High Contrast Imaging: New Techniques and Scientific Perspectives for ELTs

Is there a path to life finding with ELTs ?
What game changing technologies can get us there ?

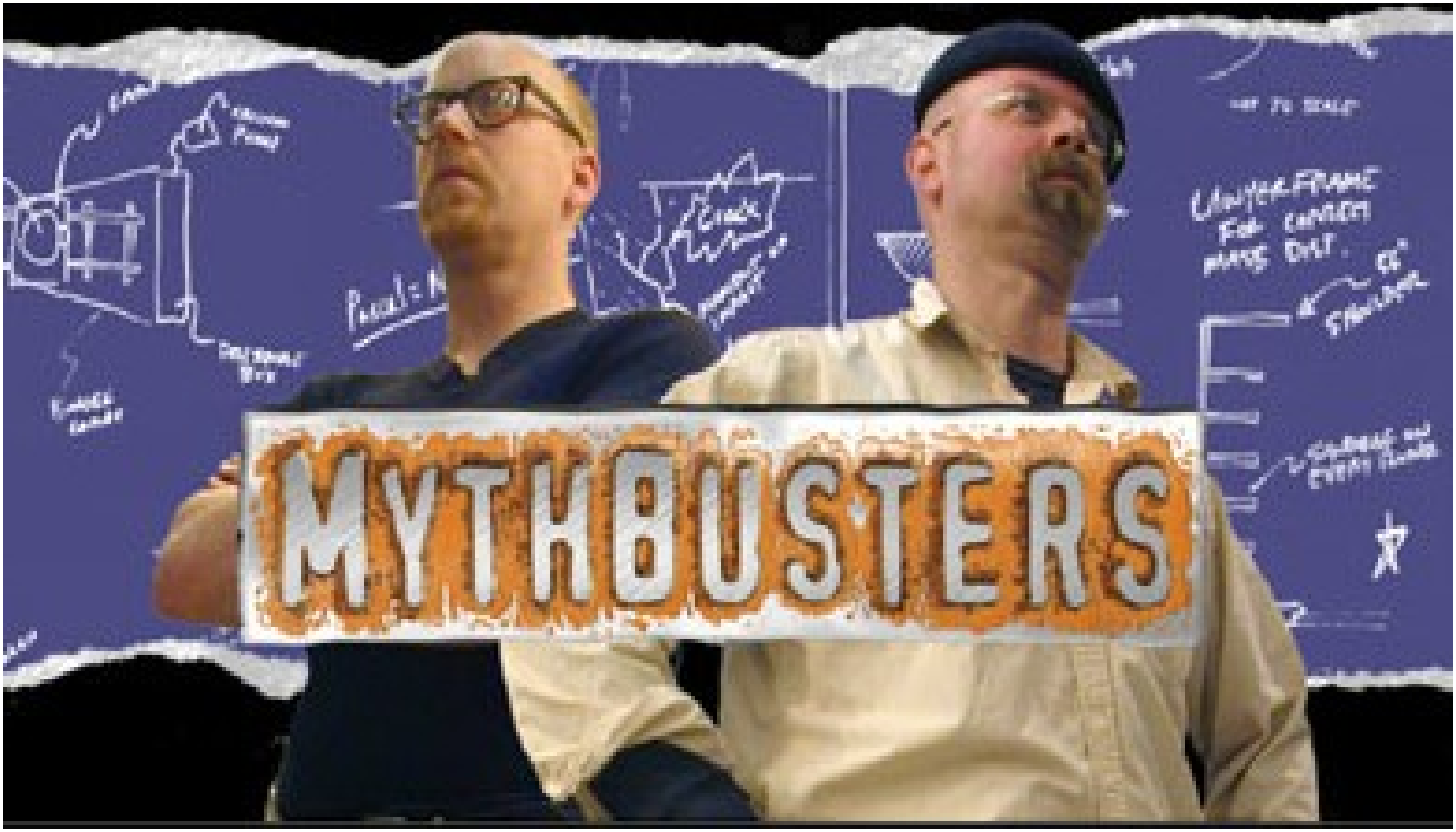
Olivier Guyon

Subaru Telescope & University of Arizona

Florence, May 28, 2013

Contact: oliv.guyon@gmail.com

Extreme AO systems (superAO+coronagraph) myths



Extreme AO myth #1

ExAO = "Extremely complicated/costly AO", and should be the last thing to think about installing on an ELT

Extreme AO myth #1

ExAO = "Extremely complicated/costly AO", and should be the last thing to think about installing on an ELT

→ 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 on ELTs needs DMs with many 1000s of actuators

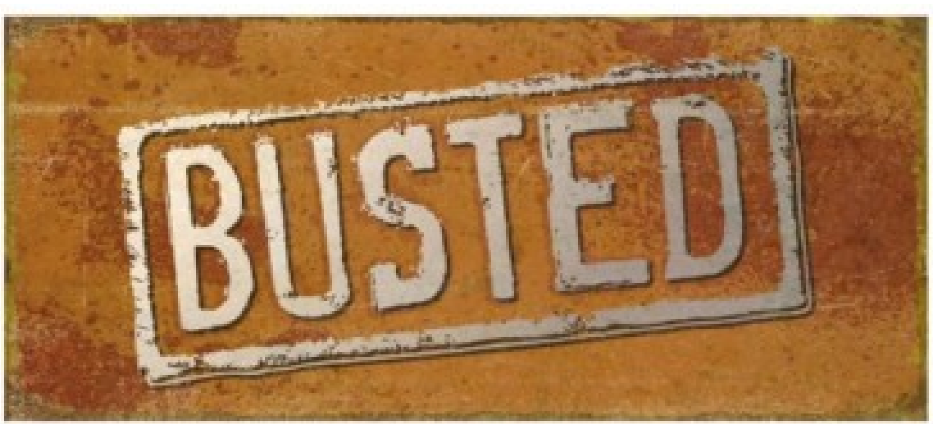
→ needs insane computing power

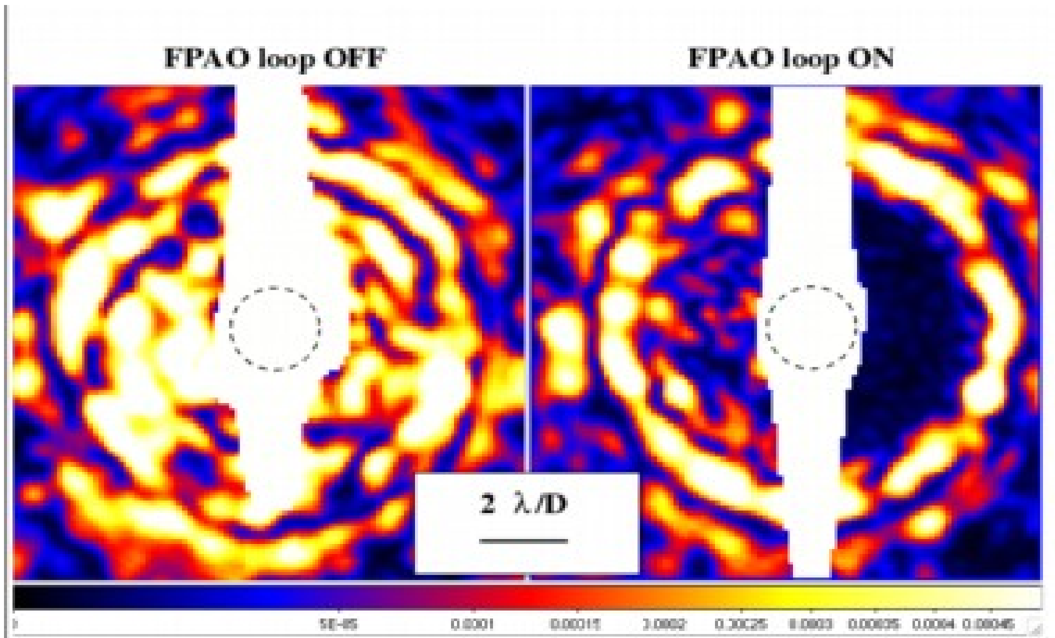
→ needs development of new DM technologies

Extreme AO myth #2

ExAO on ELTs needs DMs with many 1000s of actuators
→ needs insane computing power
→ needs development of new DM technologies

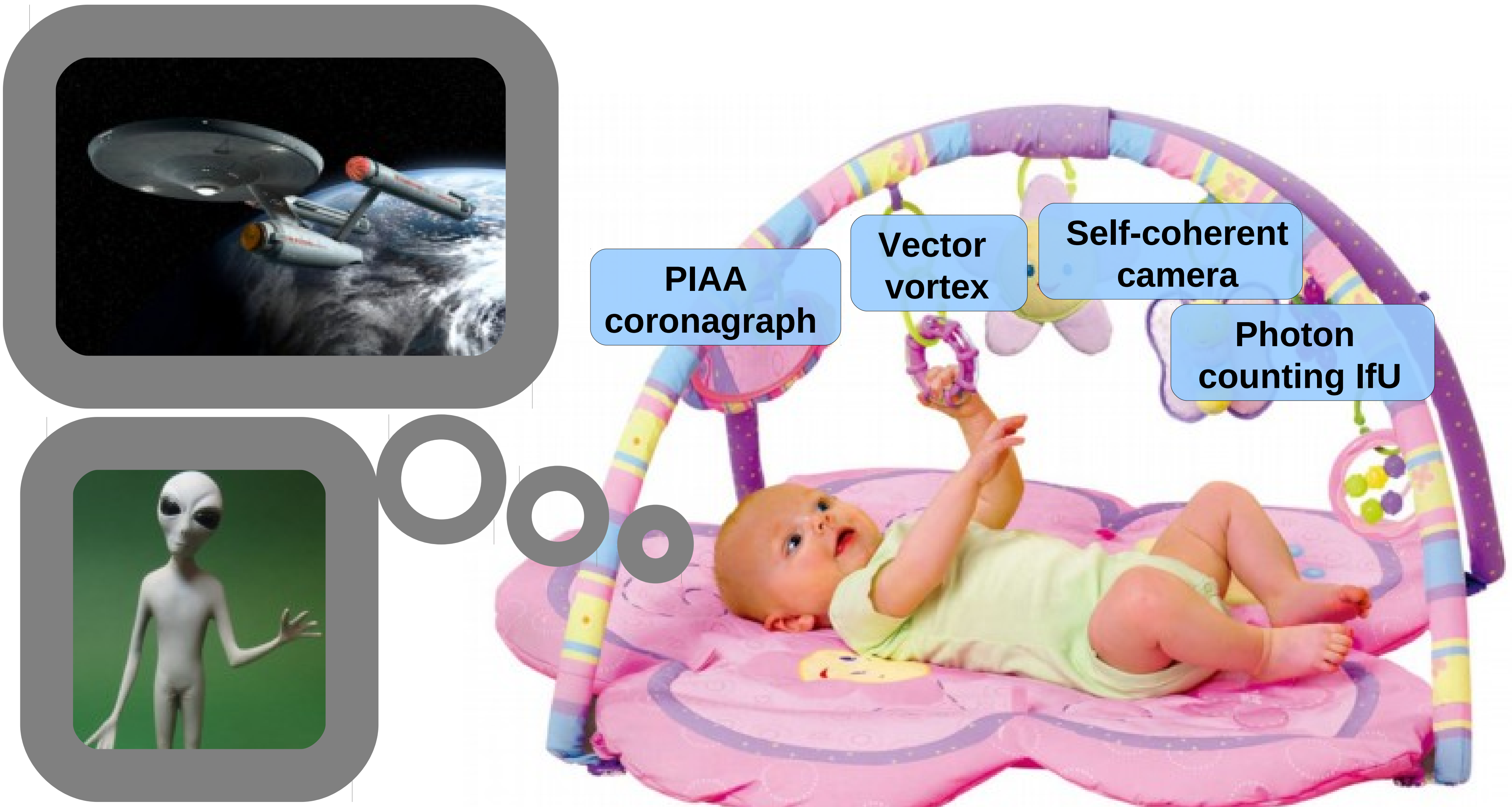
In ExAO, the number of actuators in the DM defines the field of view, not the contrast
→ small field = no need for high number of actuators
→ detection of planets at up to 15 l/D can be done with existing 32x32 actuators DM (fewer actuators than facility AO is OK !!!)





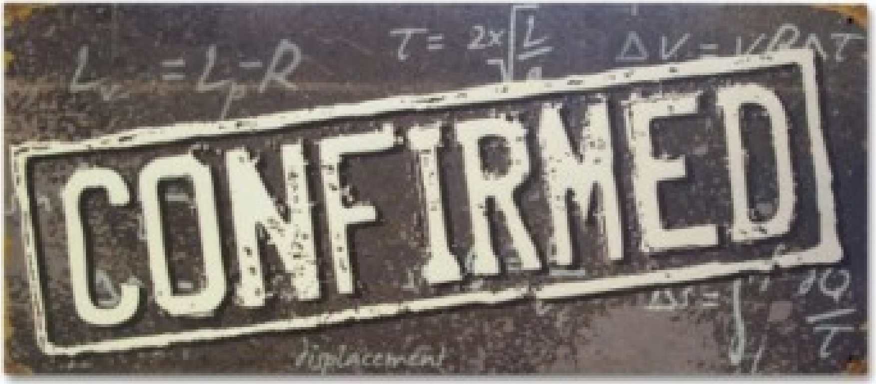
Extreme AO myth #3

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



Extreme AO myth #3

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



→ 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

Outline

Science opportunities with ELTs

What would it take for an ELT to characterize habitable planets ?

Coronagraphy

Wavefront control (ExAO)

PSF calibration techniques

How should we proceed ?

Outline

Science opportunities with ELTs

What would it take for an ELT to characterize habitable planets ?

Coronagraphy

Wavefront control (ExAO)

PSF calibration techniques

How should we proceed ?

