Coronagraphy: from state of the art to near future

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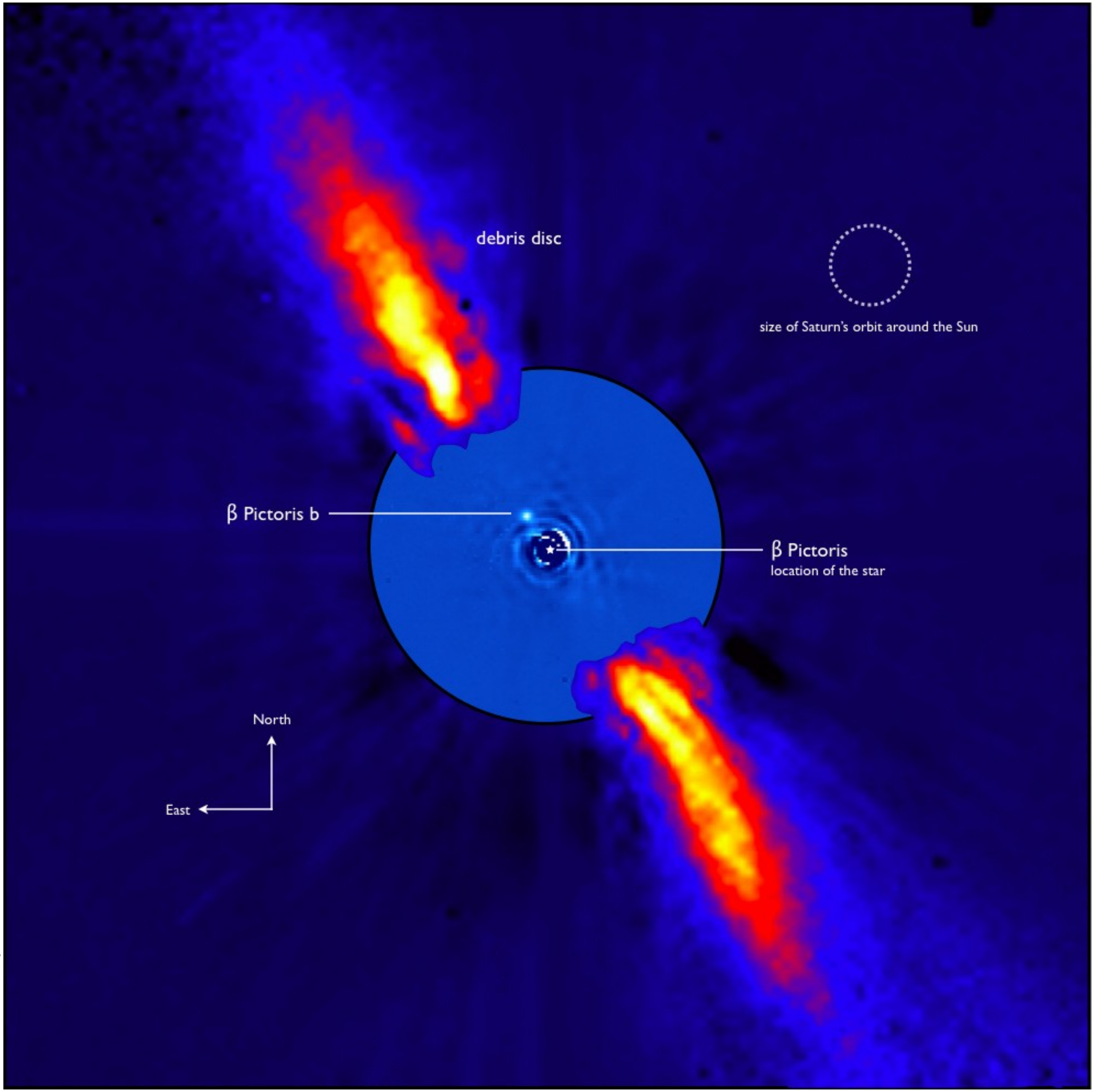
Exoplanets & dust disks

Protoplanetary disk:
Disk in the process of forming planets

Debris disk:
Disk generated by collision between small bodies

Ability to image planets and disks → study planetary formation and evolution of planetary systems



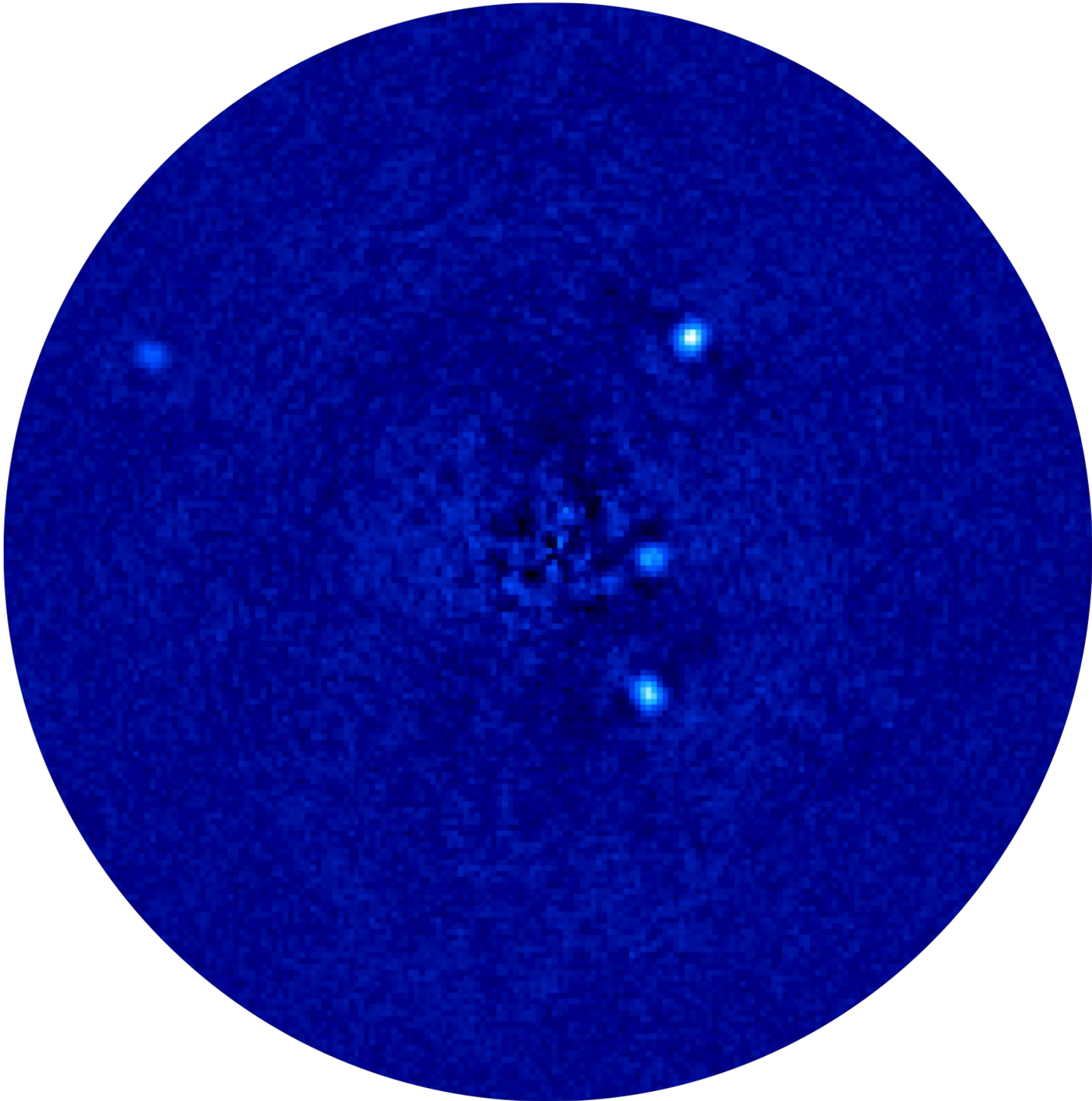
Beta Pic exoplanet and dust disk (Lagrange et al. 2009)

HR8799 imaged with coronagraphy on LBT

1 l/D IWA, using vortex coronagraph

N' band

Inner planets ~1e-4 contrast



See Defrere et al. Poster

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

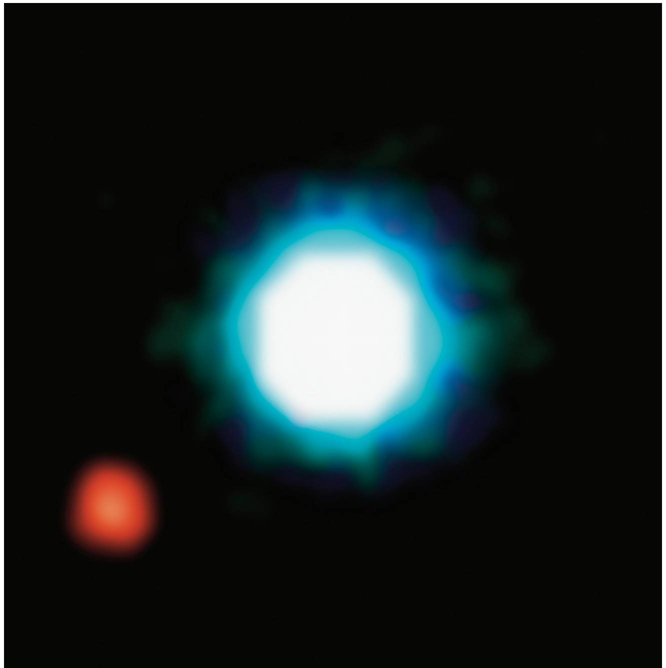
Reflected light: luminosity goes as d^{-2}
High contrast required

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)

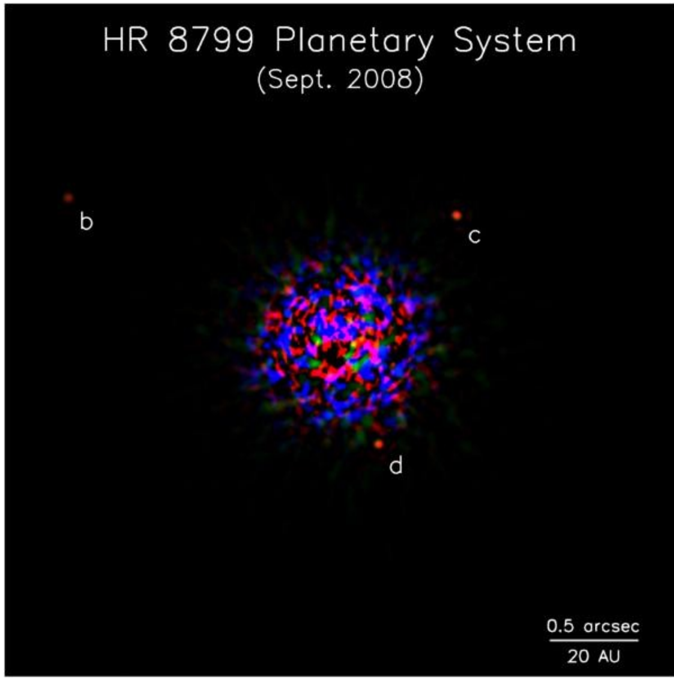
But, habitable planets are not bright in near-IR

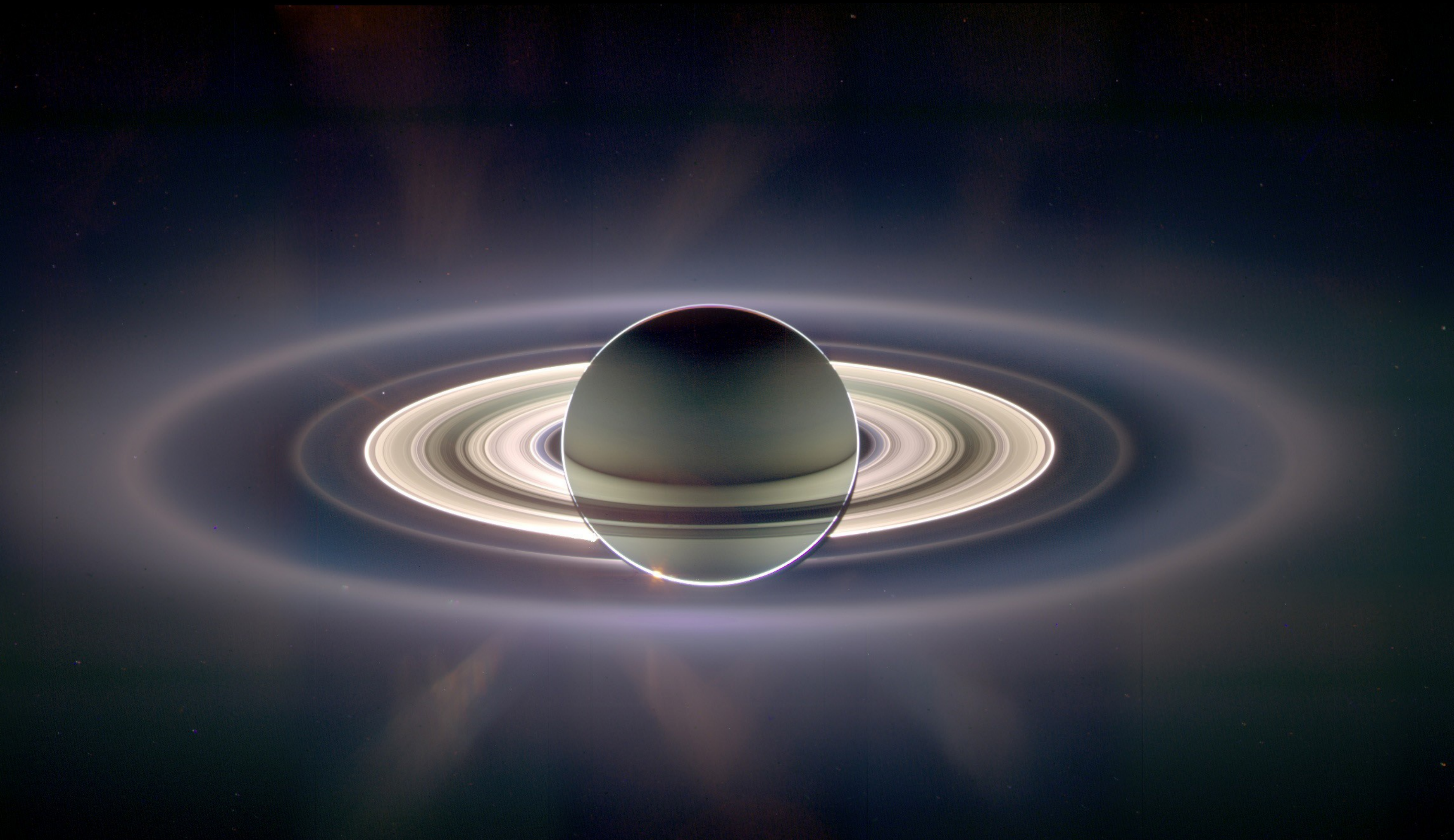
In the Thermal IR (~10 um), contrast is more favorable for habitable planets.

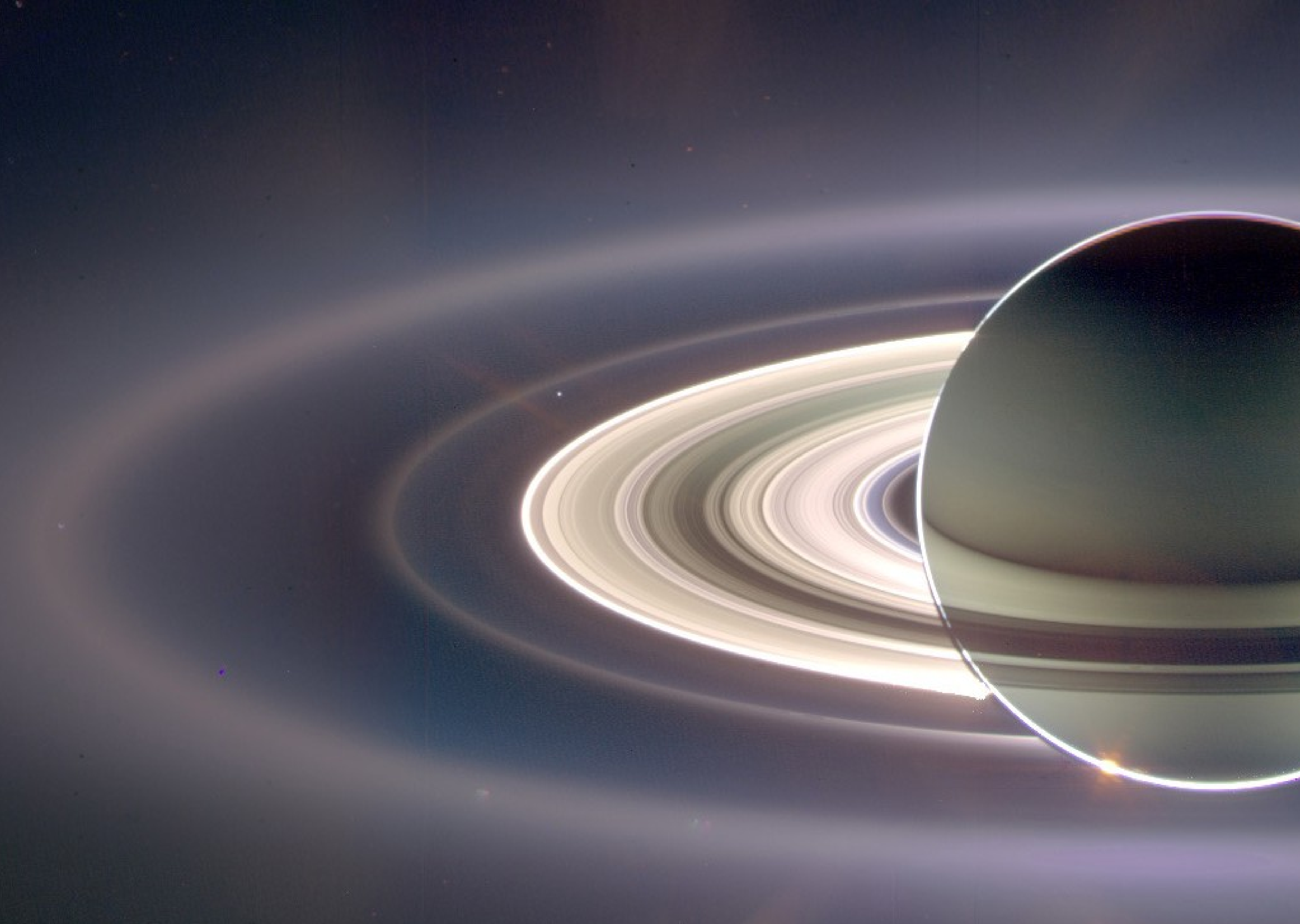


2M1207 exoplanet (Chauvin et al., ESO, 2004)
Probably the first direct image of an exoplanet

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







Spectroscopy of Earth-like planets … may allow detection of life

Spectroscopy can identify biomarkers: molecular species, or combinations of species that can only be explained by biological activity

On Earth: water + O_2 + O_3 + CH_4

Spectra of Earth obtained through Earthshine observation also reveals vegetation's red edge !

