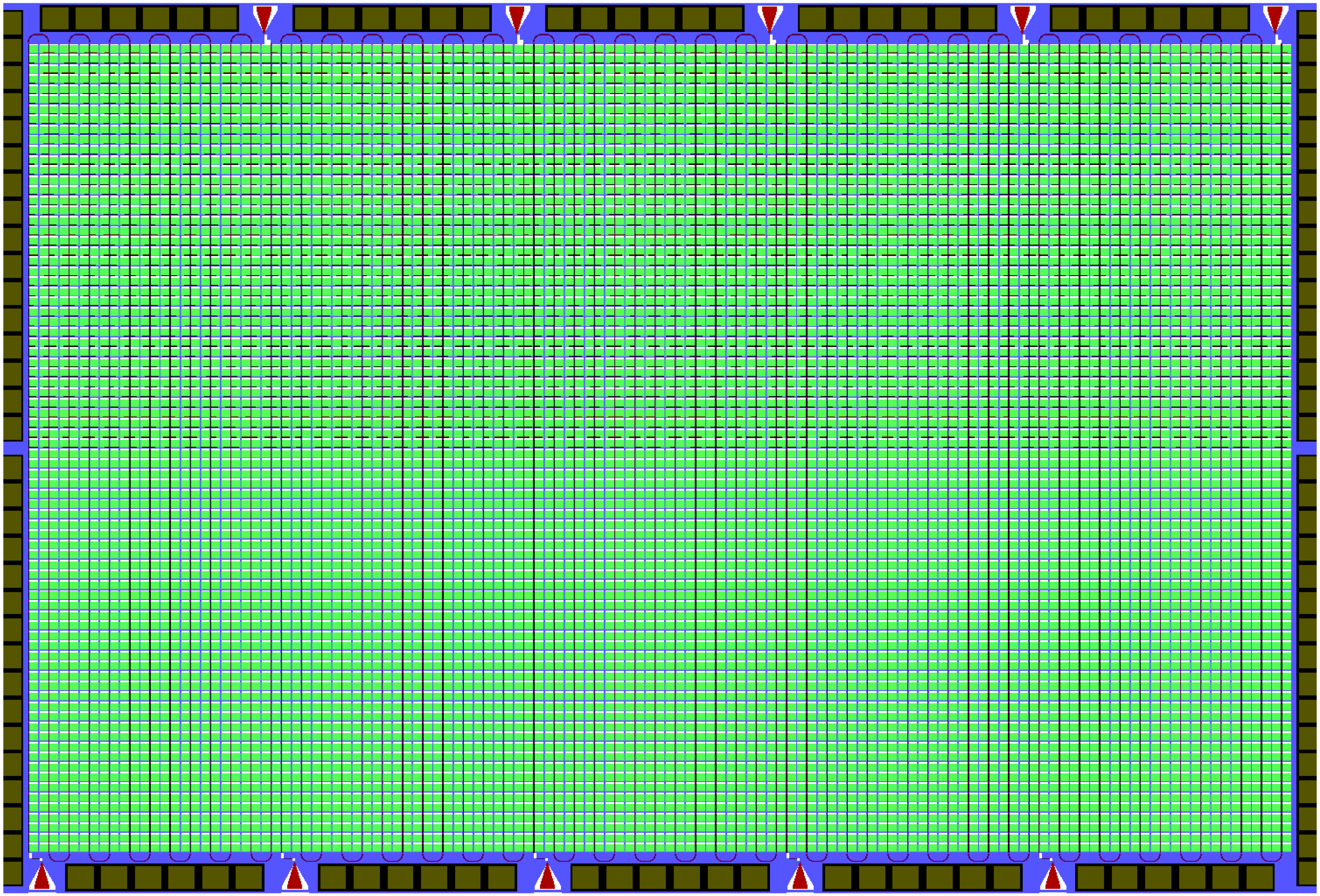
- Each resonator (pixel) has a unique resonant frequency in the GHz range
- A comb of sine waves is generated and sent through the device
- Thousands of resonators can be read out on a single microwave transmission line (FDM)

UVOIR MKIDs

- Directly absorb photons in the TiNx (800 mK) MKID inductor
- Nb ground planes with SiO2 crossovers
- Microlens array boosts fill factor to 92%
- Many harsh lessons learned about array design!

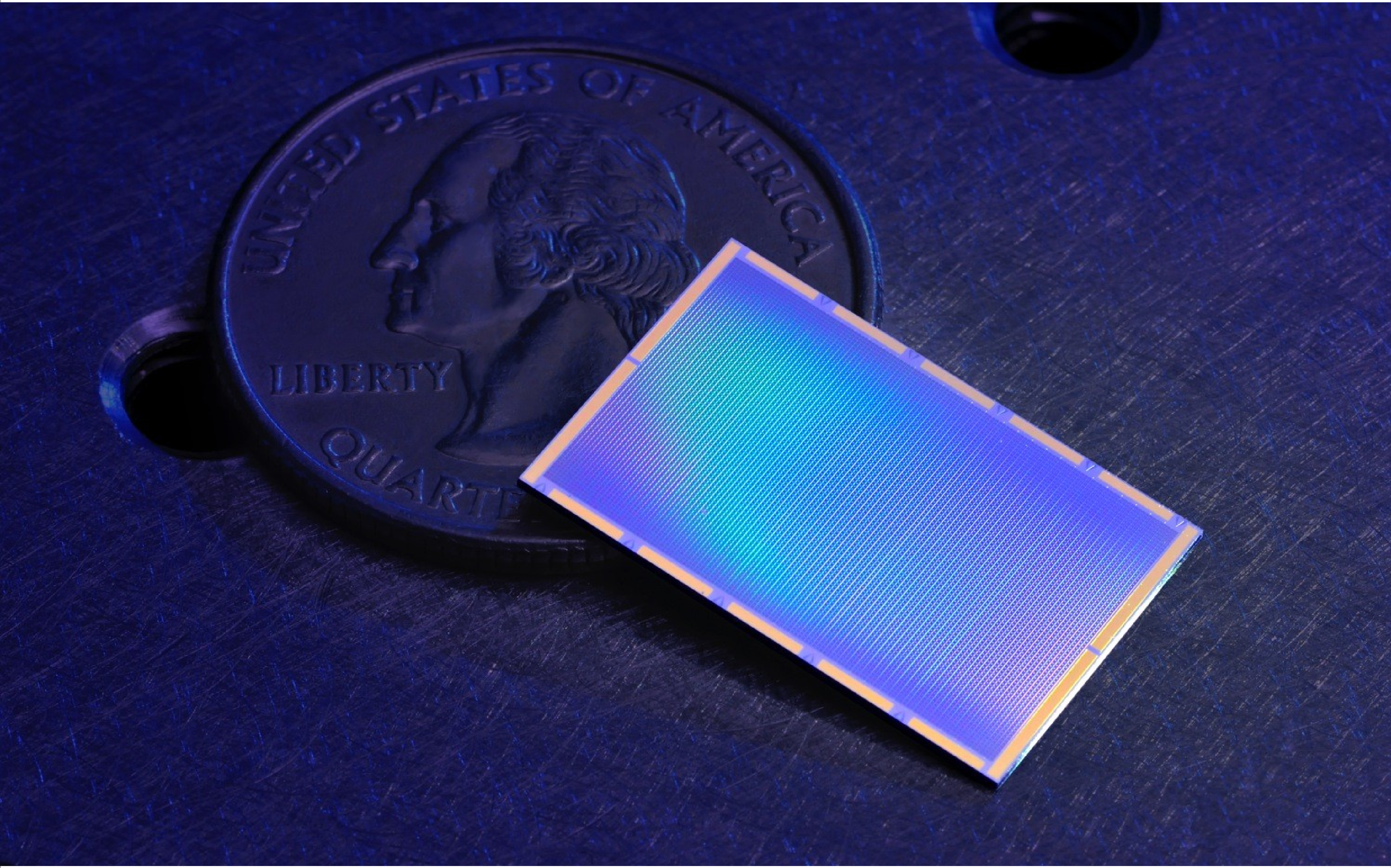


10 kpix Array Design



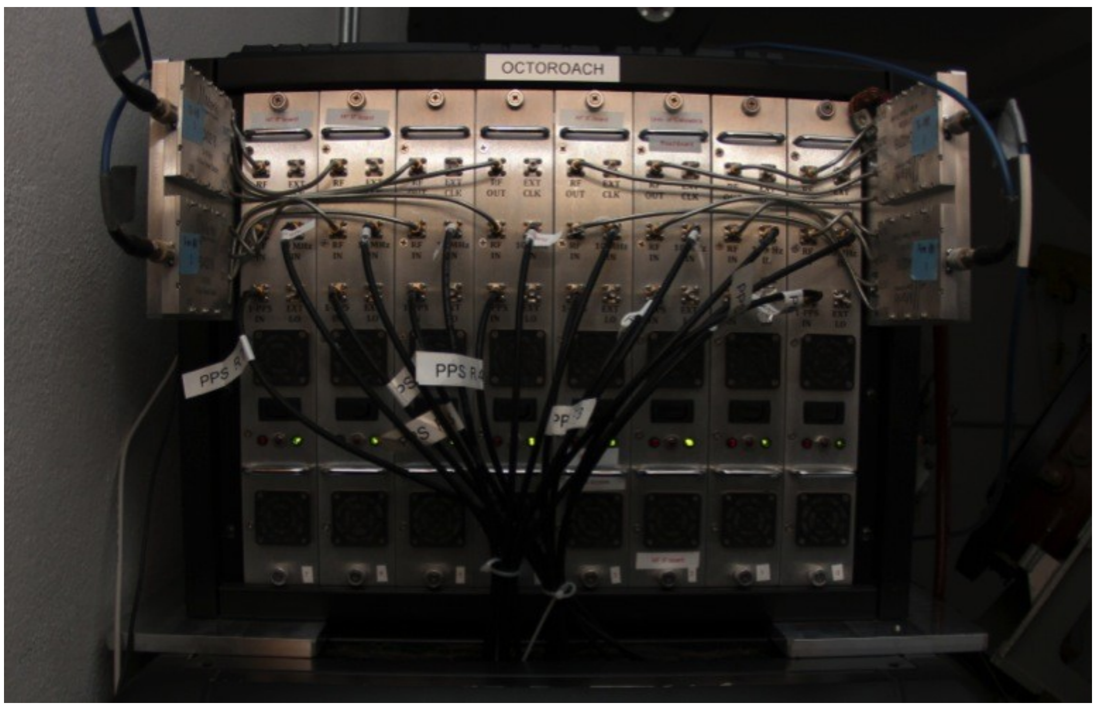
- Array for NSF-funded DARKNESS IFU. 150 micron pitch.
- Stepper patch from 80x125 (10 kpix) to 80x600 (50 kpix)
- Optimized for 0.7-1.4 microns

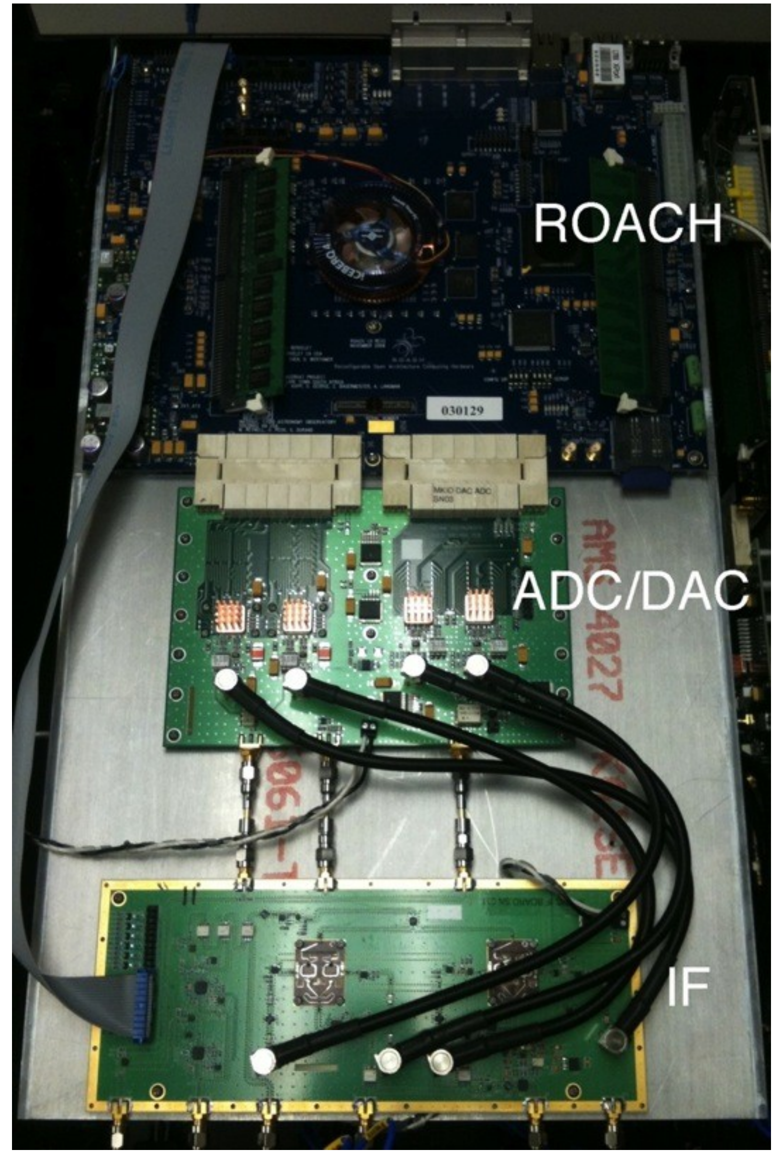
10 kpix DARKNESS Array



Current Readout System (Gen 1)

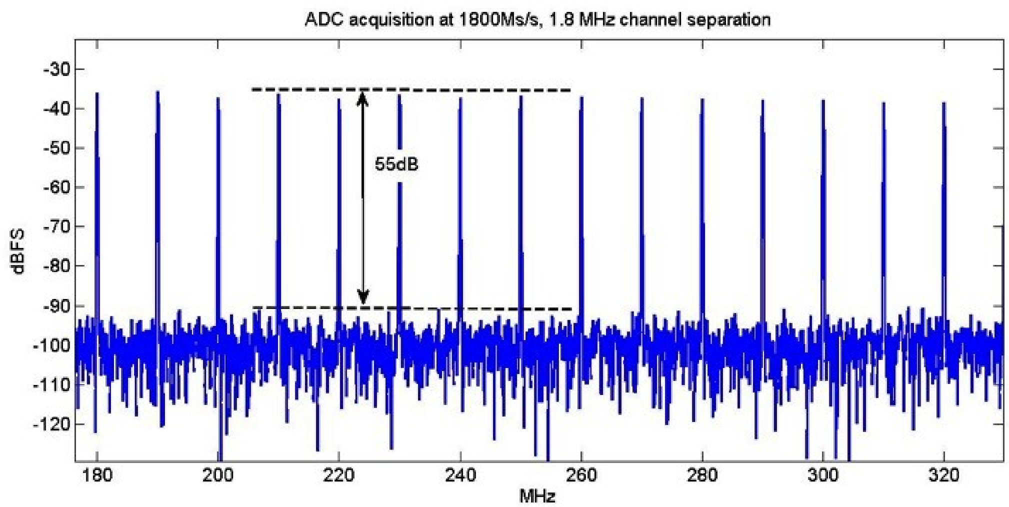
- Dual 1 GSPS 16-bit DACs
- Dual 550 MSPS 12-bit ADCs
- ROACH with Virtex 5 SX95T
- Complete readout for 256 resonators in 550 MHz of bandwidth
- 8 ROACH boards read out 2048 pix
- ~$25/pixel (Gen2 - $3/pixel)

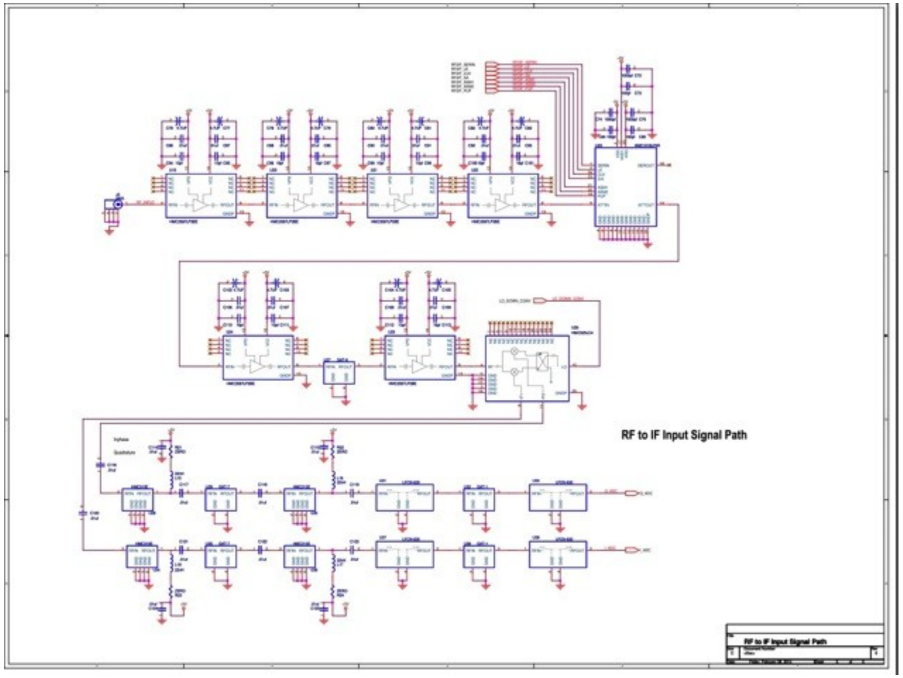




Gen2 Readout

- Designed in collaboration with Fermilab
- Based on Casper ROACH2 (Virtex 6)
- Uses TI Dual 1.8 GSPS 12 bit ADC
- Will read out 1024 resonators in 1.8 GHz of bandwidth
- 2 boards per feedline in 4-8.5 GHz band, scalable to 30+ kpix
- Incorporates many lessons from Gen1!
- Prototypes by September
- Cost Goal: ~$5/pixel