Planetary systems formation (disks)

Mapping and characterizing (chemistry, physical conditions, dynamics) protoplanetary and transition disks

Increased aperture:

→ closer in to the star
→ more sensitivity
→ more resolving power (gaps, structures)

Much better than possible with 10m telescopes

Self-luminous planets

More planets:

- lower masses (<1MJ)
- older
- closer in (~1.5 AU in Taurus)

Spectral characterization in near-IR (+ visible and mid-IR)

Re-radiated heat from planets

Near to mid-IR

High sensitivity to lower mass objects in close orbits around nearby stars

NEW CAPABILITY

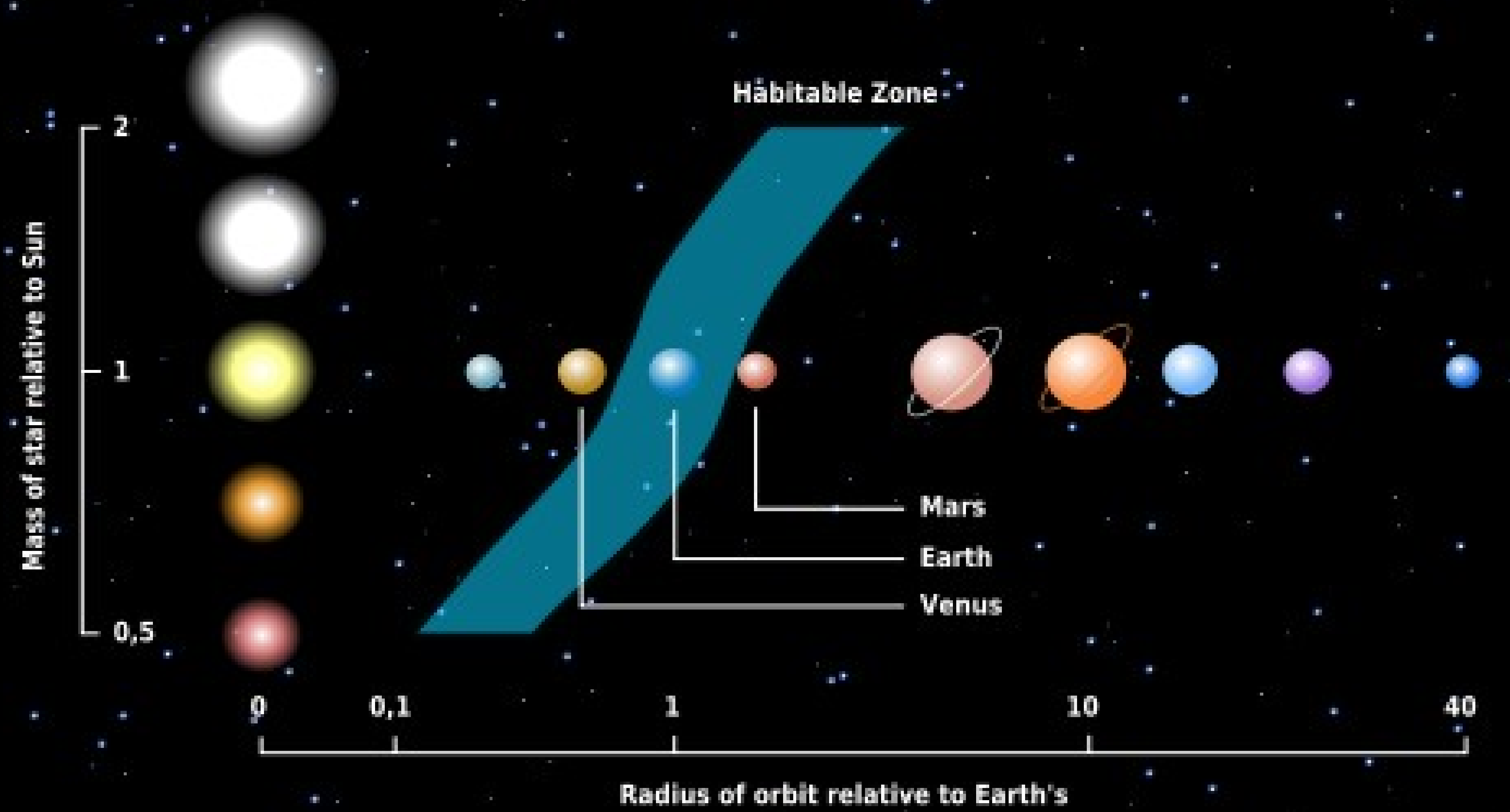
Reflected light from planets

Higher contrast + closer in → opens up access to reflected light

High sensitivity to lower mass objects in close orbits around nearby stars

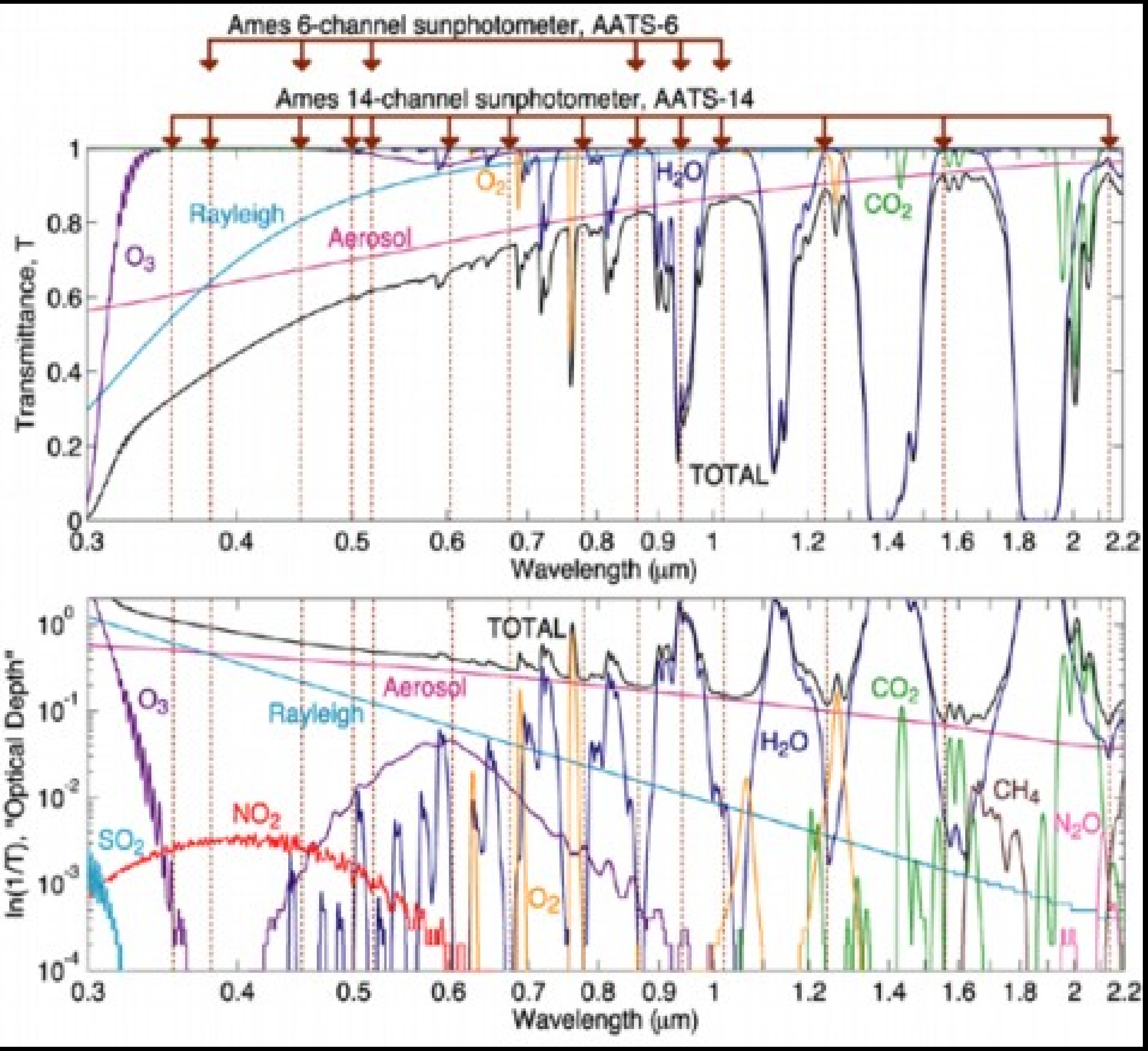
Spectroscopic characterization in near-IR (visible and mid-IR difficult)

Habitable zone of a star



Every star has a habitable zone, ~10% of stars have habitable planets

Habitable Planets Spectroscopy in near-IR



Credit: NASA/Ames Airborne Tracking Sunphotometer (AATS)

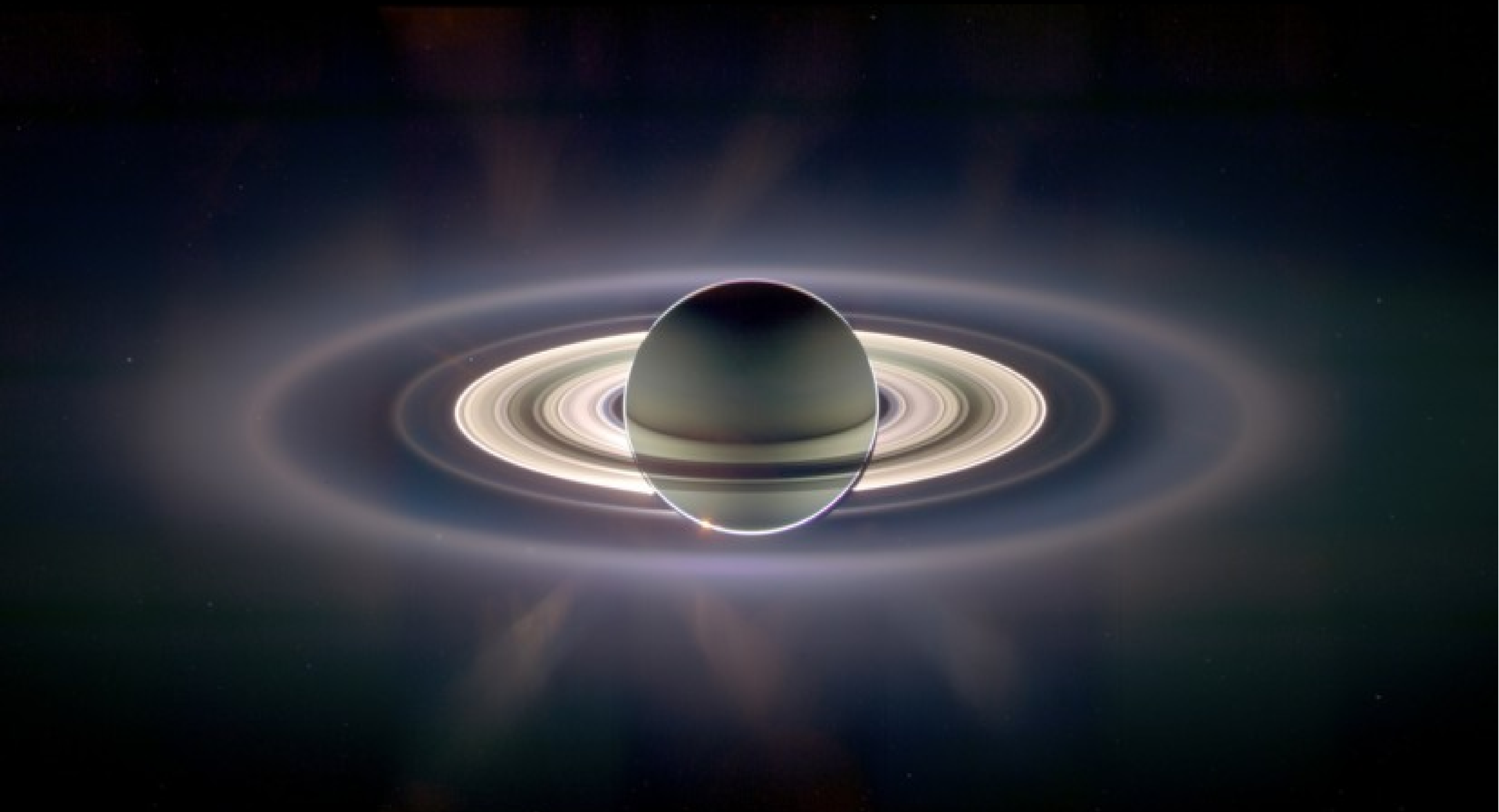
Atmosphere transmission:
O_2 (see Kawara et al. 2012)
H_2O
CO_2
CH_4

