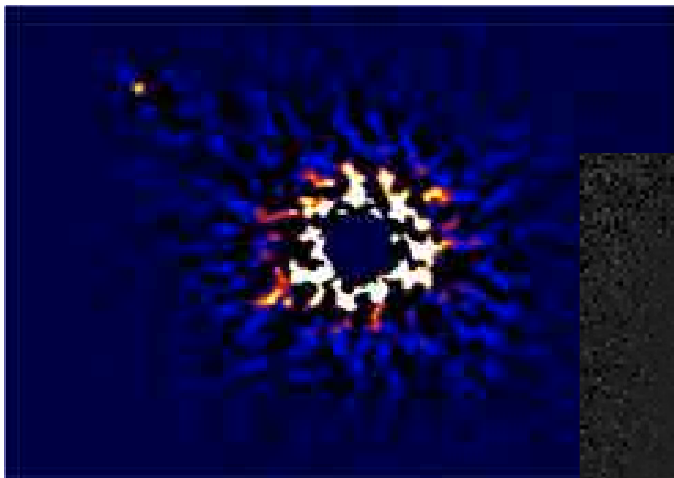
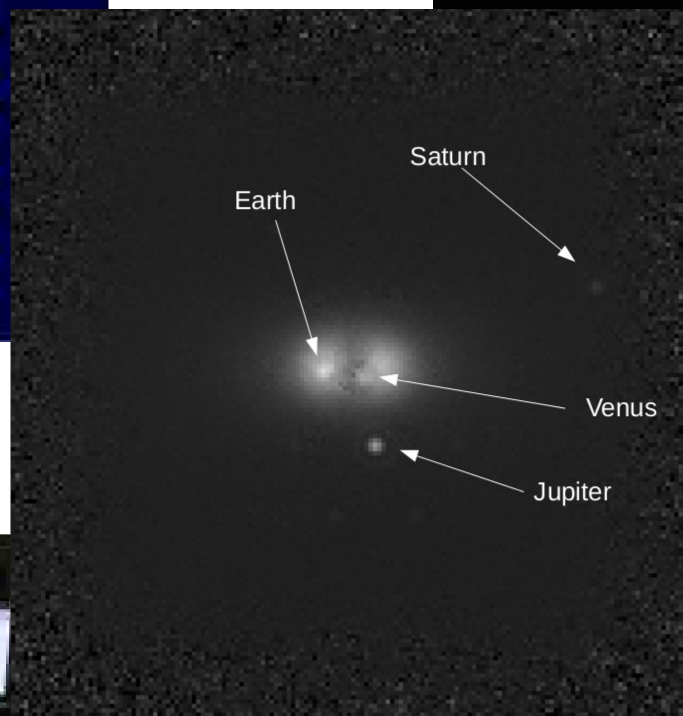
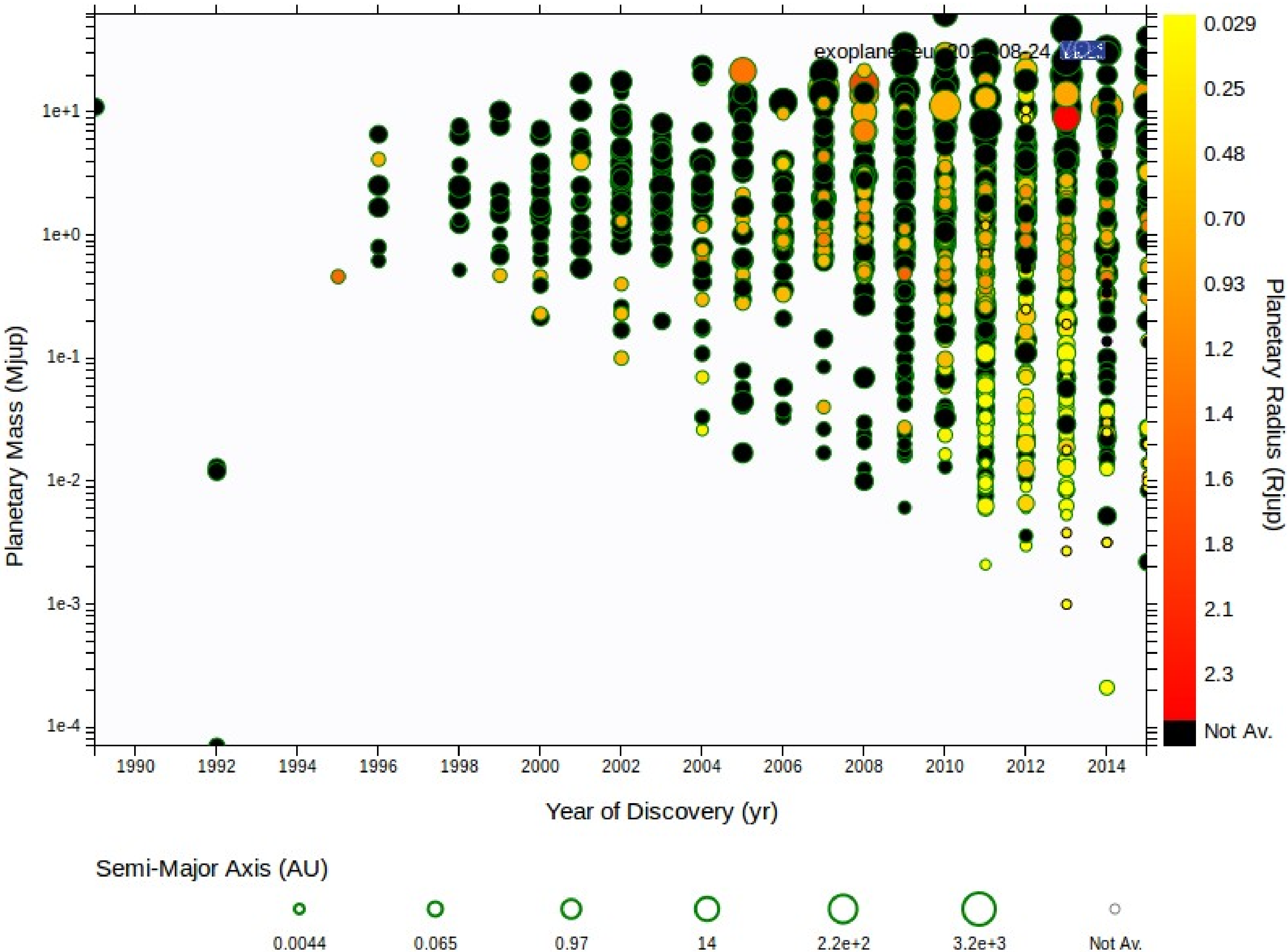
Coronagraphic imaging of habitable exoplanets