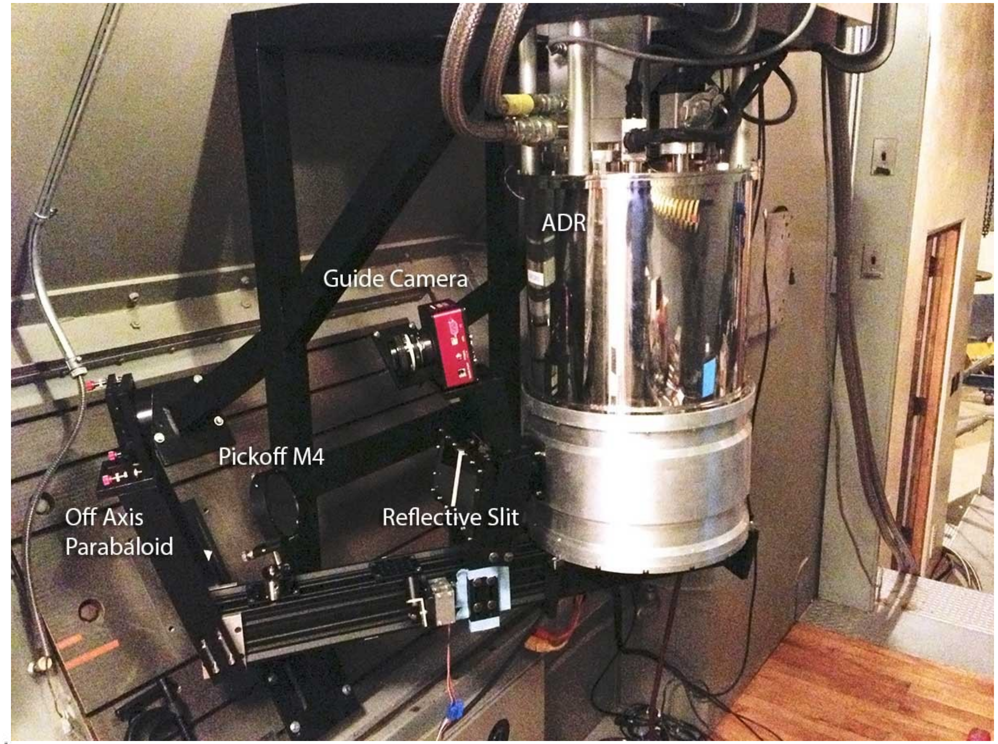


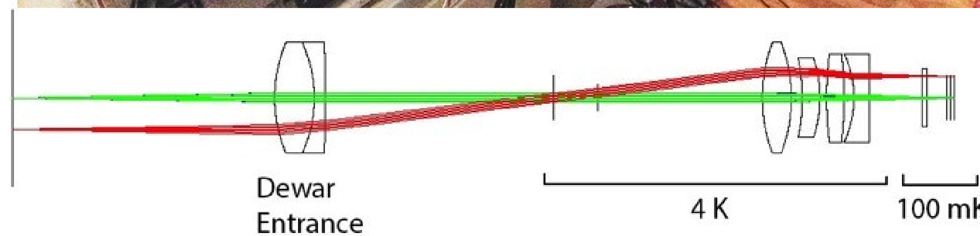


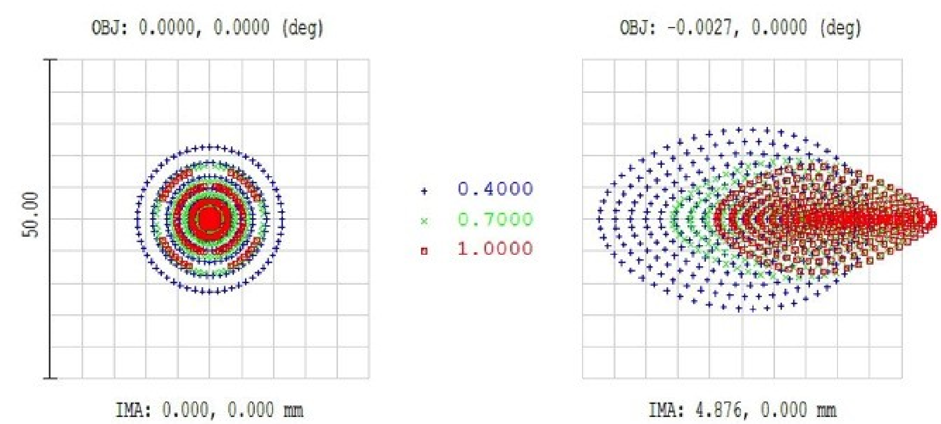
Proven at the Telescope with ARCONS

- Array Camera for Optical to Near-IR Spectrophotometery (ARCONS)
- First Light: July 28, 2011, Palomar 200” Coudé
- Now 29 observing nights (Palomar+Lick)
- Lens coupled 2024 (44x46) pixel array in cryogen-free ADR
- 0.5” pixels yields 22”x23” FOV
- 400 nm to 1100 nm simultaneous bandwidth with maximum count rate of ~2000 cts/pixel/sec
- 350-1350 nm soon
- Energy resolution R~8 at 400 nm

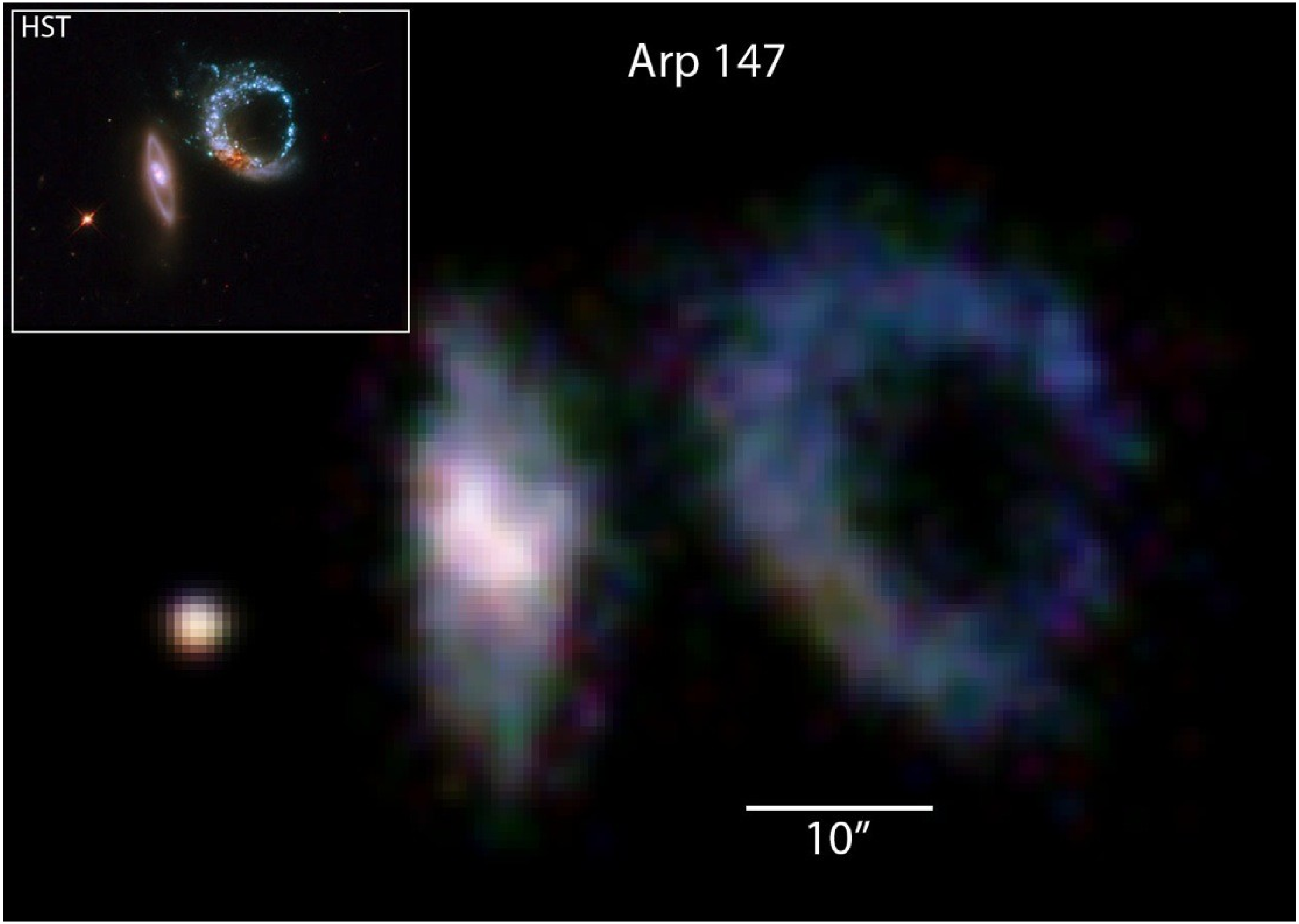
Mazin et al. 2013, PASP





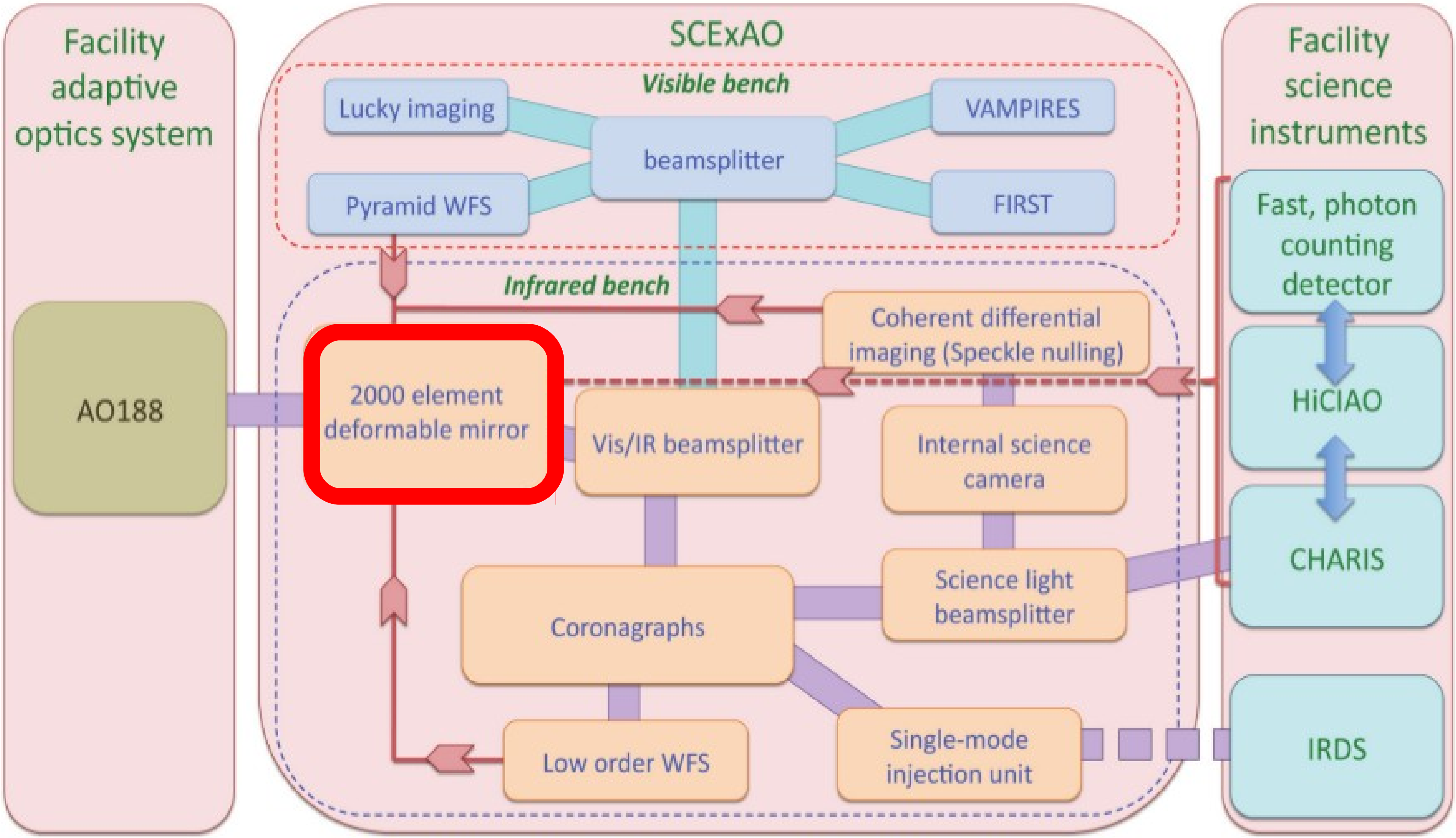


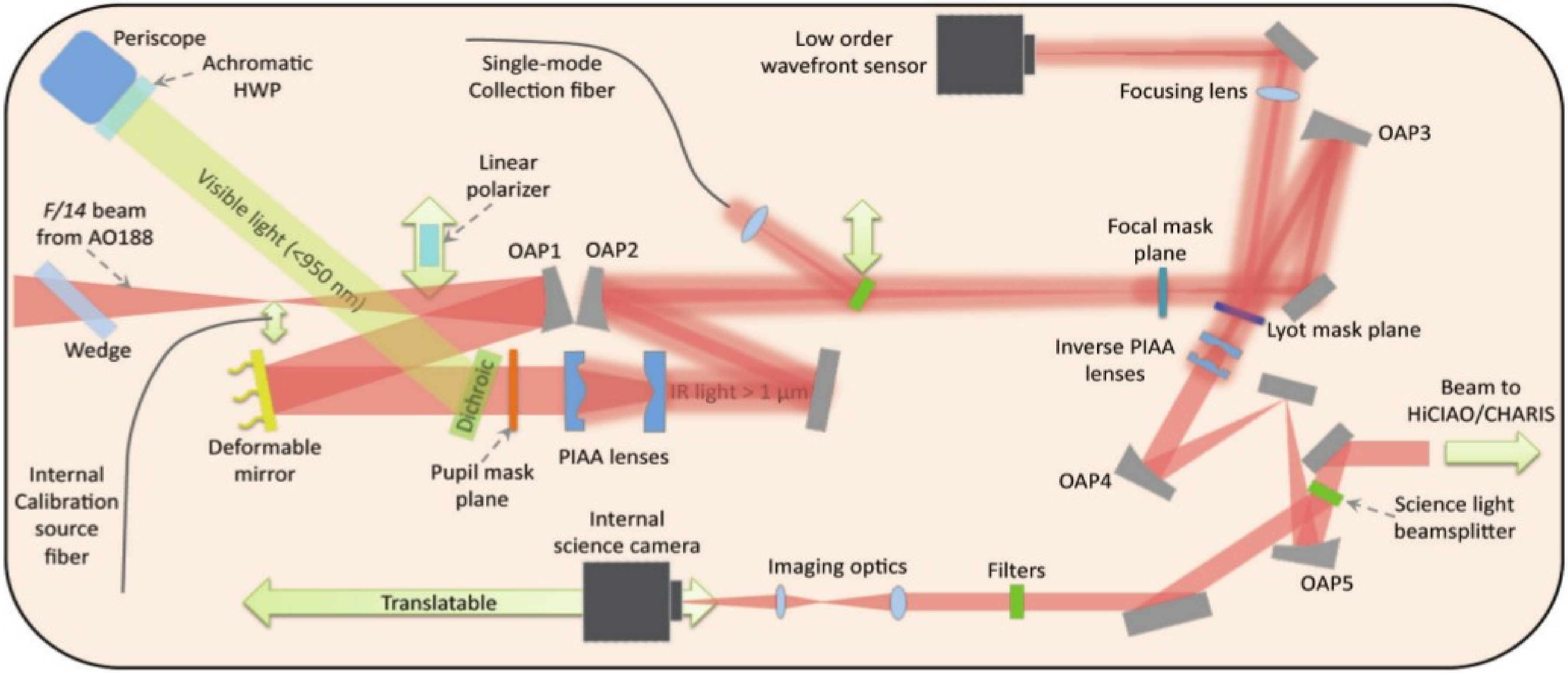
Mosaic of Arp 147



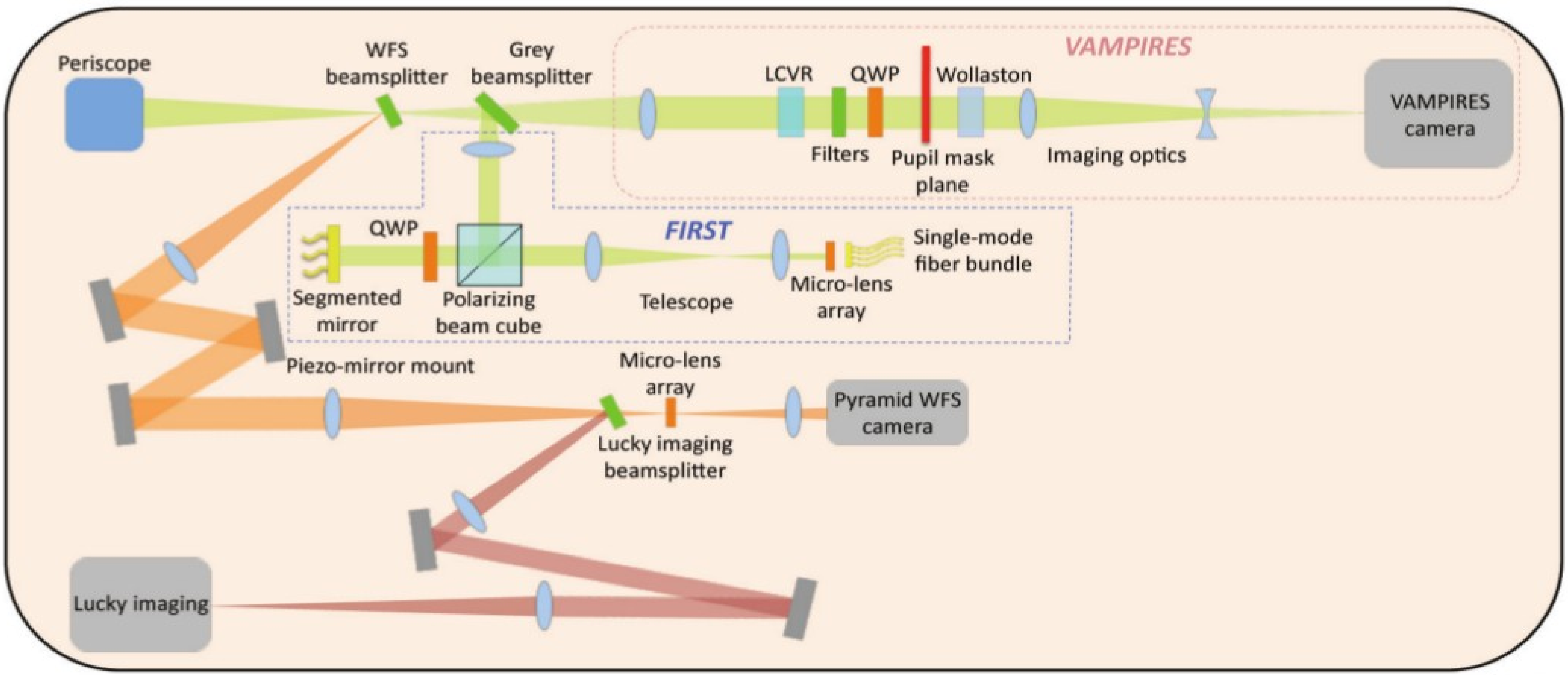
- Mosaic of Arp 147 taken at the Palomar 200” in December 2012 with ARCONS
- 36 pointings on 6” x 6” grid, 1 minute obs. time/pointing
- Colors generated from MKID wavelength information!