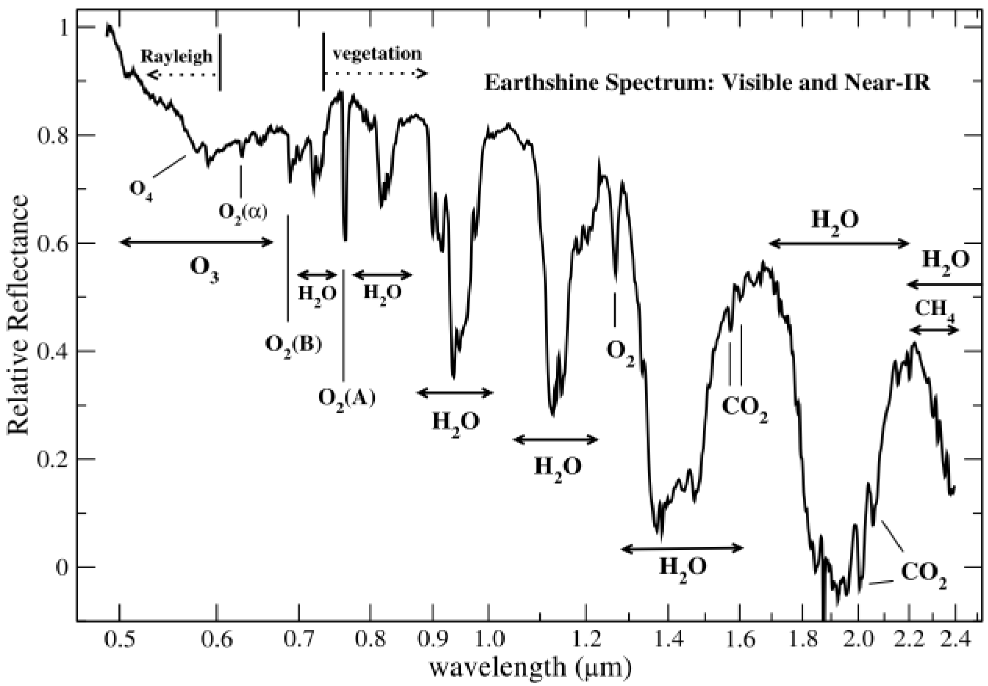
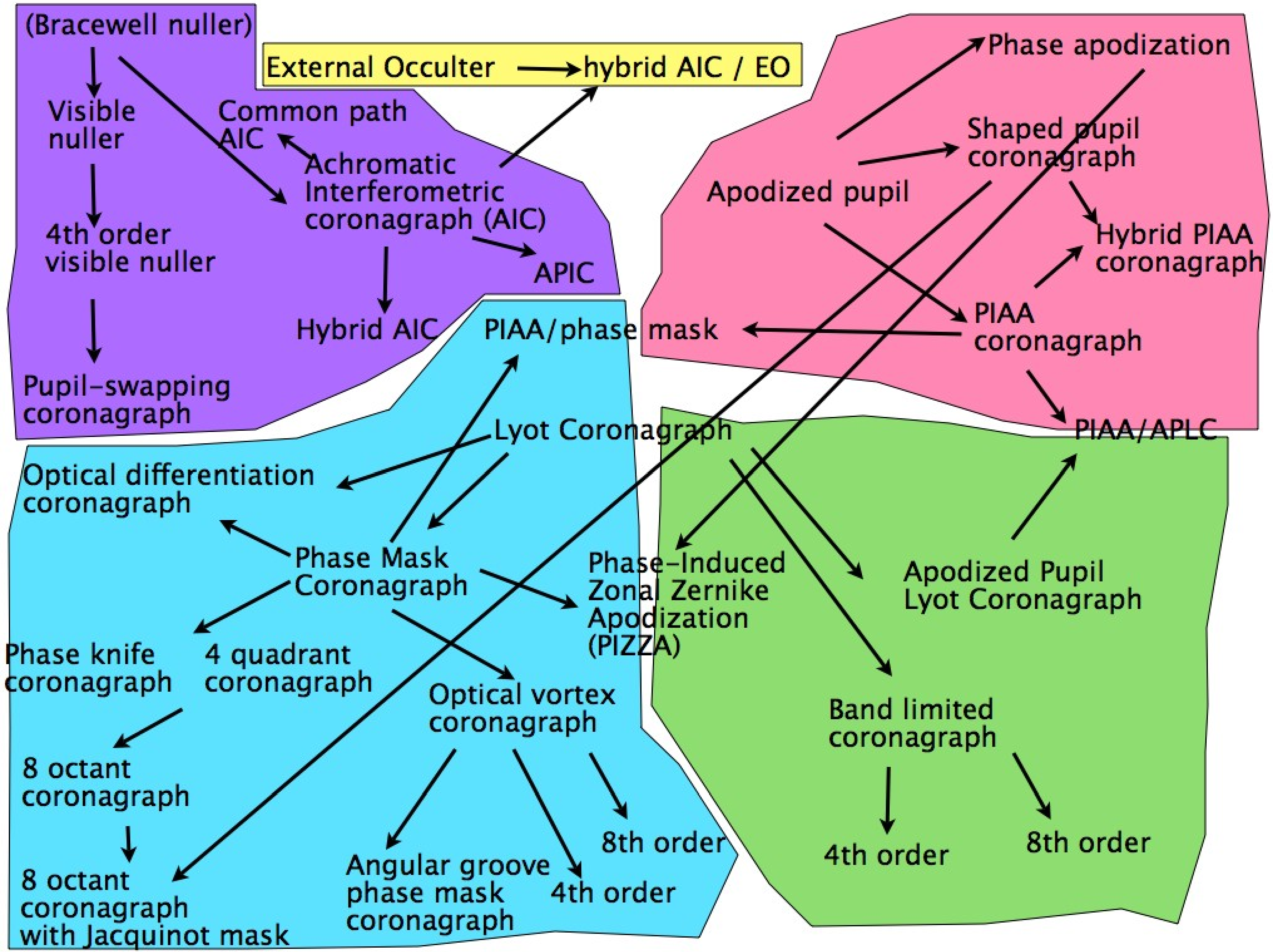


FIG. 7.—Earth's observed reflectance spectrum, at visible and near-infrared wavelengths, created from a composite of the data in this paper (0.8–2.4 μm) and the data presented in Paper I (0.5–0.8 μm). The strongest molecular signatures are indicated, as are the wavelengths where Rayleigh scattering and vegetation reflection are most significant.

Turnbull et al. 2006

Coronagraph concepts & systems

Olivier's thumb...
the slimplest coronagraph
Doesn't work well enough to
see planets around other stars

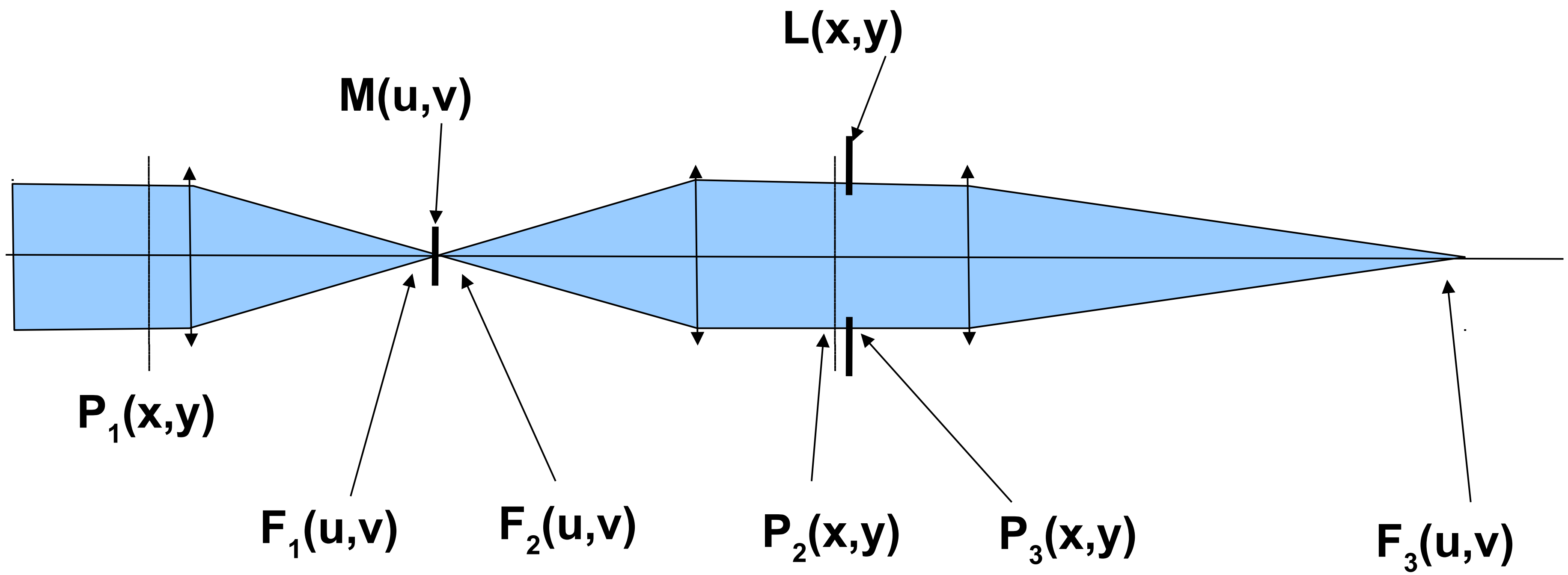

(Bracewell nuller)
External Occulter
hybrid AIC / EO
Phase apodization
Visible nuller
Common path AIC
Achromatic Interferometric coronagraph (AIC)
Shaped pupil coronagraph
Apodized pupil
4th order visible nuller
APIC
Hybrid PIAA coronagraph
Hybrid AIC
PIAA/phase mask
PIAA coronagraph
Pupil-swapping coronagraph
Lyot Coronagraph
PIAA/APLC
Optical differentiation coronagraph
Phase Mask Coronagraph
Phase-Induced Zonal Zernike Apodization (PIZZA)
Apodized Pupil Lyot Coronagraph
Phase knife coronagraph
4 quadrant coronagraph
Optical vortex coronagraph
Band limited coronagraph
8 octant coronagraph
8th order
4th order
8th order
Angular groove phase mask coronagraph
4th order
8 octant coronagraph with Jacquinot mask

Lyot Coronagraph

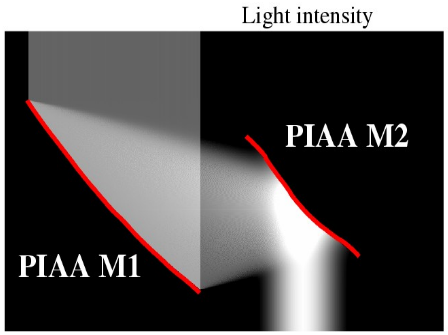
Pupil plane complex amplitude ↔ focal plane complex amplitude

→ Fourier transform
← Inverse Fourier transform

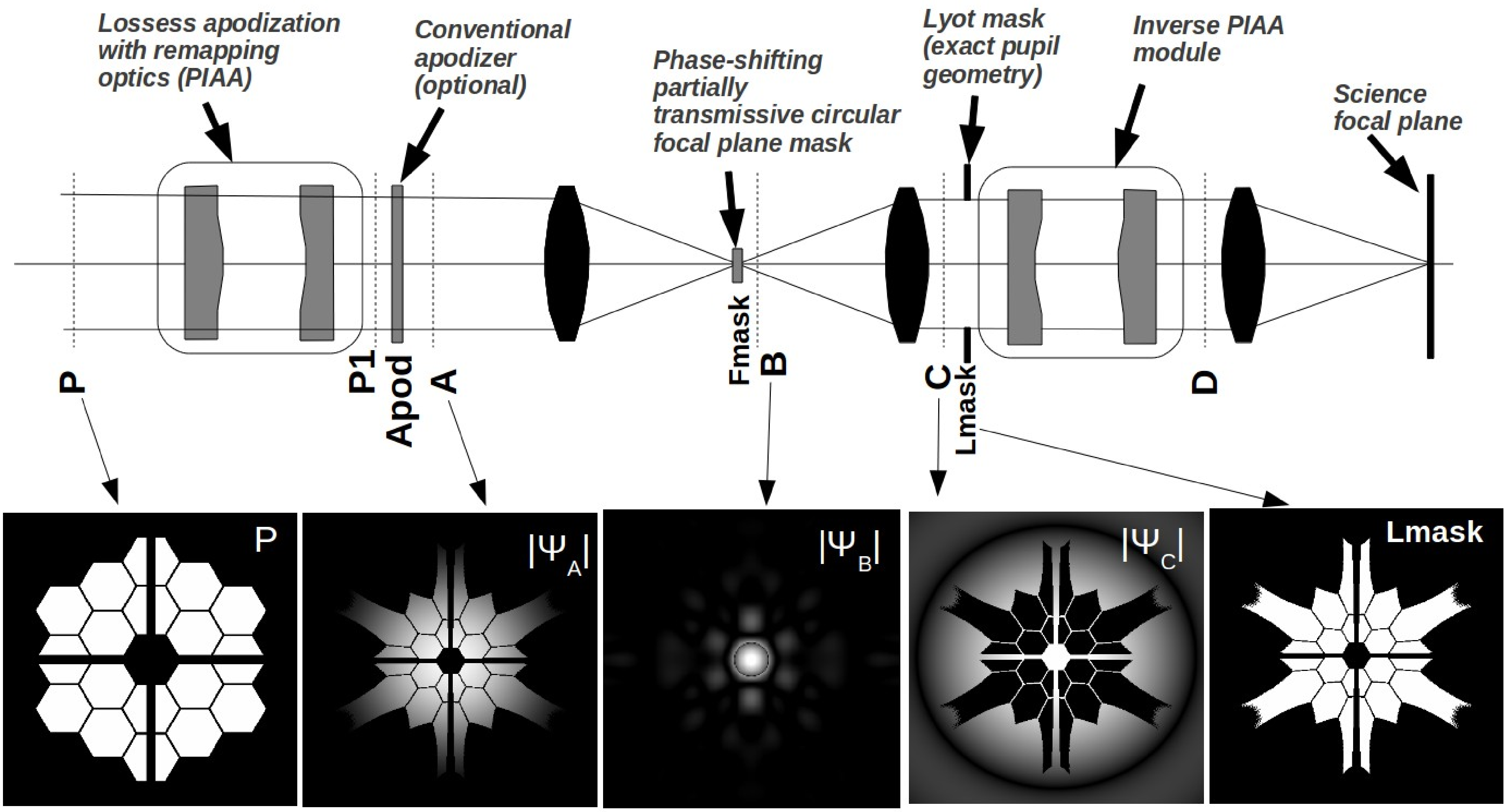
Coordinates in pupil plane: x,y
Coordinates in focal plane : u,v
* denoting convolution (product = convolution in Fourier transform)



A more fancy coronagraph design

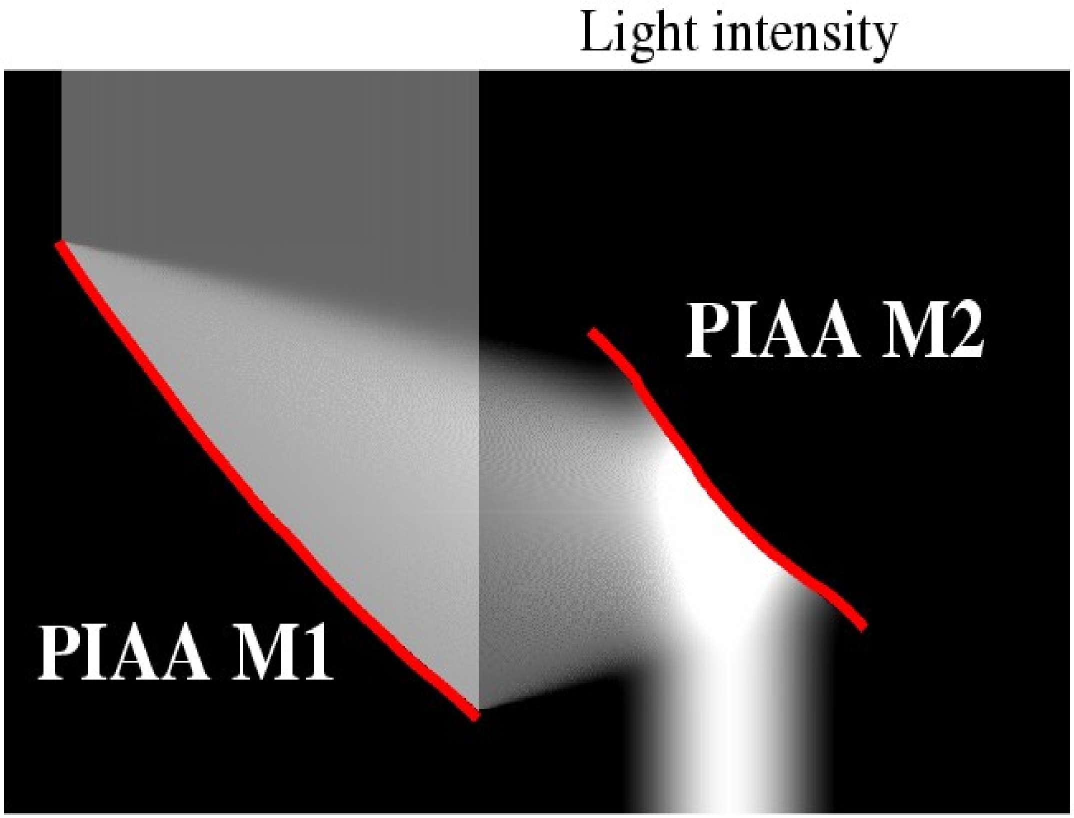


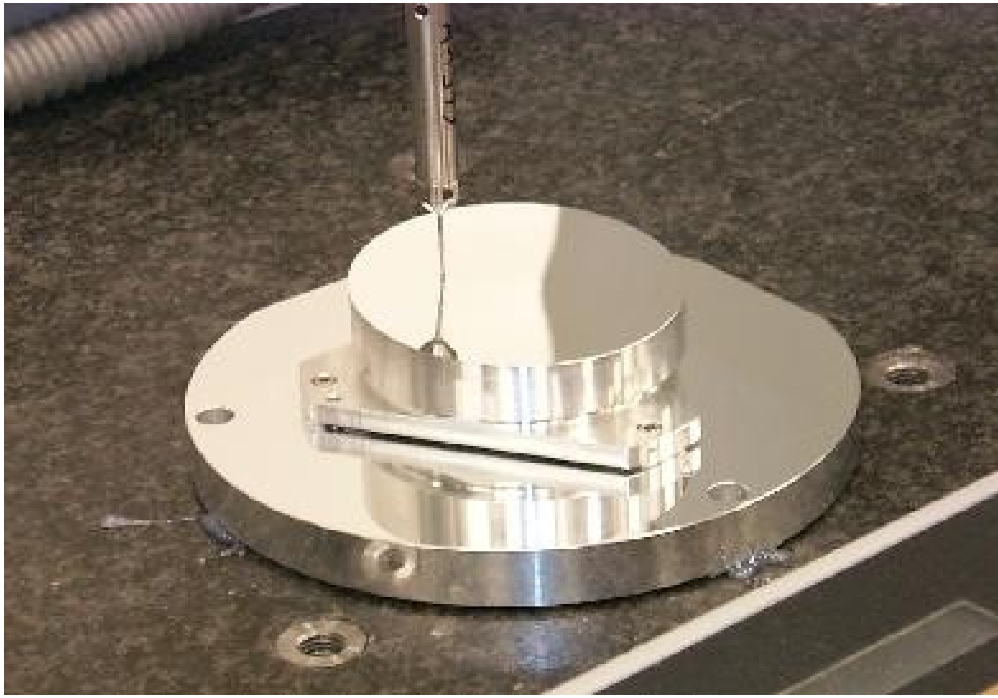
Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.