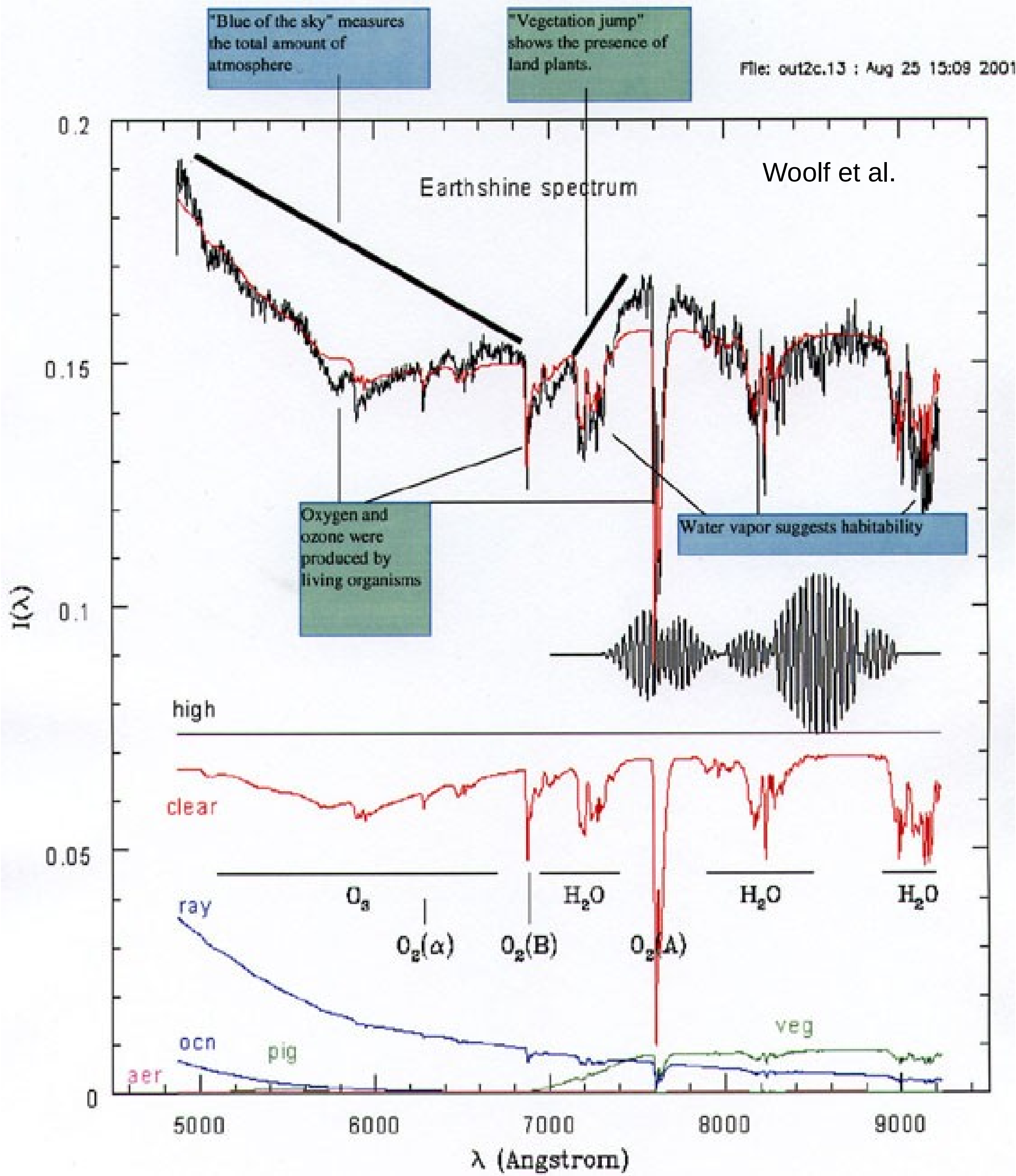


Planetary Mass (Mjup)
1e+1
1e+0
1e-1
1e-2
1e-3
1e-4
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
Year of Discovery (yr)
Planetary Radius (Rjup)
0.029
0.25
0.48
0.70
0.93
1.2
1.4
1.6
1.8
2.1
2.3
Not Av.