SCExAO overview



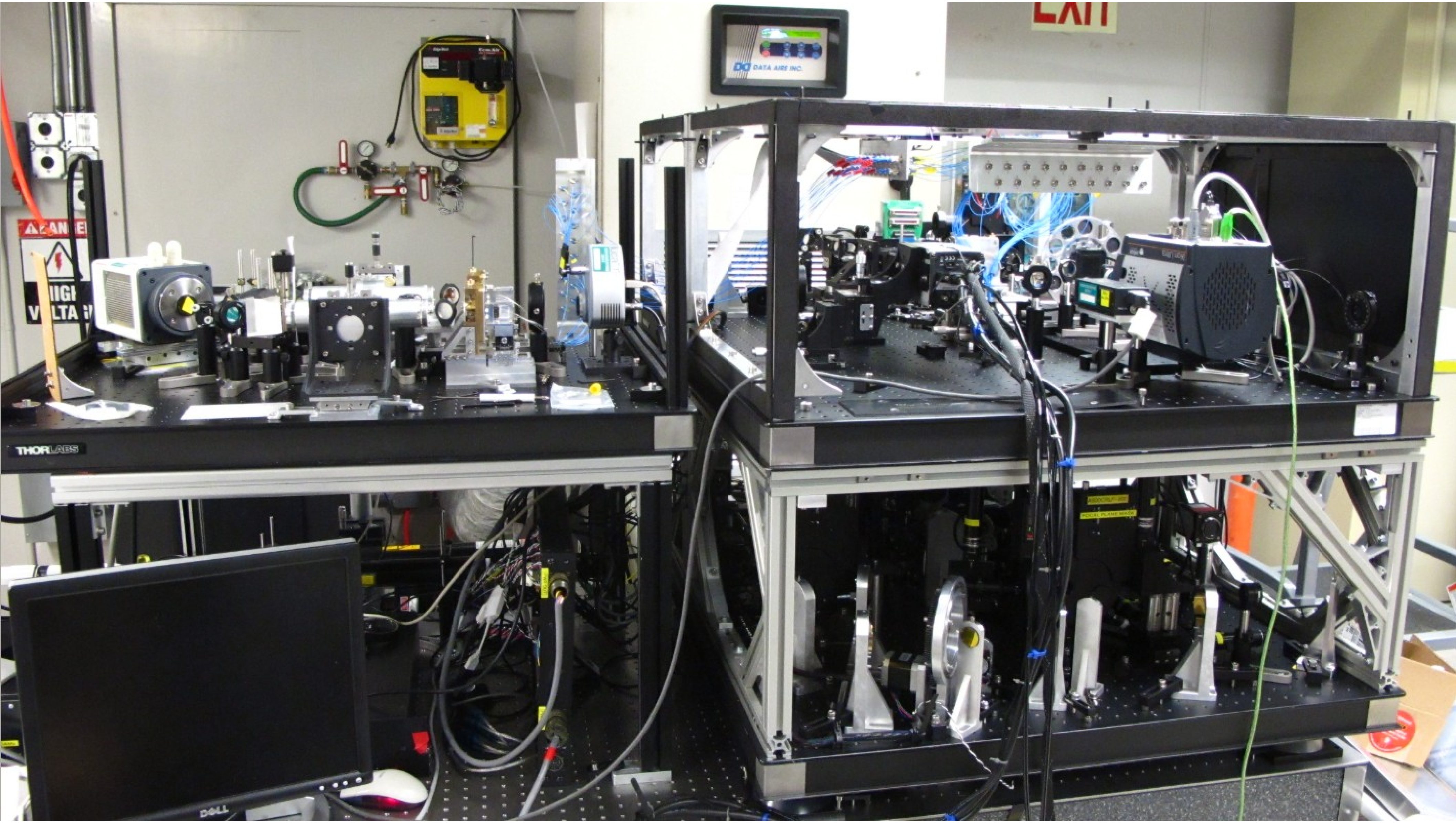


Periscope
Achromatic HWP
Single-mode Collection fiber
Low order wavefront sensor
Focusing lens
OAP3
Linear polarizer
Visible light (<950 nm)
F/14 beam from AO188
OAP1
OAP2
Focal mask plane
Wedge
Lyot mask plane
Inverse PIAA lenses
Dichroic
IR light > 1 µm
Beam to HiCIAO/CHARIS
Deformable mirror
Pupil mask plane
PIAA lenses
OAP4
Internal Calibration source fiber
Science light beamsplitter
Internal science camera
Imaging optics
Filters
OAP5
Translatable

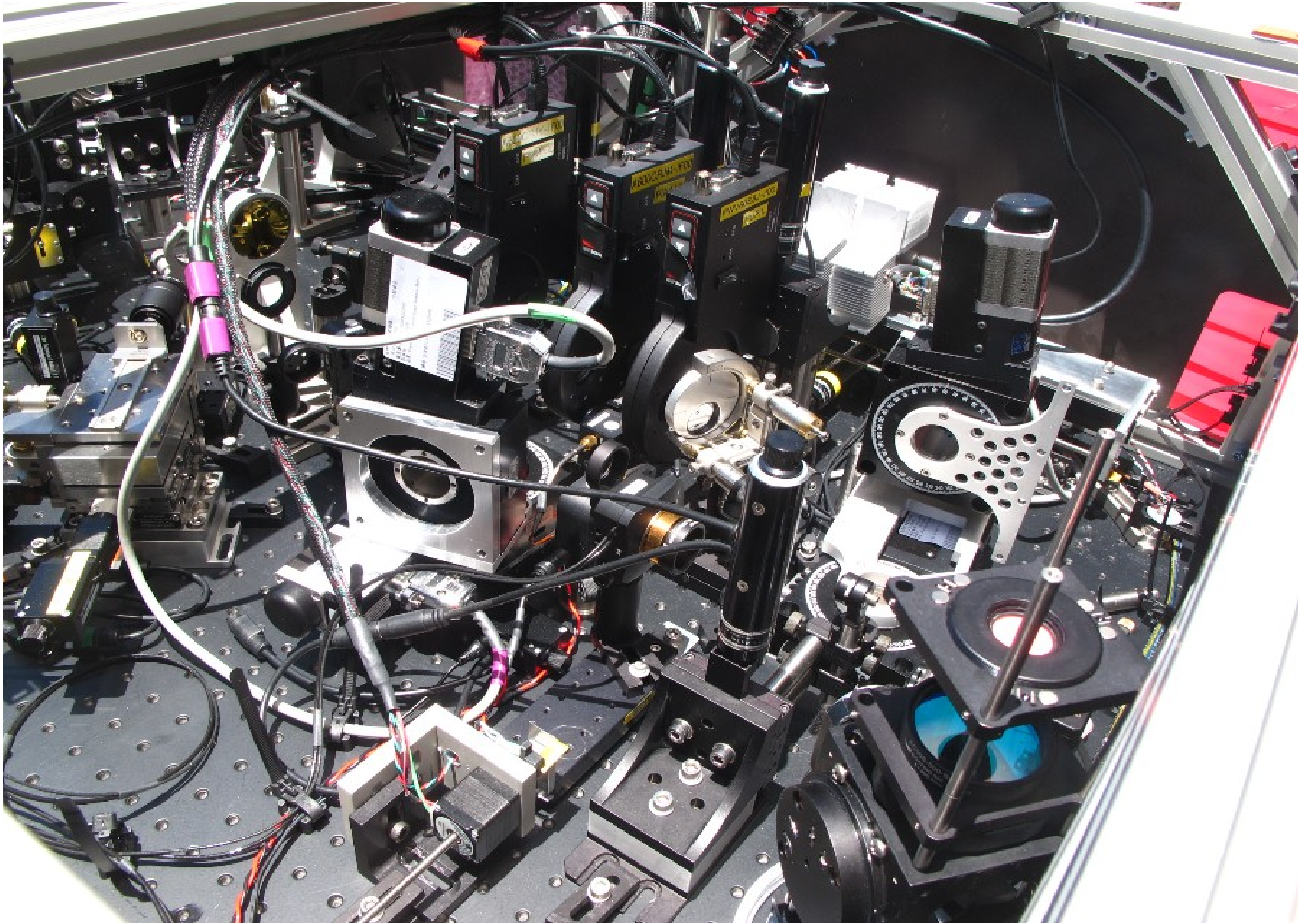


Periscope
WFS beamsplitter
Grey beamsplitter
VAMPIRES
LCVR
QWP
Wollaston
VAMPIRES camera
Filters
Pupil mask plane
Imaging optics
QWP
FIRST
Single-mode fiber bundle
Segmented mirror
Polarizing beam cube
Telescope
Micro-lens array
Piezo-mirror mount
Micro-lens array
Pyramid WFS camera
Lucky imaging beamsplitter
Lucky imaging

Subaru Coronagraphic Extreme-AO (SCExAO) system
(July 10 2013)

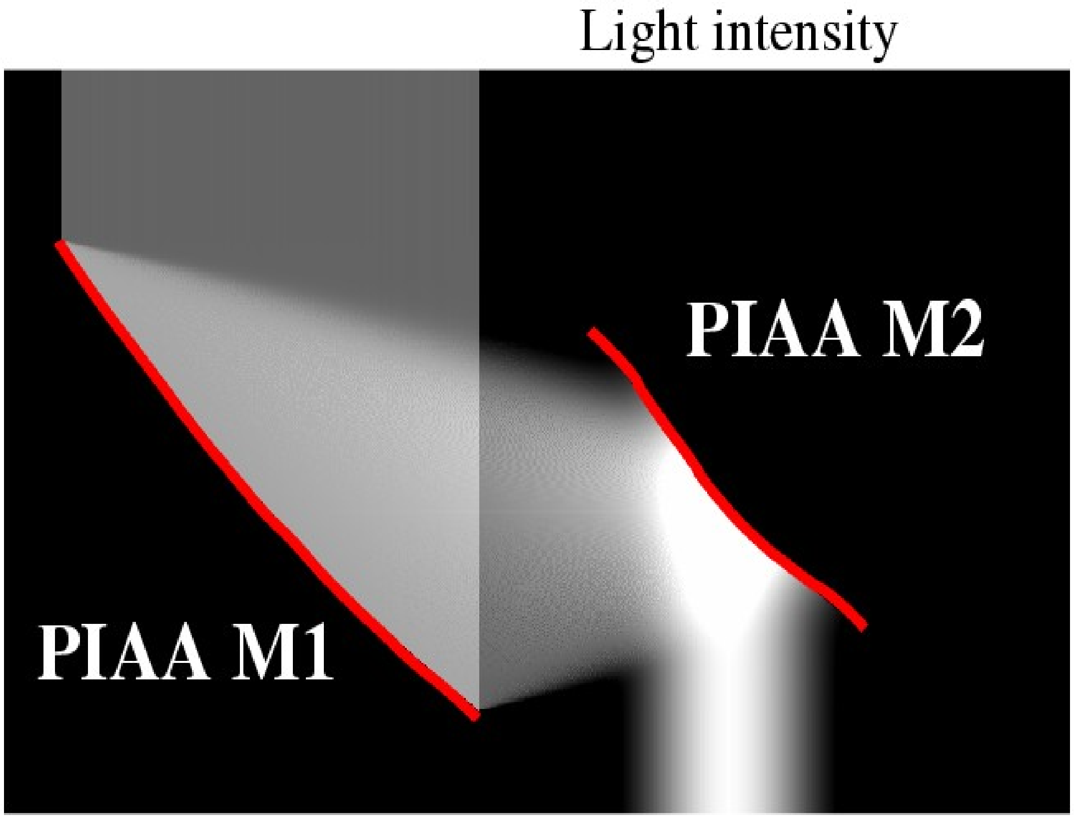


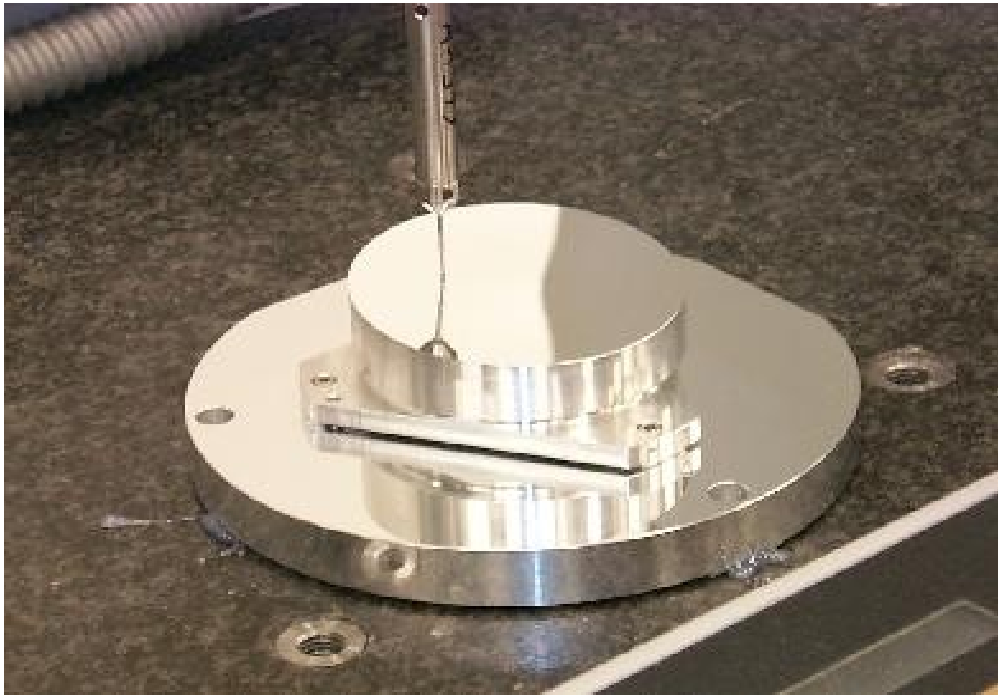
Detail (PIAA optics)



Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.





Guyon, Belikov, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present

Speckle noise

After all correction, calibrations, differential imaging :

$$\text{DETECTION CONTRAST LIMIT} = \sqrt{\frac{\text{SPECKLE INTENSITY LEVEL}}{\text{Exp. time / SPECKLE COHERENCE TIME}}}$$

Time scales:

- **Photon noise in science camera photon arrival rate**
- **Photon noise in WFS: AO loop speed**
- **Atm turbulence: wind crossing time D/v**
- **Optics, telescope: minutes, hours, days**

Chromatic and time lag speckle:
1e-5 speckles, lasting 5s → 14h to get to 1e-7 contrast

WFS noise speckle:
1e-4 speckles, lasting 1ms →17mn to get to 1e-7 contrast

Speckle noises

Slow speckles (SLO)
Due to optics, NCPEs
1e-5 contrast
~10 mn timescale

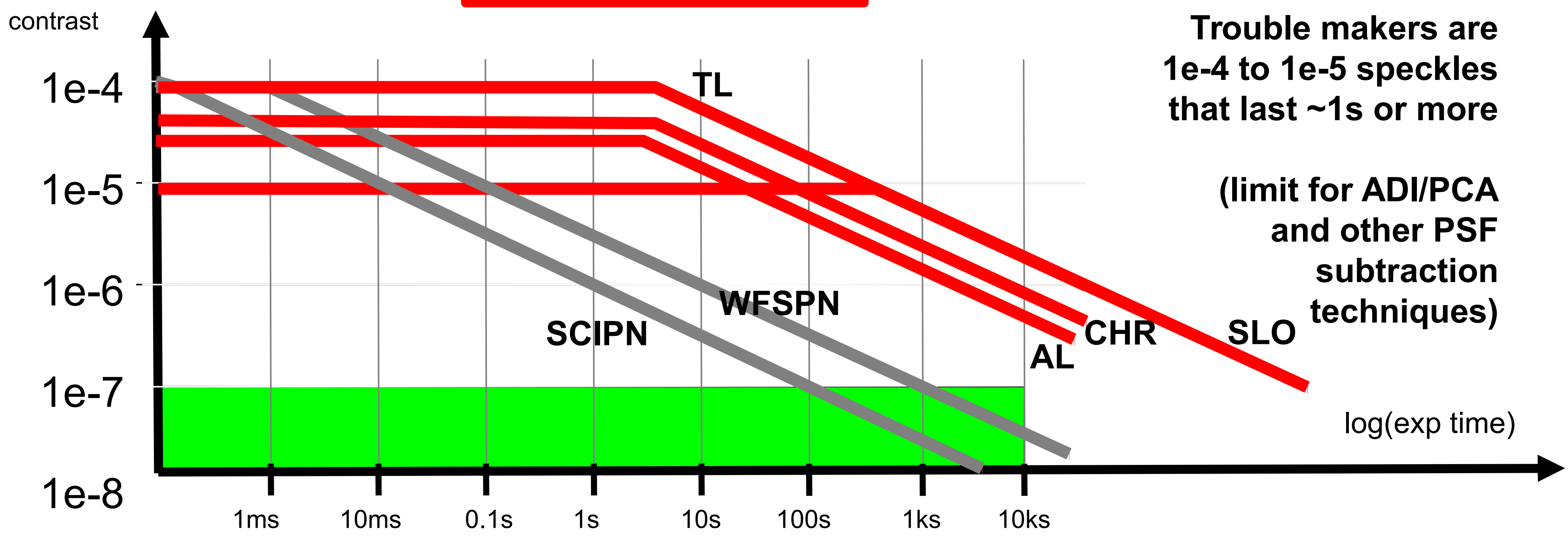
WFS Aliasing (AL)
Aliasing within WFS
few x1e-5 contrast
D/v timescale

WFS photon noise (WFSPN)
Photon noise in WFS
1e-4 contrast
T_{WFS} timescale

Time Lag (TL)
Due to finite AO loop speed / time delay
1e-4 contrast
D/v timescale

Chromaticity (CHR)
Due chromaticity between WFS and science instrument
few x1e-5 contrast
D/v timescale

Science photon noise (SCIPN)
Photon noise in science image
1e-4 contrast
Photon arrival rate timescale (>kHz)

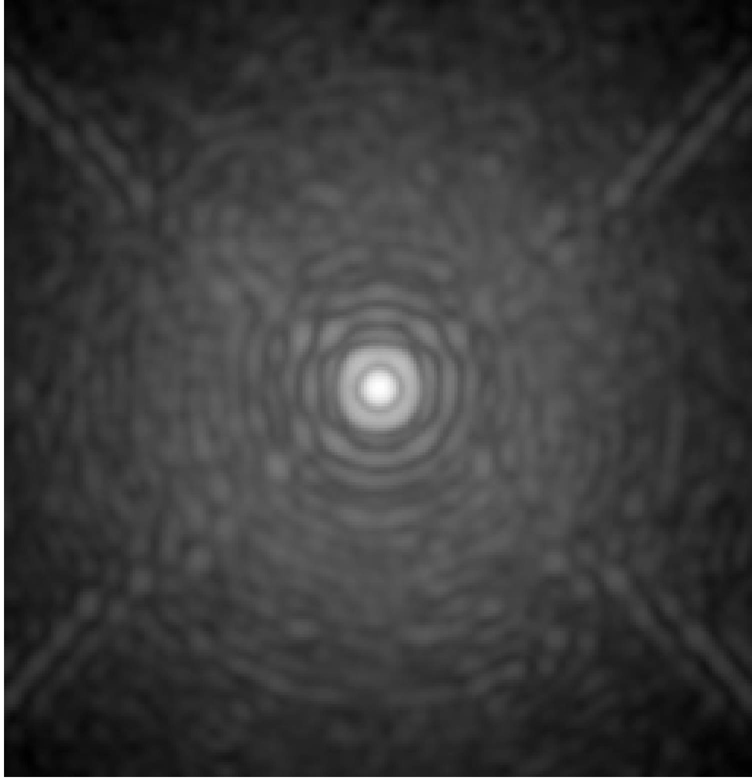


Trouble makers are 1e-4 to 1e-5 speckles that last ~1s or more

(limit for ADI/PCA and other PSF subtraction techniques)

Focal plane speckle control

"It is much easier to break something in a way you understand than to fix something you don't understand"



Use Deformable Mirror (DM) to add speckles

SENSING: Put "test speckles" to measure speckles in the image, watch how they interfere

CORRECTION: Put "anti speckles" on top of "speckles" to have destructive interference between the two (Electric Field Conjugation, Give'on et al 2007)

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

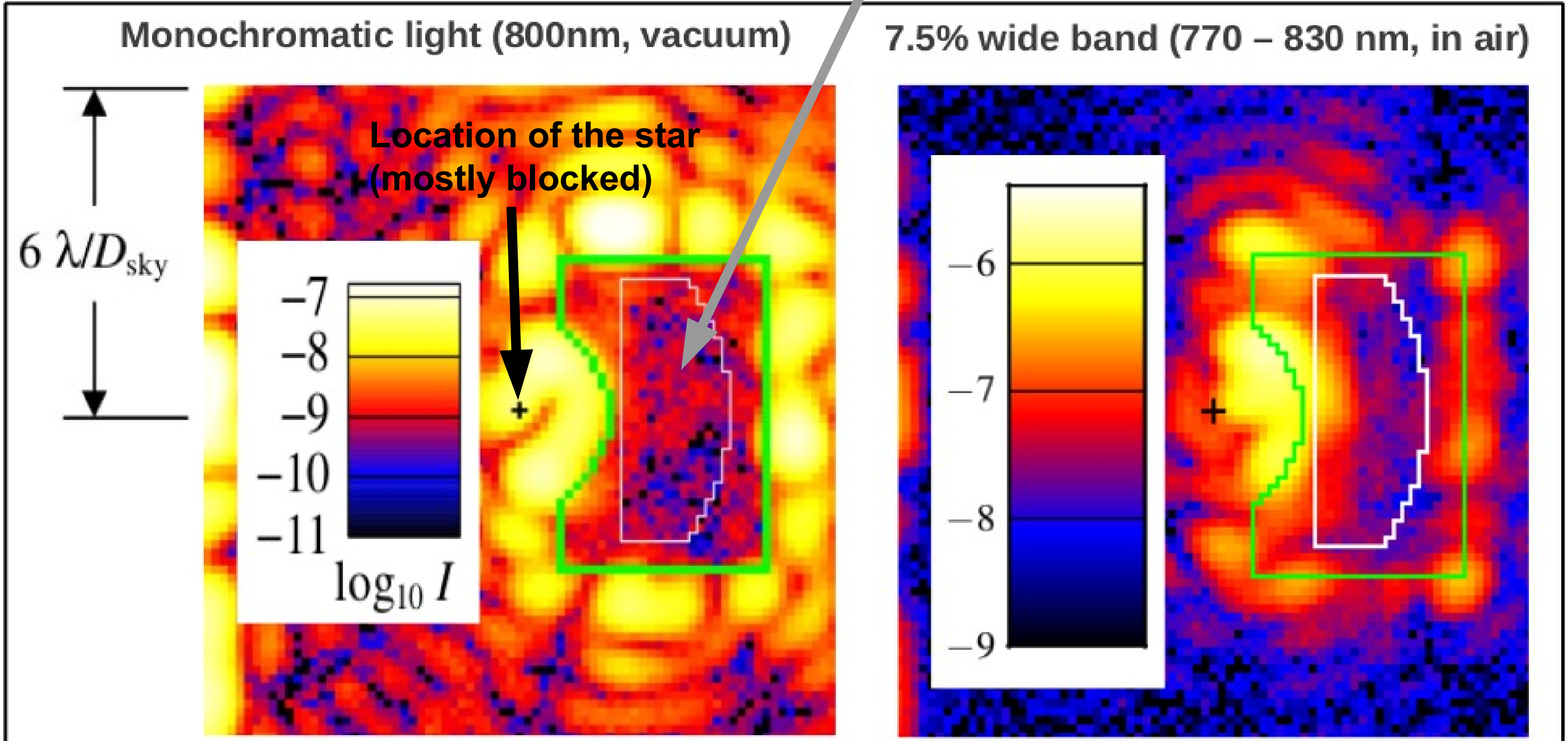
Fundamental advantage:
Uses science detector for wavefront sensing:
"What you see is EXACTLY what needs to be removed / calibrated"

Coronagraphy testbeds for high contrast (~ 1e-9)

High Contrast Imaging Testbed (HCIT) vacuum facility at NASA JPL

PIAA testbed at NASA JPL : lab results (B. Kern, O. Guyon, A. Kuhnert et al.)