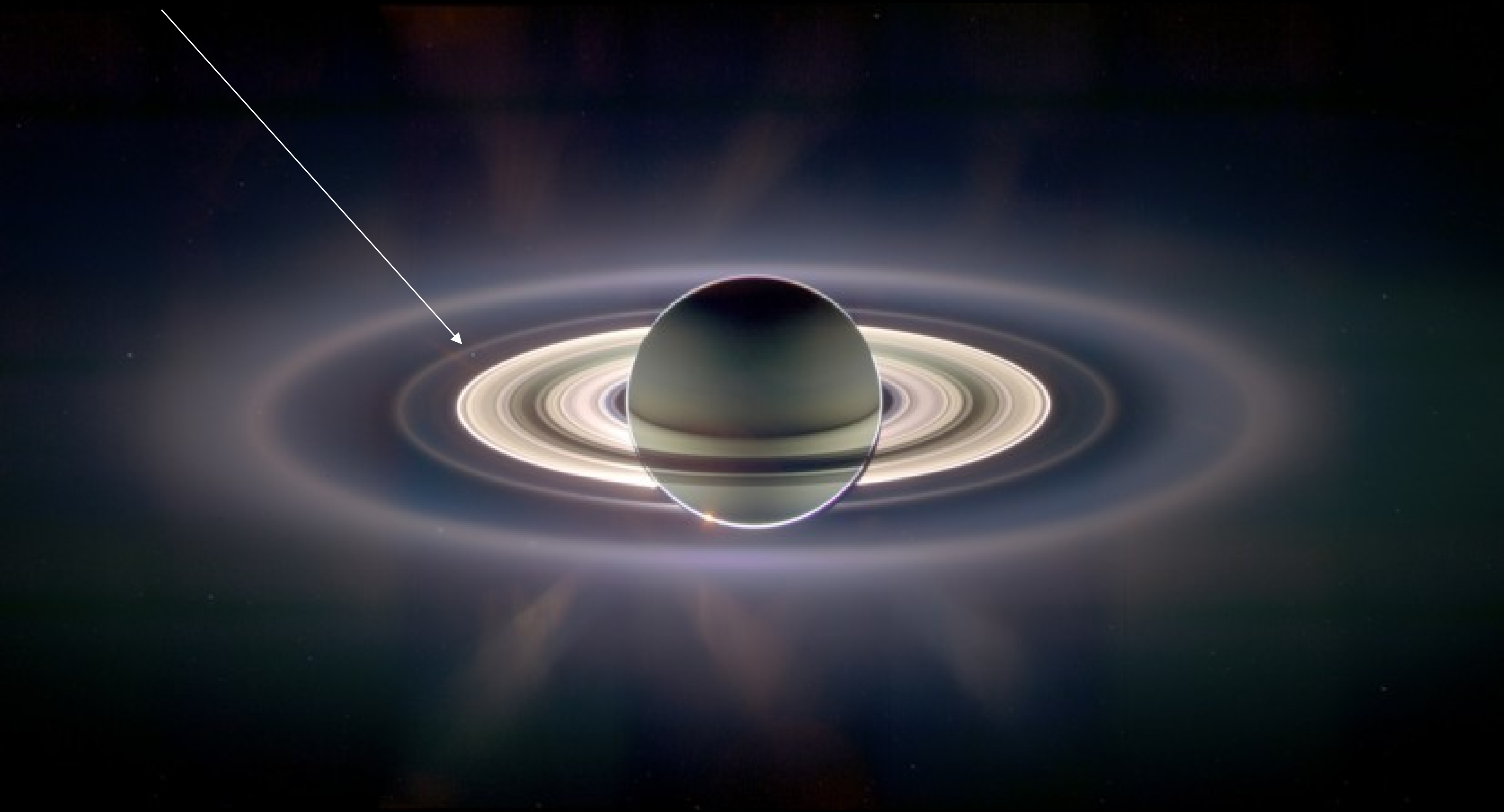
Polarimetry

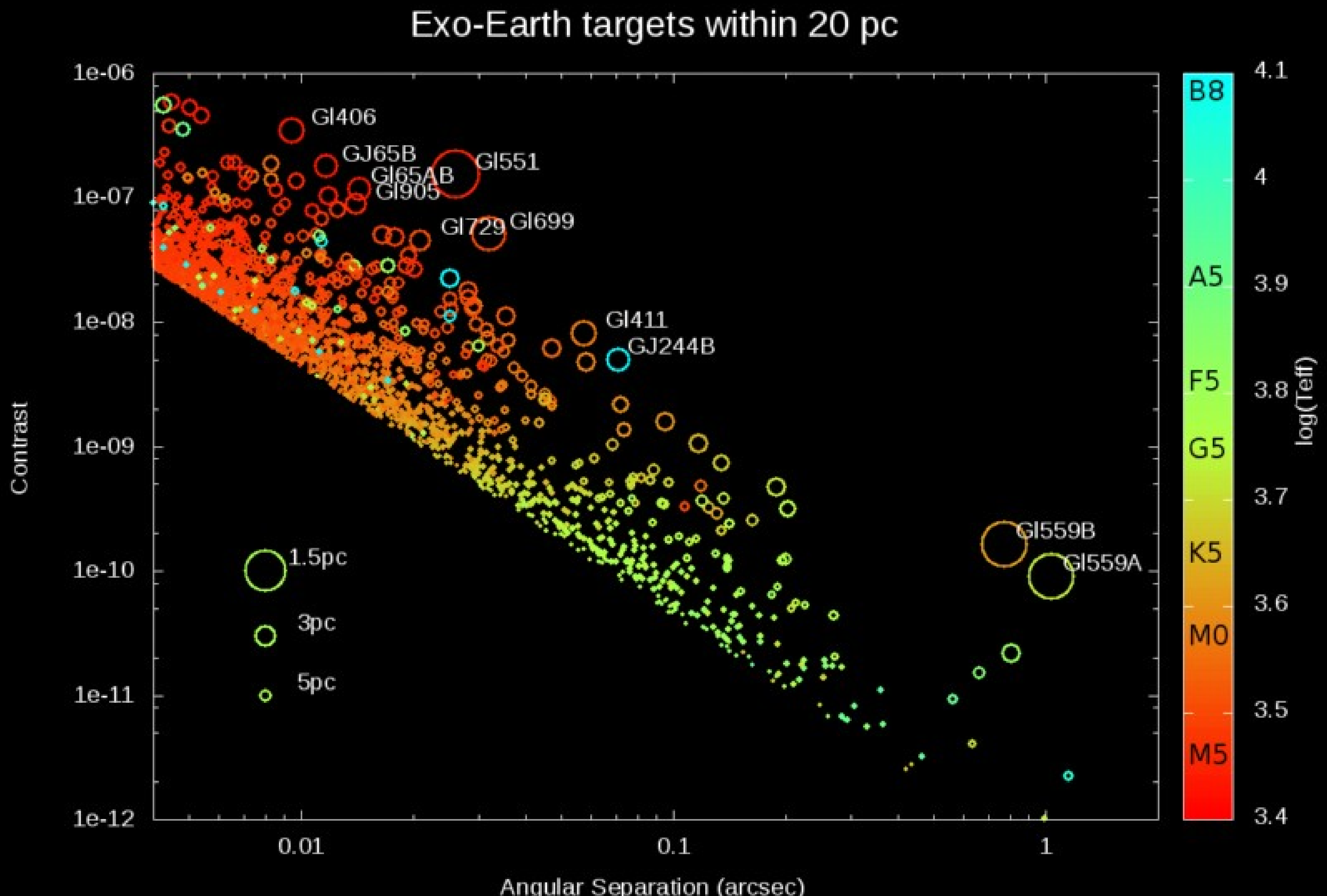
Cloud cover, variability
Rotation period

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

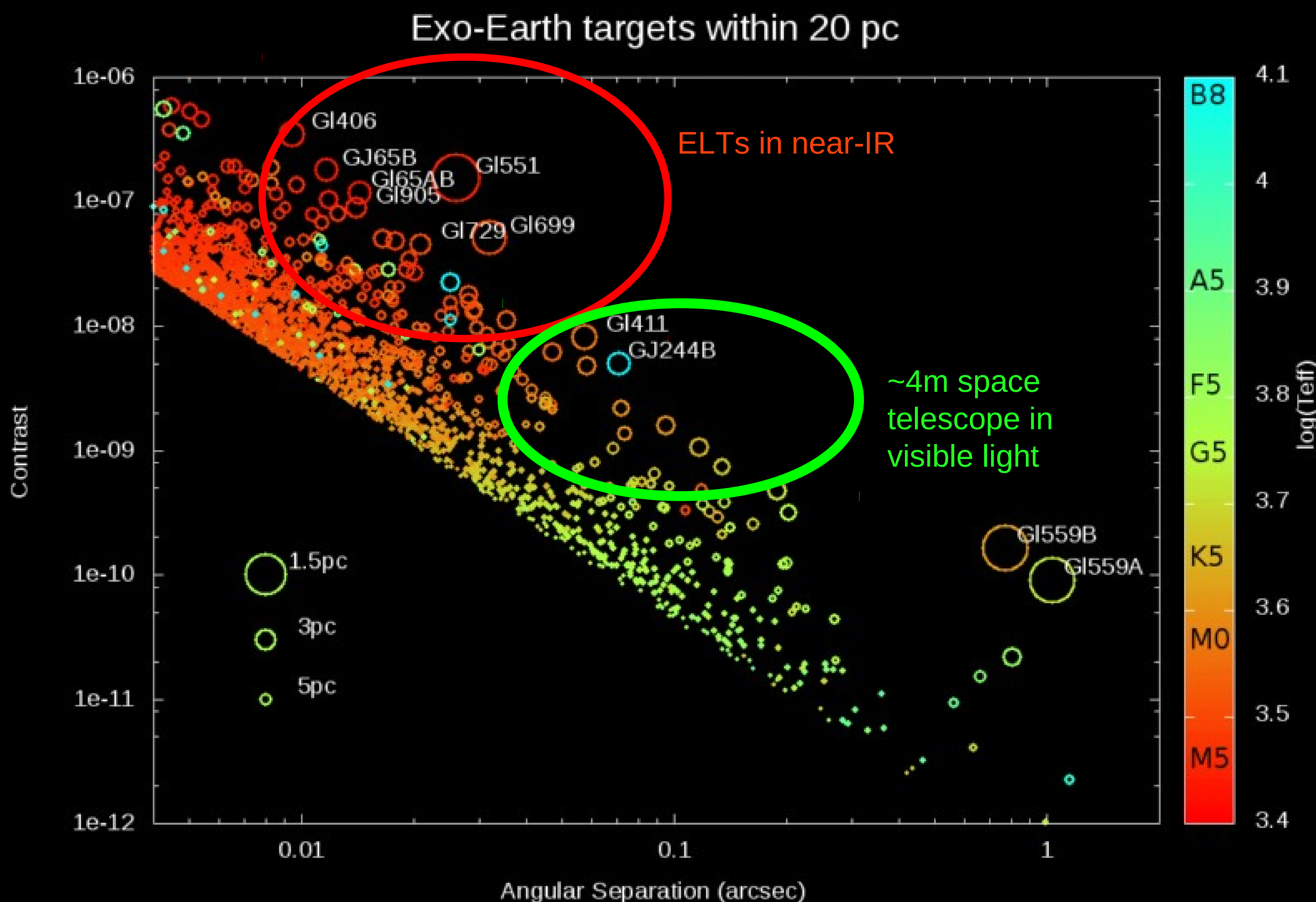
CORONAGRAPHIC IMAGE OF HABITABLE PLANET !!




Earth



Exo-Earth targets within 20 pc
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
Contrast
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)


Exo-Earth targets within 20 pc
ELTs in near-IR
~4m space telescope in visible light
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

Outline

Science opportunities with ELTs

What would it take for an ELT to characterize habitable planets ?

Coronagraphy

Wavefront control (ExAO)

PSF calibration techniques

How should we proceed ?

Top 10 targets

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

RAW contrast required ?

Photon-noise limited SNR limit in H band

Earth like planet around M4 type star at 5pc

Assumptions:

- D = 30m telescope, m_H=14.4 $arcsec^{-2}$ background, 20mas aperture
- 15% efficiency (coatings, detector), 0.3 um bandpass (H band), 1 hr exposure
- planet mH = 25.2 (Earth at 5pc)

background = 230 ph/sec

Planet = 27.5 ph/sec

Star = 9.98e8 ph/sec (mH=6.3, M4 stellar type)

Star / Planet contrast = 3.6e7

	Detection SNR H band (R~5)	**Spectroscopy SNR R = 100**
Imaging, no starlight	**102 [356]**	**23.5 [83]**
Imaging, 1e5 raw contrast	**16.31 [65]**	**3.8 [15]**
Imaging, 1e4 raw contrast	**5.16 [20.6]**	**1.2 [4.8]**
No coronagraphy, 100% efficiency	**0.05 [0.2]**	**hopeless...**

SuperEarth at 5pc around M star (4x Earth flux, 2x diameter)

Key Requirements

AO system:

RAW contrast : ~1e-5 contrast between 10 and 40 mas

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

Coronagraph:

15 mas IWA, 10mas if possible (~1 l/D in near-IR)

High efficiency (throughput, angular resolution)

DETECTION contrast: ~1e-8

Outline

Science opportunities with ELTs

What would it take for an ELT to characterize habitable planets ?

Coronagraphy (Easy !!!)

Wavefront control (ExAO)

PSF calibration techniques

How should we proceed ?

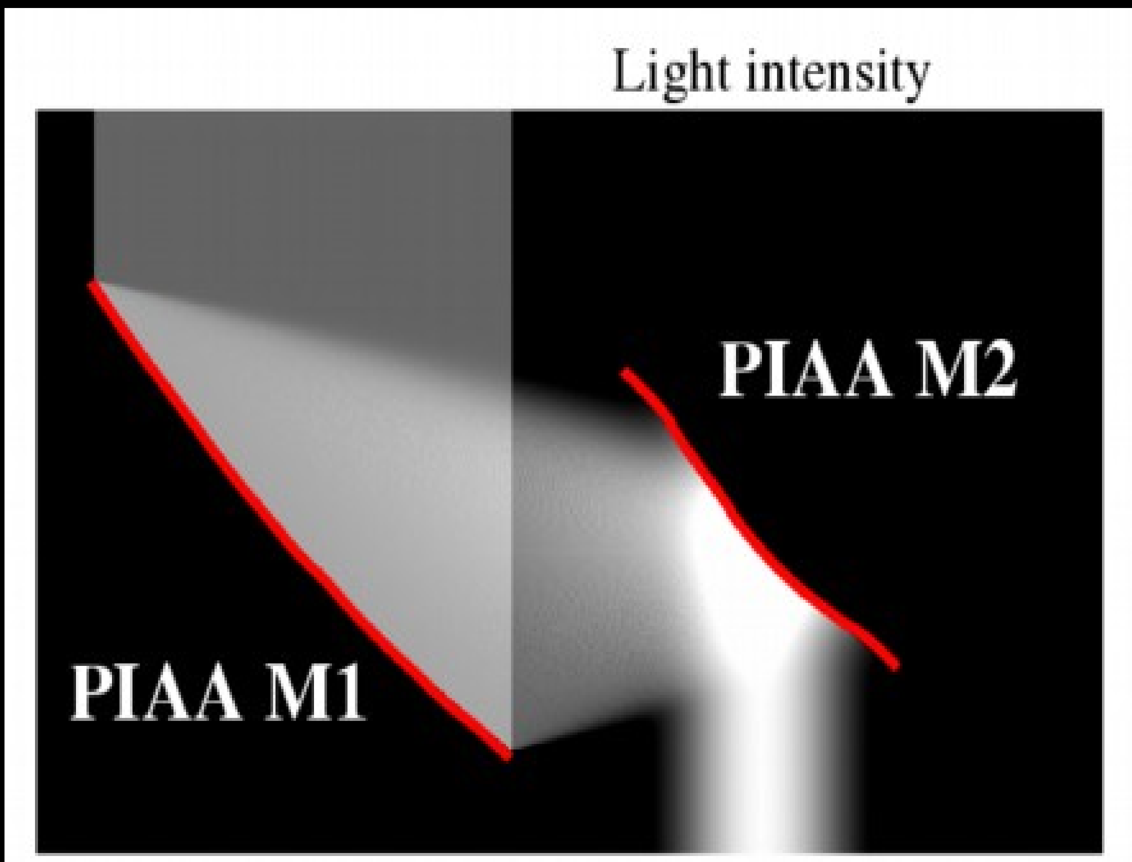
Coronagraphy … Using optics tricks to remove starlight (without removing planet light)

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

We need a better coronagraph... and a larger eye (telescope)

Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.

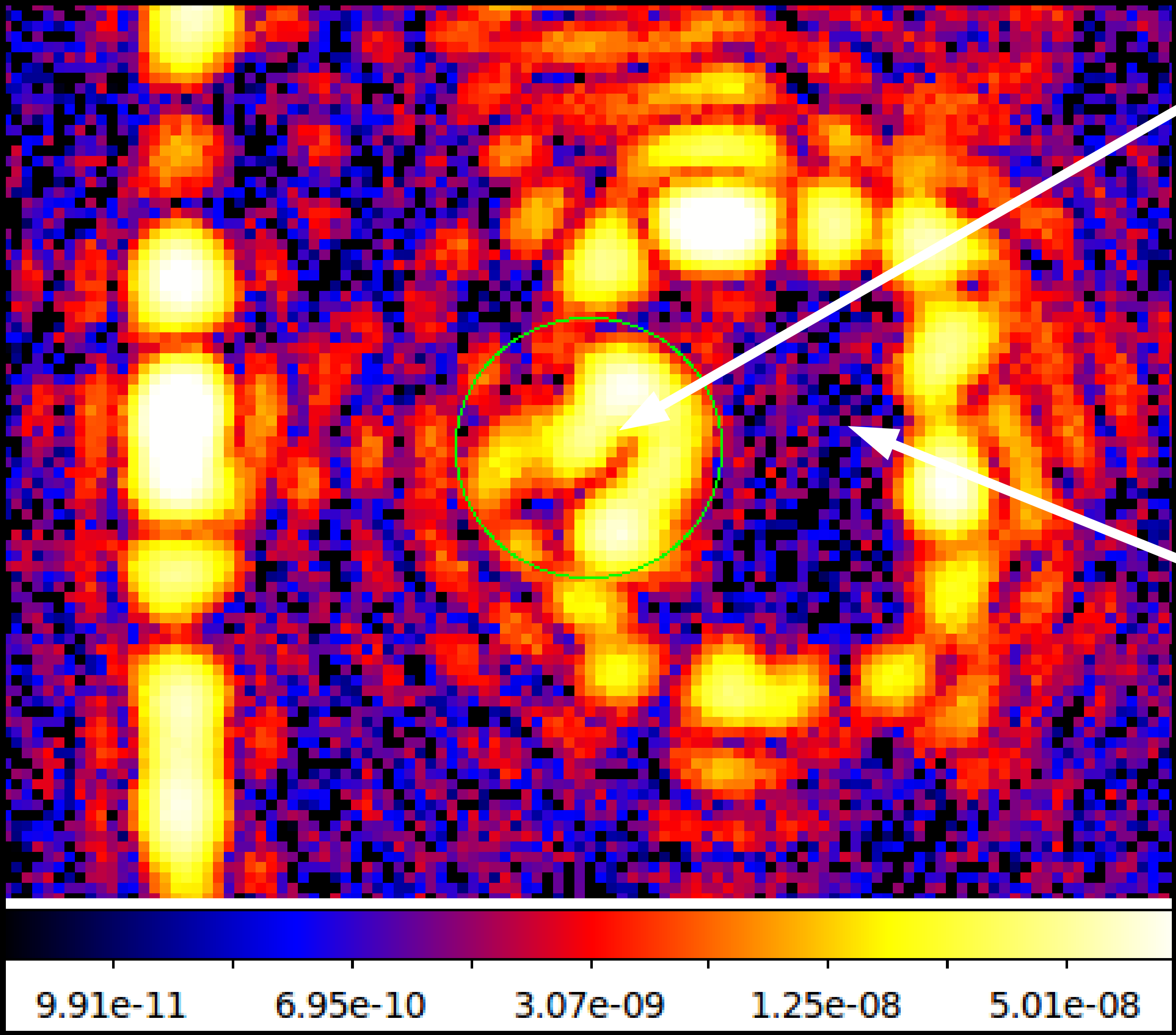


No loss in angular resolution or sensitivity
Achromatic (with mirrors)
Small inner working angle