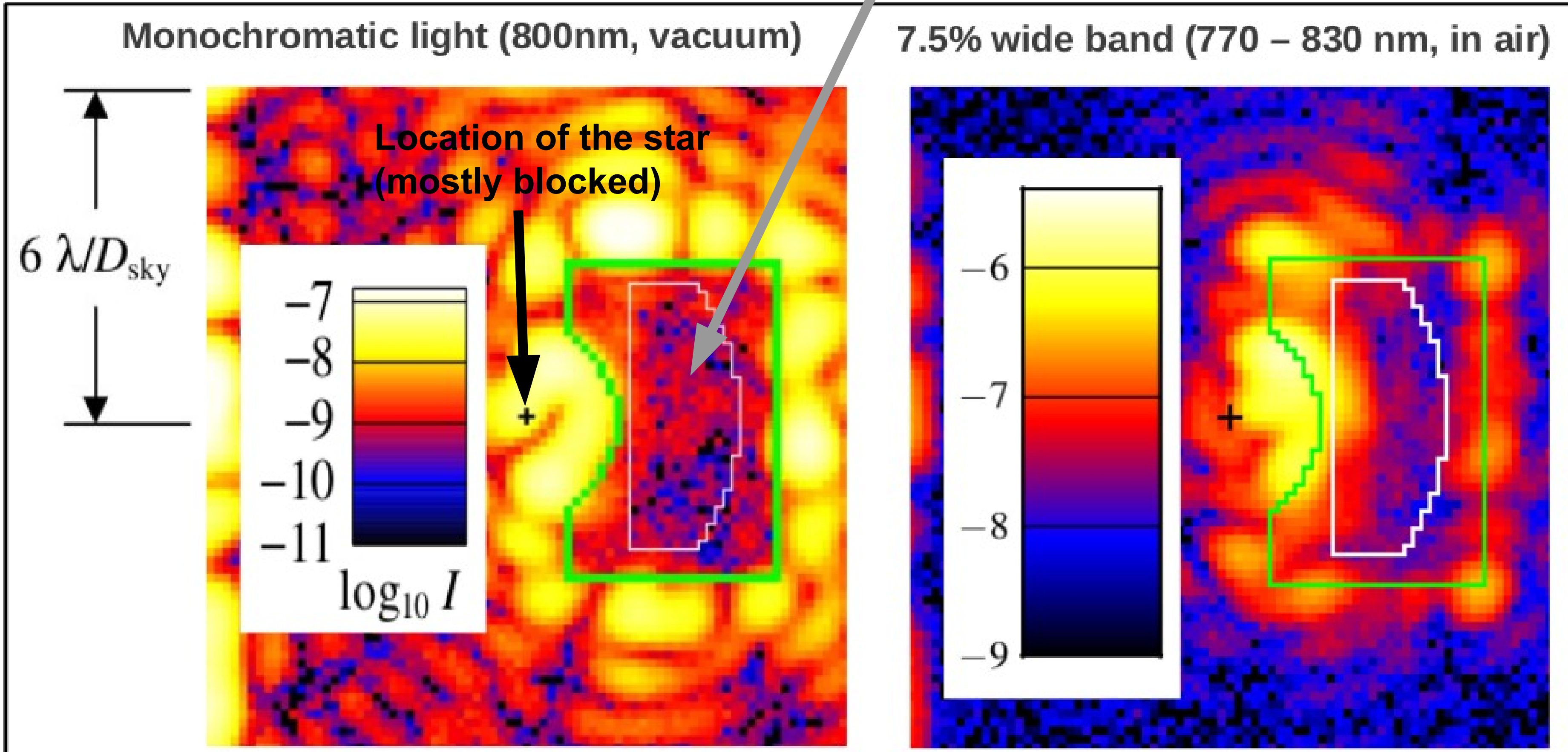
Guyon, Belikov, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present

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)

Science return: 2.4 m telescope with 1.3 l/D IWA PIAACMC

Assuming photon-noise limited sensitivity

19 targets for Earths (SNR>5, R=5, 10hr)

Background (1 zodi):
~ 5x planet light

Star diameter:
~ 30x planet light

→ **REQUIRES ~1% PSF calibration to reach photon noise**

Typical star diam:
1 to 5 mas

Table 1. Most favorable targets for the direct imaging of an Earth analog, ranked by decreasing SNR. The planet is assumed to be observed at maximum angular separation (given both in arcsec and λ/D) at 0.8 μm. The light contribution are given in contrast unit for the source, the background flux (zodi+exozodi) and stellar leak due to the star finite angular size. The SNR for a 10hr observation is given assuming only photon noise, with a 20% system efficiency and a 20% wide spectral band.

Target	Teff [K]	Dist [pc]	L_{bol} [L_{sun}]	max sep. ["]	max sep. [λ/D]	m_V	star Diam [mas]	star Diam [λ/D]	Contrast source	Contrast background	Contrast star	10hr SNR (R=5)
α Cen A	5809	1.34	1.52	0.92	13.39	0.01	8.47	0.1232	1.15e-10	3.05e-11	2.95e-09	43.4
α Cen B	5259	1.34	0.50	0.53	7.68	1.34	5.93	0.0862	3.48e-10	8.92e-11	1.13e-08	39.7
ϵ Eri	5104	3.21	0.34	0.18	2.64	3.73	2.16	0.0314	5.12e-10	7.44e-10	7e-09	24.0
ϵ Ind	4621	3.62	0.22	0.13	1.88	4.68	1.88	0.0274	7.91e-10	1.47e-09	1.16e-08	20.4
τ Cet	5527	3.65	0.55	0.20	2.95	3.49	2.06	0.0300	3.18e-10	6.67e-10	5.2e-09	18.2
40 Eri	5311	4.98	0.46	0.14	1.98	4.43	1.50	0.0218	3.78e-10	1.49e-09	4.21e-09	14.7
61 Cyg A	4530	3.50	0.15	0.11	1.63	5.20	1.69	0.0246	1.14e-09	2.13e-09	4.7e-08	12.8
Procyon	6546	3.51	6.93	0.75	10.91	0.37	5.44	0.0791	2.51e-11	5.1e-11	1.21e-09	11.4
82 Eri	5418	6.04	0.74	0.14	2.07	4.26	1.51	0.0219	2.35e-10	1.39e-09	3.1e-09	10.7
70 Oph	4857	5.10	0.69	0.16	2.36	4.21	2.14	0.0311	2.53e-10	1.14e-09	6.96e-09	9.6
η Cas A	6105	5.94	1.29	0.19	2.78	3.46	1.59	0.0231	1.35e-10	7.88e-10	3.32e-09	8.6
δ Pav	5582	6.11	1.22	0.18	2.63	3.55	1.80	0.0262	1.43e-10	7.44e-10	4.86e-09	8.0
σ Dra	5418	5.75	0.47	0.12	1.74	4.67	1.26	0.0184	3.69e-10	1.92e-09	1.61e-08	7.2
Altair	7524	5.12	10.60	0.64	9.25	0.77	3.49	0.0507	1.64e-11	9.03e-11	8.96e-10	6.3
ξ Boo A	4761	6.78	0.83	0.13	1.96	4.67	1.85	0.0268	2.08e-10	1.98e-09	6.4e-09	5.9
36 Oph B	5104	5.95	0.40	0.11	1.55	5.08	1.27	0.0184	4.35e-10	2.66e-09	2.63e-08	5.7
β CVn	5638	8.44	1.15	0.13	1.85	4.24	1.24	0.0180	1.51e-10	1.53e-09	5.05e-09	5.5
ζ Tuc	5926	8.59	1.44	0.14	2.03	4.23	1.24	0.0180	1.21e-10	1.54e-09	2.87e-09	5.3
β Com	5926	9.13	1.36	0.13	1.85	4.23	1.13	0.0164	1.28e-10	1.51e-09	4.17e-09	5.0
χ^1 Ori	5926	8.66	1.08	0.12	1.74	4.39	1.06	0.0154	1.61e-10	1.77e-09	6.63e-09	4.8
χ Dra	6105	8.06	2.34	0.19	2.76	3.55	1.58	0.0230	7.45e-11	8.47e-10	3.27e-09	4.6
γ Pav	6105	9.26	1.52	0.13	1.93	4.21	1.11	0.0161	1.14e-10	1.57e-09	4.02e-09	4.5
γ Lep A	6417	8.93	2.69	0.18	2.67	3.59	1.39	0.0201	6.46e-11	9.2e-10	2.7e-09	4.1
ι Per	5985	10.54	2.55	0.15	2.20	4.05	1.31	0.0191	6.83e-11	1.31e-09	2.26e-09	3.6
61 Vir	5582	8.56	0.85	0.11	1.57	4.74	1.07	0.0156	2.05e-10	2.25e-09	1.89e-08	3.4
θ Per	6045	11.13	2.70	0.15	2.15	4.10	1.25	0.0182	6.45e-11	1.44e-09	2.06e-09	3.3

Space-based direct imaging of habitable planets

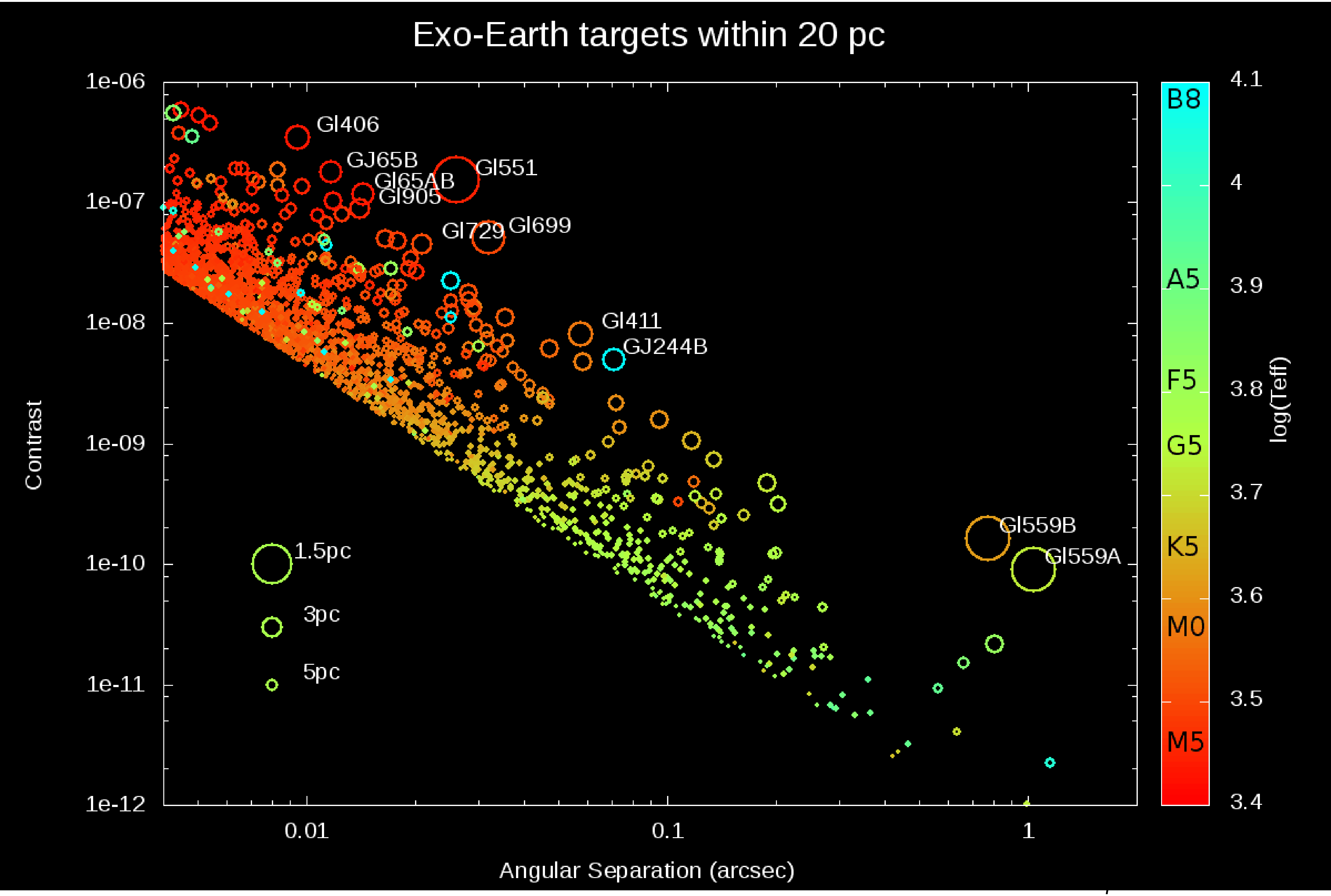
Coronagraphs now reaching performance required for direct imaging of Earth-like planets around sun-like stars

Internal or external (occulter) coronagraph

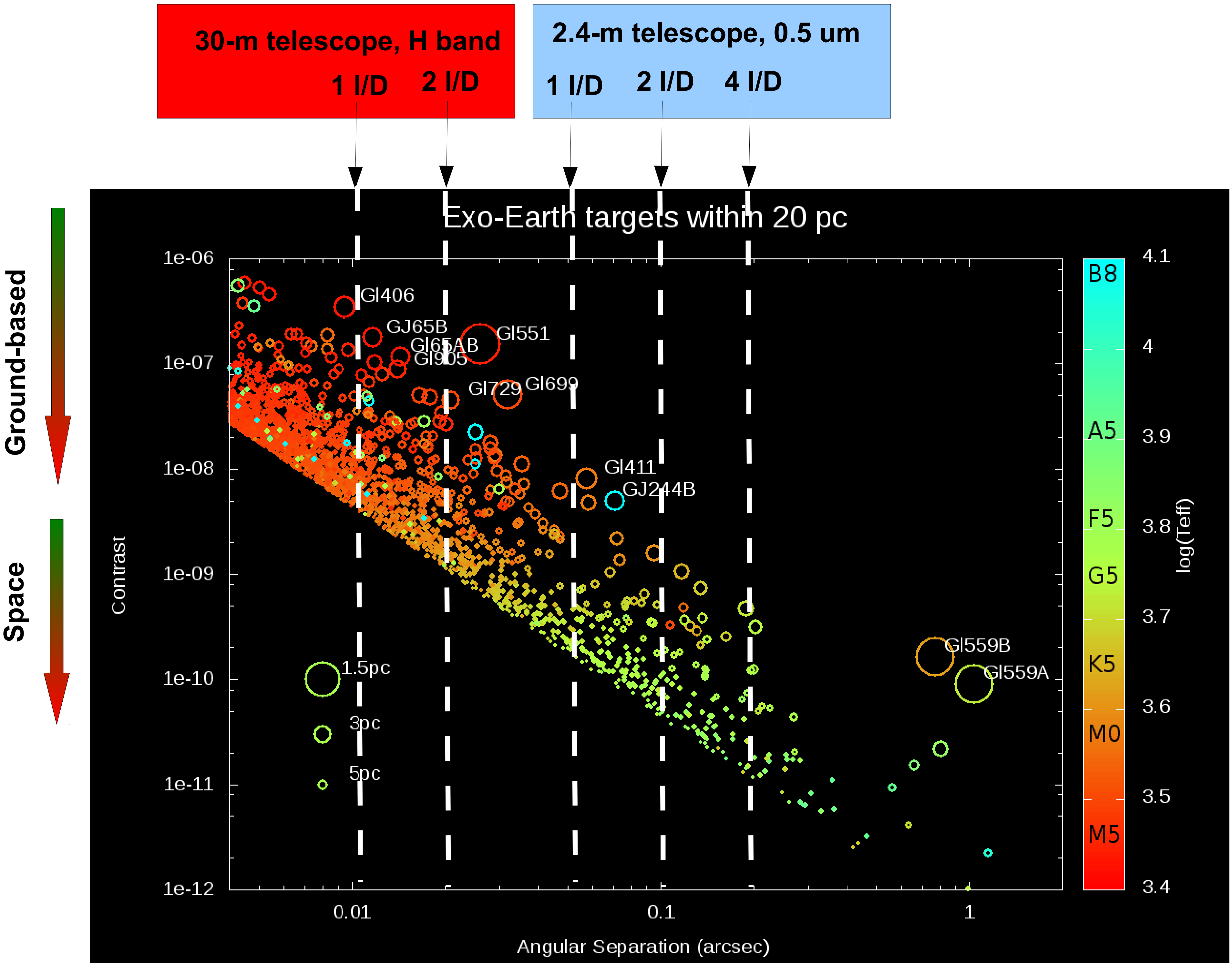
Minimum telescope size to access Earths around >10 stars: ~2-4m

Exposure times for spectroscopy ~week

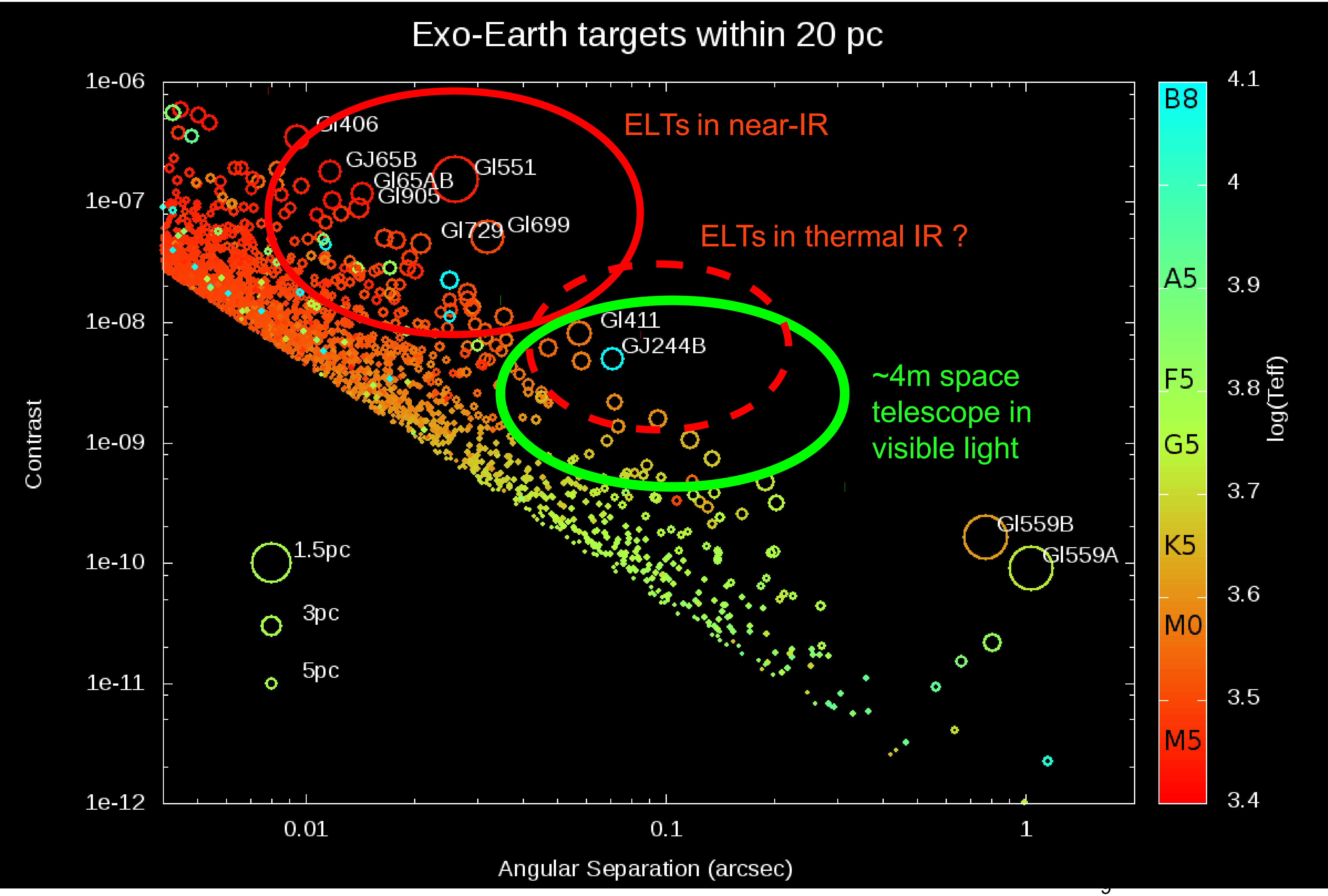
Timescale: late 2030s, 2040s ?