An Earth-like planets could be seen !

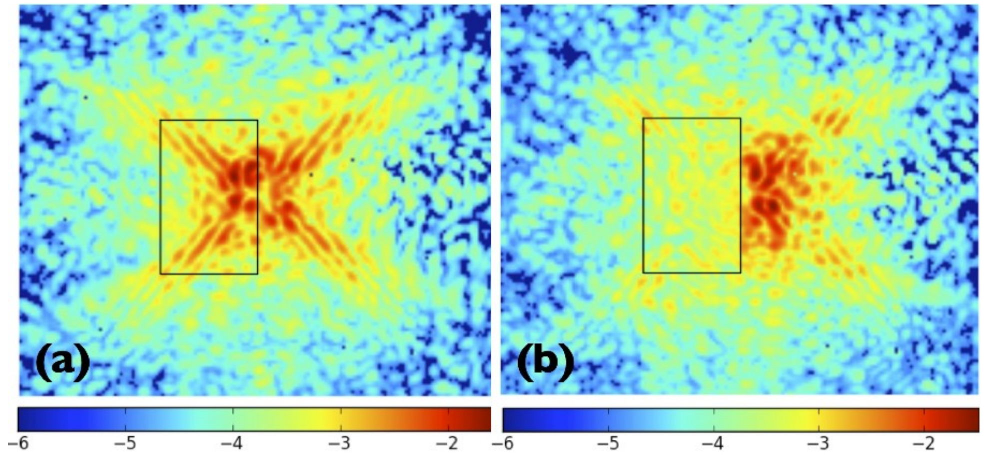


3 runs, contrast values averaged from 2 to 4 λ/D between 5.10^{-10} to 9.10^{-10} (figure shows $7.3.10^{-10}$ result)

5.10^{-8} contrast from 2 to 4 λ/D,
2.10^{-8} contrast from 3 to 4 λ/D
Contrast performance limited by wavefront instability (test in air)

Using a deformable mirror to measure and control focal plane speckles

In lab →

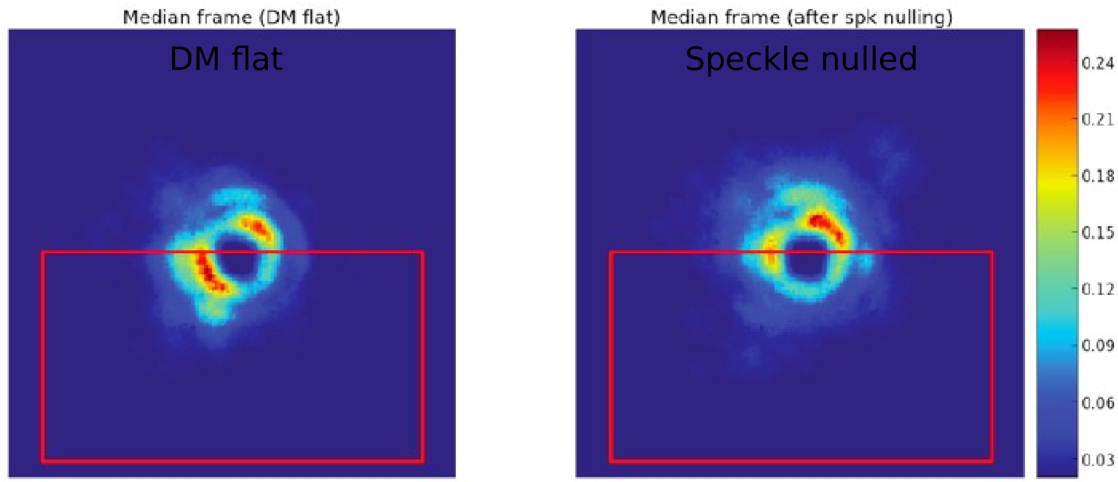


Taking advantage of the full PIAA - focal plane mask - PIAA^{-1} optical configuration

SCExAO's PIAA coronagraph permits speckle control from 1.5 to 14 λ/D
Raw contrast ~ 3e-4 inside the DM control region

On sky →

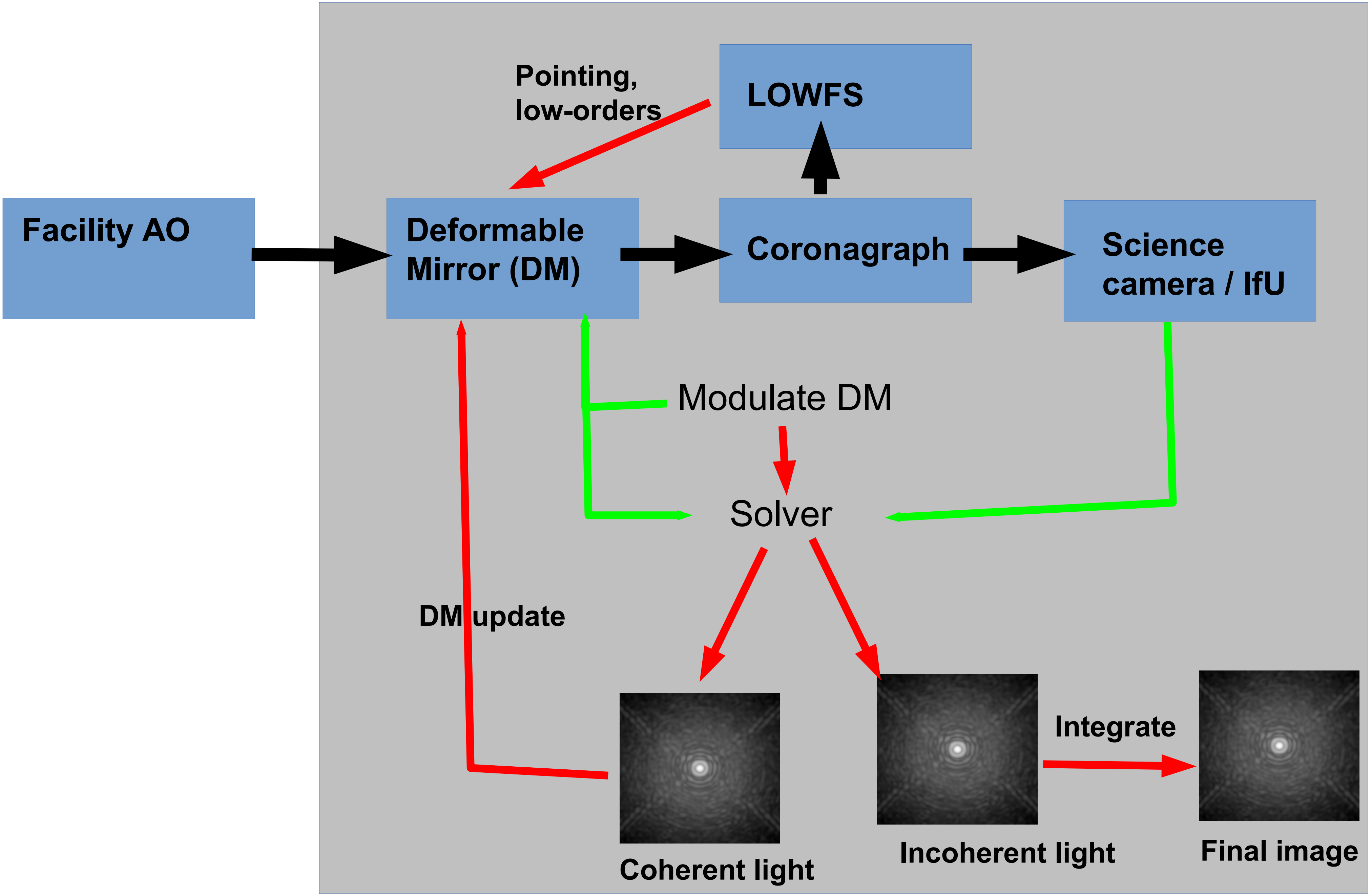
SCExAO DM control region



Single pair of long exposures (1.5 sec) on Pollux by HiCIAO
Reduction of the diffraction features in raw images – mean increase in contrast of ~2 for brightest ring.
Standard deviation reduced by 7x

Martinache et al. 2013-2014

System architecture

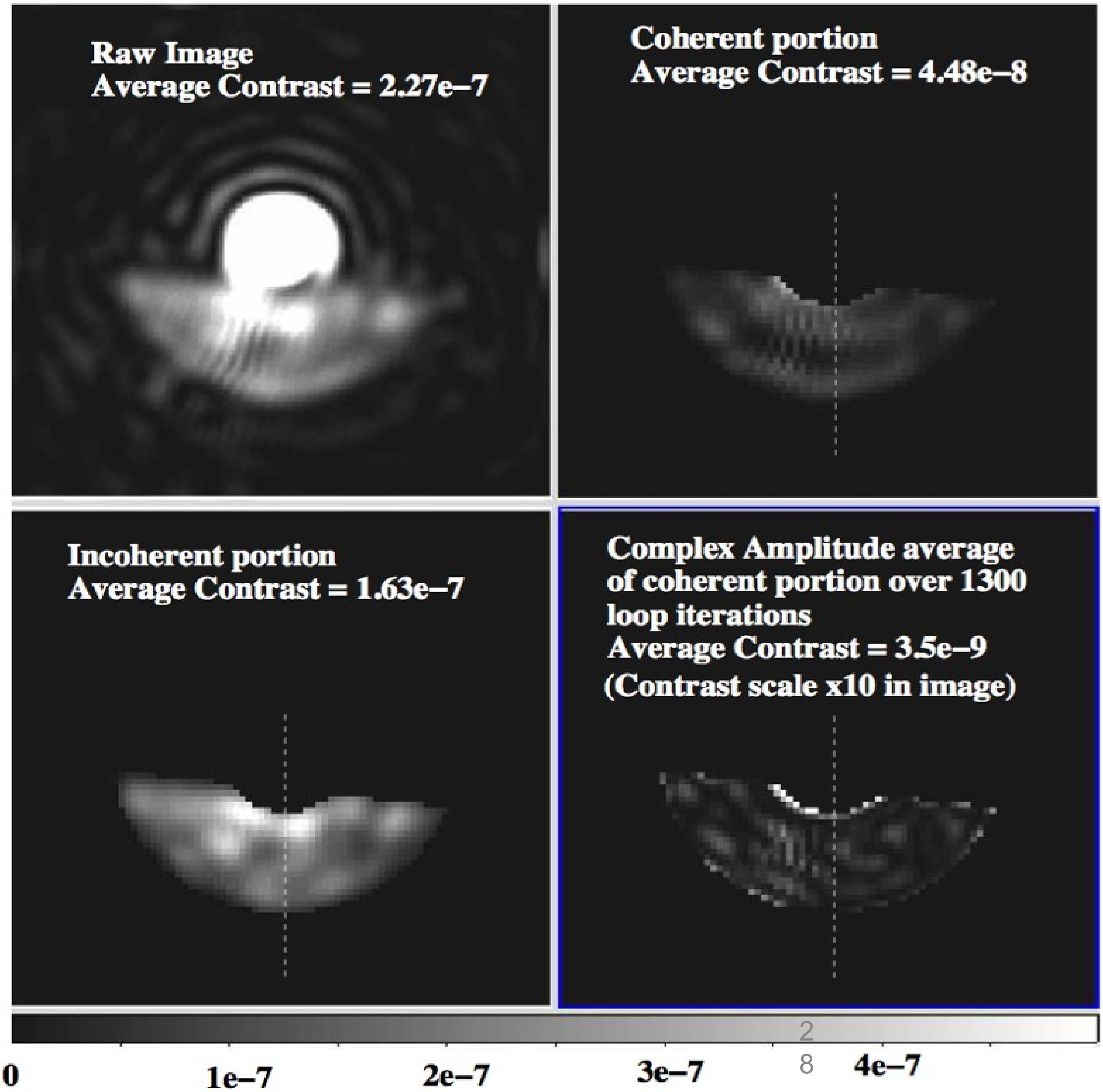


Focal plane WFS based correction and speckle calibration

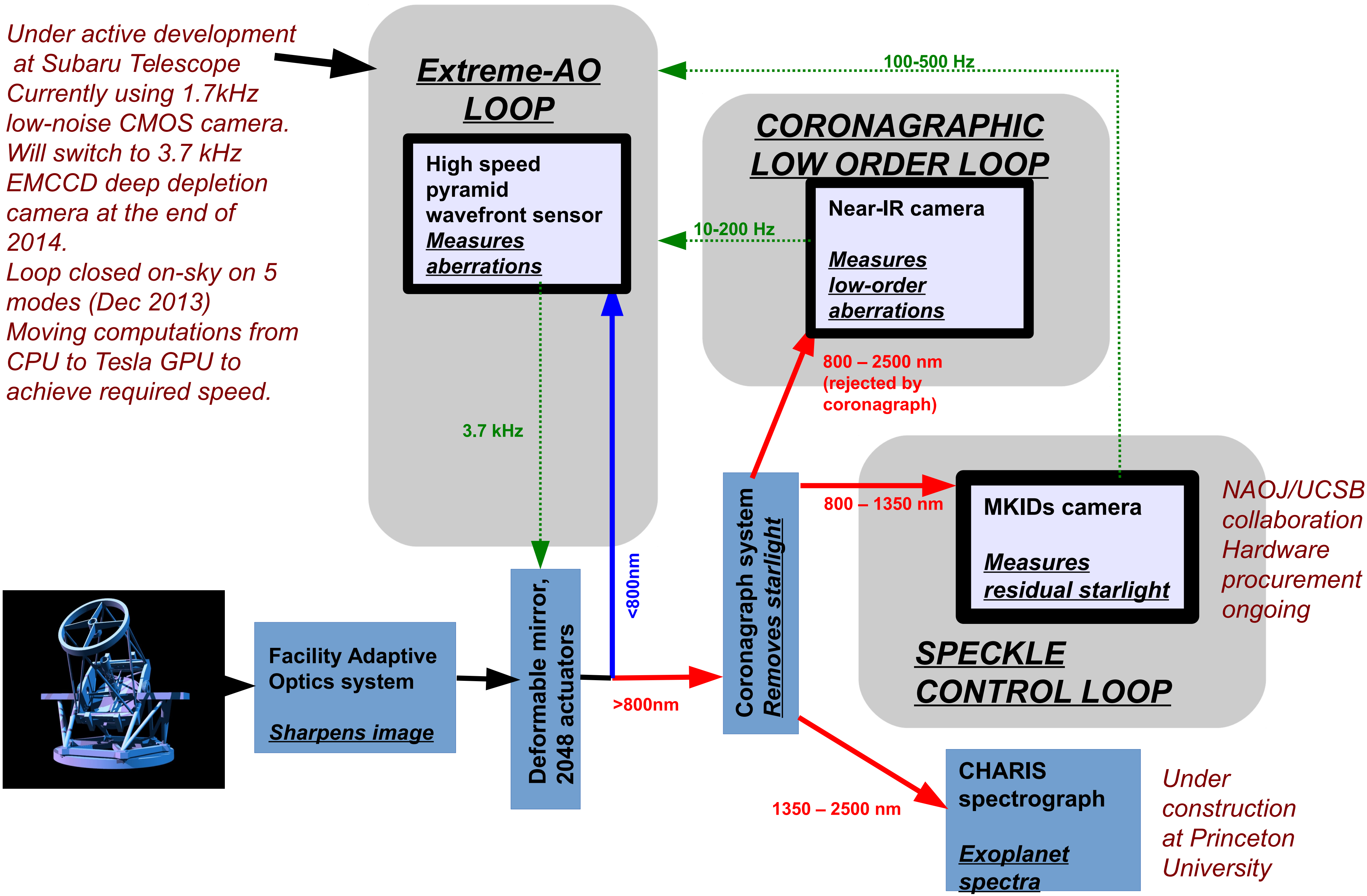
2e-7 raw contrast obtained at 2 λ/D

Incoherent light at 1e-7
Coherent fast light at 5e-8
Coherent bias <3.5e-9

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



SCExAO Wavefront control architecture



Performance limit

What residual will look like planet ?

Temporal effects: complex amplitude changes with time

→ ***need FAST detector to resolve***

Chromaticity: complex amplitude changes with lambda

→ ***need energy resolution***

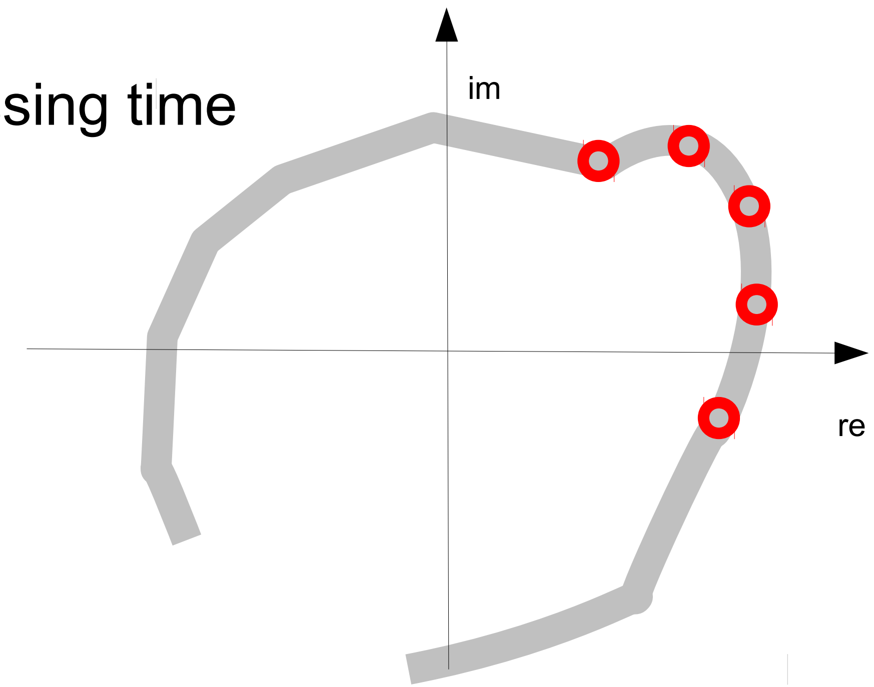
Static and slow speckles (due to optics) well calibrated with low speed

Temporal timescale:

Intensity : crossing time D/v ~ few sec

Complex amplitude : D / (2 π α v) < crossing time

(α = separation in λ/D)



ATTENUATION = π dt v α / D

Target m_H=5

1e-7 speckle, D=8m

→ 500 ph/s/um → few ph per 10ms

Speed vs performance:
~100 Hz frame rate would achieve significant gain:
~1e-8 contrast in 1hr exposure