→ Gain ~x2 to x3 in telescope diameter over previous concepts

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

PIAA testbed at NASA JPL : lab results

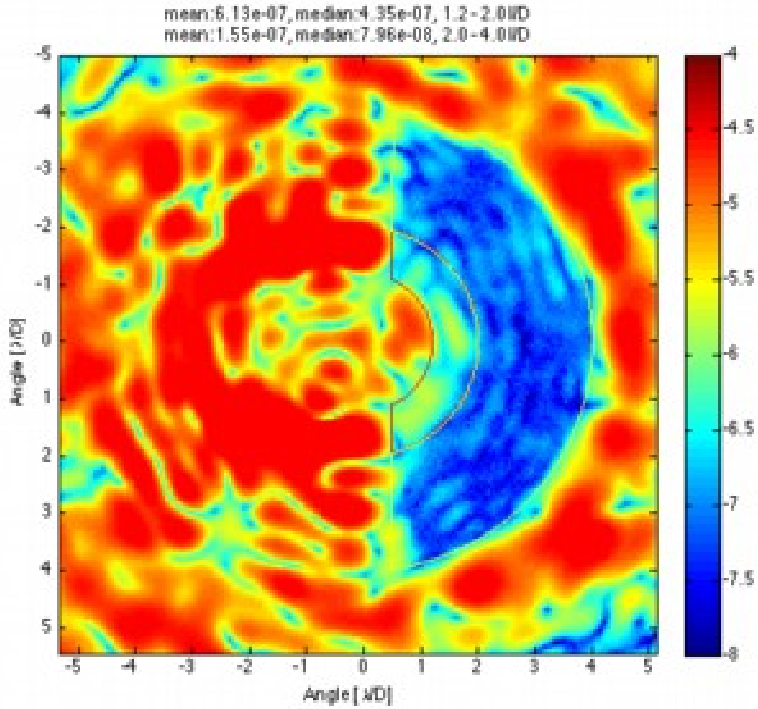


Location of the star (mostly blocked)

Contrast ~5e-10 between 2 and 4 l/D

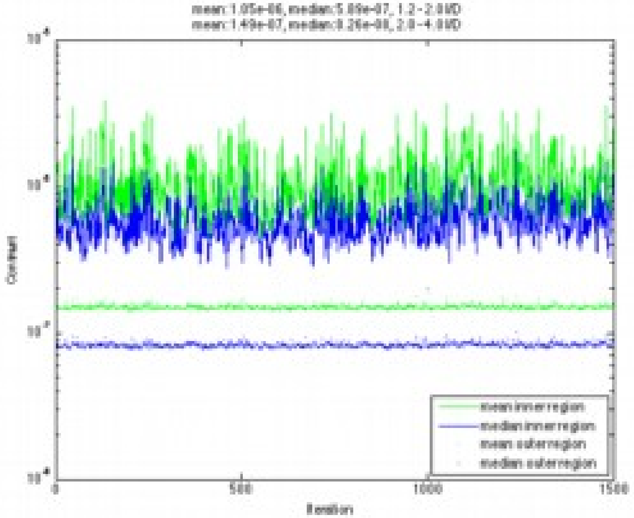
An Earth-like planets could be seen !

EXCEDE latest results from the ACE laboratory @ NASA Ames



- PIAA coronagraph (mirrors from Tinsley)
- MEMS deformable mirror from Boston Micromachines
- Focal plane wavefront control (Speckle Nulling and EFC, see S. Thomas Poster)
- LOWFS (see J. Lozi poster)
- Monochromatic light

Contrast of 4.35x1e-7 between 1.2 and 2 λ/D
Simultaneously with 7.96x1e-8 between 2 and 4 λ/D



Ultimate goals for the EXCEDE mission:
- 1e-6 raw contrast between 1.2 and 2.0 λ/D and 1e-7 raw contrast between 2 and 22 λ/D
- Two 20% bands at 0.4 and 0.8 micron with polarimetry

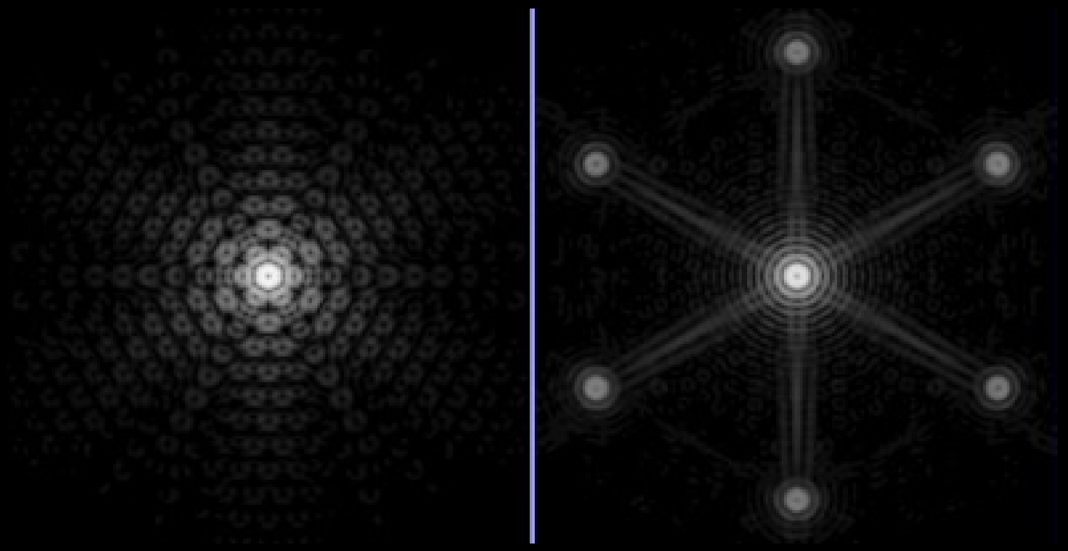
- Stable over an hour representing 1500 images.
- Same performance obtained in three independent tests
- Reapplying a MEMS map 1 day after the correction without changing the calibration keeps the results within 10%

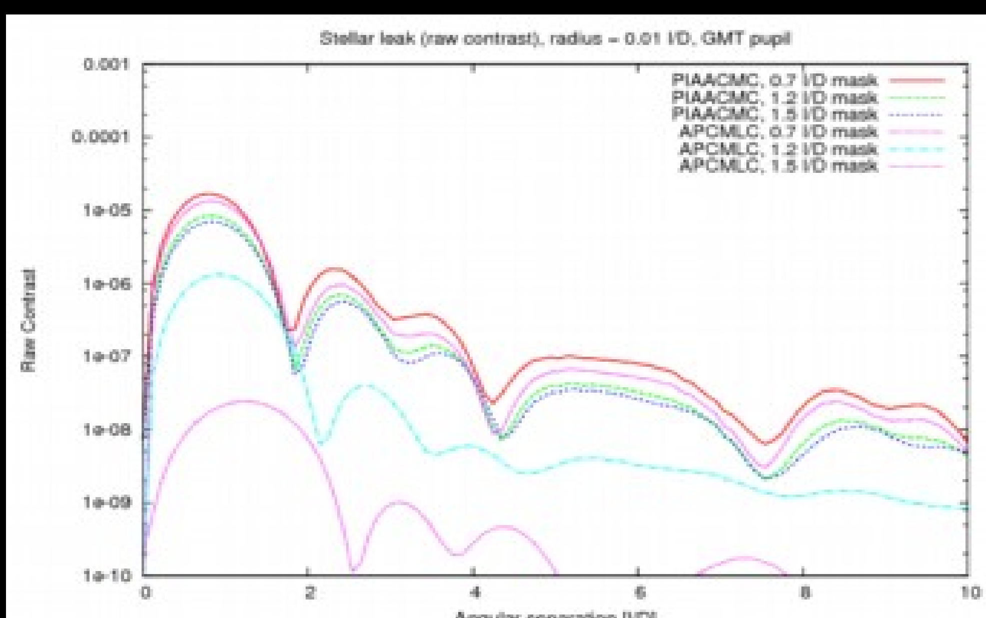
S. Thomas, E. Pluzhnik, J. Lozi, R. Belikov

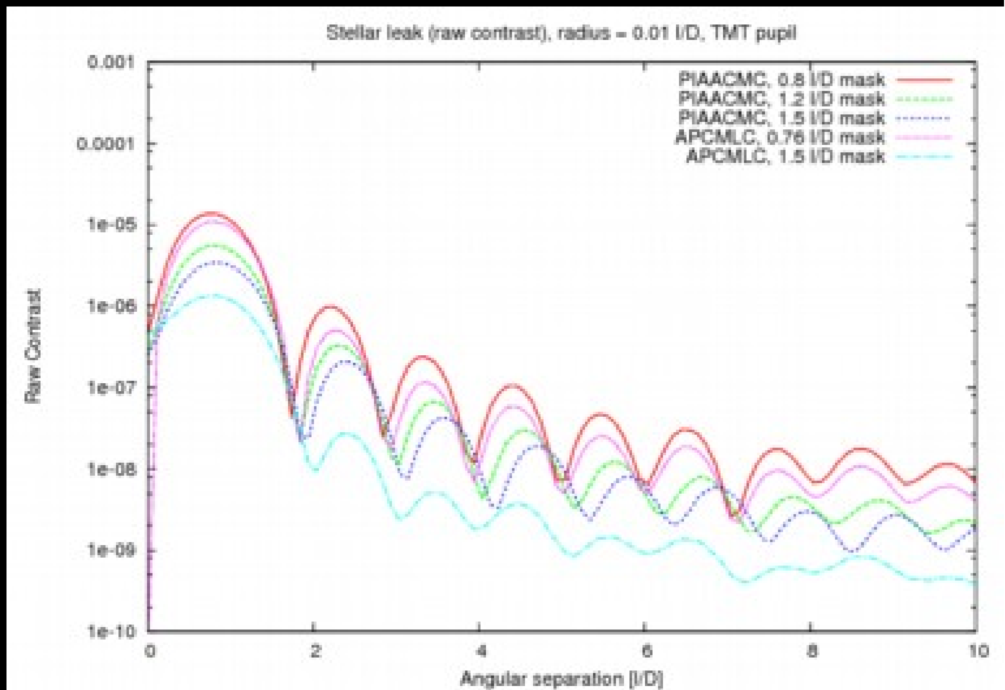
Coronagraphy: Stellar angular size

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

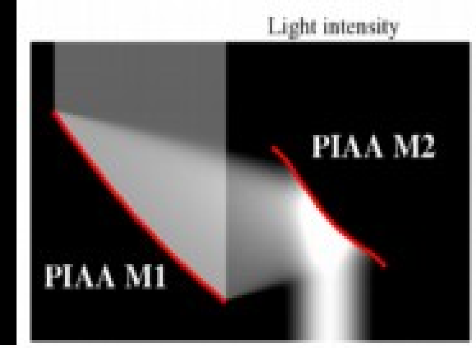
→ for 1 l/D IWA coronagraph
RAW contrast limited to ~1e5