Exo-Earth targets within 20 pc
Contrast
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
Angular Separation (arcsec)
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
log(Teff)



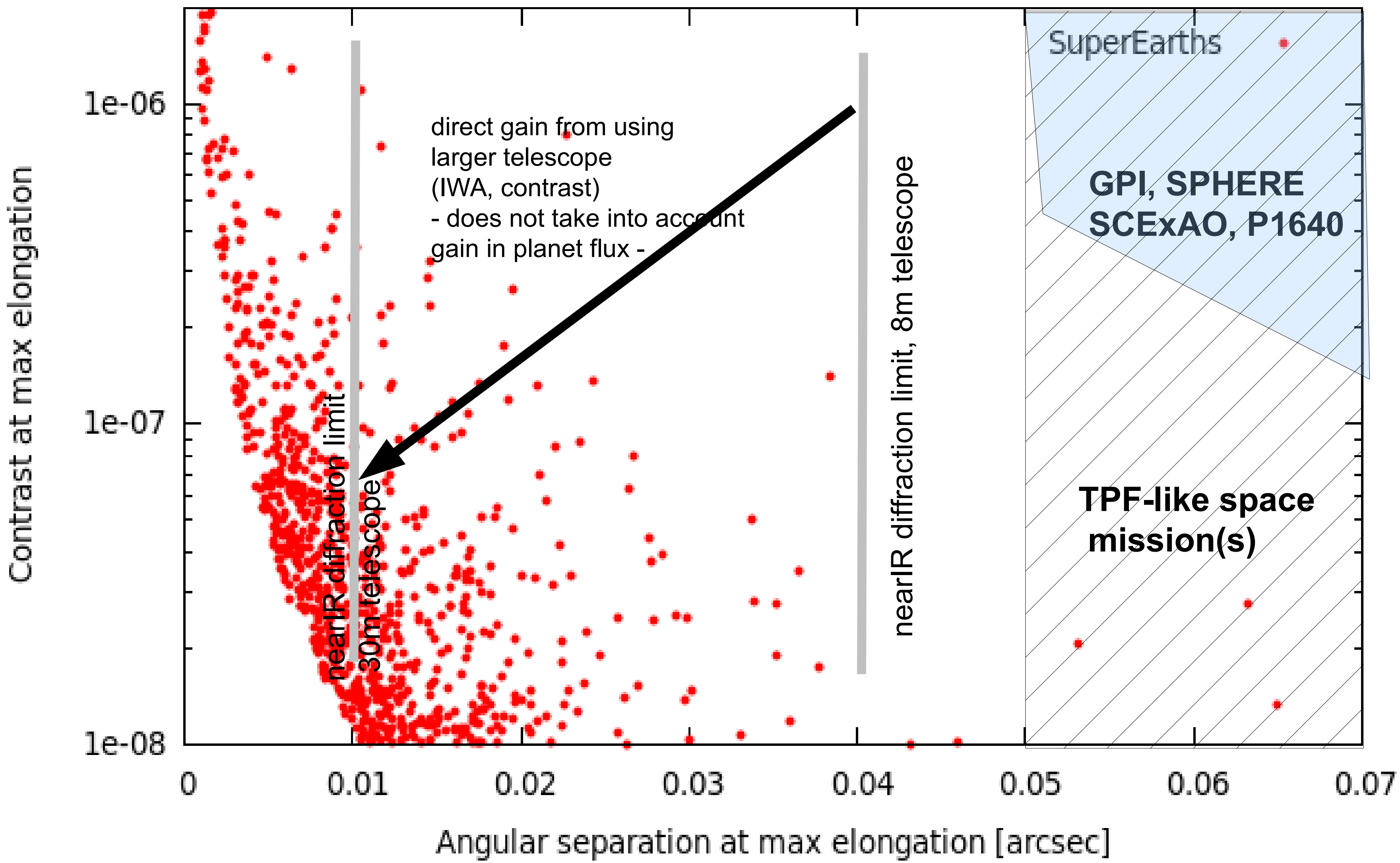
30-m telescope, H band
1 l/D
2 l/D
2.4-m telescope, 0.5 um
1 l/D
2 l/D
4 l/D
Ground-based
Space
Exo-Earth targets within 20 pc
Contrast
Angular Separation (arcsec)
log(Teff)
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
Gl406
GJ65B
Gl65AB
Gl905
Gl551
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc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


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
Angular Separation (arcsec)
log(Teff)
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
B8
A5
F5
G5
K5
M0
M5
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

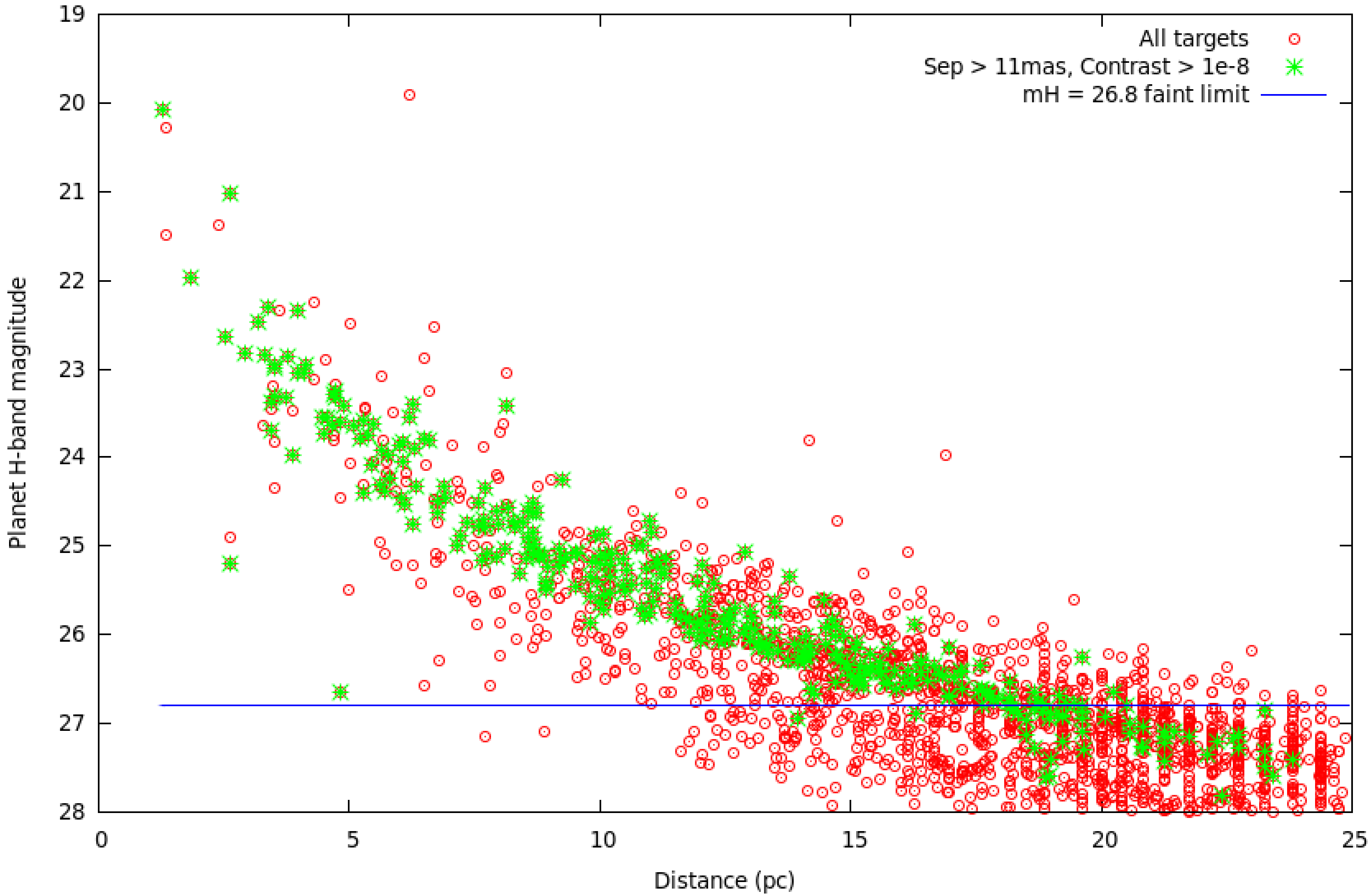
	Limit/constraints	Comments
Angular Separation	Must be > 1.0 λ/D	Limit imposed by coronagraph (see section 4). Corresponds to 11mas on a 30-m telescope in H band.
Contrast	Must be > 1e-8	High contrast imaging limit (see section 5)
Star brightness	Must be brighter than $m_R = 15$	Required for high efficiency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

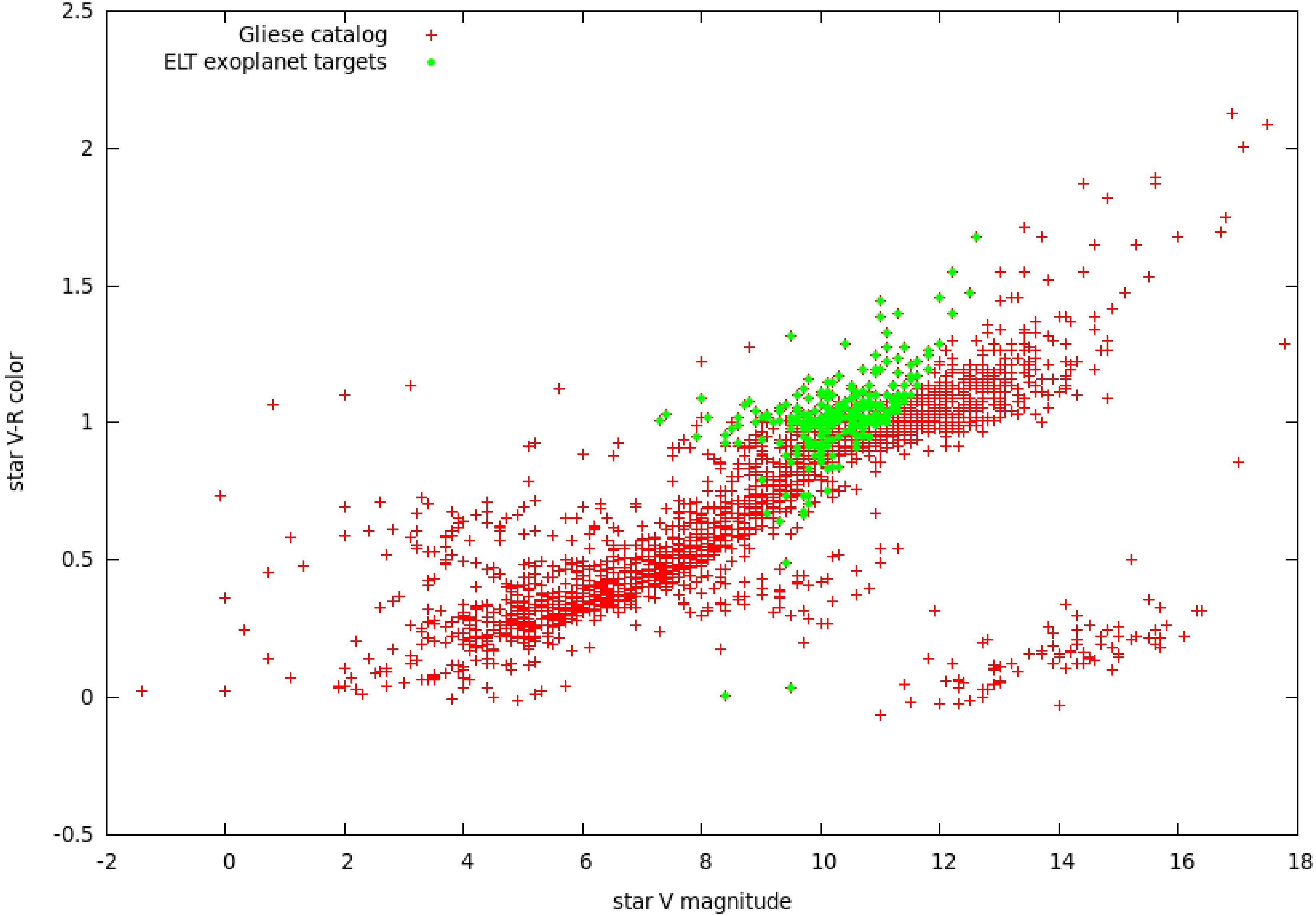
Strong correlation between planet apparent brightness and system distance



Reflected light planets

2 white dwarfs : 40 Eri B and Sirius B

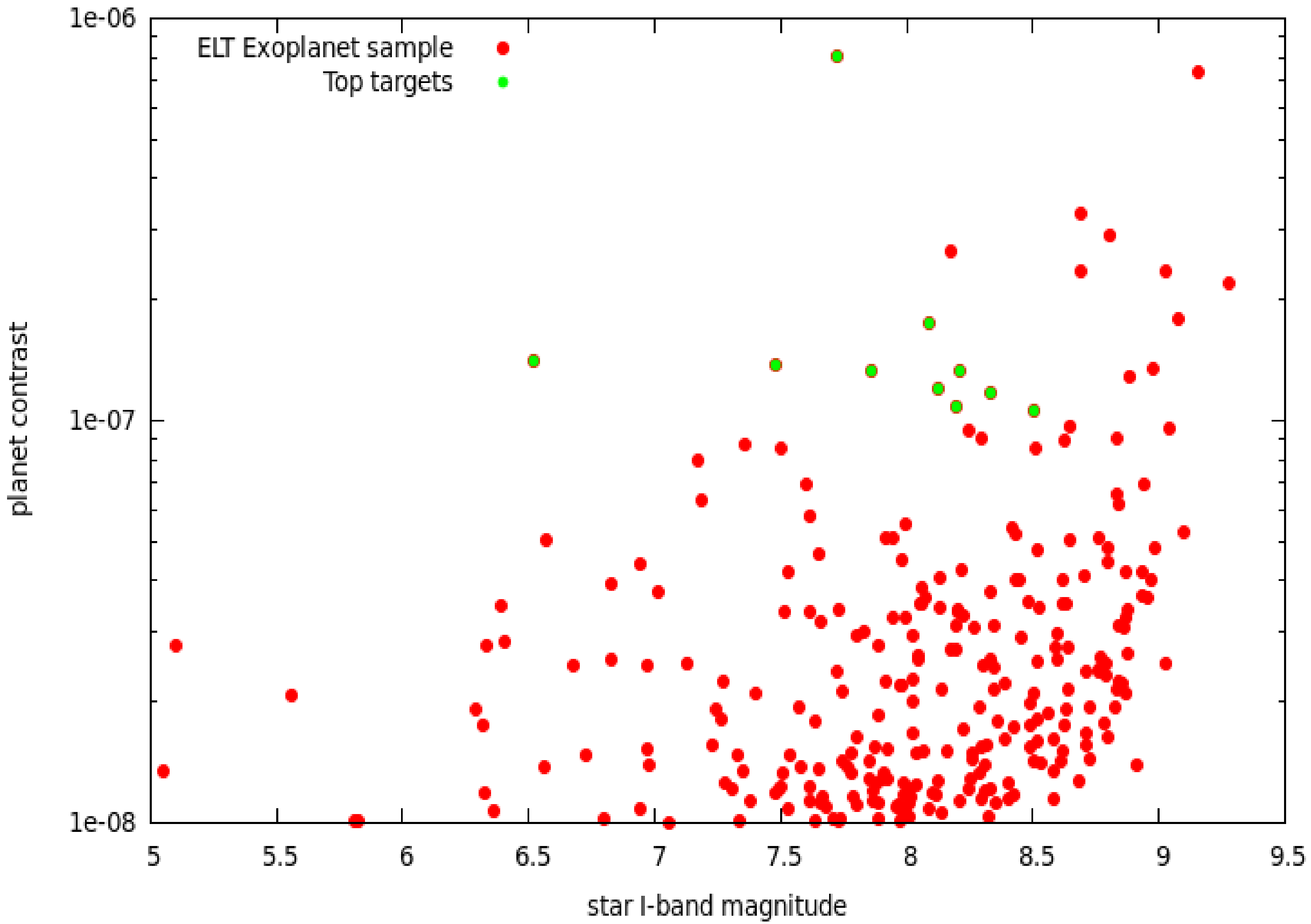
Early type stars → contrast too challenging



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

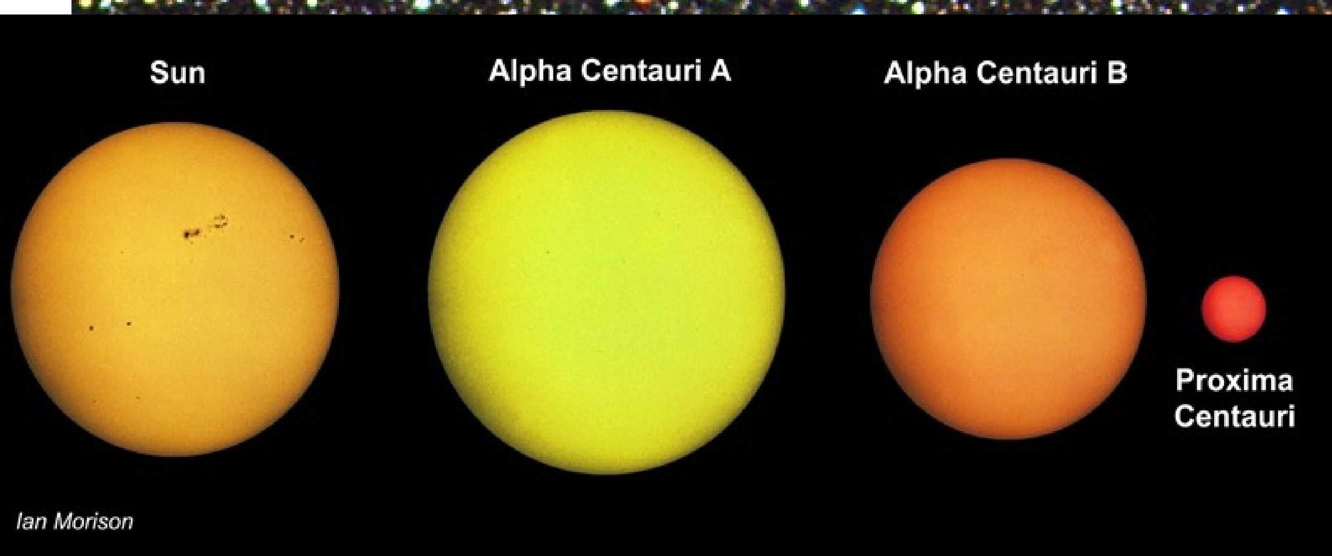
STAR							PLANET				
Name	**Type**	**Distance**	**Diameter**	L_{bol}	m_V	m_R	m_H	**Separation**	**Contrast**	m_H	**Notes, Multiplicity**
Proxima Centauri (Gl551)	M5.5	1.30 pc	0.138 R_{Sun} 0.990 +- 0.050 mas [1]	8.64e-04	11.00	9.56	4.83	22.69 mas	8.05e-07	20.07	RV measurement exclude planet above 3 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 Super-Earths:
Key Requirements for ELTs

Coronagraph:

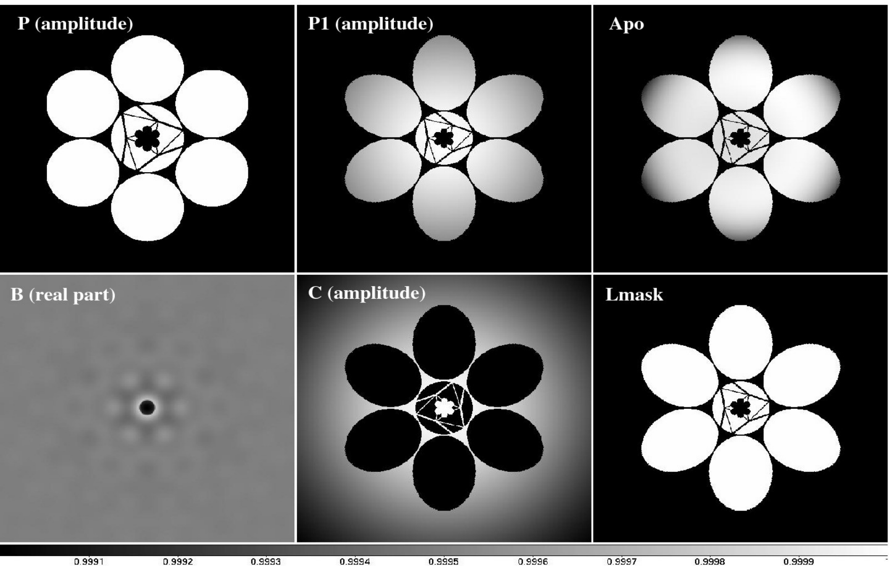
15 mas IWA (~1.5 l/D in near-IR), <1e-4 contrast
High efficiency (throughput, angular resolution)

AO system:

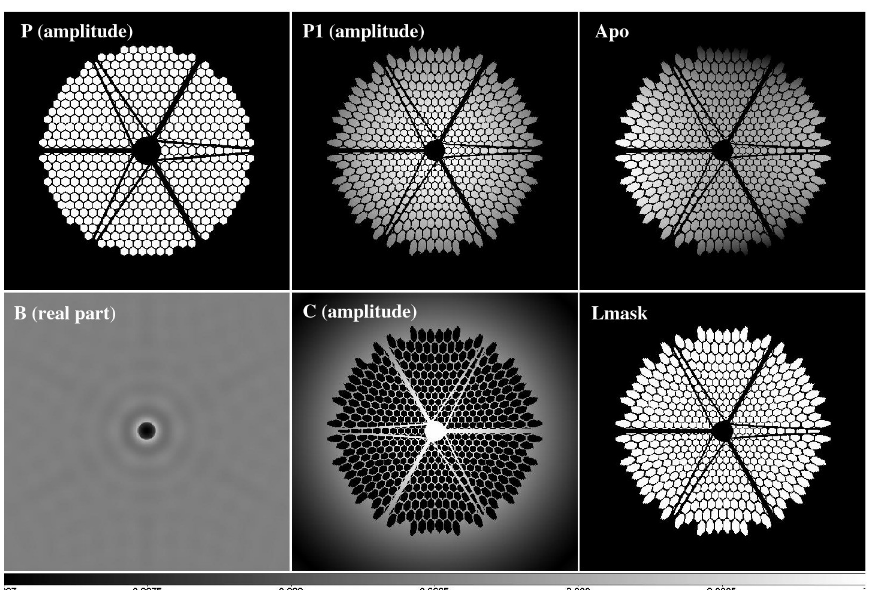
RAW contrast : ~1e-4 contrast between 10 and 40 mas
Guide star: V~11, R~9.5, I~8

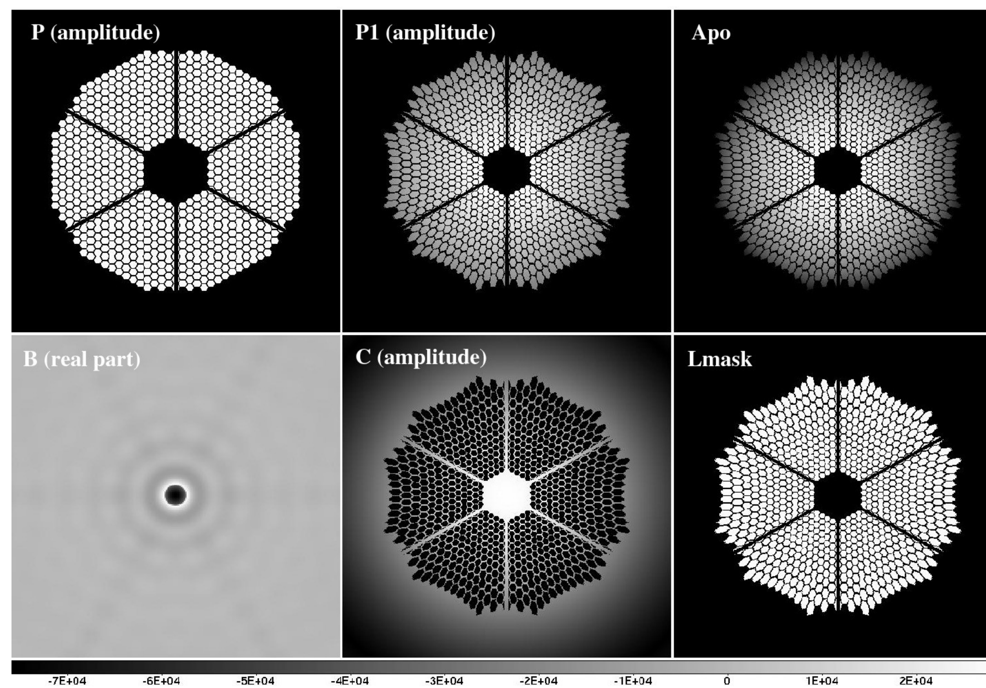
DETECTION contrast: ~1e-7 to 1e-8

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

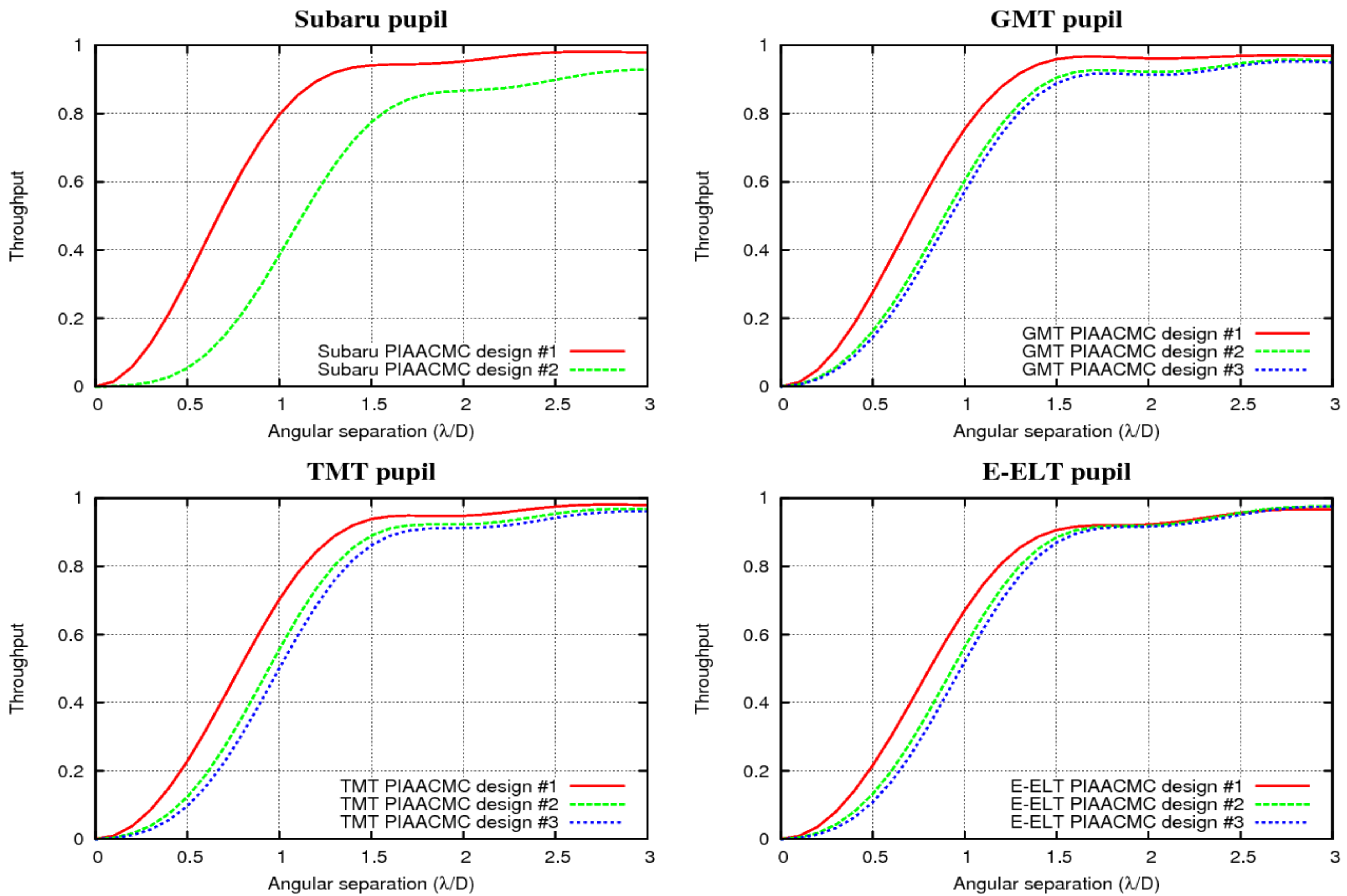


<u>Pupil shape does not matter !!!</u>





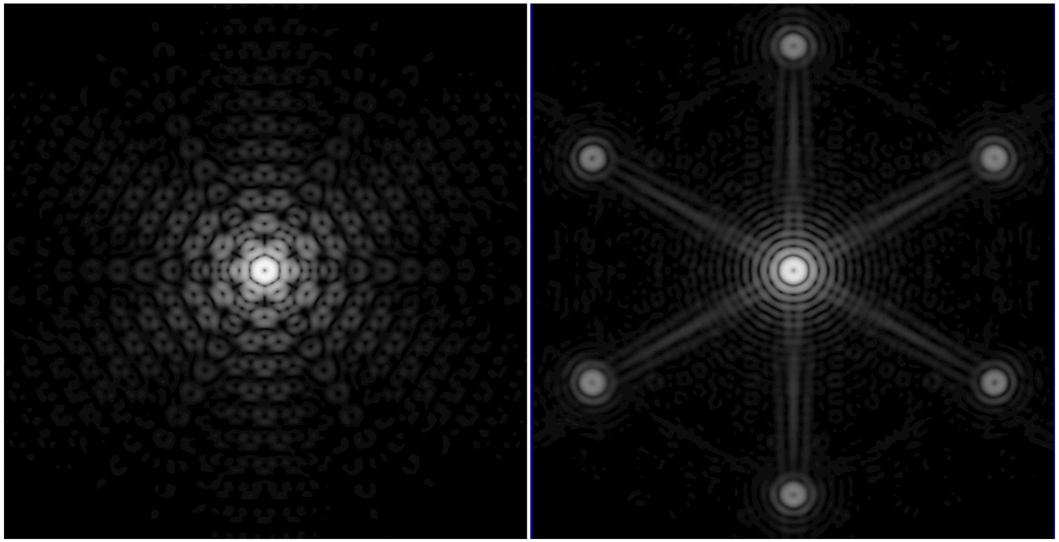
PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit

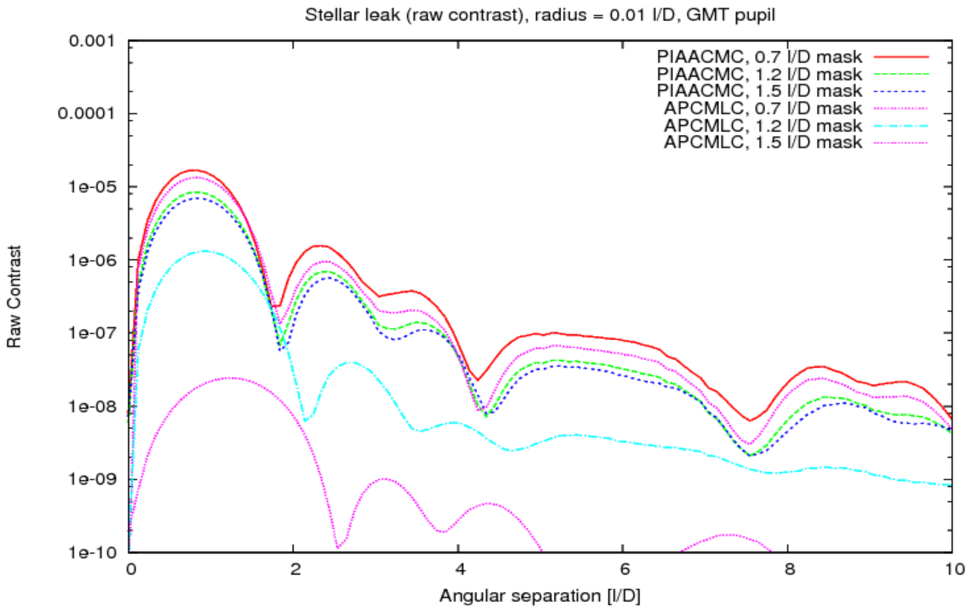


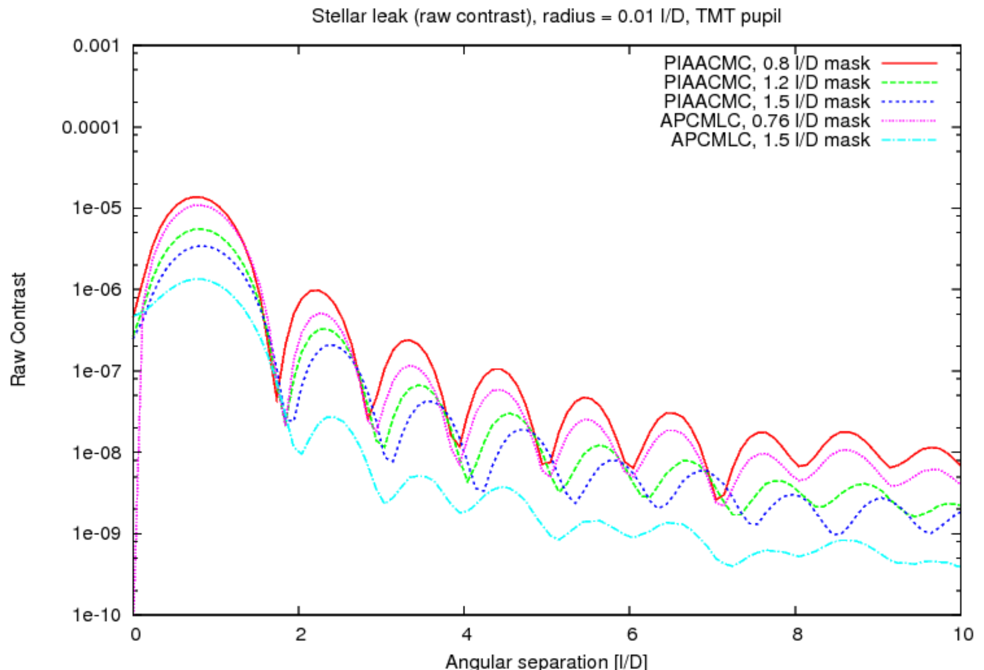
Coronagraphy: Stellar angular size

On ELT in near-IR, nearby M dwarf is about 0.1 to 0.5 mas radius = 0.01 to 0.05 l/D

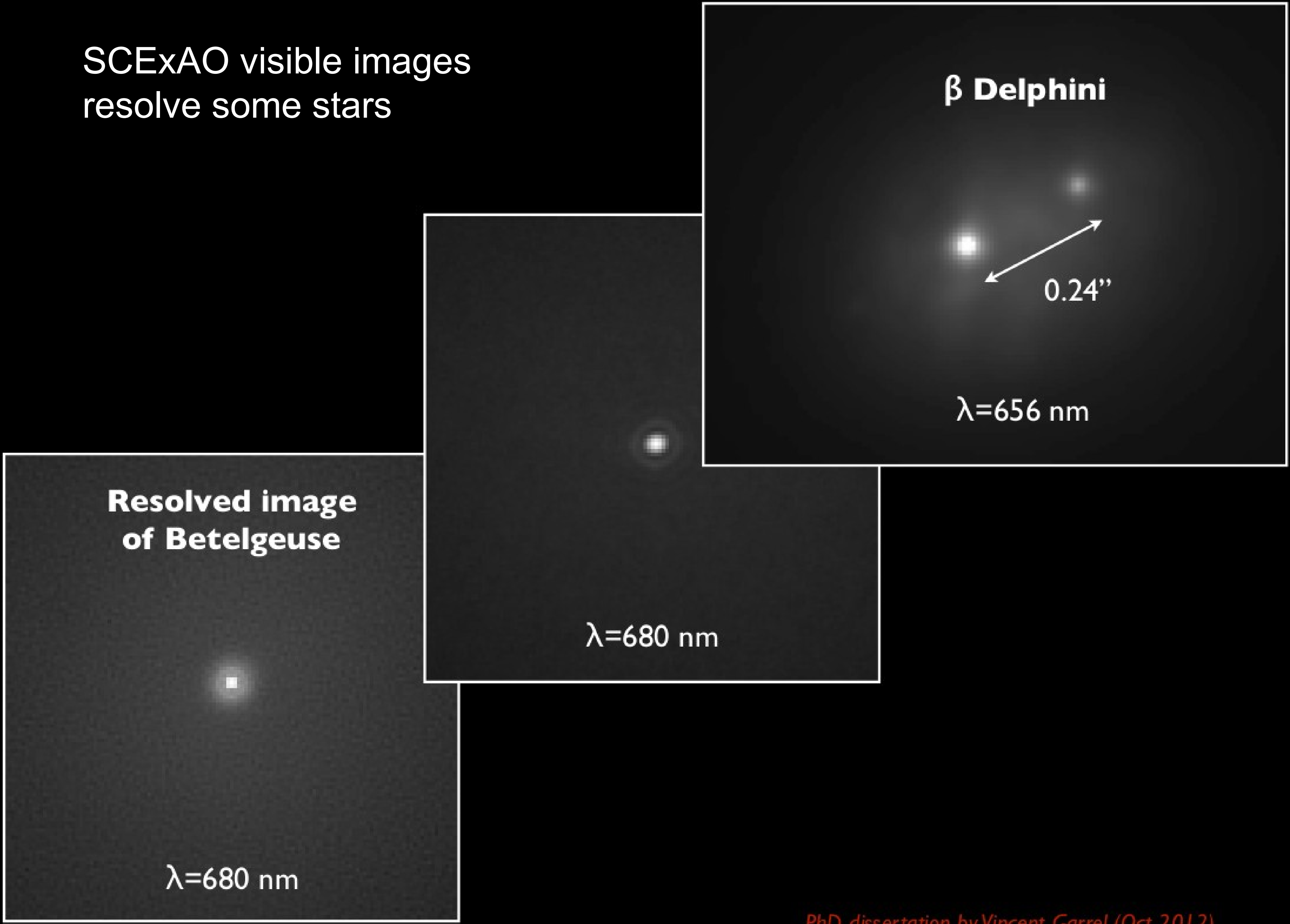
→ for 1 l/D IWA coronagraph
RAW contrast limited to ~1e5 to 1e-6







SCExAO visible images
resolve some stars



PhD dissertation by Vincent Garrel (Oct 2012)