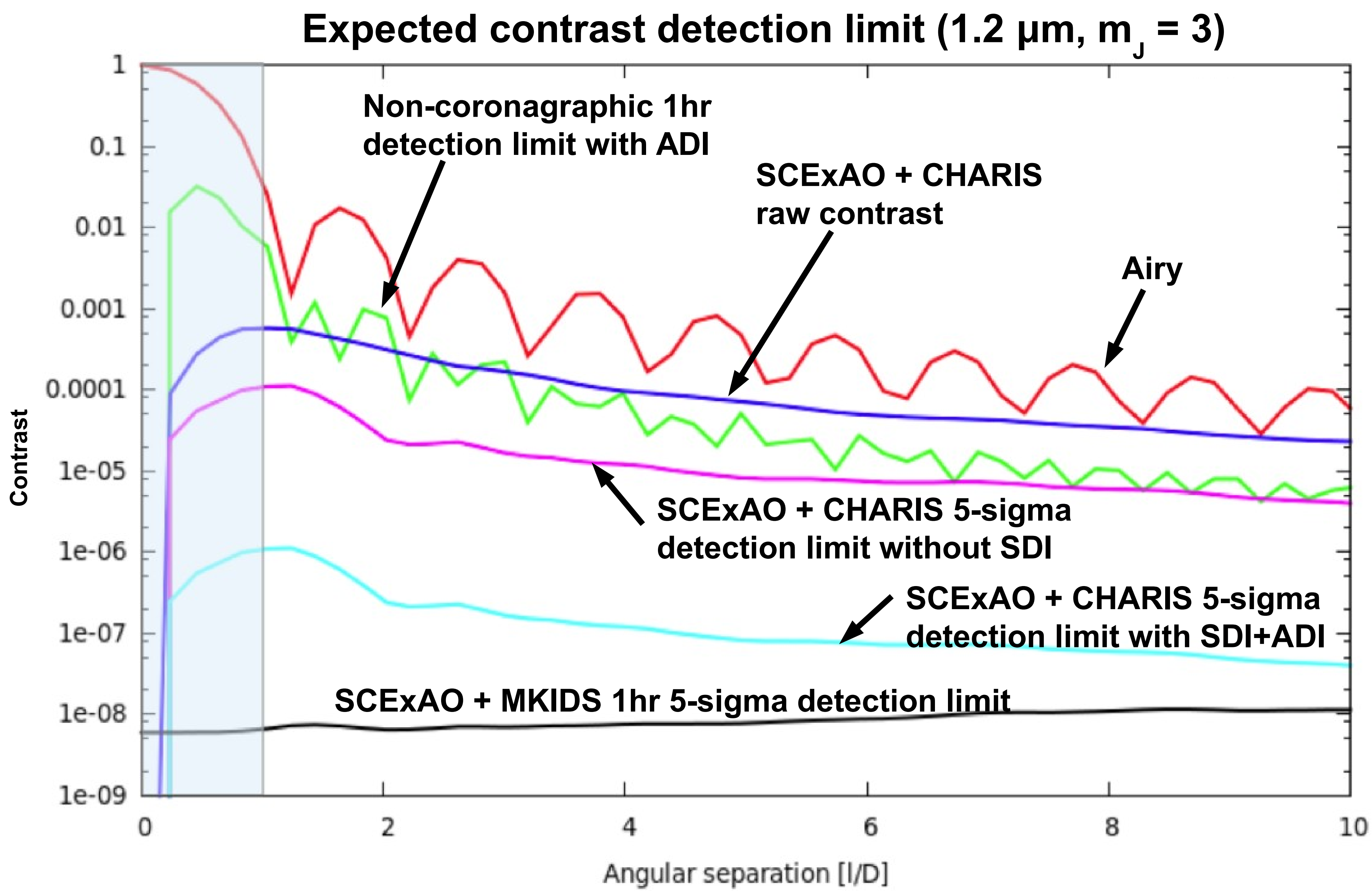
Near-IR detector technology is key

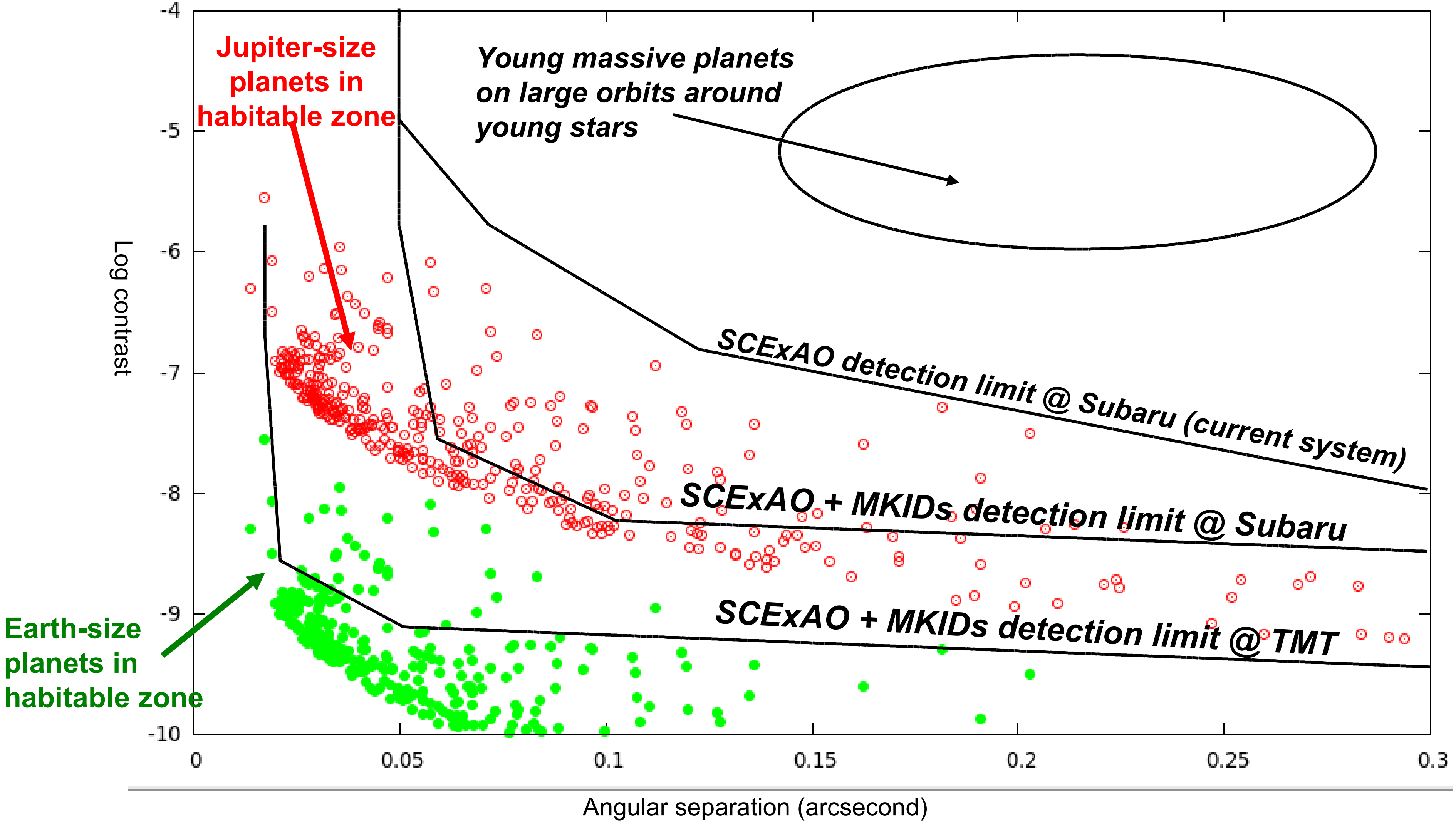
SPEED: Low noise / high speed (ideally photon counting)
WAVELENGTH: Wavelength resolution/IFU

MKIDs is ideal technology:

- Photon counting, low latency
- Small # of pixel is OK (very small FOV required)
- Wavelength resolution → can be used in broadband light

Speed vs performance for D=8m (no predictive control):
~100 Hz required for significant gain
(photon noise excluded – bright star case, valid to mJ~5)

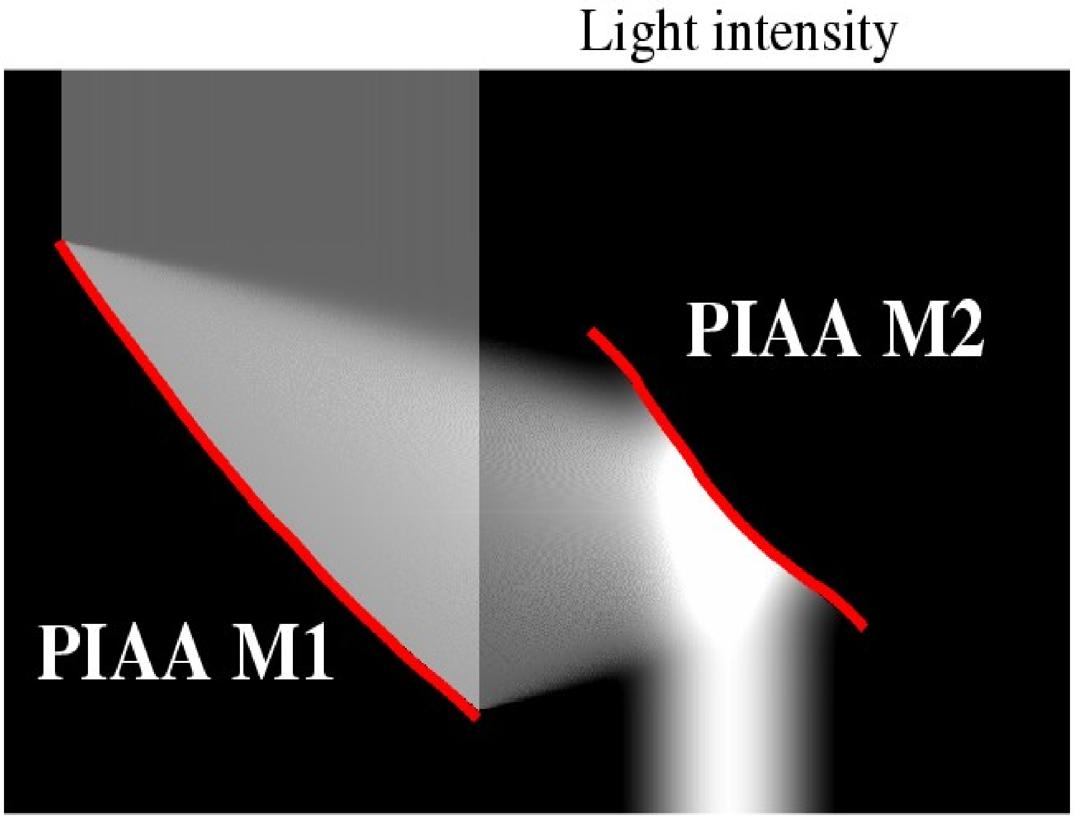


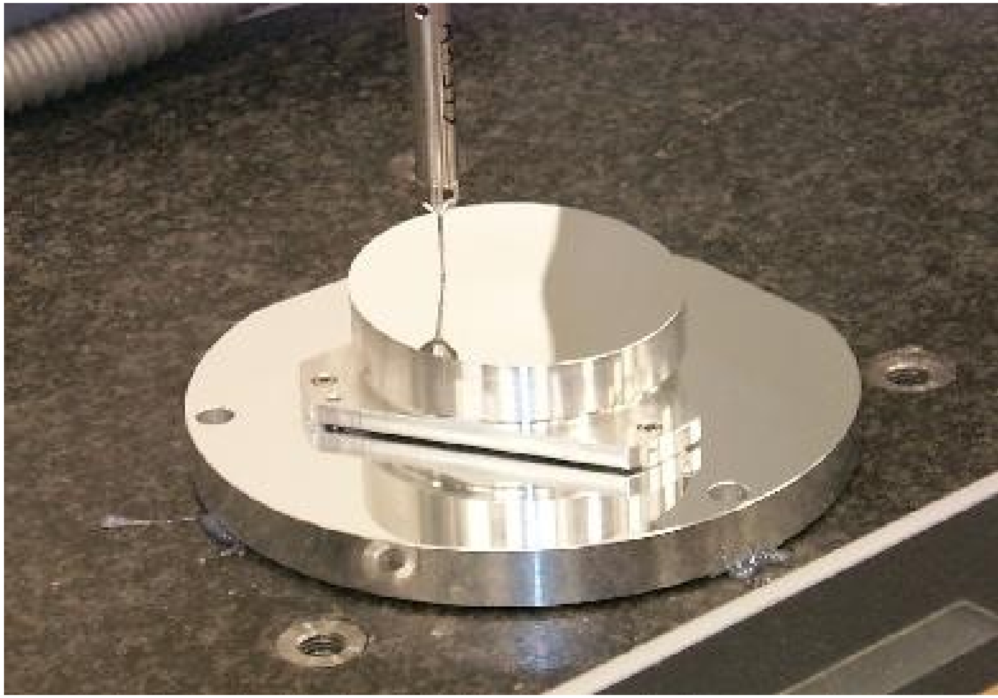


Jupiter-size planets in habitable zone
Young massive planets on large orbits around young stars
SCExAO detection limit @ Subaru (current system)
SCExAO + MKIDs detection limit @ Subaru
SCExAO + MKIDs detection limit @ TMT
Earth-size planets in habitable zone
Log contrast
-4
-5
-6
-7
-8
-9
-10
0
0.05
0.1
0.15
0.2
0.25
0.3
Angular separation (arcsecond)

Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

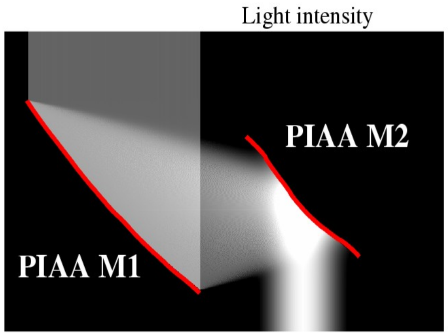
Lossless apodization by aspheric optics.



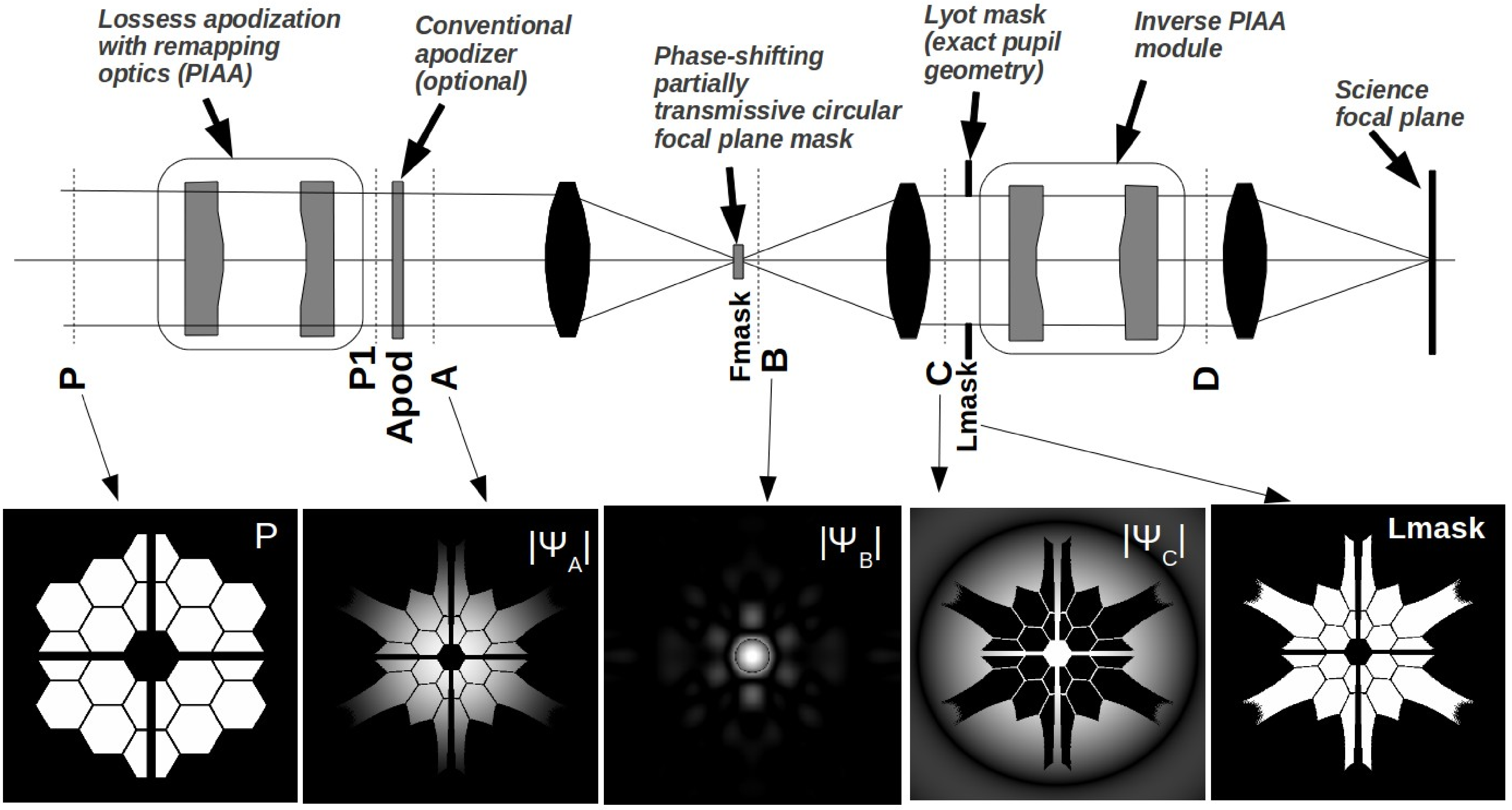


Guyon, Belikov, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present

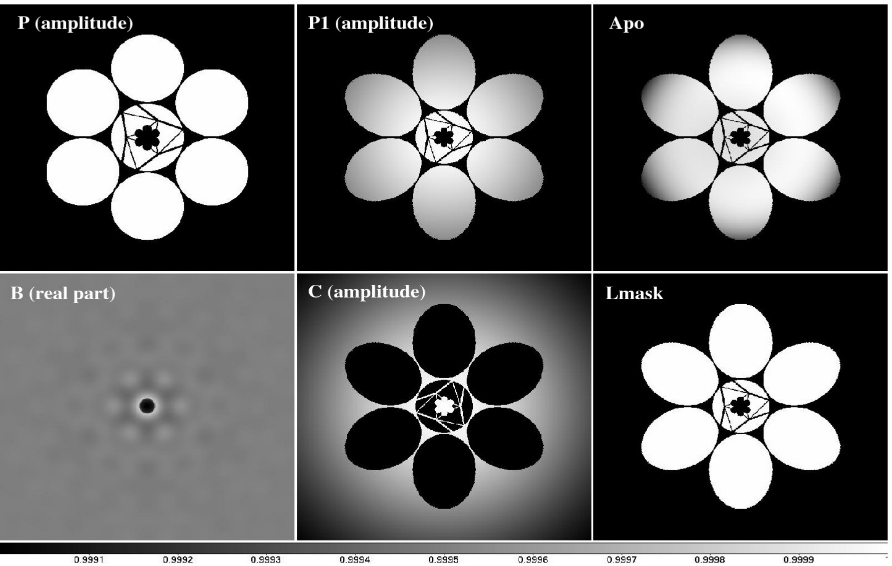
PIAACMC coronagraph design



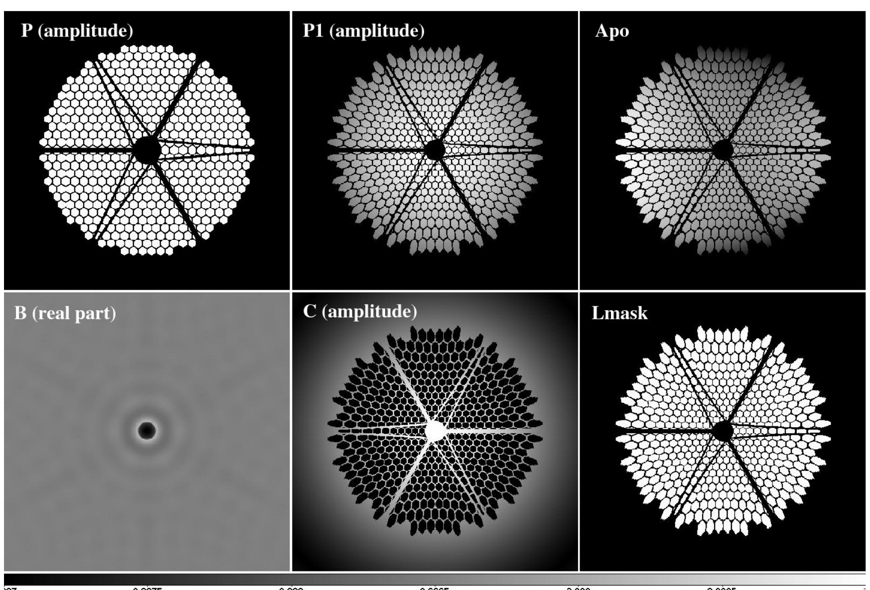
Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