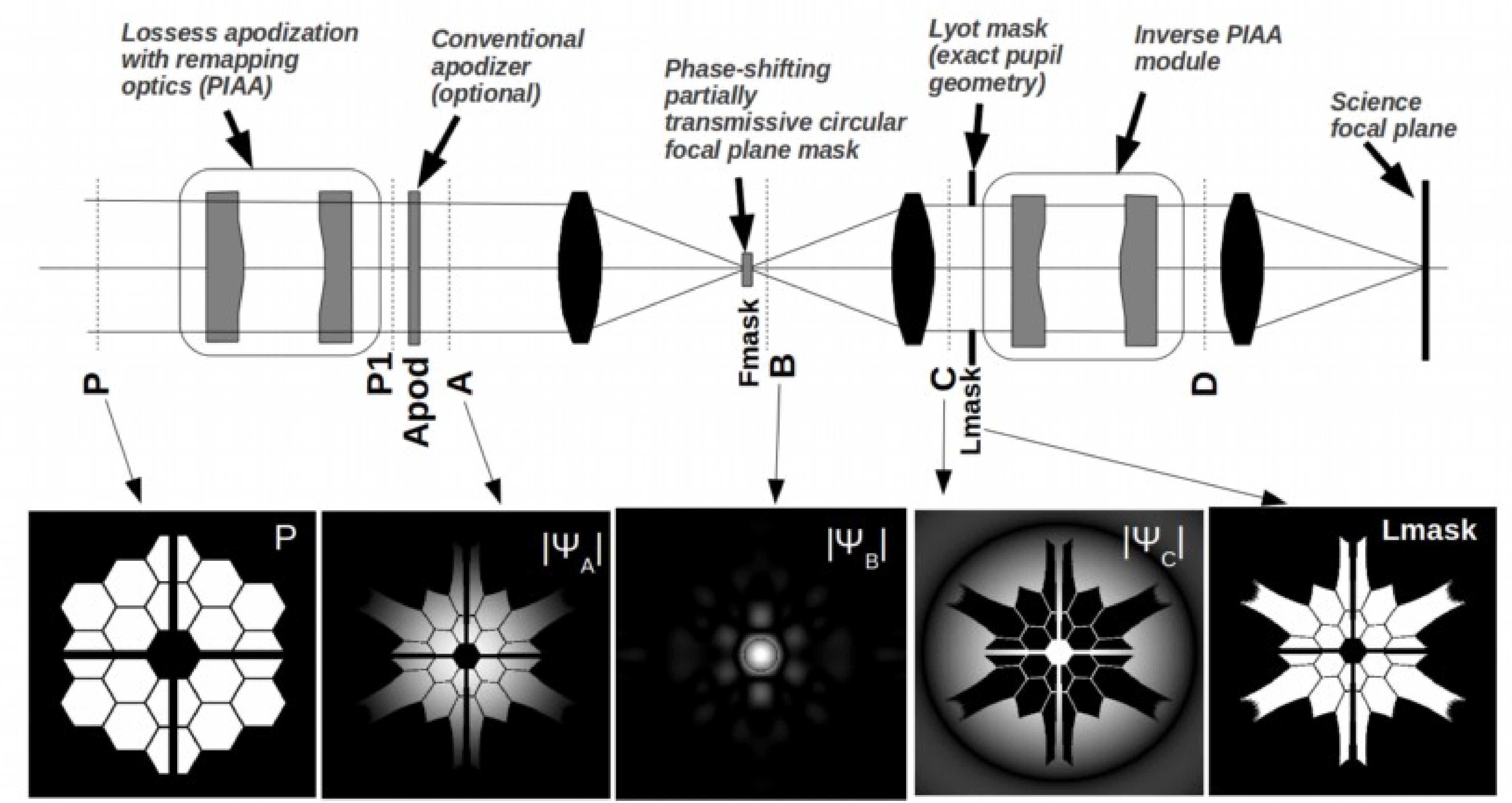




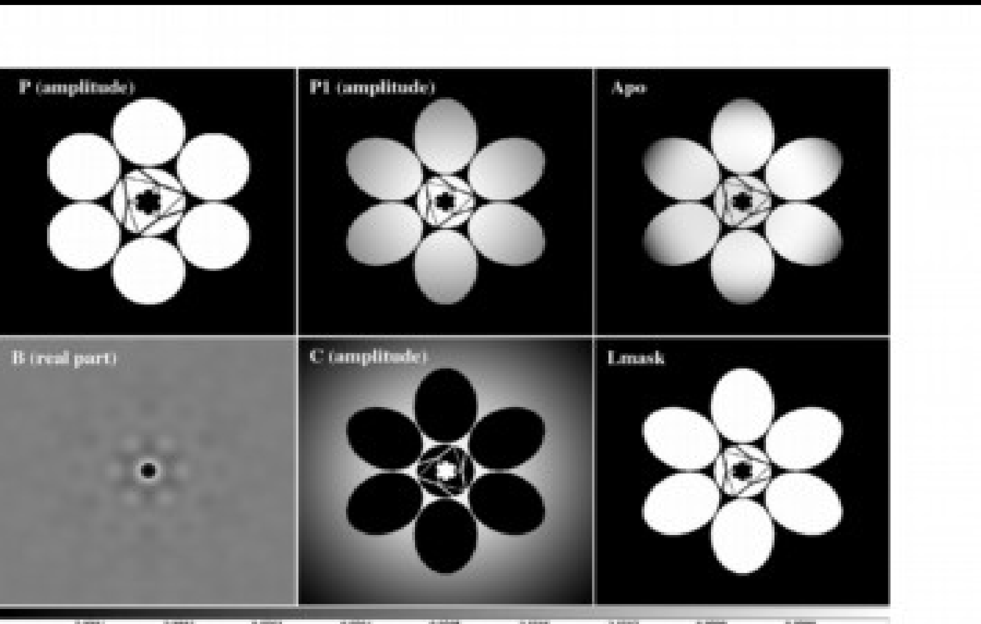
PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit



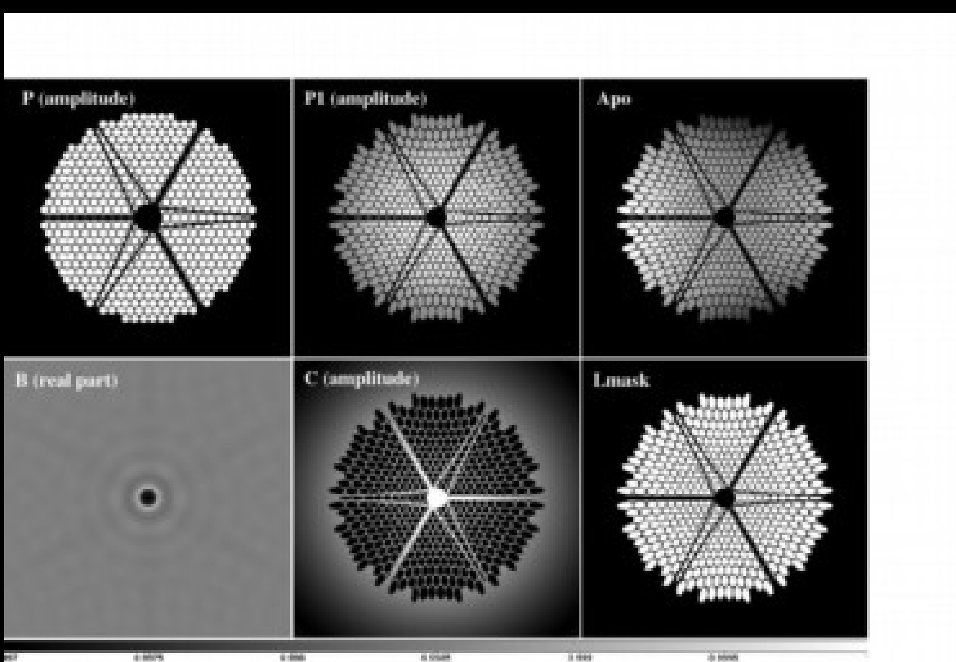
Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

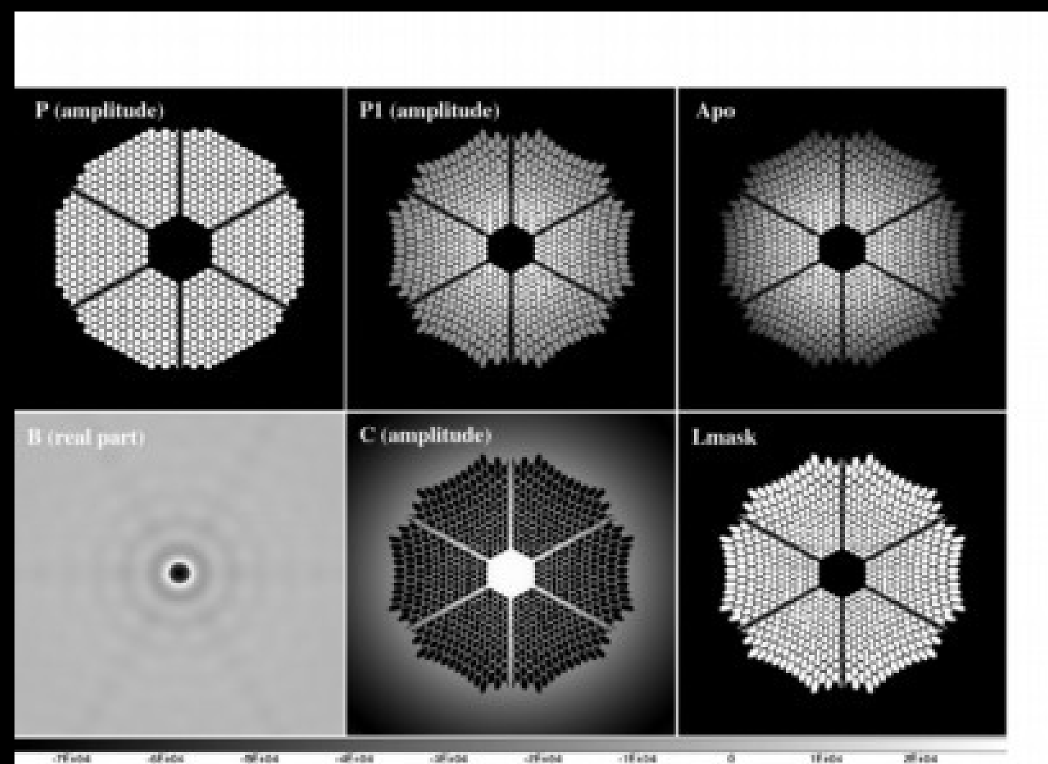


PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit

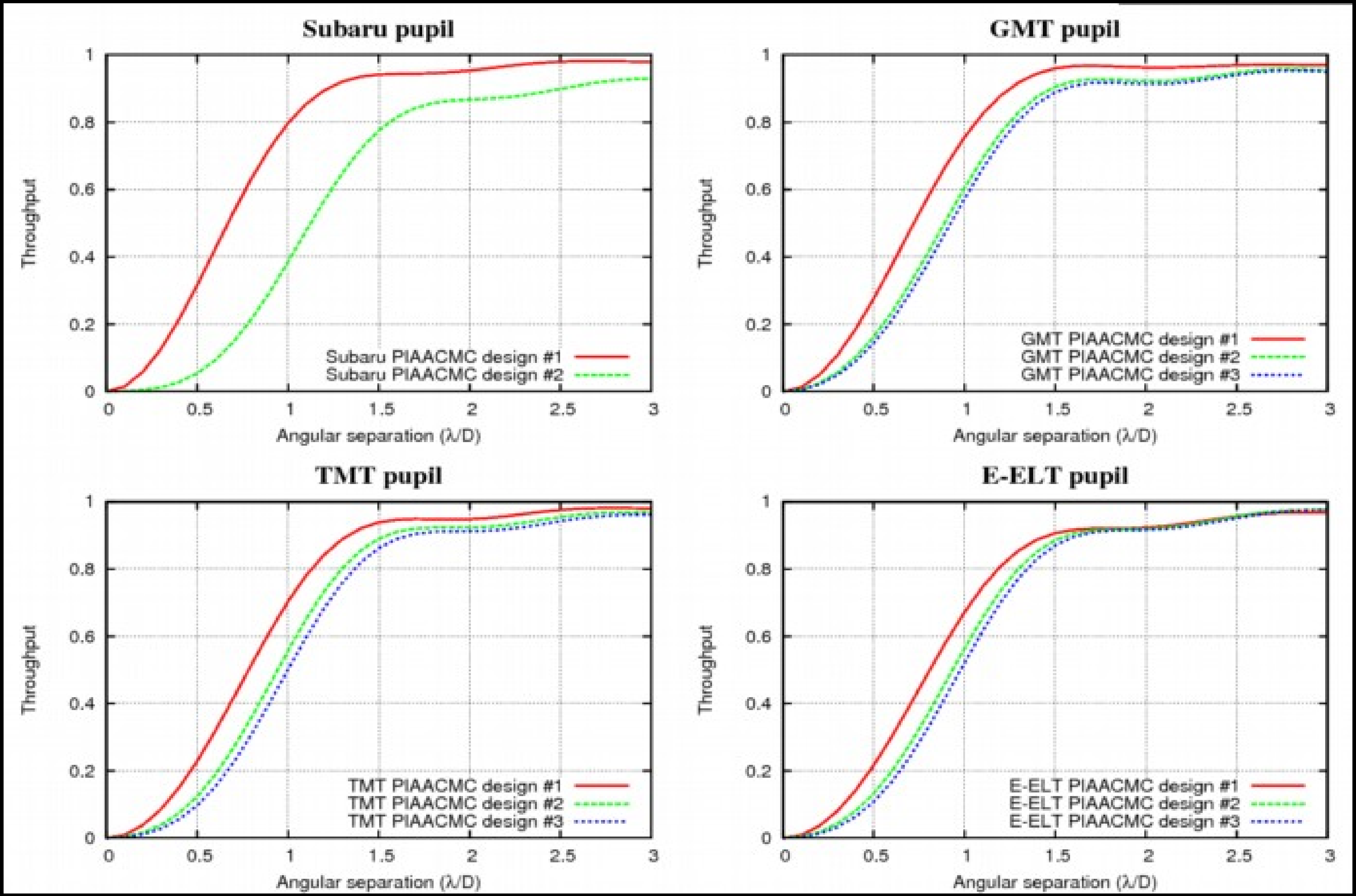


<u>**Pupil shape does not matter !!!**</u>

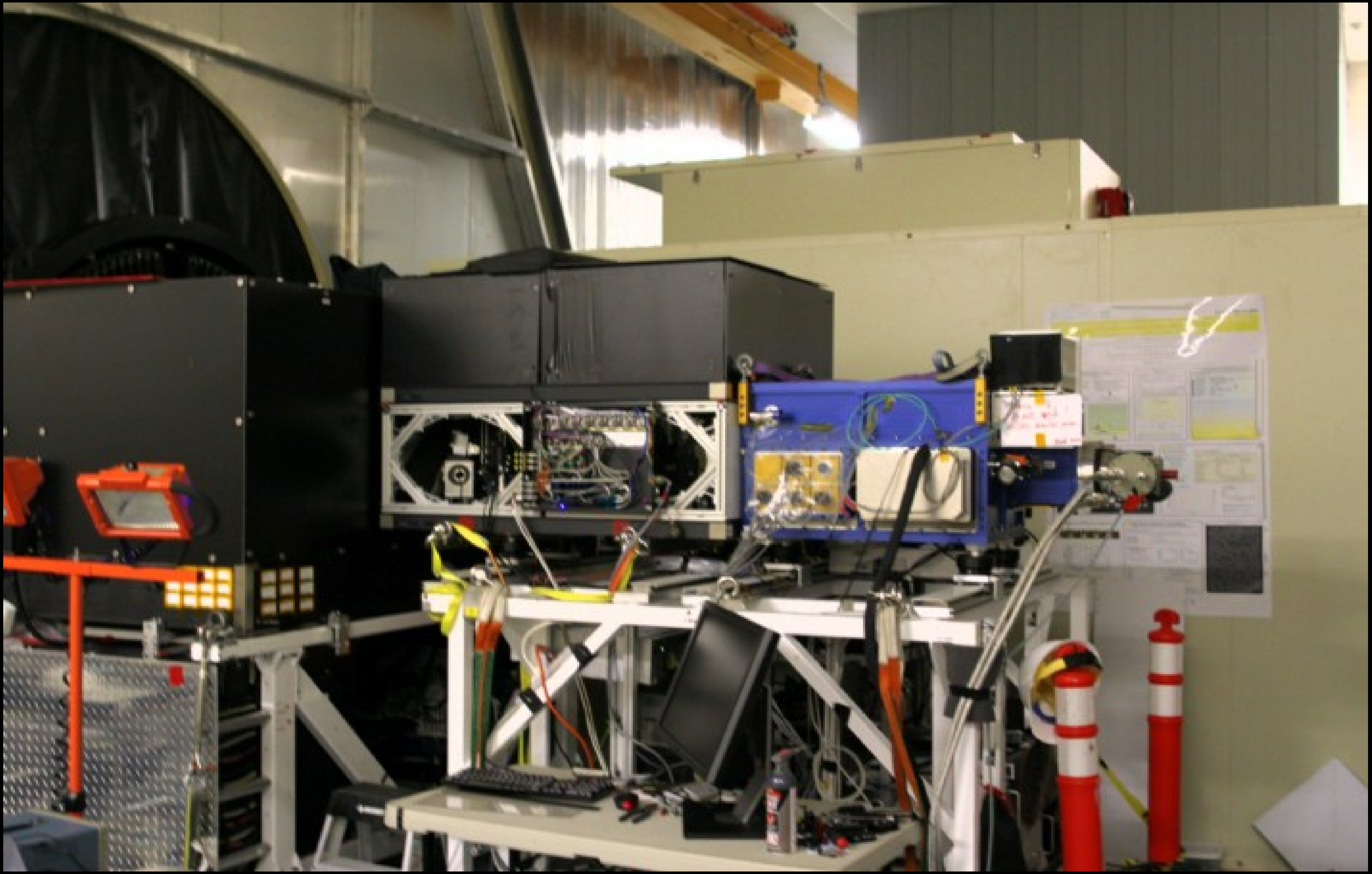




PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit



The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system



Outline

Science opportunities with ELTs

What would it take for an ELT to characterize habitable planets ?