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

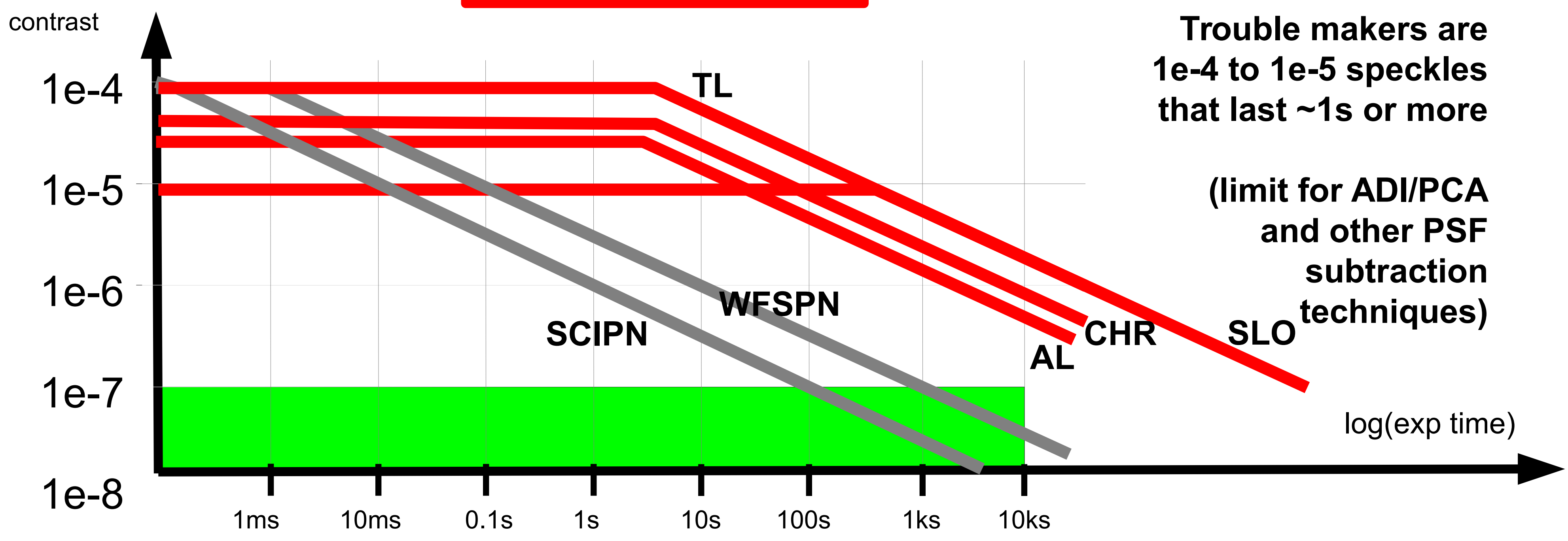
WFS Aliasing (AL)
Aliasing within WFS
few x1e-5 contrast
D/v timescale

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

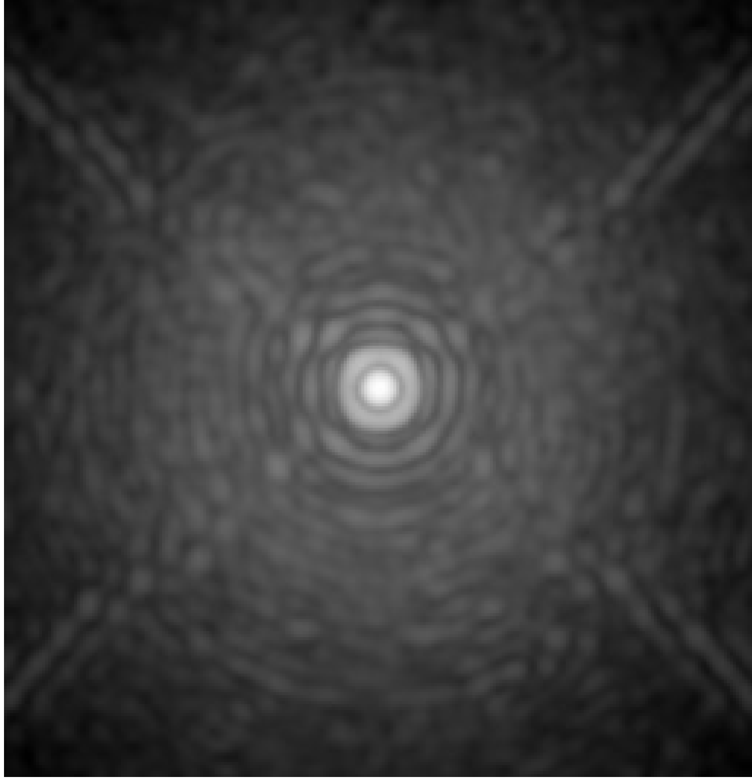
Science photon noise (SCIPN)
Photon noise in science image
1e-4 contrast
Photon arrival rate timescale (>kHz)



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

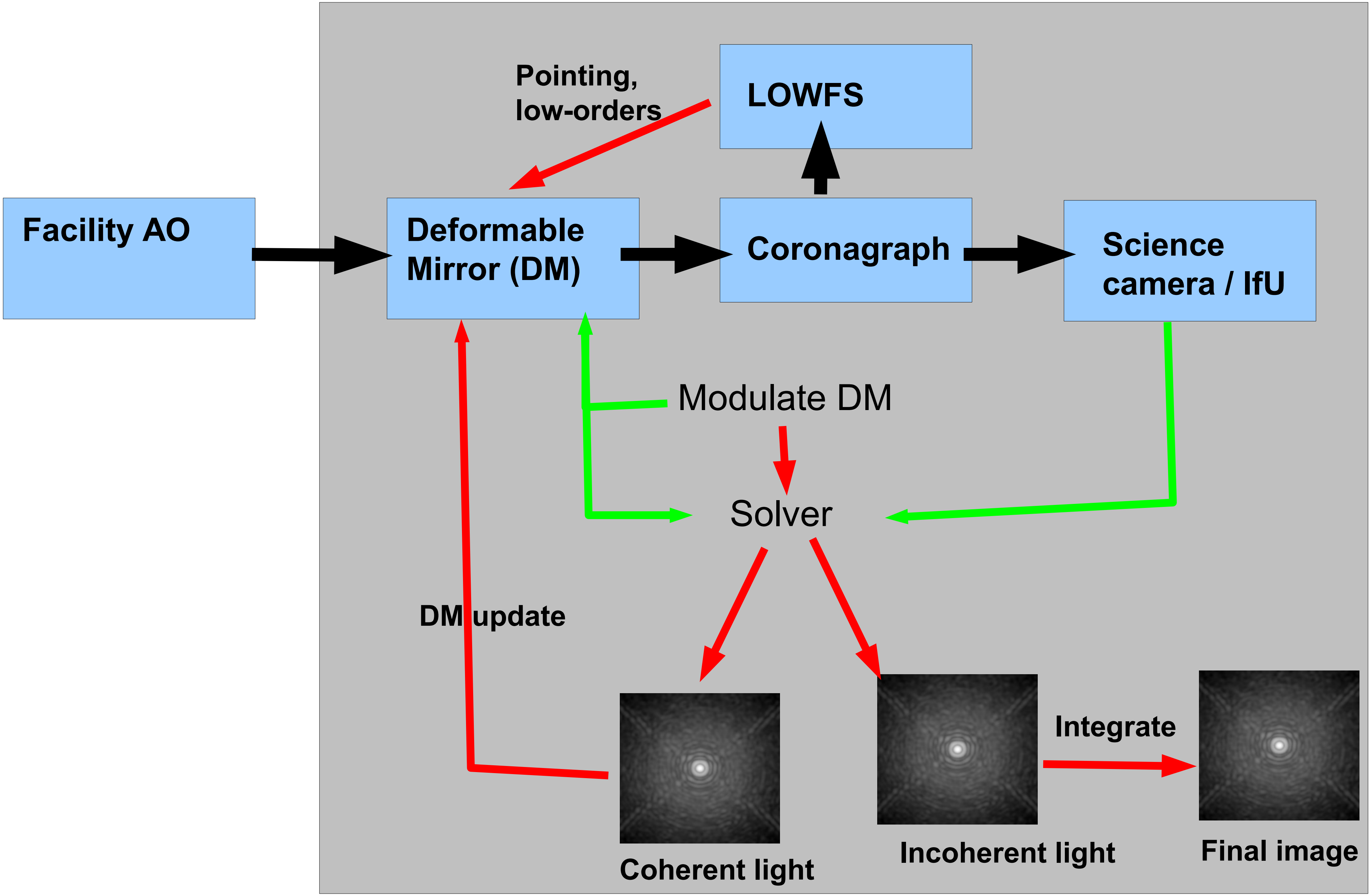
SENSING: Put "test speckles" to measure speckles in the image, watch how they interfere

CORRECTION: Put "anti speckles" on top of "speckles" to have destructive interference between the two (Borde & Traub 2006, 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"

System architecture

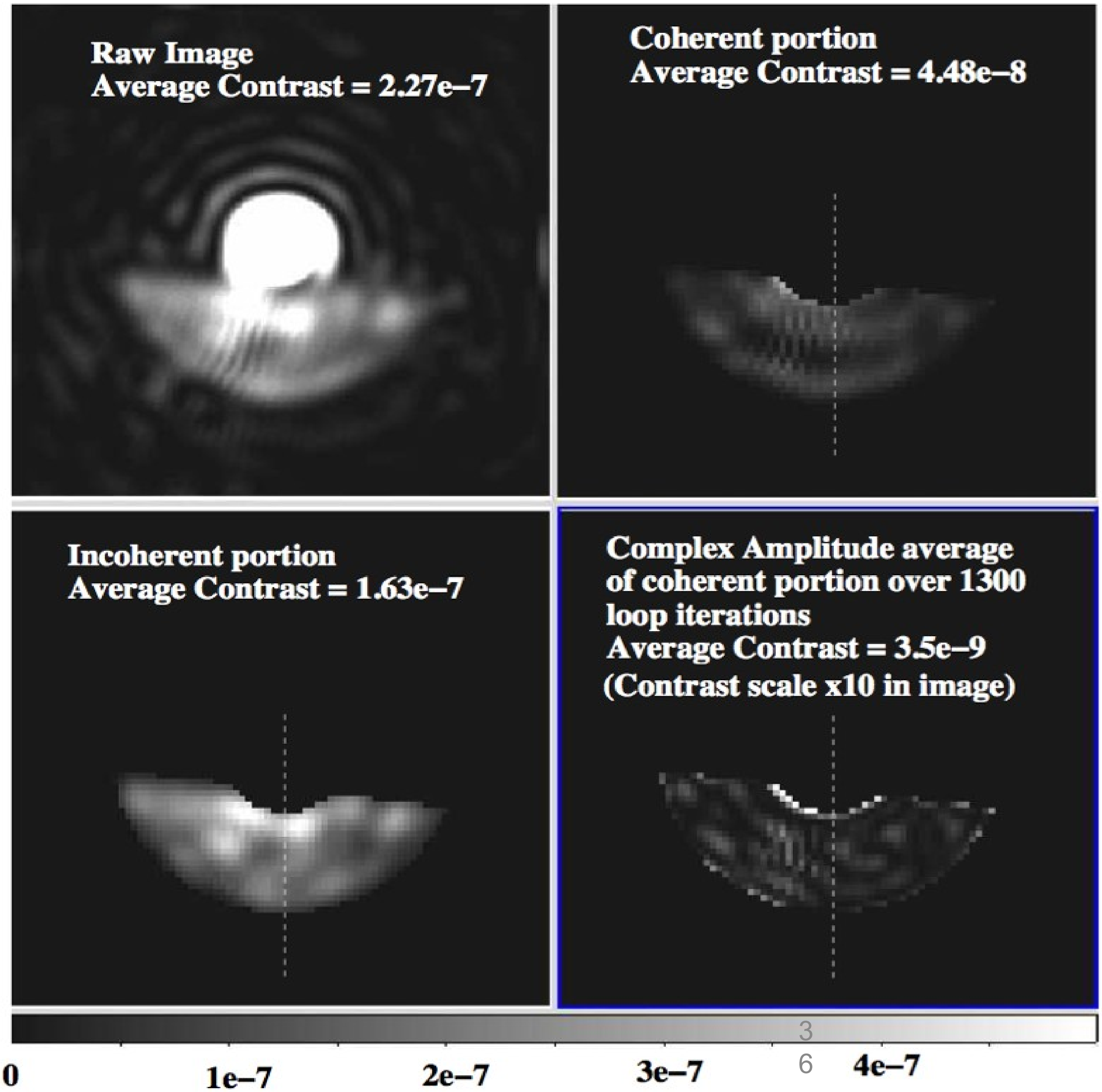


Focal plane WFS based correction and speckle calibration

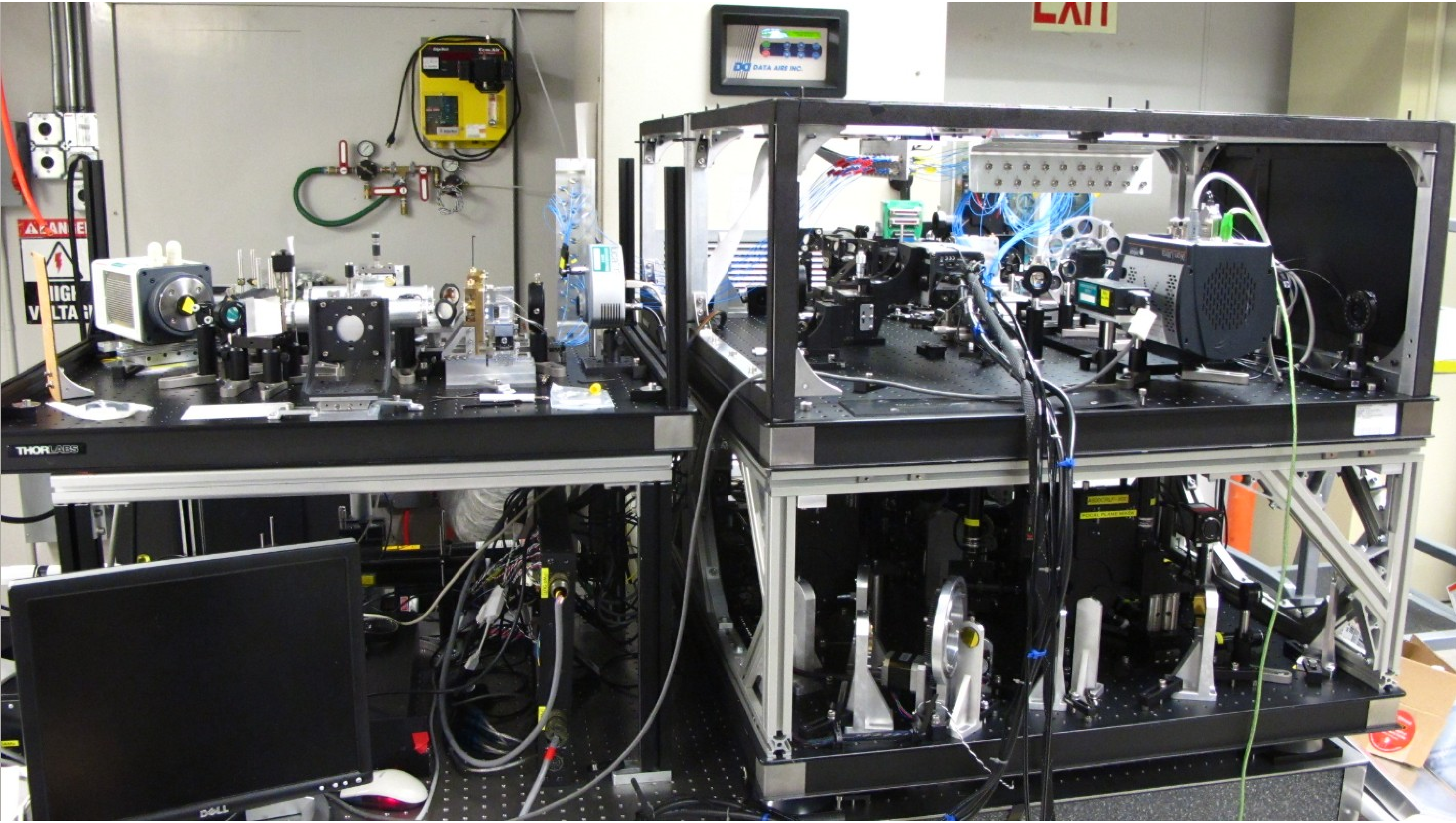
2e-7 raw contrast obtained at 2 λ/D

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

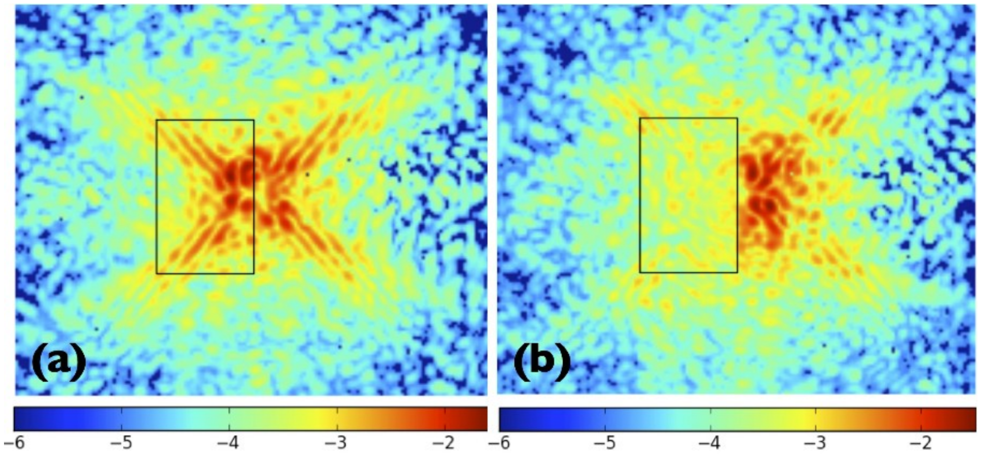


Subaru Coronagraphic Extreme-AO (SCExAO) system
(July 10 2013)



Using a deformable mirror to measure and control focal plane speckles

In lab →

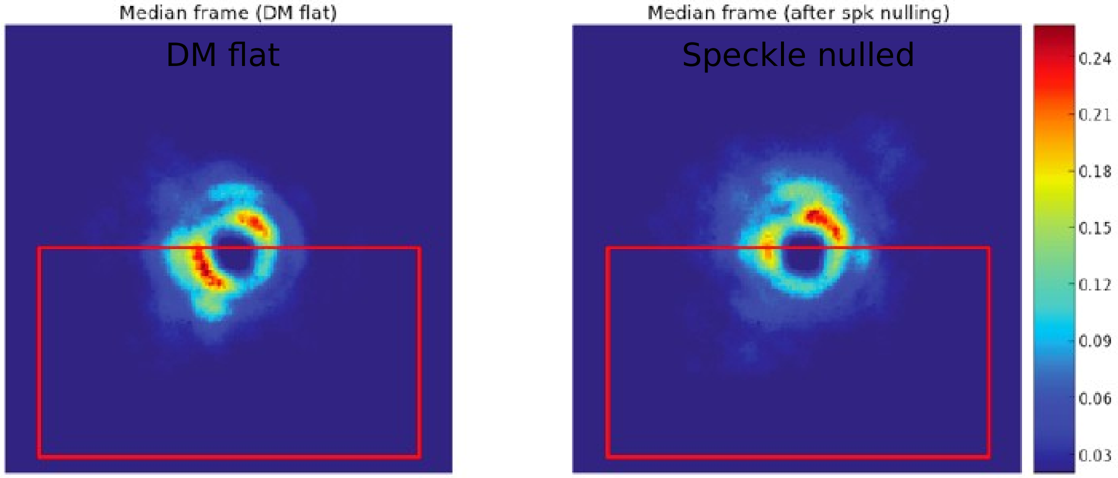


Taking advantage of the full PIAA - focal plane mask - PIAA^{-1} optical configuration

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

Performance limit

What residual will look like planet ?