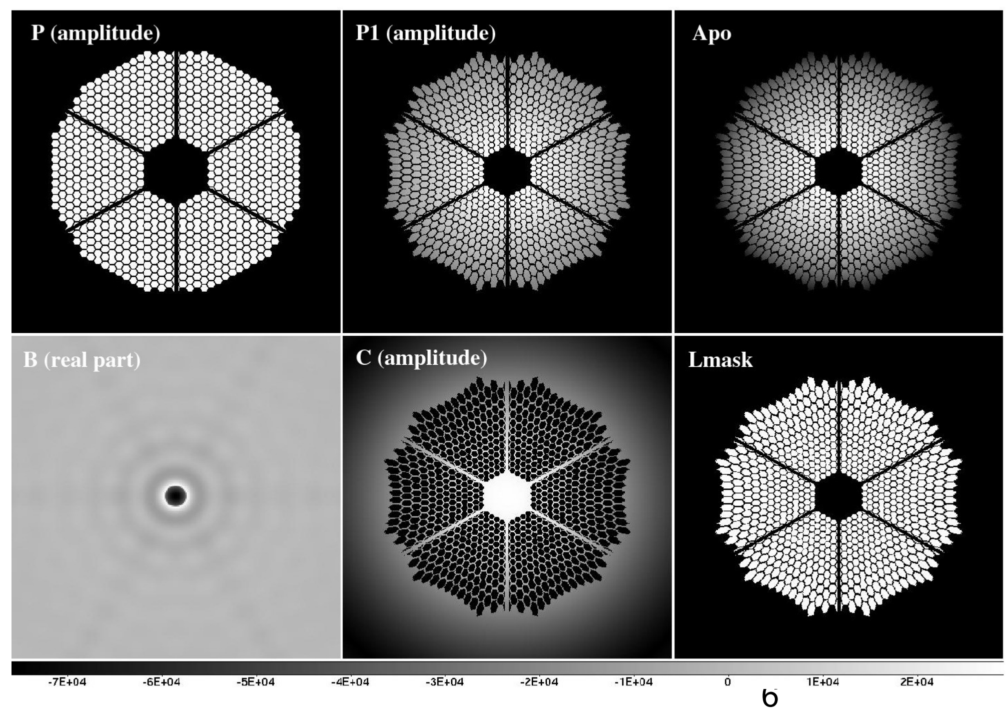


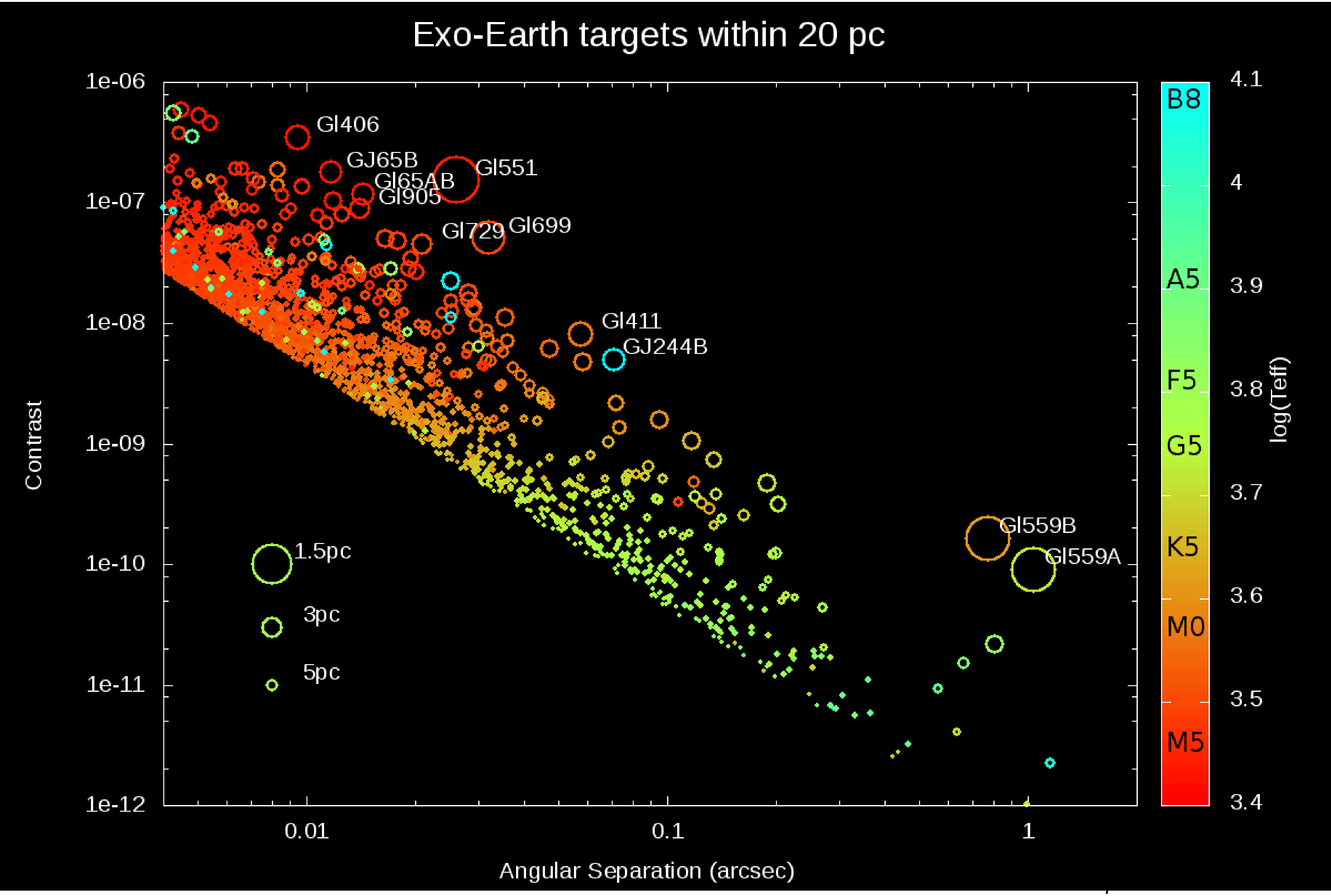
PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit



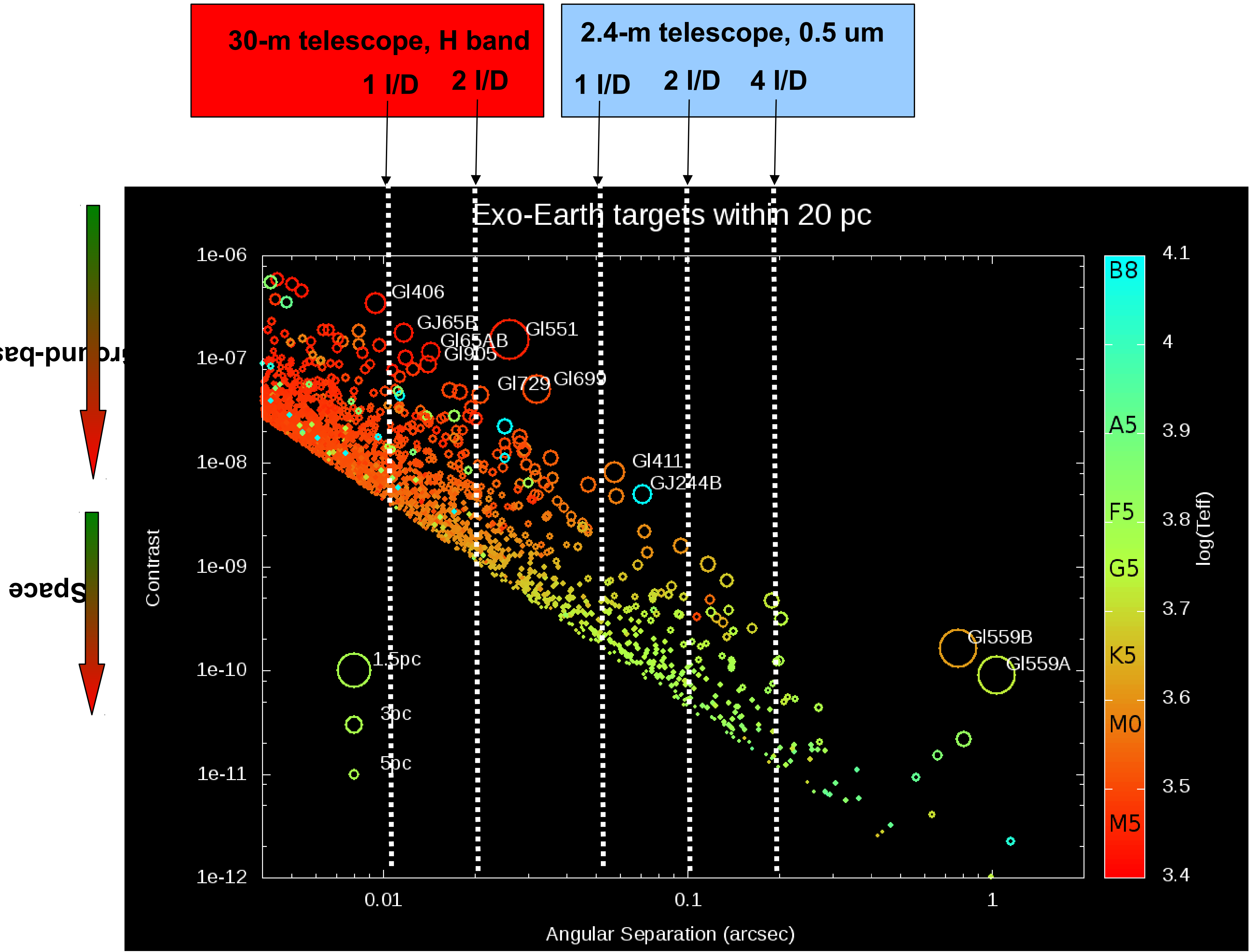
<u>Pupil shape does not matter !!!</u>



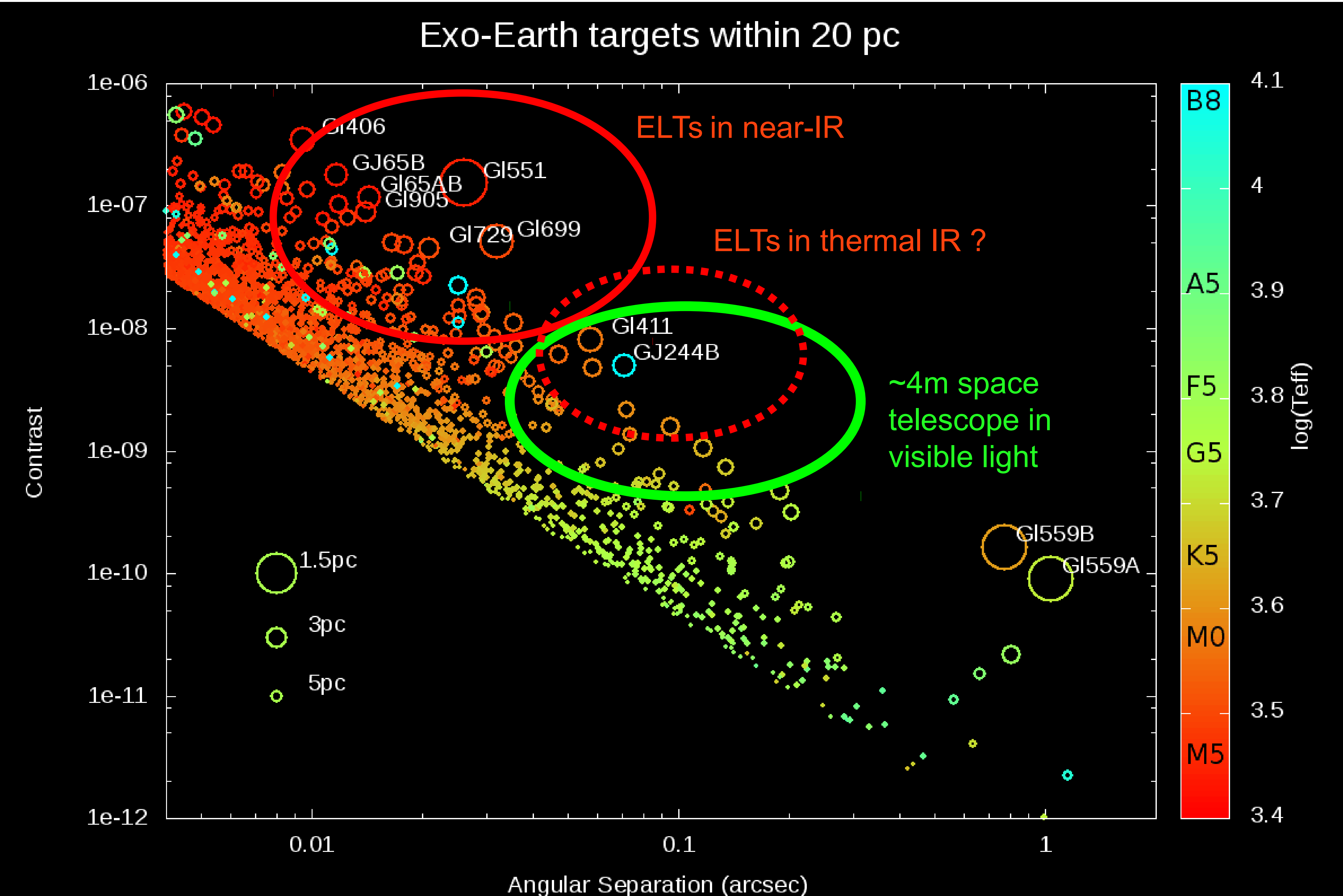




Exo-Earth targets within 20 pc
Contrast
Angular Separation (arcsec)
log(Teff)
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
Gl406
GJ65B
Gl551
Gl65AB
Gl905
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc
B8
A5
F5
G5
K5
M0
M5
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4



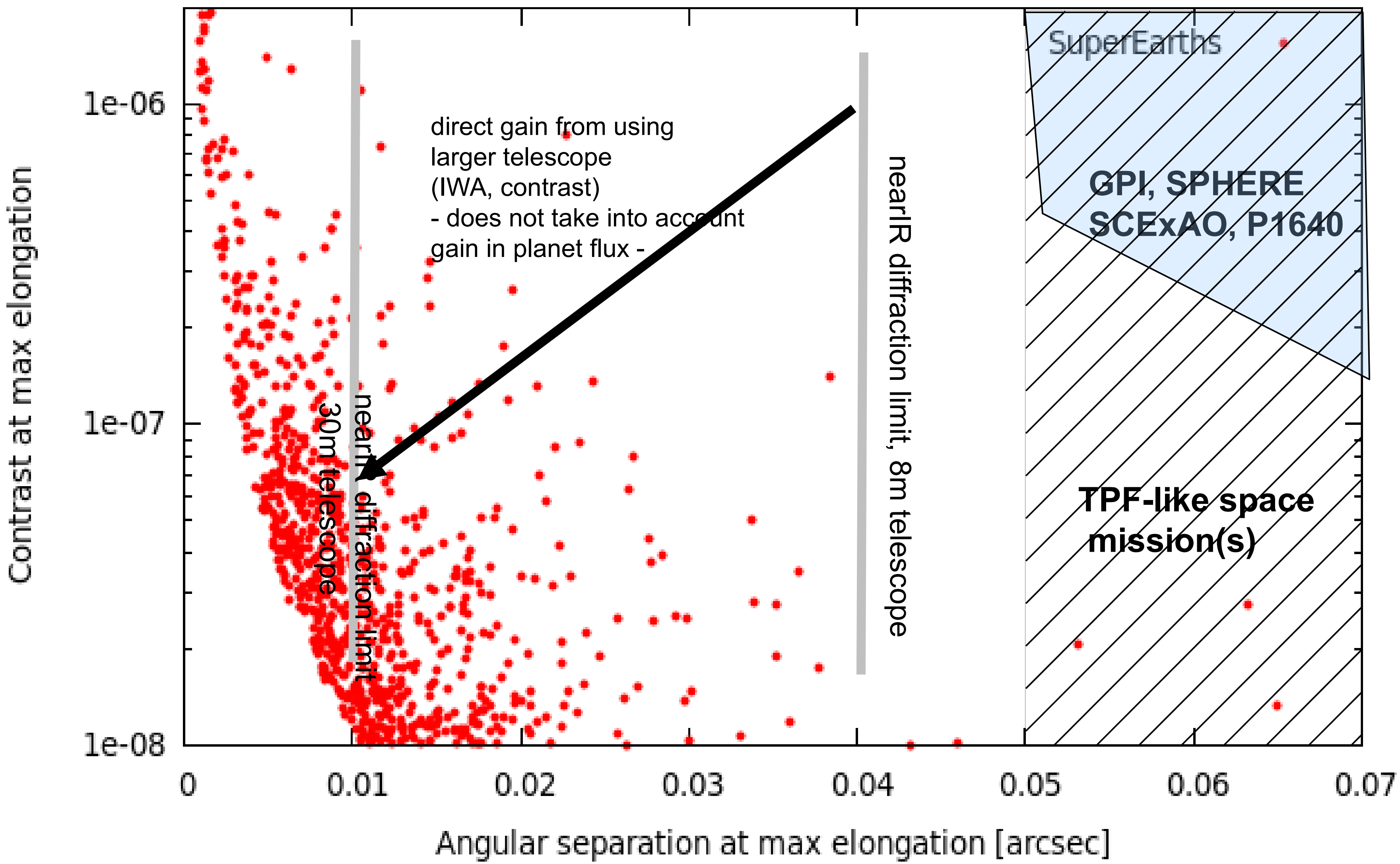
30-m telescope, H band
1 l/D
2 l/D
2.4-m telescope, 0.5 um
1 l/D
2 l/D
4 l/D
Exo-Earth targets within 20 pc
Gl406
GJ65B
Gl65AB
Gl905
Gl551
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
Contrast
0.01
0.1
1
Angular Separation (arcsec)
B8
A5
F5
G5
K5
M0
M5
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
log(Teff)


Exo-Earth targets within 20 pc
ELTs in near-IR
ELTs in thermal IR ?
~4m space telescope in visible light
Gl406
GJ65B
Gl551
Gl65AB
Gl905
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc
Contrast
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
Angular Separation (arcsec)
0.01
0.1
1
B8
A5
F5
G5
K5
M0
M5
log(Teff)
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4

Reflected light planets

Assuming that each star has a SuperEarth (2x Earth diameter) at the 1AU equivalent HZ distance

(assumes Earth albedo, contrast and separation for max elongation)