Coronagraphy (Easy !!!)

Wavefront control (ExAO) (within reach today)

PSF calibration techniques

How should we proceed ?

Wavefront control

Can we reach 1e-4 RAW contrast in the 1 to 2 l/D range … on a R~9.5 source?

Goal: ~1e-5 contrast at 1 l/D

We are not that far from it with current technology...

Conventional high order ExAO on 8-m class telescope achieves ~1e-3 contrast in near-IR at few l/D

Moving to 3x larger telescope diameter will help (dilute speckle halo) – at equal SR, 10x gain in contrast → 1e-4

BUT **we can do much better** by :

(1) Using diffraction-limited WFS (Pyramid with little or no modulation, nlCWFS, Zernike etc...)

For Tip-tilt, gain in flux is $(D/r_0)^2$ = 90,000 on 30m telescope (12.8 mag)

(2) Making use of predictive control in the control loop (inner PSF flux dominated by time lag)

Wavefront control

Can we reach 1e-4 RAW contrast in the 1 to 2 l/D range … on a R~9.5 source?

Goal: ~1e-5 contrast at 1 l/D

We are not that far from it with current technology…

Conventional high order ExAO on 8-m class telescope achieves ~1e-3 contrast in near-IR at few l/D

Moving to 3x larger telescope diameter will help (dilute speckle halo) – at equal SR, 10x gain in contrast → 1e-4

BUT **we can EASILY do much better** by :

(1) Using diffraction-limited WFS (Pyramid with little or no modulation, nlCWFS, Zernike etc…)

For Tip-tilt, gain in flux is $(D/r_0)^2$ = 90,000 on 30m telescope (12.8 mag)

(2) Making use of predictive control in the control loop (inner PSF flux dominated by time lag)

See poster on non-modulated PWFS (Clergeon et al.)

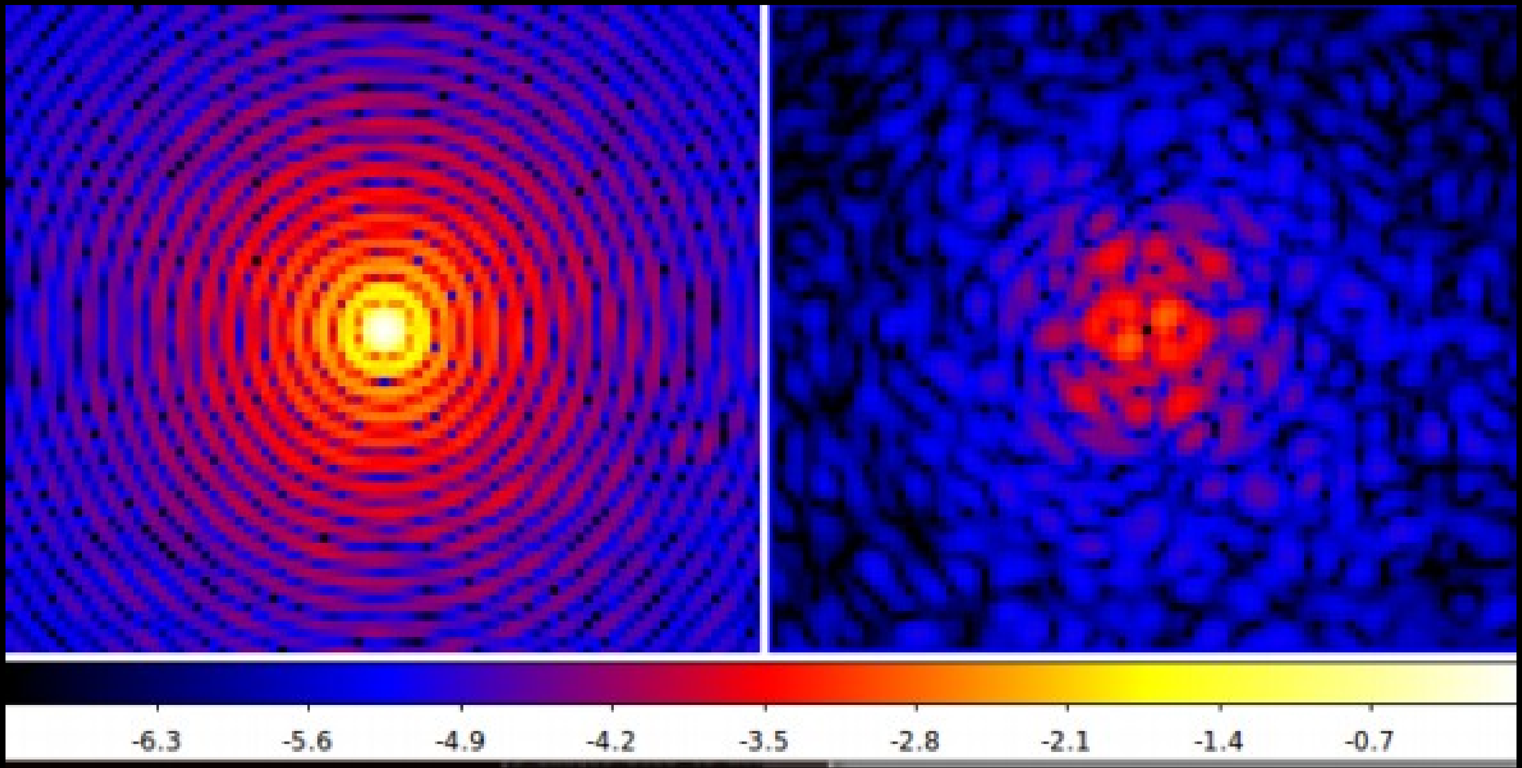
See oral presentation on nlCWFS (Mateen et al.)

ELT simulated ExAO PSF

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

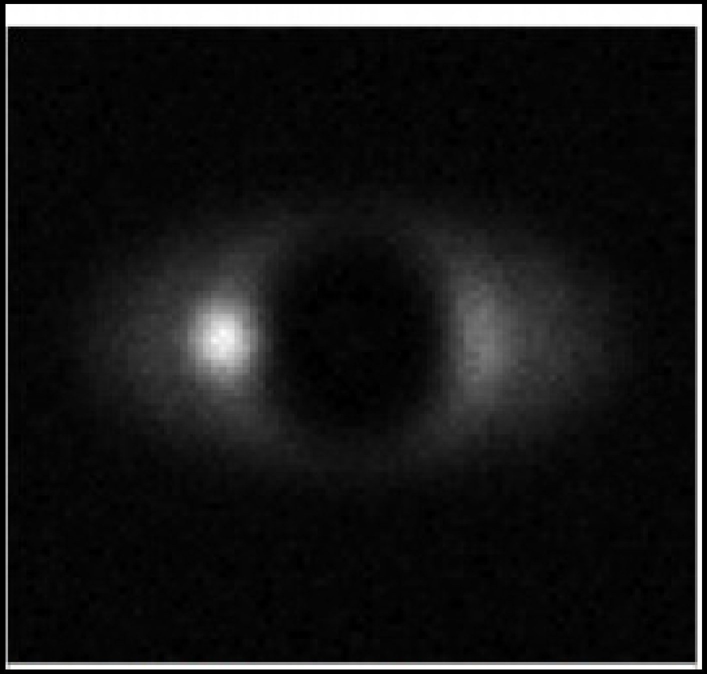
Time lag
→ predictive control

Scintillation

Pointing and coronagraphy

Pointing errors put light in the 1 to 2 λ/D region of the focal plane, where planets should be seen

A pointing error and a planet at the inner working angle of the coronagraph look identical



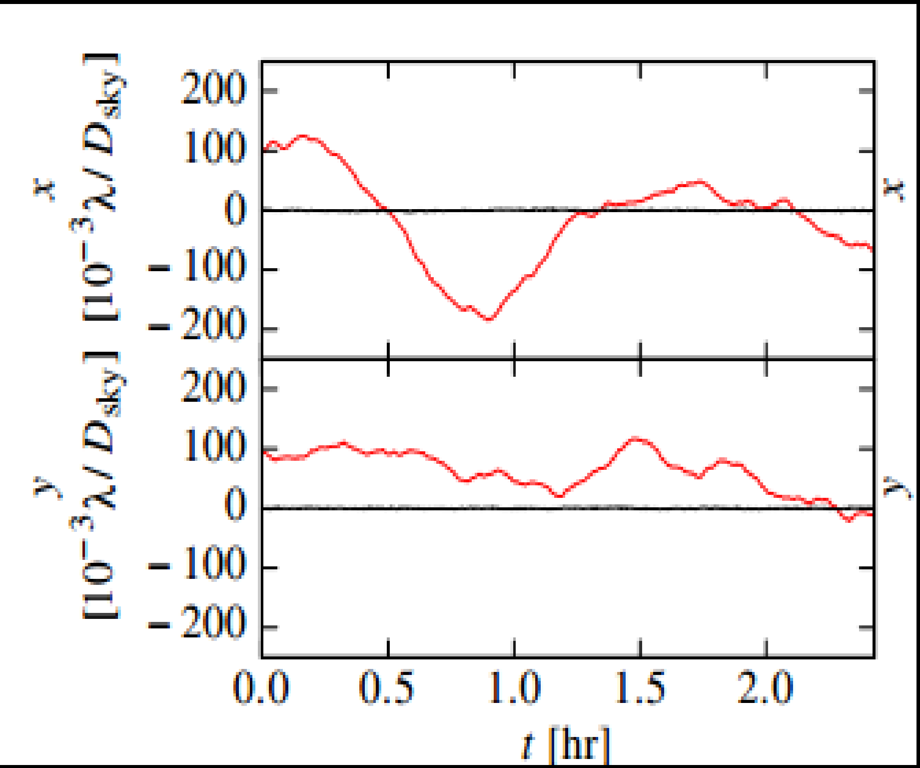
Small IWA coronagraphy requires exquisite pointing control and knowledge

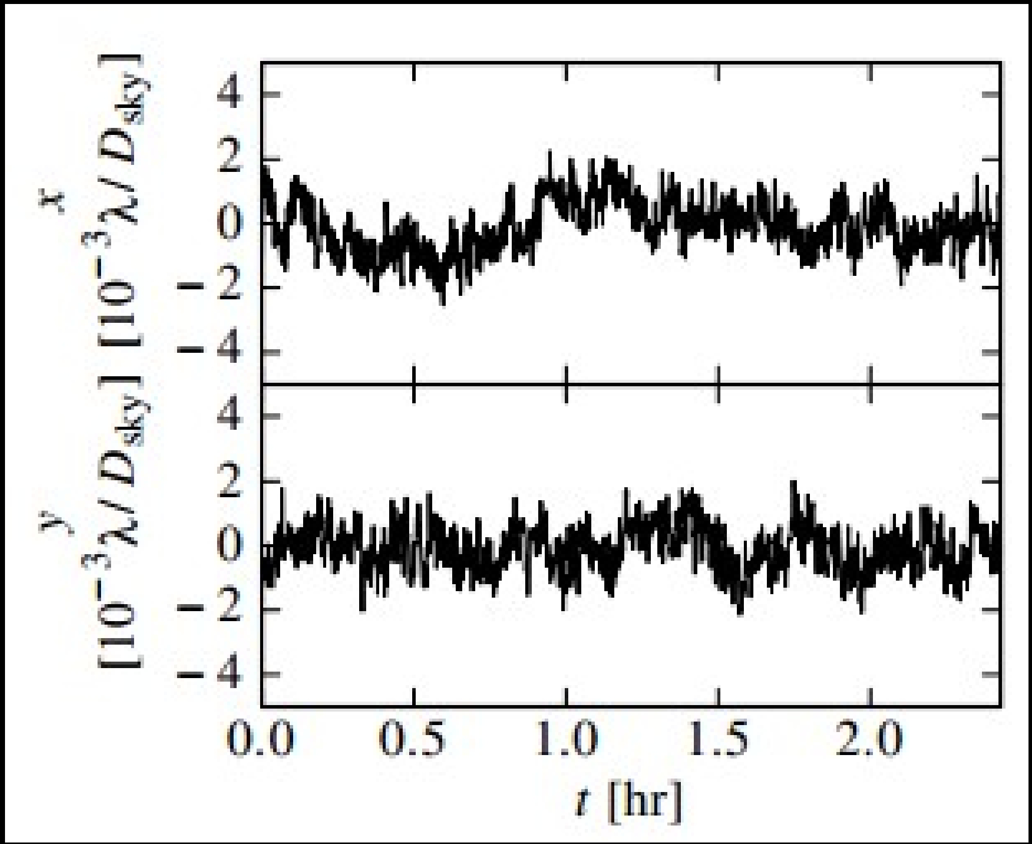
Pointing errors should be detected before they become large enough to induce a strong leak in the coronagraph

Pointing should be measured at the same λ as used for science
Should be measured at the diffraction limit of telescope
Should be measured at coronagraph focal plane mask

CLOWFS+PIAA at JPL demonstrate 3e-4 l/D control

At 10 kHz, ~1e4 ph per frame allows <1e-3 l/D measurement on ELT
This is 1/100 stellar diameter → ~1e-9 contrast calibration error





CLOWFS+PIAA at JPL demonstrate 3e-4 l/D control

At 10 kHz, ~1e4 ph per frame allows <1e-3 l/D measurement on ELT
This is 1/100 stellar diameter → ~1e-9 contrast calibration error

See poster on CLOWS
(Singh et al.)

Outline

Science opportunities with ELTs

What would it take for an ELT to characterize habitable planets ?

Coronagraphy (Easy !!!)

Wavefront control (ExAO) (within reach today)

PSF calibration techniques (where the magic is)

How should we proceed ?