Temporal effects: complex amplitude changes with time

Chromaticity: complex amplitude changes with lambda

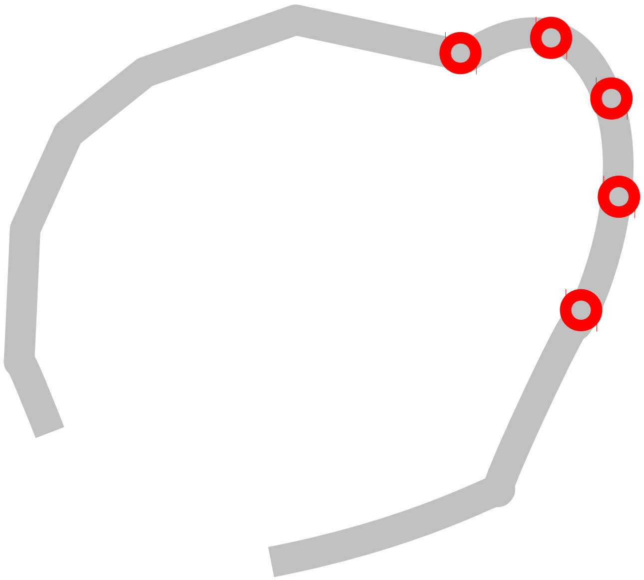
Static and slow speckles (due to optics) well calibrated with low speed

Temporal timescale:

Intensity : crossing time D/v ~ few sec

Complex amplitude : $D / (2 \pi \alpha v)$ < crossing time

(α = separation in λ/D)



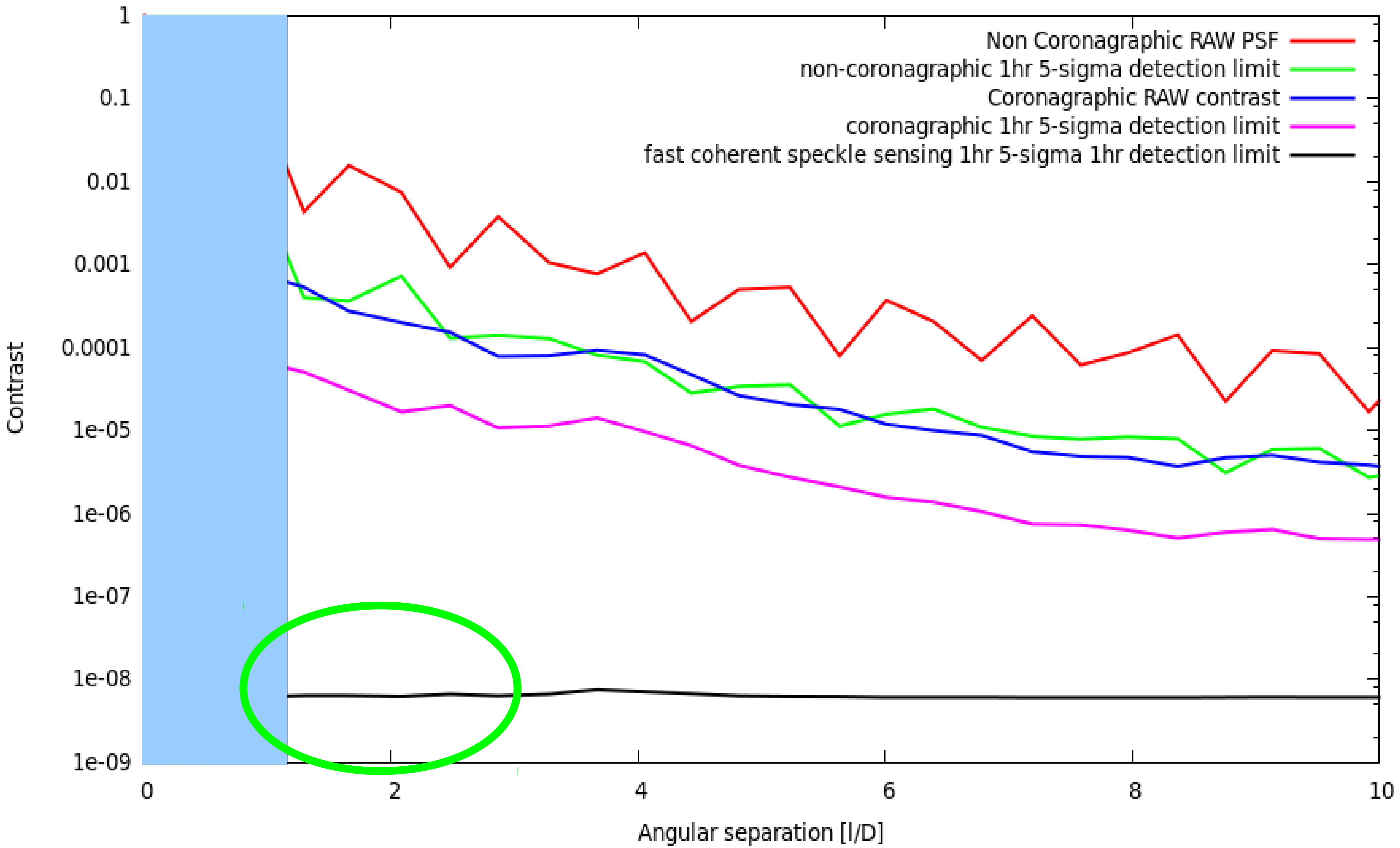
ATTENUATION = $\pi\, dt\, v\, \alpha / D$

Target $m_H=5$

1e-7 speckle, D=8m

→ 500 ph/s/um → few ph per 10ms

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



Speed vs performance:
~100 Hz frame rate would achieve significant gain

Near-IR detector technology is key

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

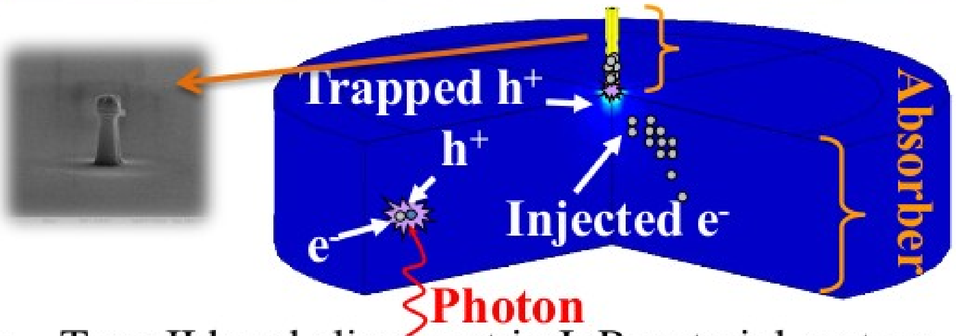
Possible technologies:

- Amplified near-IR detectors (~2e- RON, >kHz frame rate)
- Near-IR electron-injector detectors
- MKIDs (ideal)

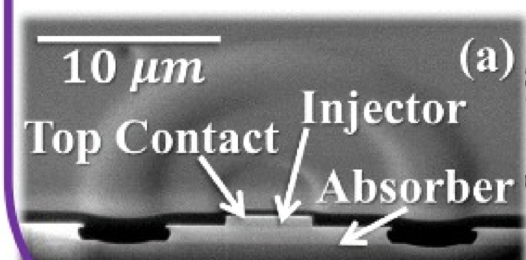
Bio-Inspired Sensors and Optoelectronics Laboratory

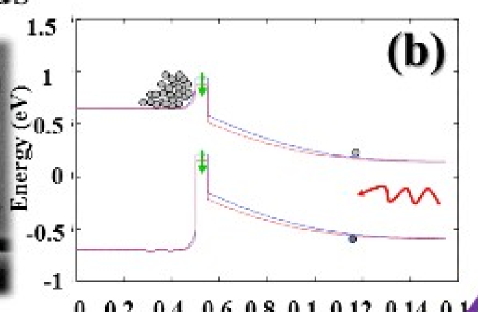
NORTHWESTERN UNIVERSITY

Design and Concept



- Type II band alignment in InP material system.
- Operation principle:
  - Photon absorbed in the thick InGaAs absorber.
  - Hole attracted towards injector.
  - Gets trapped in GaAsSb.
  - This lowers the bands and results in injection of electrons.
  - Hole recombines with an electron, relaxing the bands

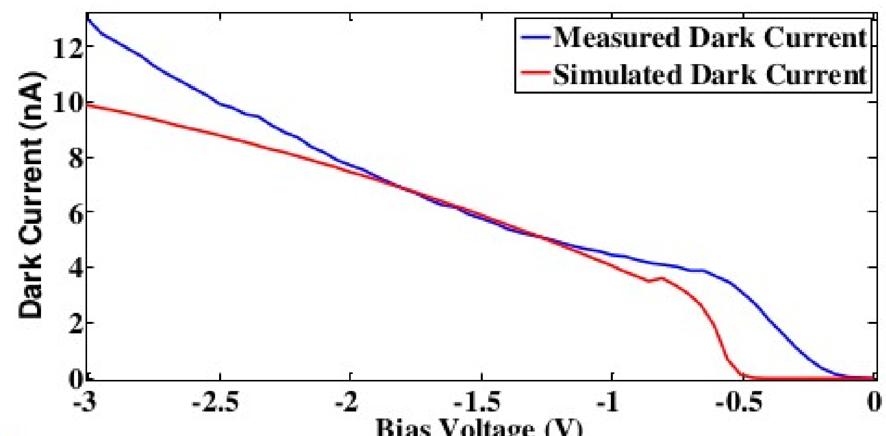




Advantages

- Low electric field (40KV/cm) → High yield
- Low voltage → avalanche free internal amplification/ compatible with almost all existing ROICs
- Negative feedback → excess noise~1
- Detector level amplification → suppression of electronic noise.
- No photon reemission → High fill factor

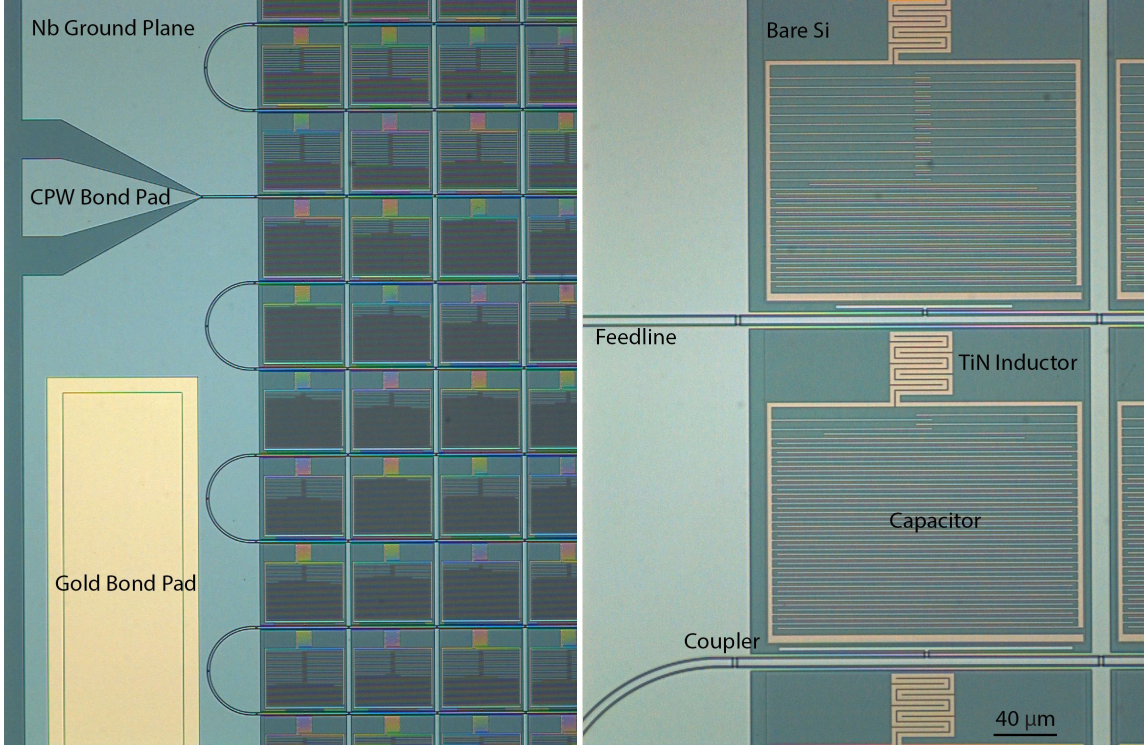
Isolated 10 μm-Detector Results



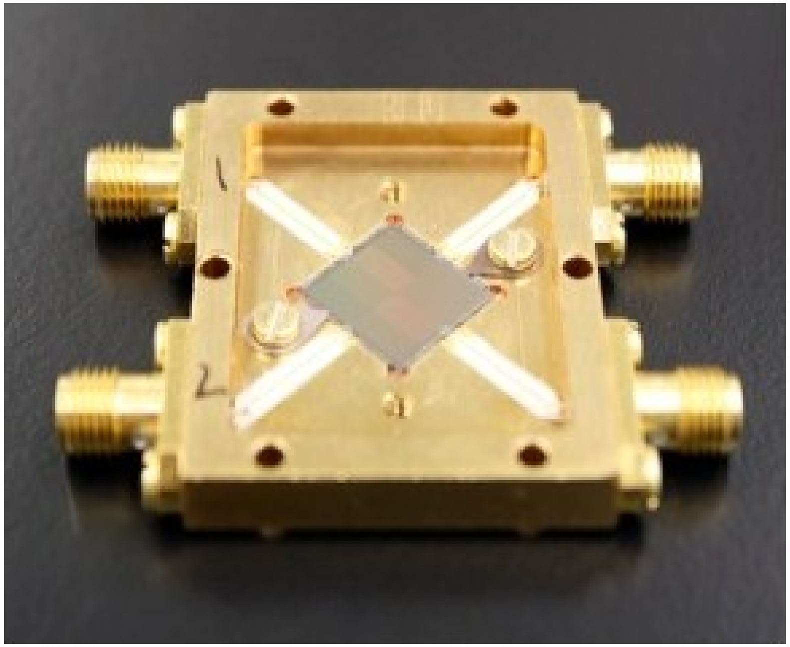
http://www.bisol.northwestern.edu/

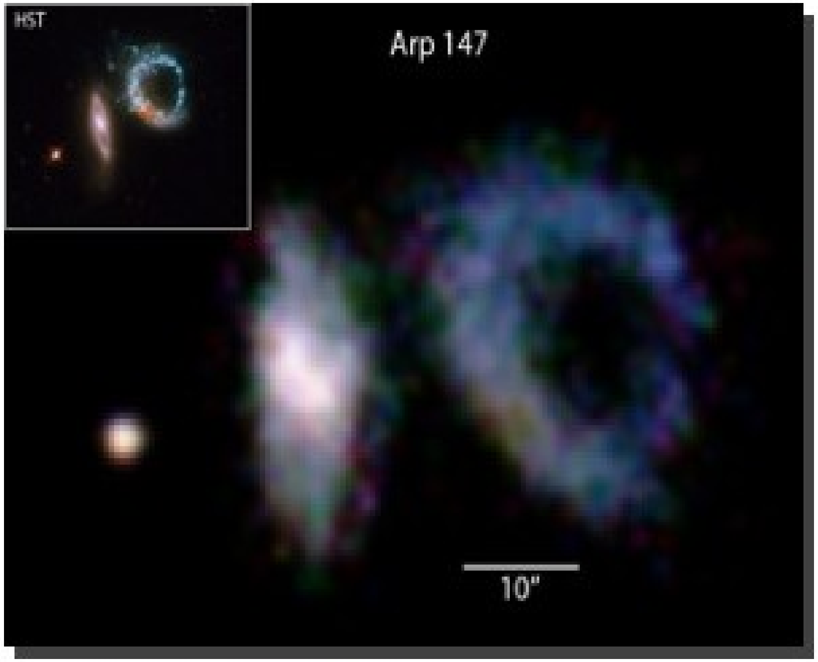
MKIDs + MEMS for a smart focal plane high contrast camera (NAOJ / UCSB)

(coming soon to SCExAO)



Enables photon-counting performance in near-IR, with energy resolution





MKIDs detector

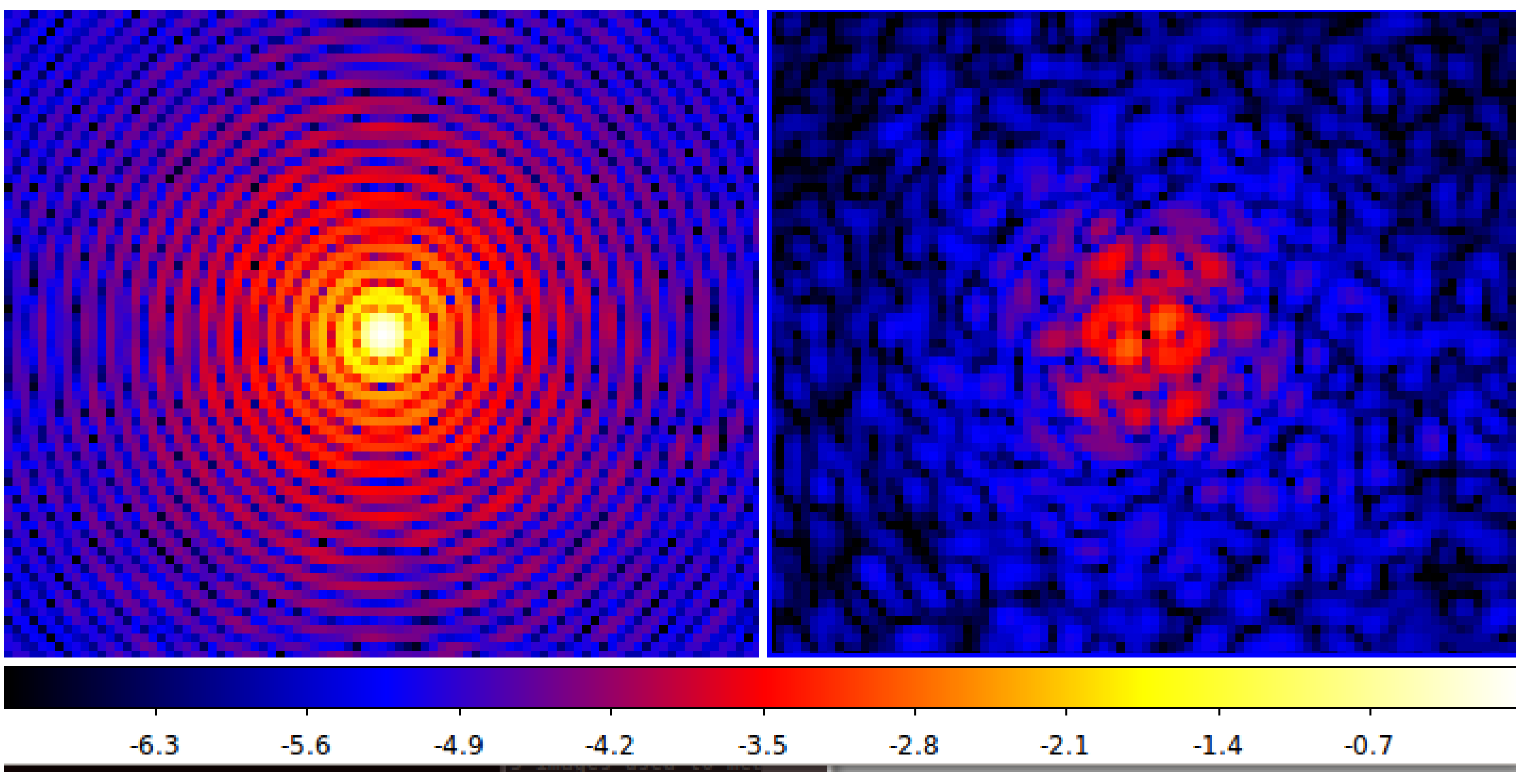
MKIDs image @ Palomar

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:

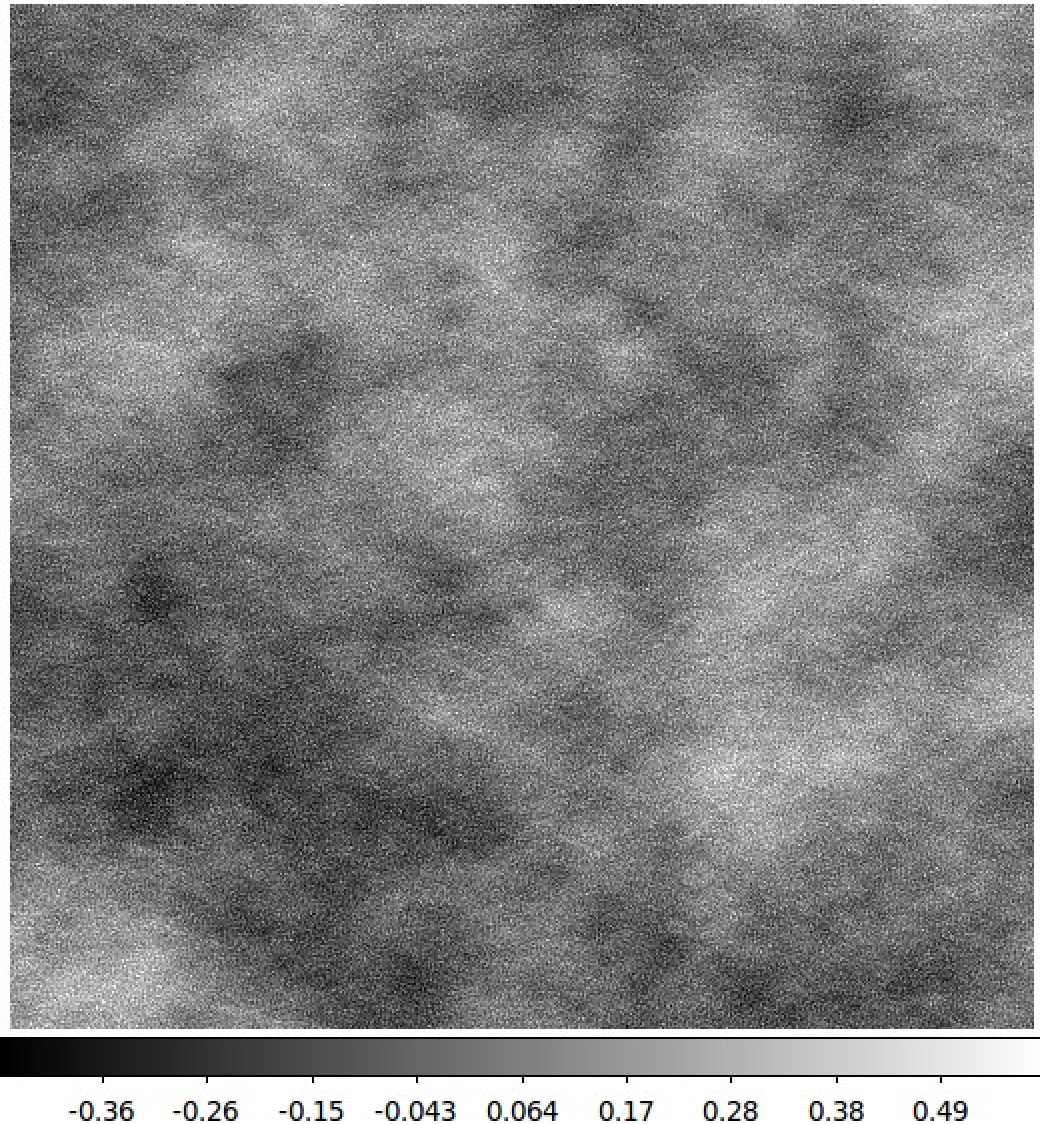
Chromaticity
→ WFS at longer wavelength (focal plane)

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

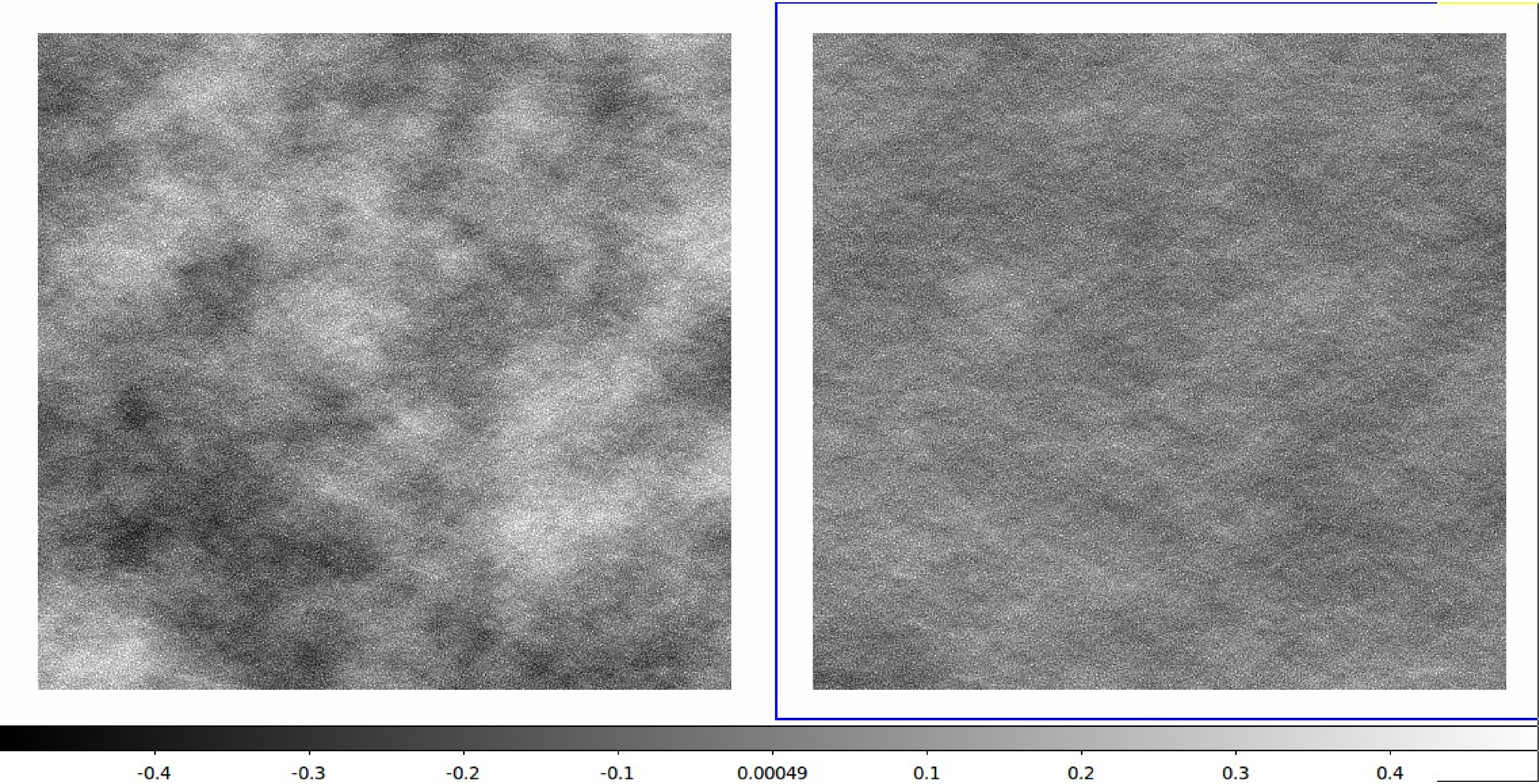
Optimal OPD scaling

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)

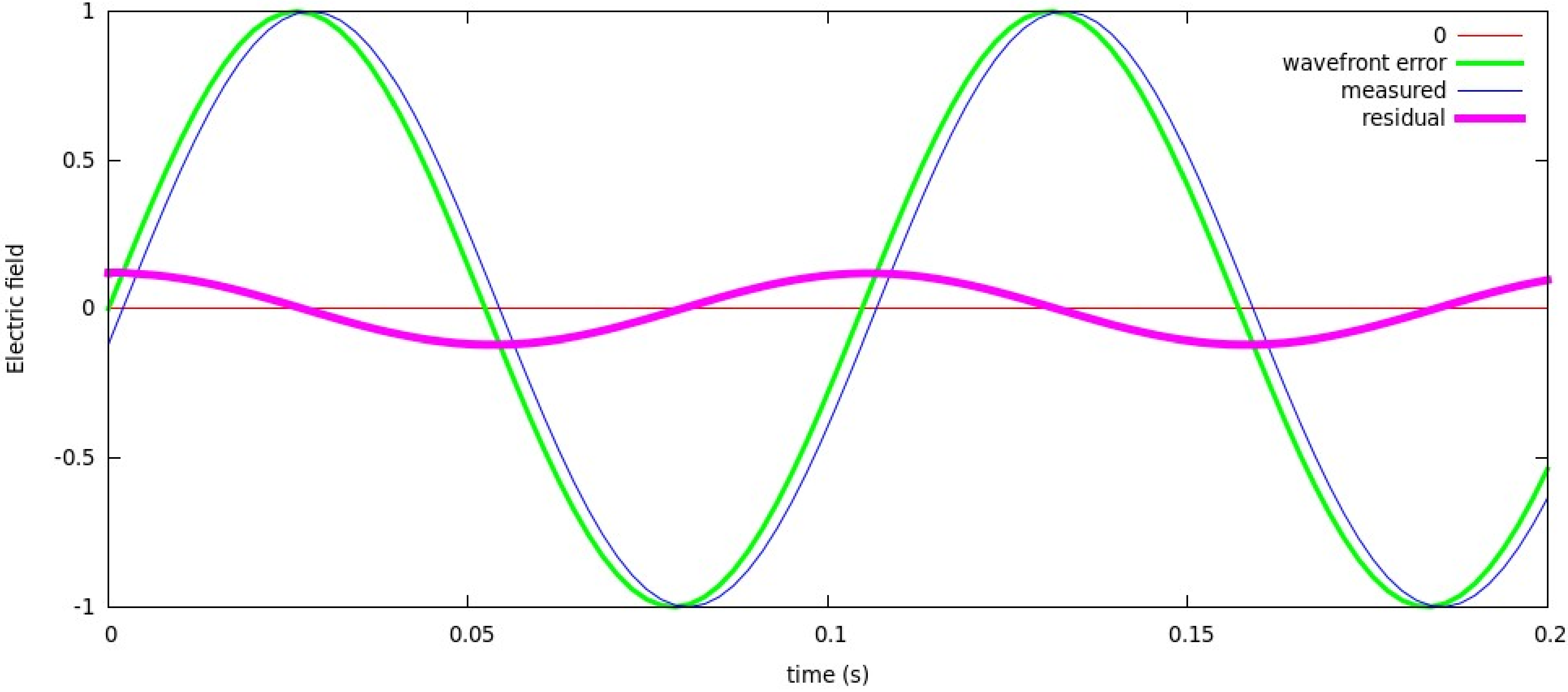
Scaling removes most of the low order OPD chromaticity

Multiplicative coefficient (here 1.017) can be computed, but difficult to separate telescope errors from atmosphere



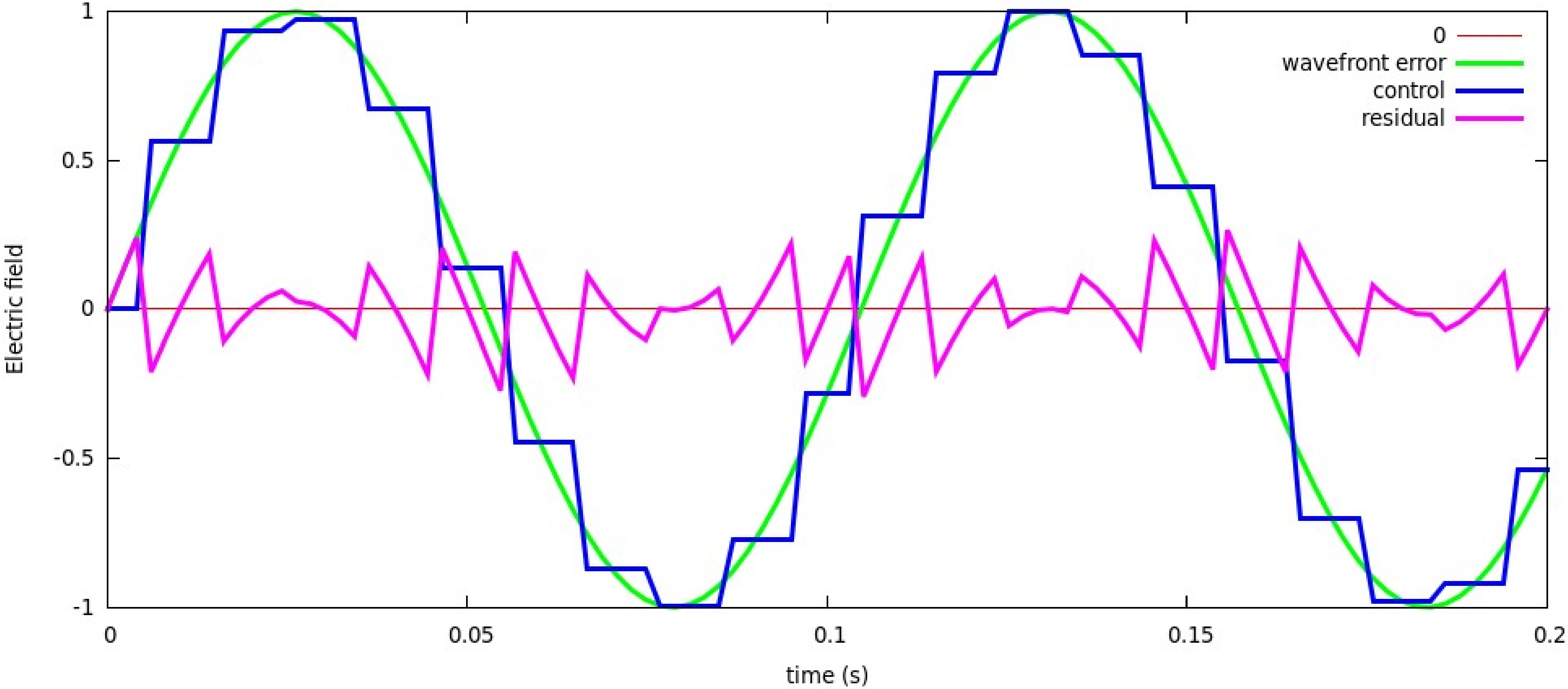
Predictive control

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)



Habitable planet coronagraphic imaging: Scientific opportunities

Space allows access to very high contrast (no atmosphere), but aperture size is limited

→ habitable planets around sun-like stars, maybe in ~2040s (2020s if "lucky")

Ground-based telescopes can be very large (~30m), but the contrast is limited due to atmosphere

→ habitable planets around M-type stars are low-hanging fruits

Key technologies

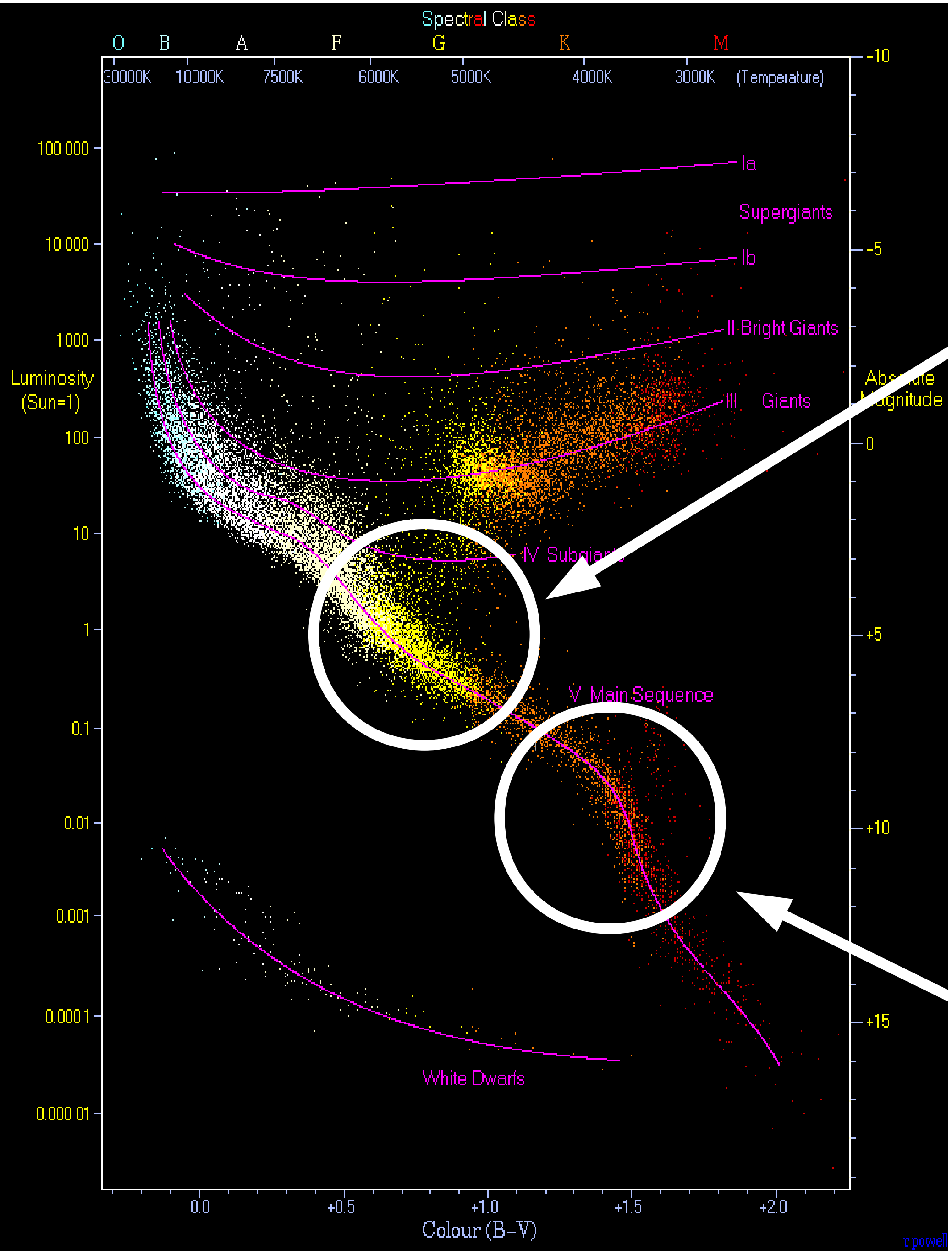
- Low-IWA high throughput coronagraphy
- Active speckle control at ~100Hz using low-noise near-IR detector (ideally wavelength-resolving)

<1e-8 contrast at 20mas appears realistic → >100 targets

Could happen in 2020s if develop system on 8m telescope and move it to ELT when NGS AO works: SCExAO system designed to allow this move

Possibly can extend to deeper contrast, shorter wavelength !

Imaging habitable planets from space and ground



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

Habitable planets can be imaged around nearby Sun-like stars with 2-4m telescope

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

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