Reflected light planets

First cut limits meant to exclude clearly impossible targets

→ used to identify potential targets → instrument requirements

FIRST CUT LIMITS

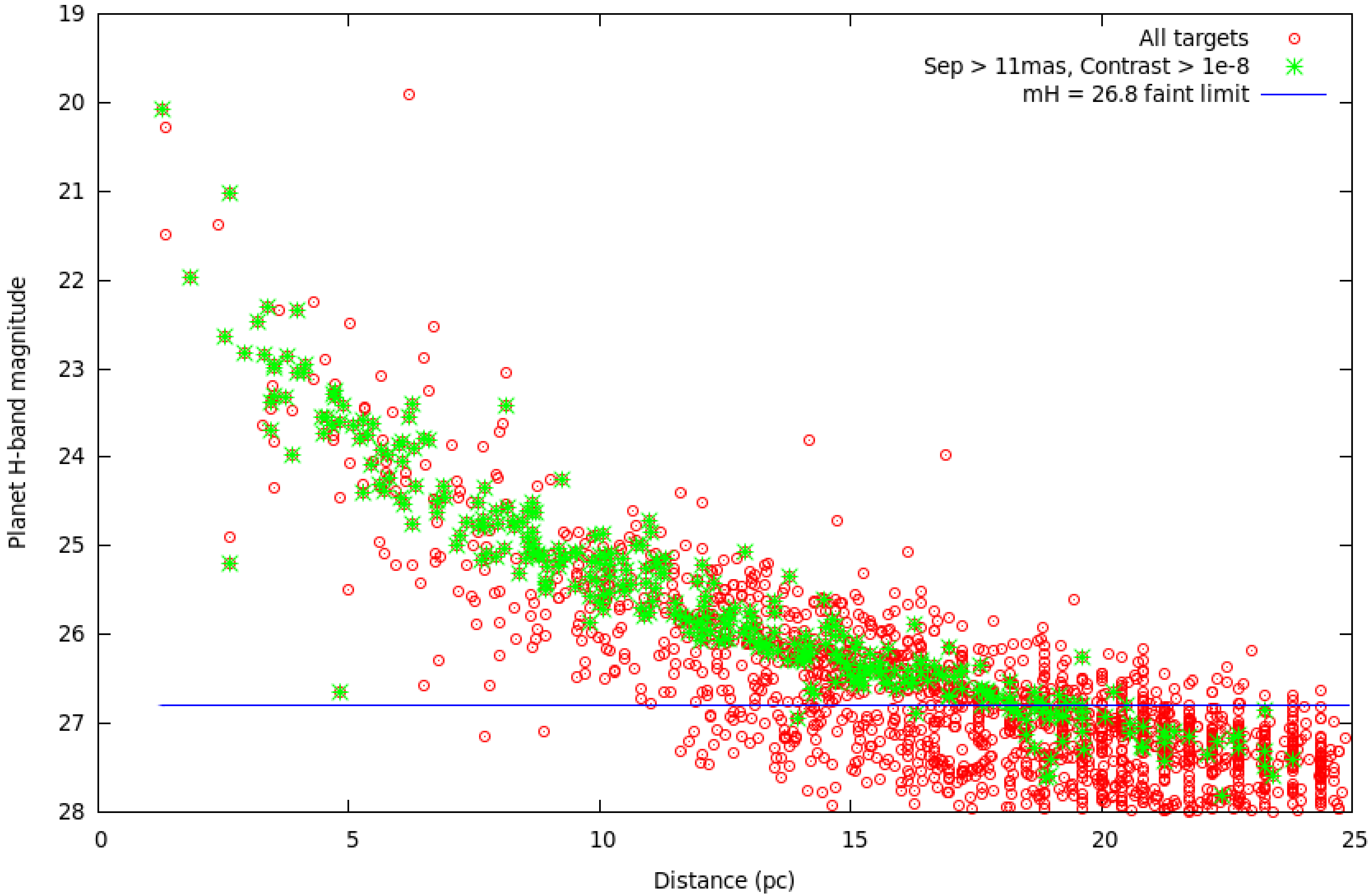
	Limit/constraints	Comments
Angular Separation	Must be > 1.0 λ/D	Limit imposed by coronagraph (see section 4). Corresponds to 11mas on a 30-m telescope in H band.
Contrast	Must be > 1e-8	High contrast imaging limit (see section 5)
Star brightness	Must be brighter than m_R = 15	Required for high efficiency wavefront correction (see section 5)
Planet Brightness	Must be brighter than m_H = 26.8	Faint detection limit

background-limited SNR > 10 in H band image in 1 hr on 30-m telescope (assuming 15% efficiency)

Reflected light planets

274 targets survive the first cut

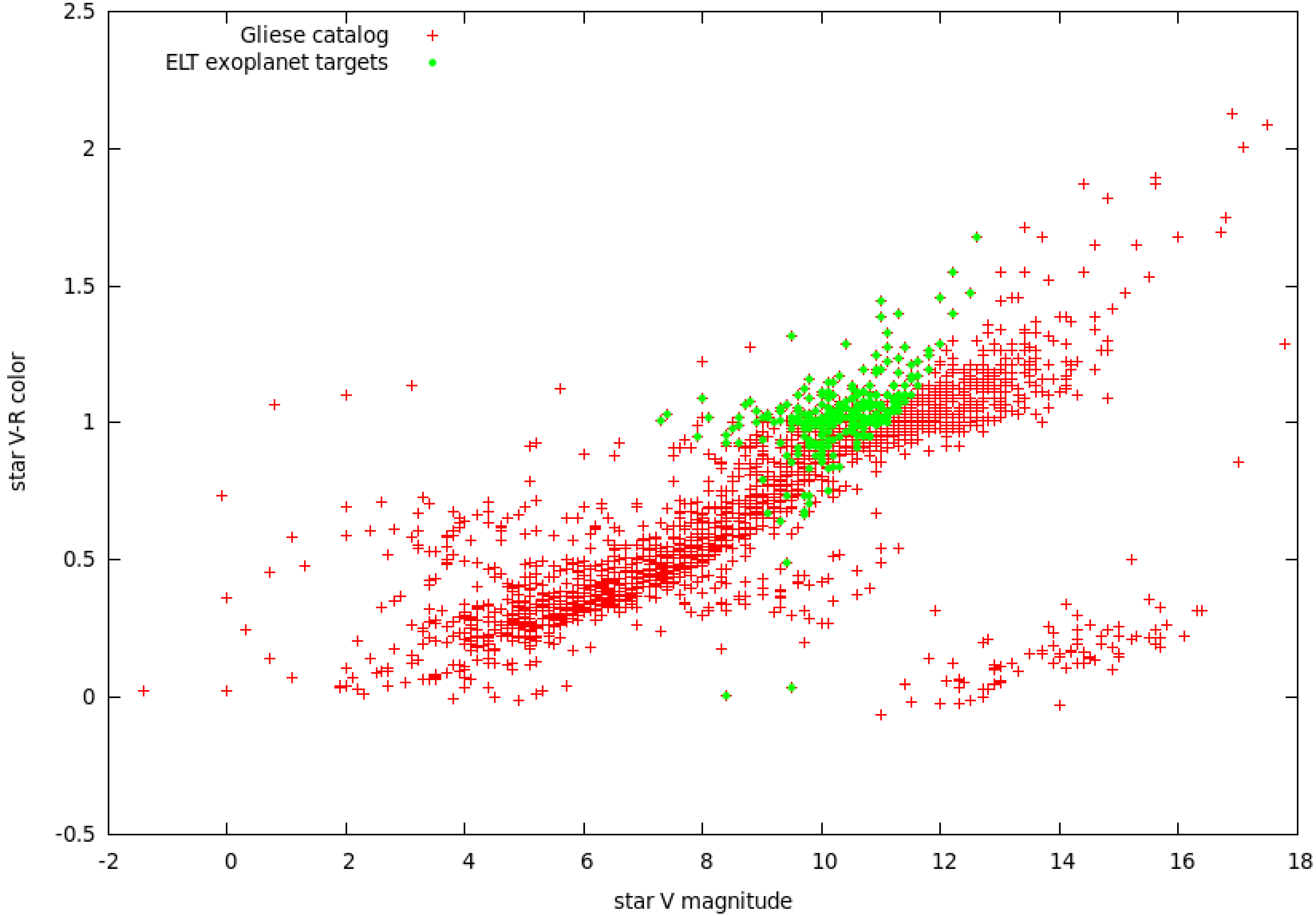
Strong correlation between planet apparent brightness and system distance



Reflected light planets

2 white dwarfs : 40 Eri B and Sirius B

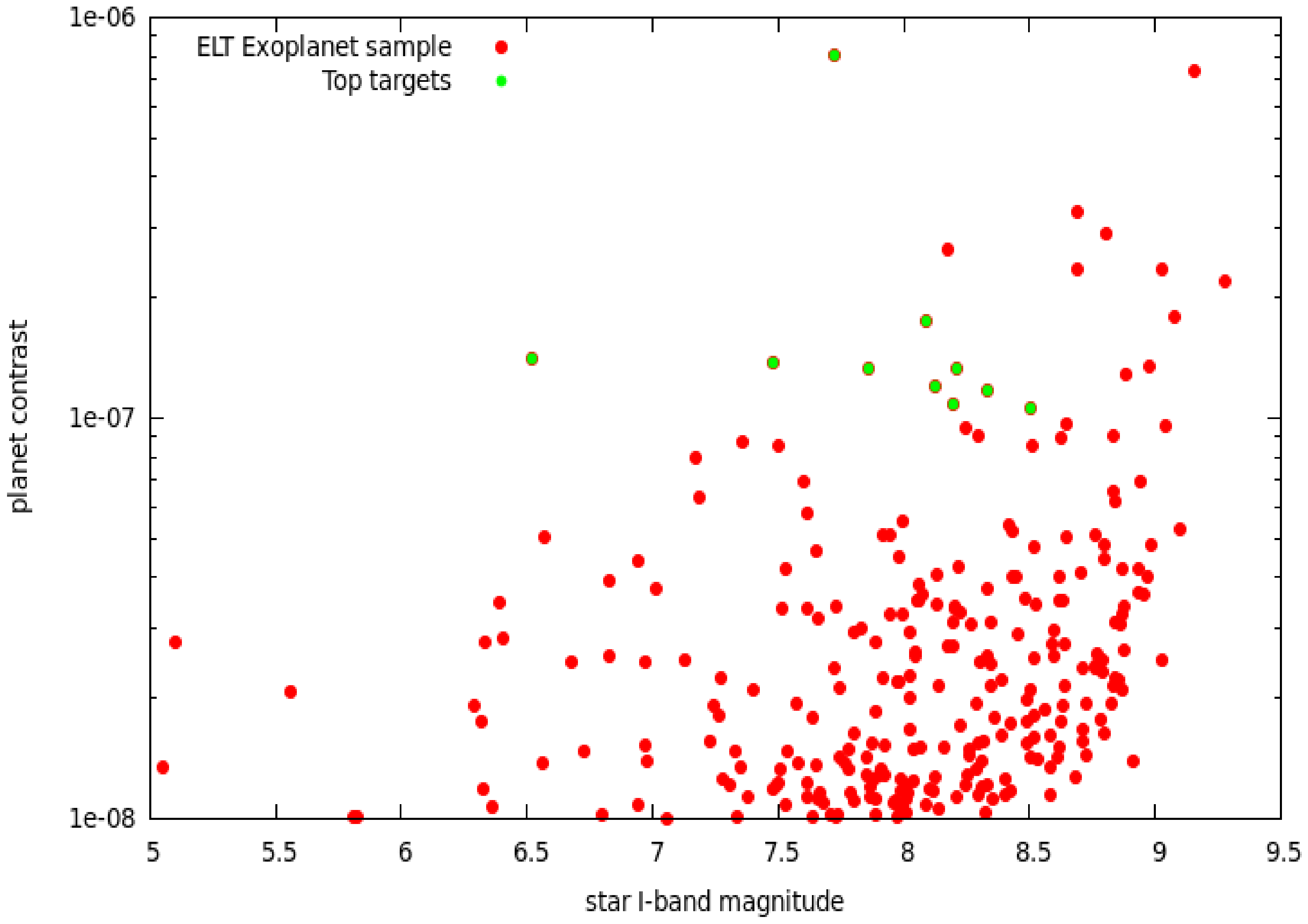
Early type stars → contrast too challenging



Reflected light planets

Assuming that each star has a SuperEarth (2x Earth diameter) at the 1AU equivalent HZ distance

(assumes Earth albedo, contrast and separation for max elongation)



Reflected light from HZ Super-Earths: Top 10 targets for a 30m telescope

Assuming that each star has a SuperEarth (2x Earth diameter) at the 1AU equivalent HZ distance

(assumes Earth albedo, contrast and separation for max elongation)

MOST FAVORABLE TARGETS

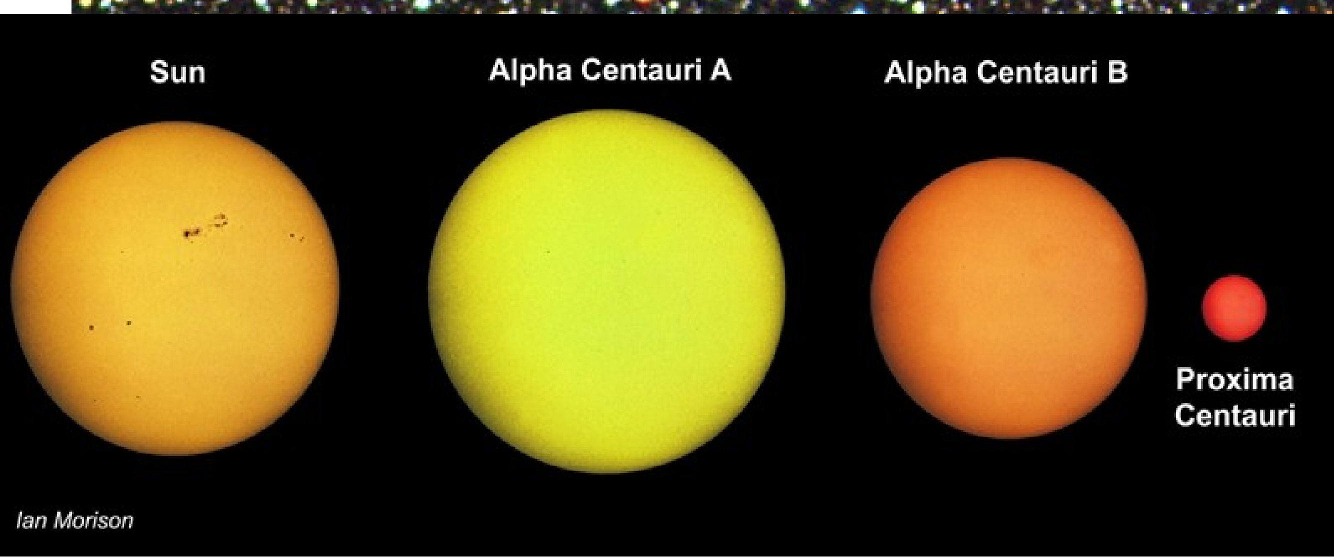
STAR							PLANET				
Name	**Type**	**Distance**	**Diameter**	**L_{bol}**	**m_V**	**m_R**	**m_H**	**Separation**	**Contrast**	**m_H**	**Notes, Multiplicity**
Proxima Centauri (Gl551)	M5.5	1.30 pc	0.138 R_{Sun} 0.990 +- 0.050 mas [1]	8.64e-04	11.00	9.56	4.83	22.69 mas	8.05e-07	20.07	RV measurement exclude planet above 3 Earth mass in HZ [Endl & Kurster 2008]
Barnard's Star (Gl699)	M4	1.83 pc	0.193 R_{Sun} 0.987 += 0.04 mas [2]	4.96e-03	9.50	8.18	4.83	38.41 mas	1.40e-07	21.97	-
Kruger 60 B (Gl860B)	M4	3.97 pc	0.2 R_{Sun}[3]	5.81e-03	11.30	9.90	5.04	19.20 mas	1.20e-07	22.35	-
Ross 154 (Gl729)	M4.5	2.93 pc	0.2 R_{Sun}[3]	5.09e-03	10.40	9.11	5.66	24.34 mas	1.37e-07	22.82	-
Ross 128 (Gl447)	M4.5	3.32 pc	0.2 R_{Sun}[3]	3.98e-03	11.10	9.77	5.95	18.99 mas	1.75e-07	22.84	-
Ross 614 A (Gl234A)	M4.5	4.13 pc	0.2 R_{Sun}[3]	5.23e-03	11.10	9.82	5.75	17.51 mas	1.33e-07	22.95	Double star (sep=3.8 AU)
Gl682	M3.5	4.73 pc	0.26 R_{Sun}[3]	6.41e-03	10.90	9.70	5.92	16.93 mas	1.09e-07	23.33	-
Groombridge 34 B (Gl15B)	M6	3.45 pc	0.18 R_{Sun}[3]	5.25e-03	11.00	9.61	6.19	20.98 mas	1.33e-07	23.39	150 AU from M2 primary
40 Eri C (Gl166C)	M4.5	4.83 pc	0.23 R_{Sun}[3]	5.92e-03	11.10	9.88	6.28	15.93 mas	1.18e-07	23.61	35AU from 40 Eri B (white dwarf), 420 AU from 40 Eri A (K1)
GJ 3379	M4	5.37 pc	0.24 R_{Sun}[3]	6.56e-03	11.30	10.06	6.31	15.09 mas	1.06e-07	23.75	-

[1] Angular diameter (uniform disk, non limb-darkened value) measured by optical interferometry with VLTI Demory et al. 2009

[2] Uniform disk angular diameter from Lane et al. 2001

[3] No direct measurement. Approximate radius is given. If possible, radius is extrapolated from photometry using K magnitude and radius vs. absolute K magnitude relationship in Demory et al. 2009

Proxima Centauri



Reflected light from HZ rocky exoplanets: Key Requirements for ELTs

Coronagraph:

15 mas IWA (~1.5 l/D in near-IR), <1e-4 contrast

High efficiency (throughput, angular resolution)

AO system:

RAW contrast : ~1e-4 contrast between 10 and 40 mas

Guide star: V~11, R~9.5, I~8

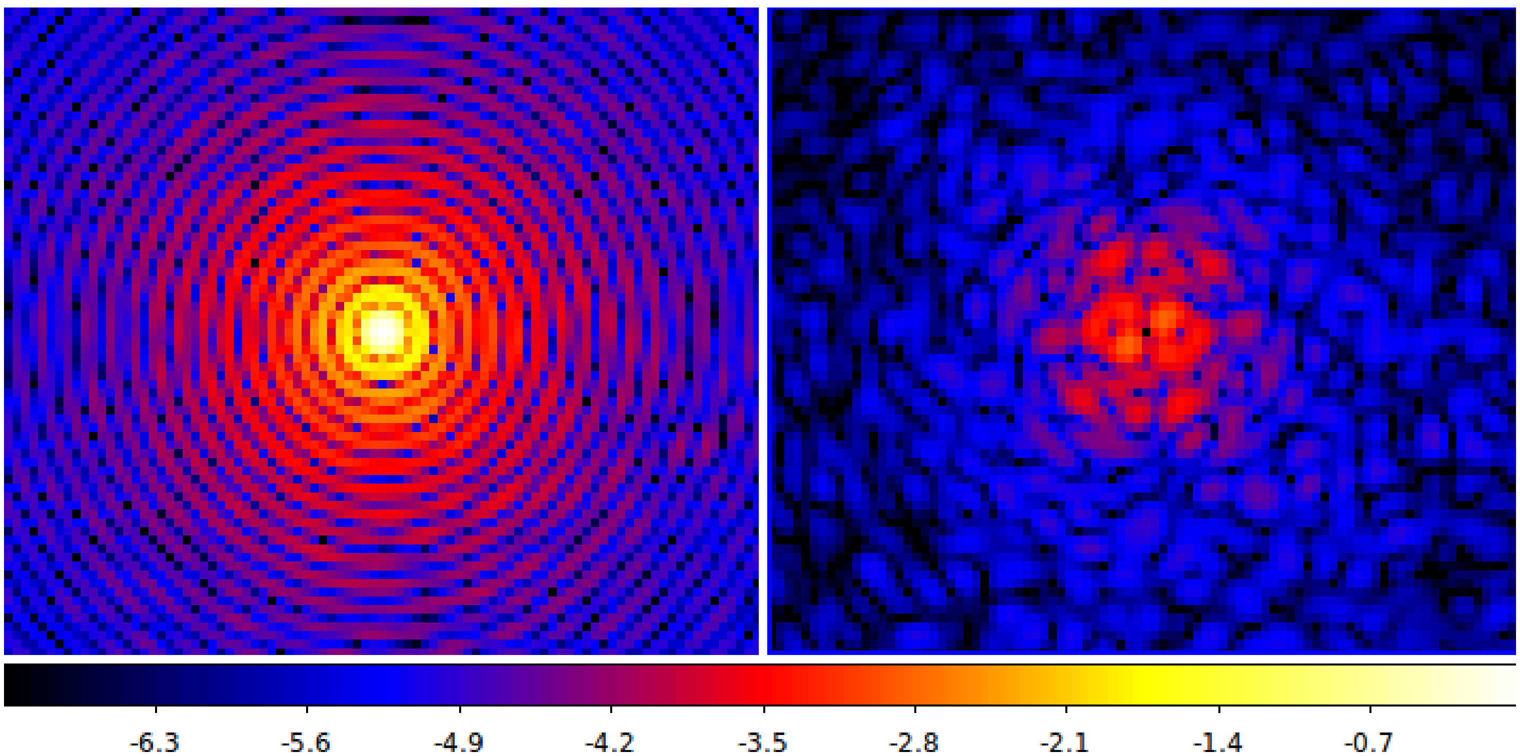
DETECTION contrast: ~1e-7 to 1e-8

ELT simulated ExAO

30m telescope, Sensing at 600nm, Imaging at 1600nm

4 kHz loop speed + 200us delay, integrator, gain = 0.5

1cm WF sampling, chromatic diffractive propagation through atmosphere computed at 4kHz, 100kHz internal frequency → 20 TB for 10 sec