Speckle noise

After all correction, calibrations, differential imaging :

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

Uncorrelated noise terms add quadratically in contrast

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 or 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

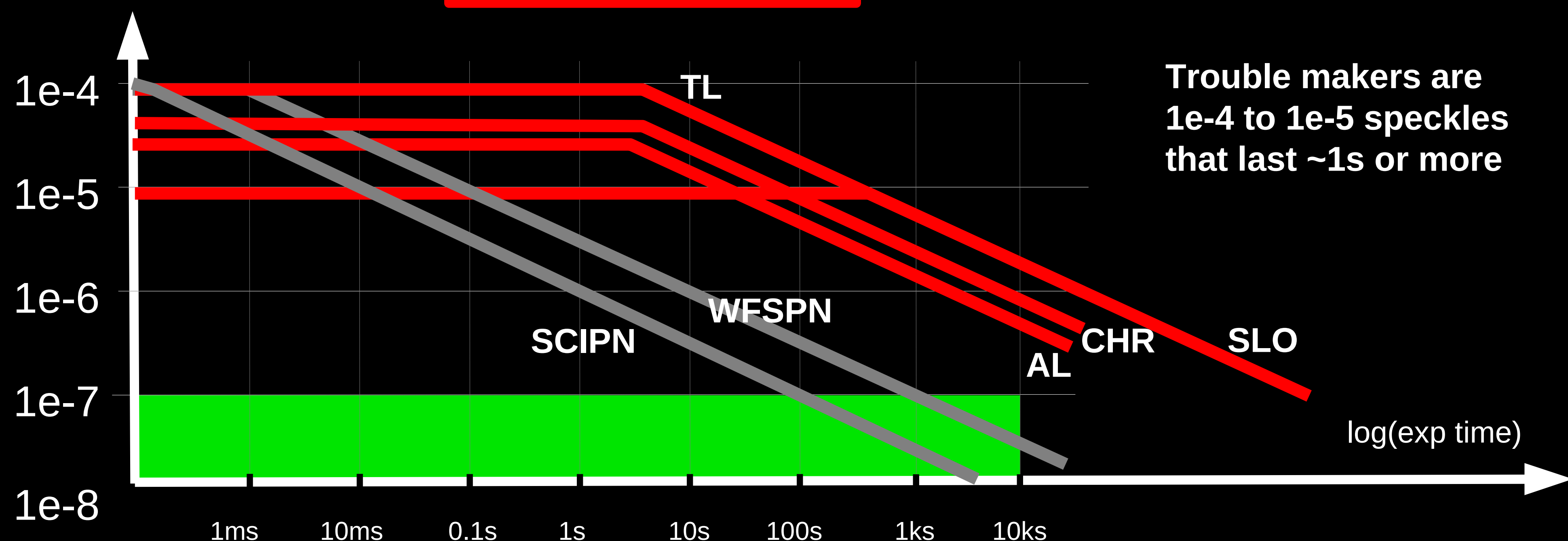
WFS Aliasing (AL)
Aliasing within WFS
few x1e-5 contrast
D/v timescale

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

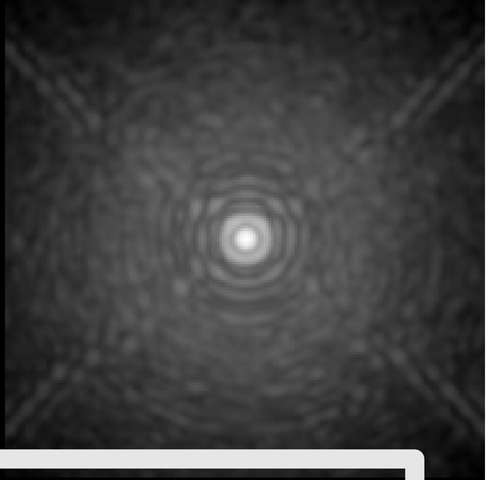
Chromaticity (CHR)
Due chromaticity between WFS and science instrument
few x1e-5 contrast
D/v timescale

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

Focal plane speckle control



Uses one of the most universal laws of physics :

"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

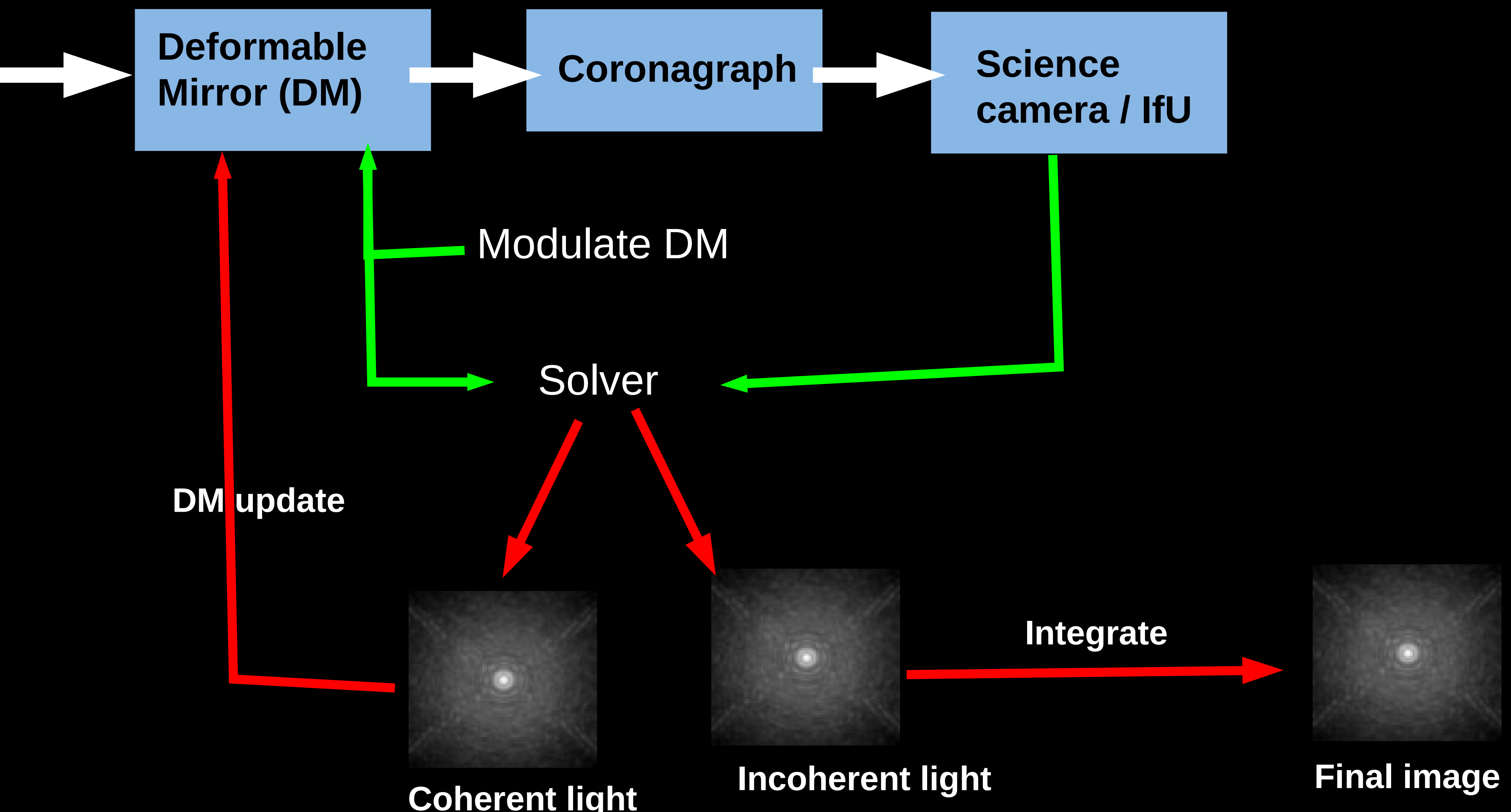
SENSING: Put "test speckles" to measure speckles in the image, watch how they interfere

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"

Algorithm description



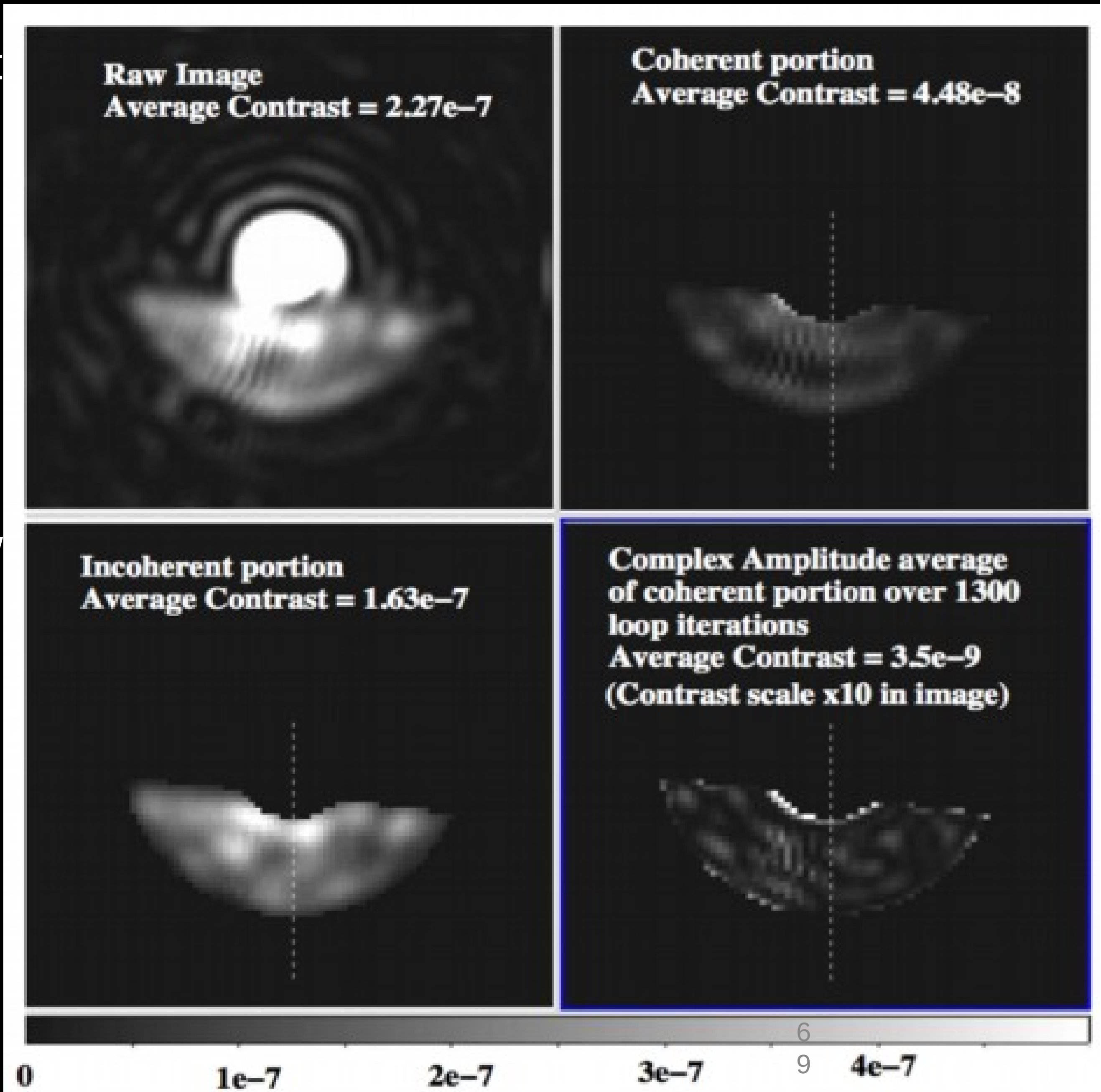
Focal plane WFS based correction and speckle calibration

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

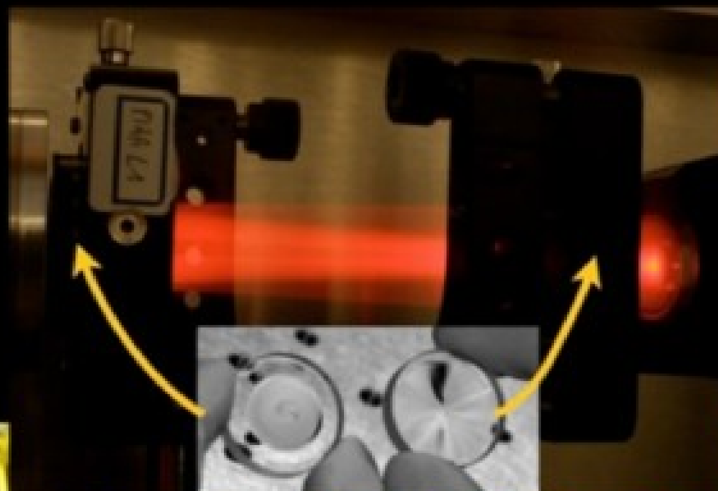
Guyon et al. 2010

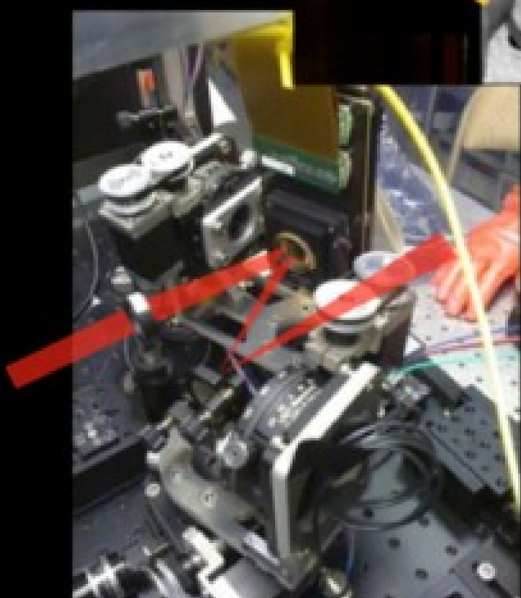


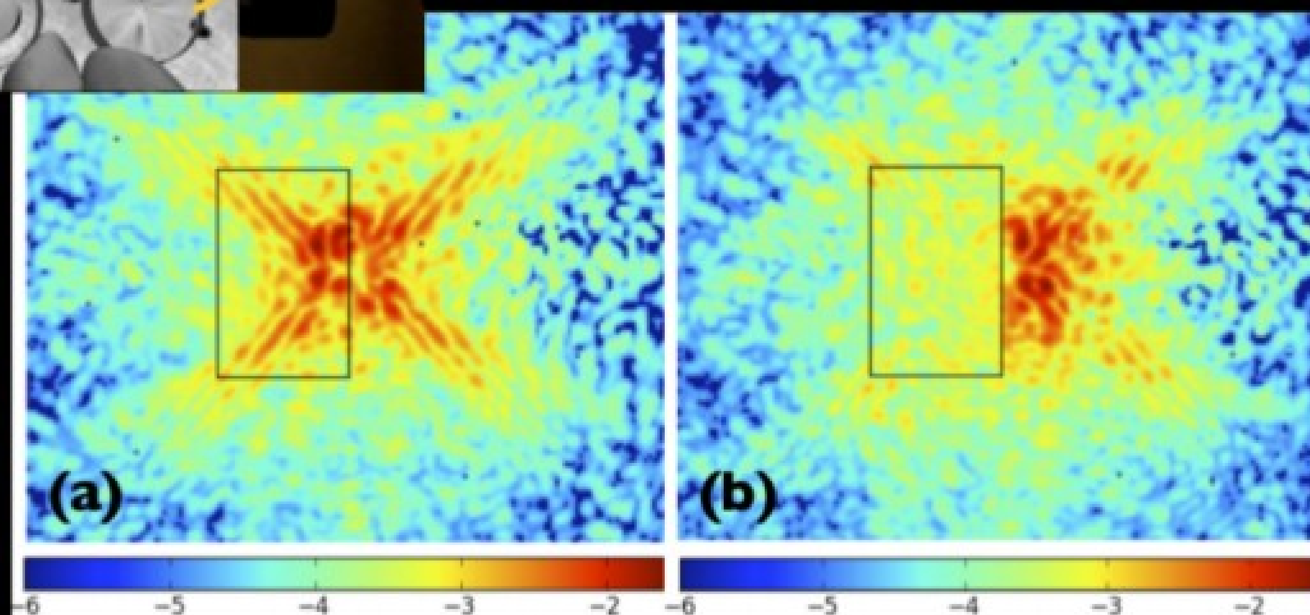
Active speckle control (Martinache et. al)

Active MEMS DM to replace a passive ADI approach at small angular separation

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





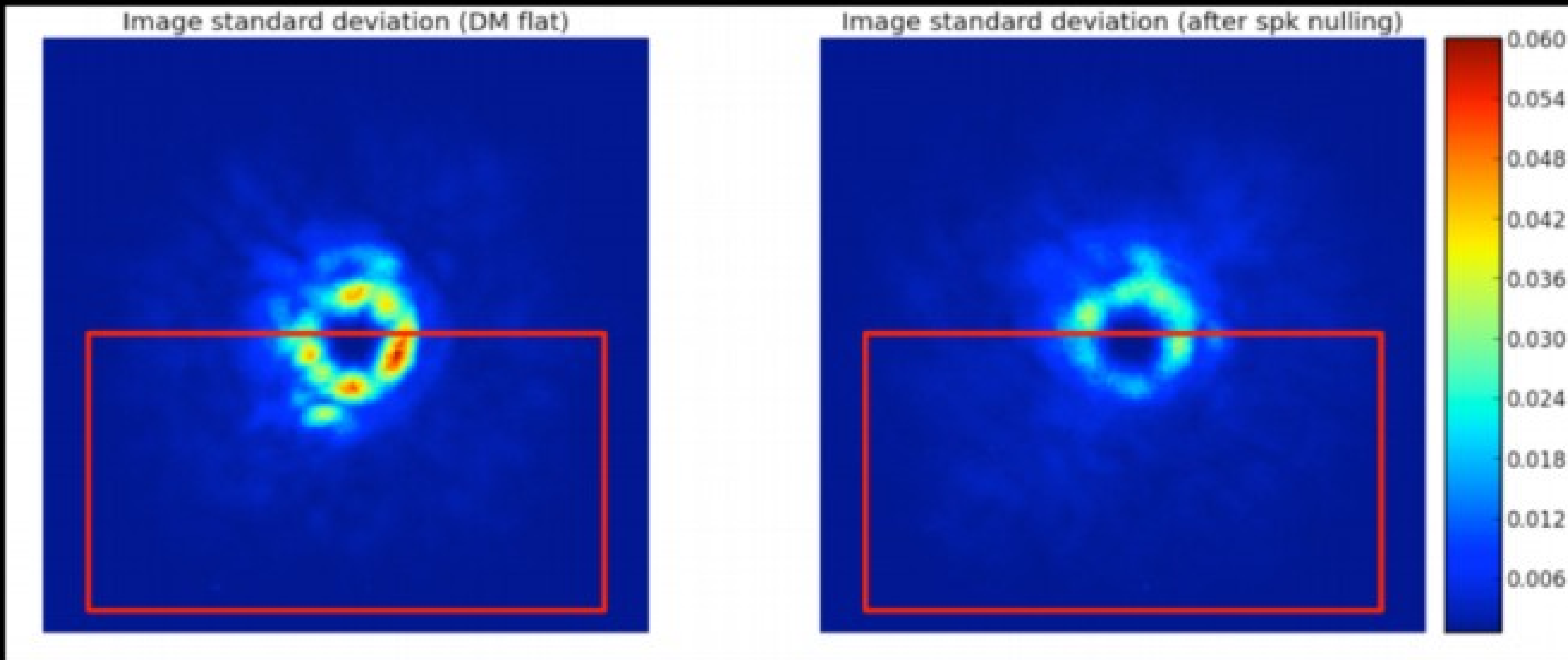


SCExAO's PIAA coronagraph permits speckle control from 1.5 to 14 λ/D

Raw contrast ~ 3e-4 inside the DM control region

Martinache et al, 2012, PASP, 124, 1288

Improved sensitivity (Martinache et. al)



Detection limits are fundamentally set by the local effect of temporal fluctuations in the diffraction.
The proper metric to estimate the benefit of the technique: standard deviation across the same data-cubes for the "flat" and the "optimized" DM volt-maps

Two observations:
- overall, the standard of the image after speckle nulling is reduced over the entire frame (x ~1/2)
- inside the control region, the sensitivity gain tops at a factor of ~7.

At the smallest angular separations (how many l/D?), the detection limit is improved by 1-2 magnitudes.

Martinache et al, 2013, in preparation

Speed vs performance:
~100 Hz required for significant gain

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

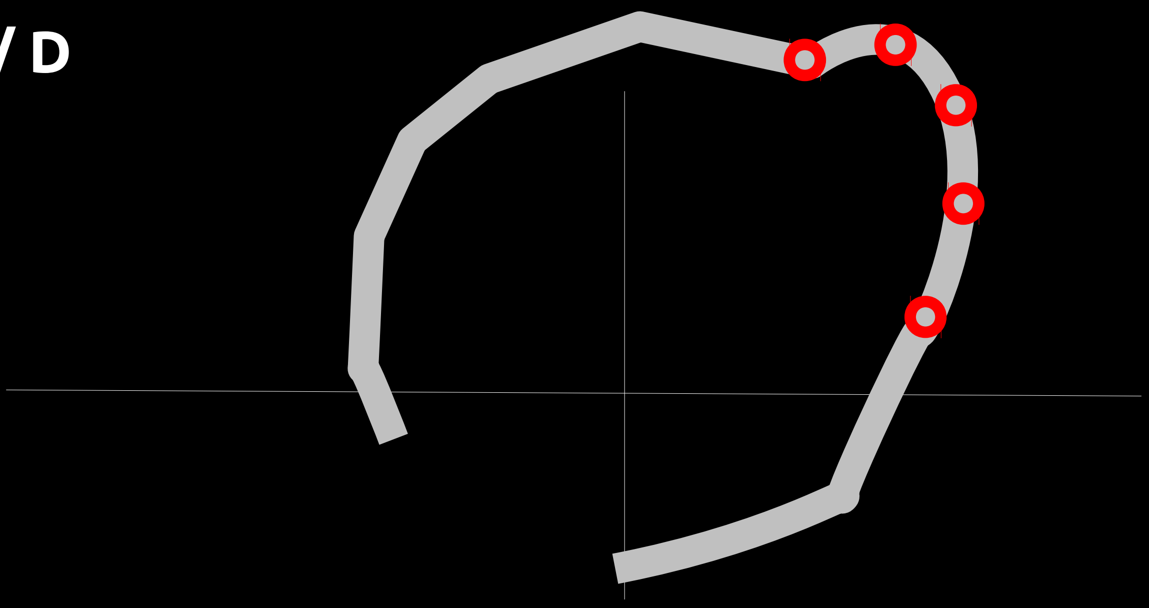
Chromaticity, Time lag (& to some degree aliasing) timescale:

Intensity : crossing time D/v ~ few sec

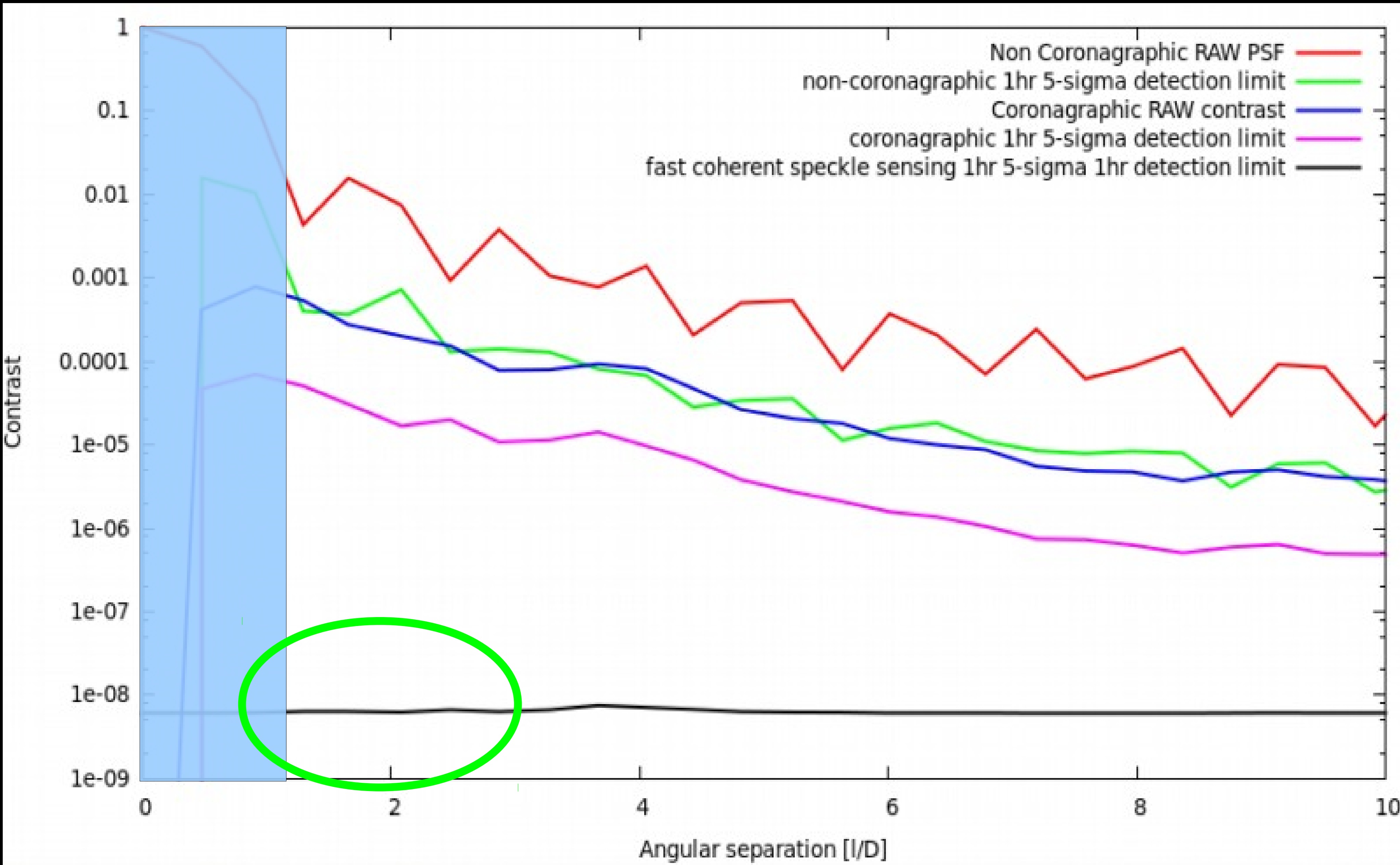
Complex amplitude : D / (2 π α v) < crossing time

(α = separation in λ/D)

ATTENUATION = π dt v α / D



Speed vs performance (no predictive control): ~100 Hz required for significant gain



Outline

Science opportunities with ELTs

What would it take for an ELT to characterize habitable planets ?

Coronagraphy (Easy !!!)

Wavefront control (ExAO) (within reach today)

PSF calibration techniques (where the magic is)

How should we proceed ?

Some game-changing technologies

Low inner working angle high efficiency coronagraphy

Low order wavefront sensing for coronagraph

Diffraction-limited wavefront sensing

Predictive WF control optimized for speckle decoherencing

Low noise red/near-IR detector for fast WFS

Coherent speckle sensing and control

Photon-counting IfU (MKIDS ?)

Imaging habitable planets with ELTs

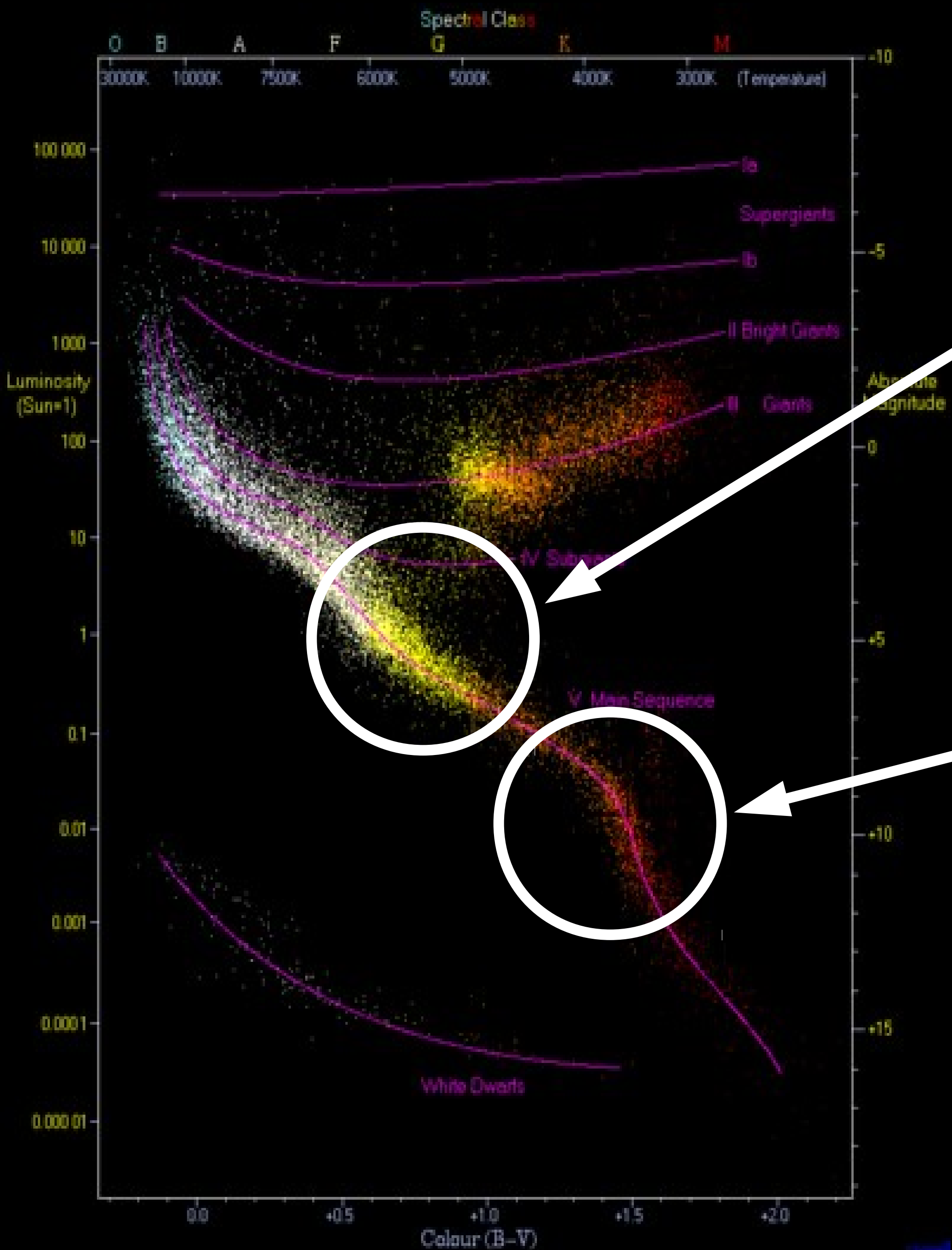
Technologies are being matured now, and should be ready in ~10yrs **ASSUMING WE WORK ON IT**

Could be a focused experiment for <100 targets. Can be deployed quickly and cheap → great science per $!!!!

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

See SCExAO poster by Nemanja Jovanovic (SCExAO)

Detecting 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