Without coronagraph **With coronagraph**

1e-4 speckles due to:

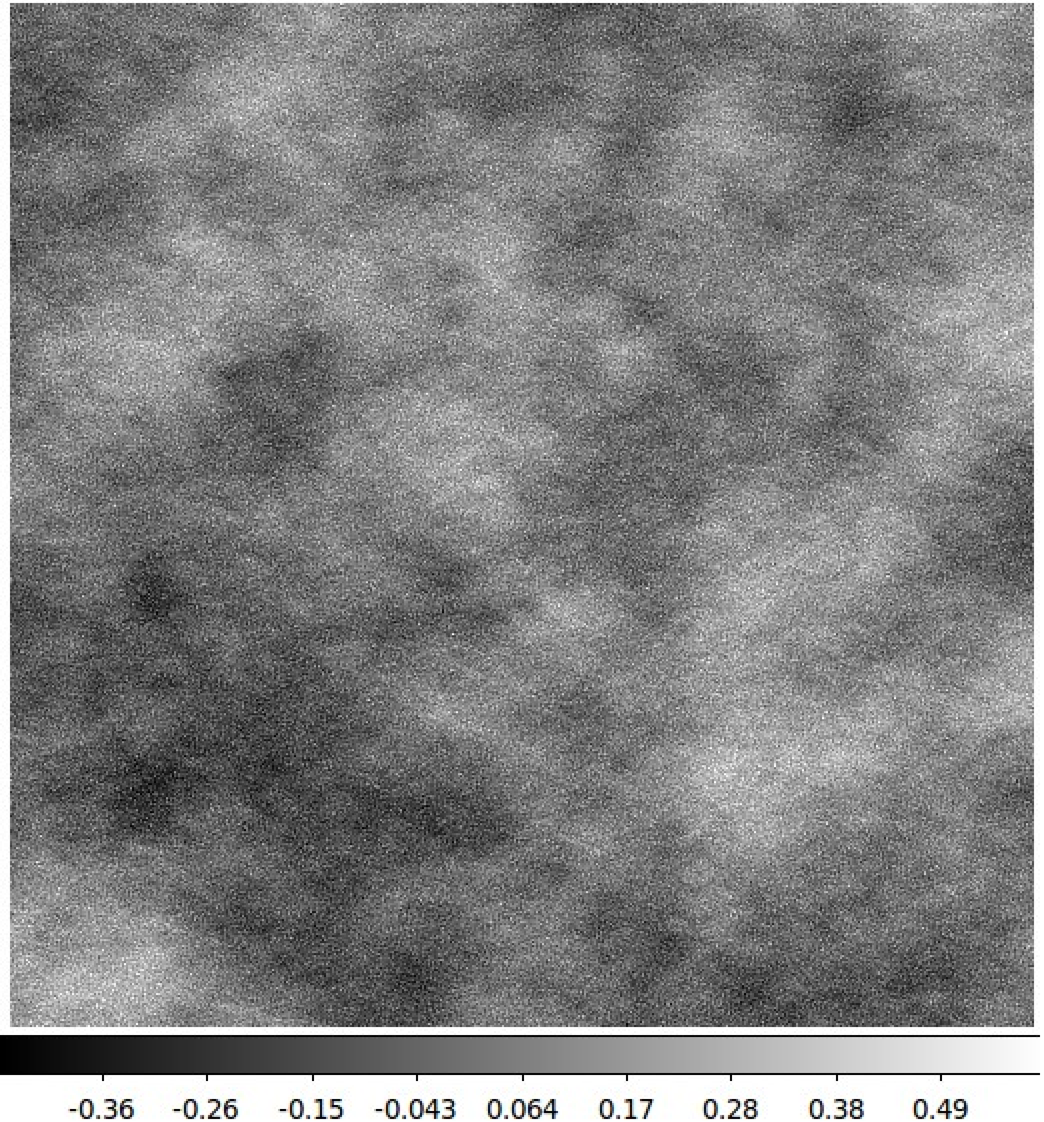
Chromaticity
→ WFS at longer wavelength (focal plane)

Time lag
→ predictive control, DM microstepping

Scintillation

OPD chromaticity

Scintillation chromaticity (nearIR[1.6um] OPD – visible[0.6um] OPD), 40x40m



Due to :
(1) change in refactive index (gain factor)
(2) atmospheric refraction
(alt-dependent translation)

(also, diffraction propagation to lesser degree)

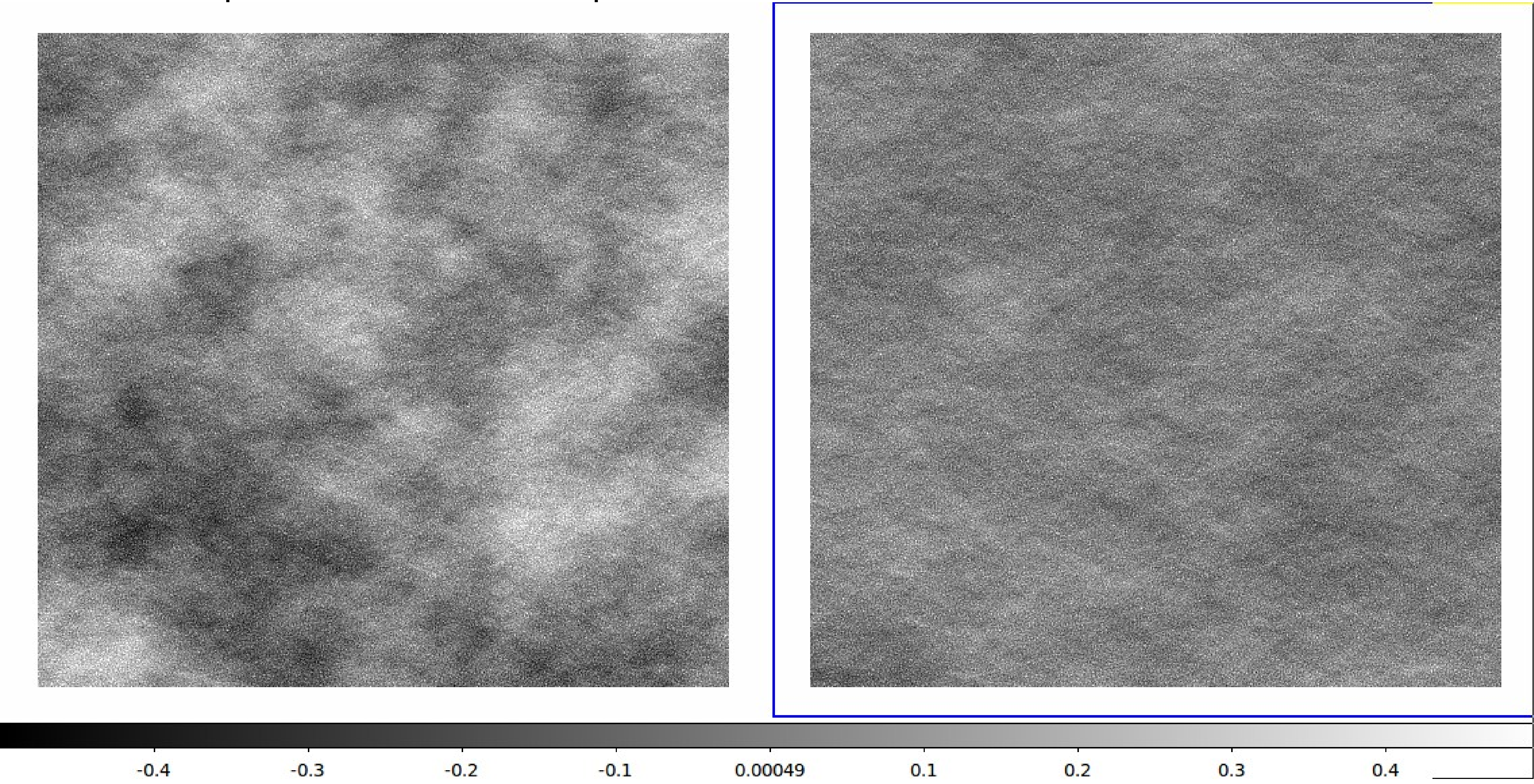
~0.1 rad RMS → 1% SR loss

But:
Dominated by low spatial frequencies
Slow (speckle lifetime up to few sec on ELT)

Creates ~1e-6 speckles with
~1 to ~5 sec lifetime
→ ~1e-7 speckles in 1hr exposure

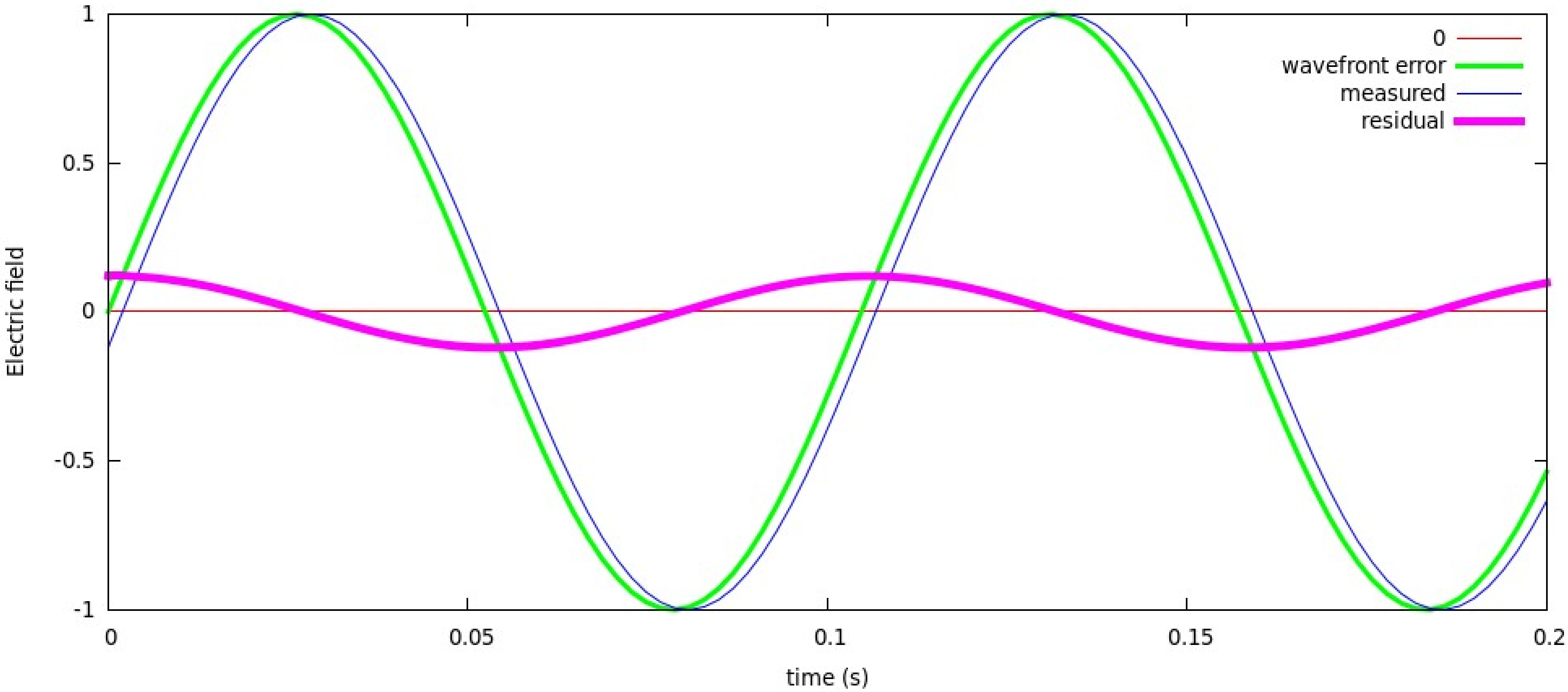
Optimal OPD scaling

- 0.6 um vs 1.6 um: 1.4% difference in (n-1)
- 0.8 um vs 1.6 um: 0.7% difference in (n-1)
- Scaling removes most of the low order OPD chromaticity
- Multiplicative coefficient (here 1.017) can be computed, but difficult to separate telescope errors from atmosphere



Predictive control

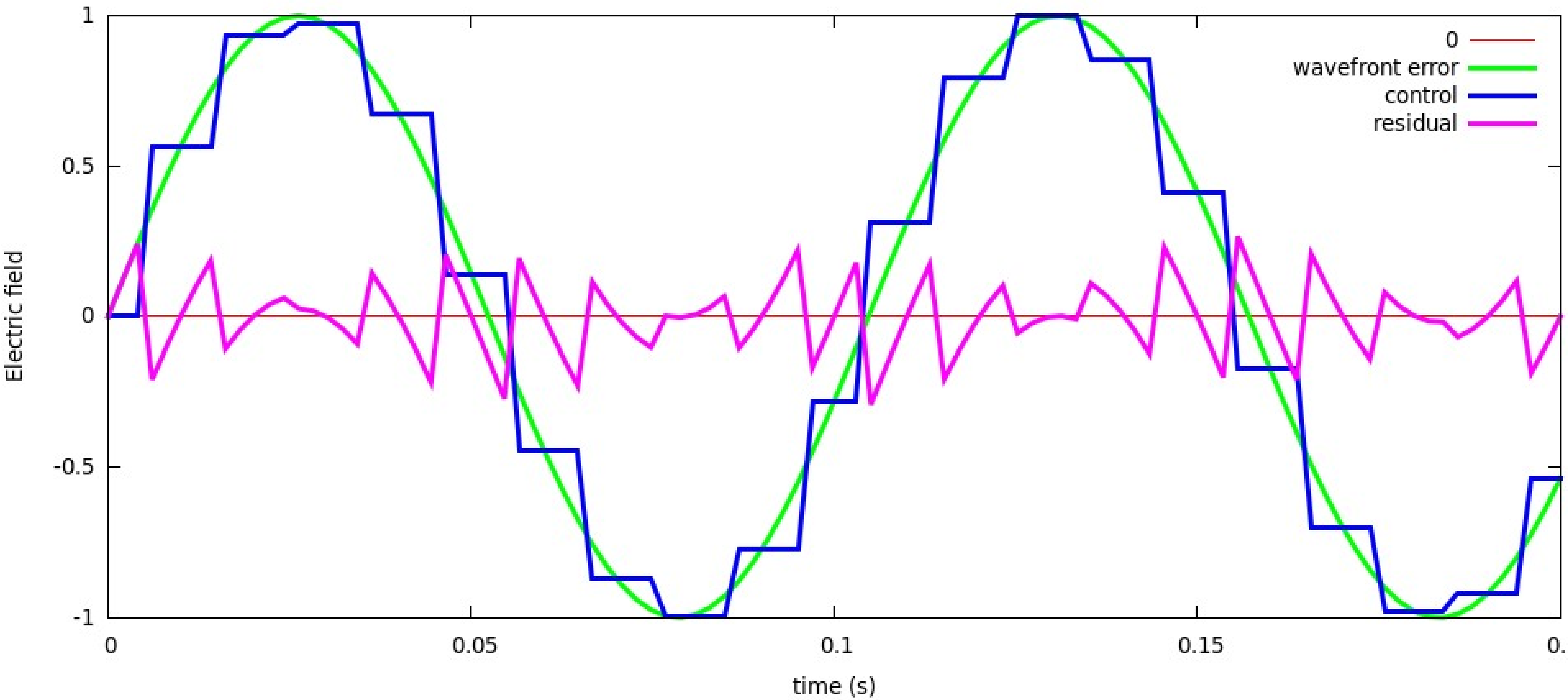
Time lag speckles are the main source of planet-looking speckles in DM control area
→ predictive control is essential



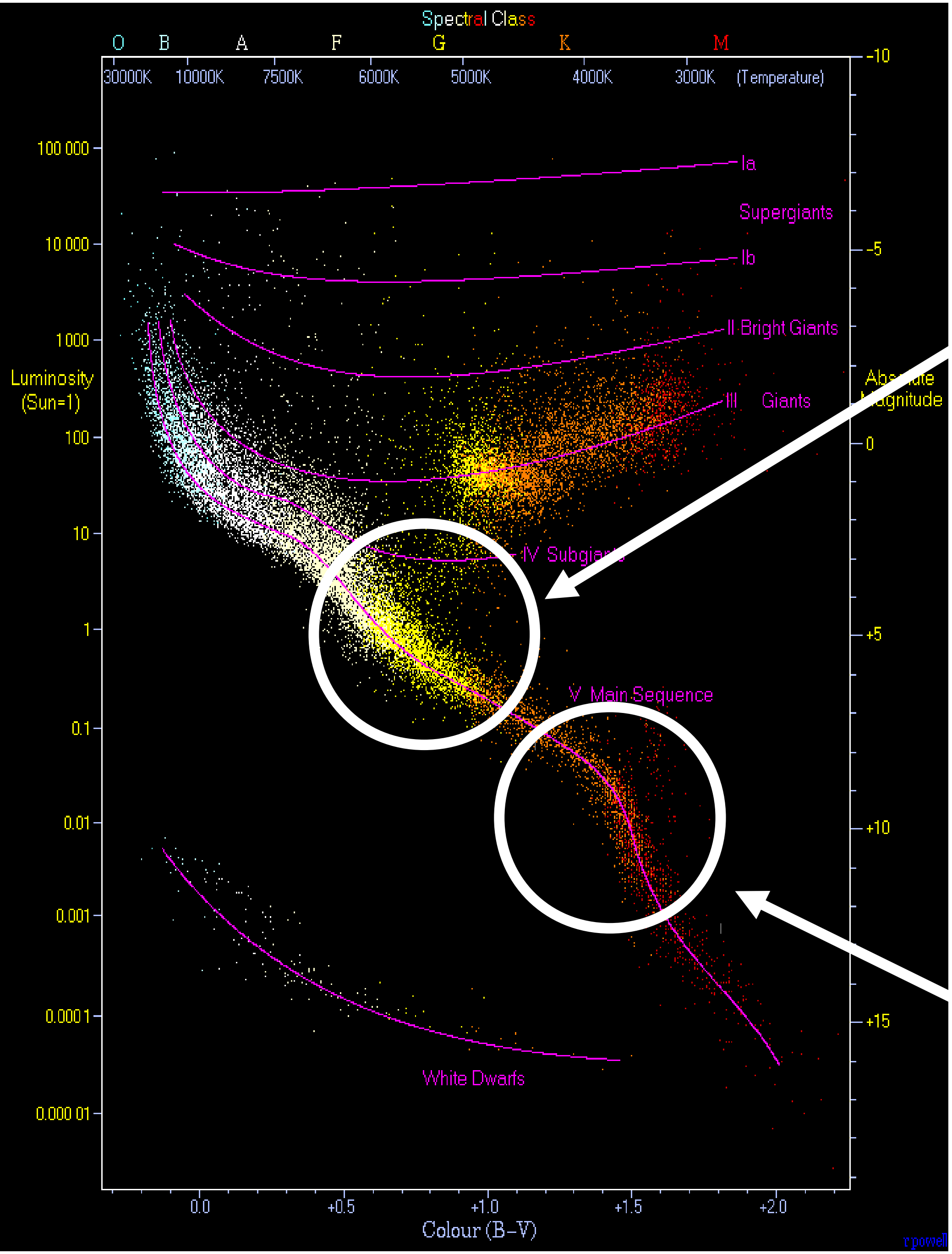
DM Microstepping/smoothing

DM motion needs to smoothly follow atmospheric speckles

→ may need to interpolate DM motion (analog/mechanical/control)



Imaging habitable planets from space and ground



-------------- Space ----------------

Habitable planets can be imaged around nearby Sun-like stars with ~4m telescope

---------- Ground --------------

Next generation of 30-m telescopes will image habitable planets around nearby low-mass stars.

MKIDs detector + small IWA coronagraph