Semi-Major Axis (AU)
0.0044
0.065
0.97
14
2.2e+2
3.2e+3
Not Av.

Directly imaging planet is necessary to find life

We need to take spectra of habitable planets

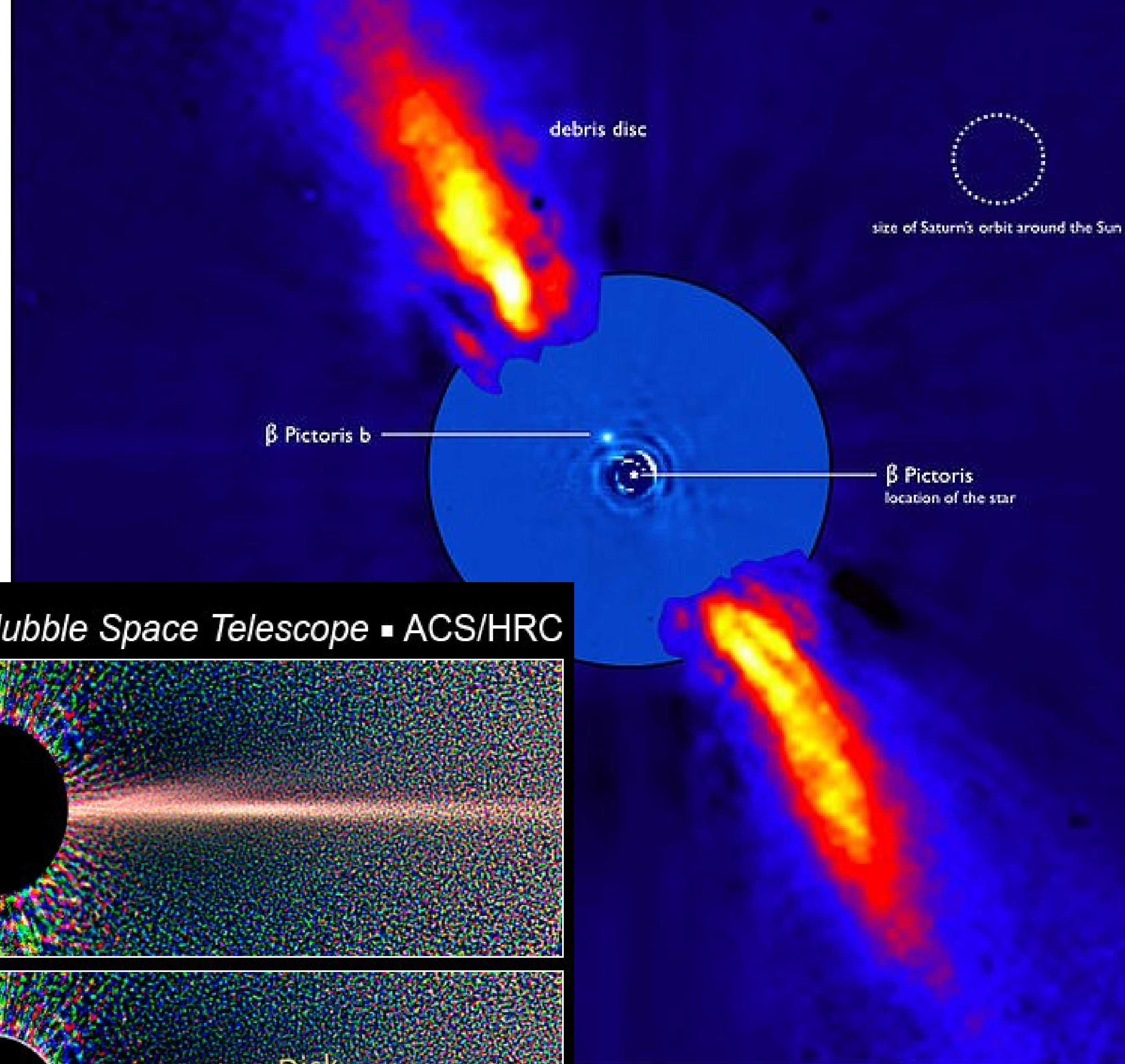
Spectra of Earth (taken by looking at Earthshine



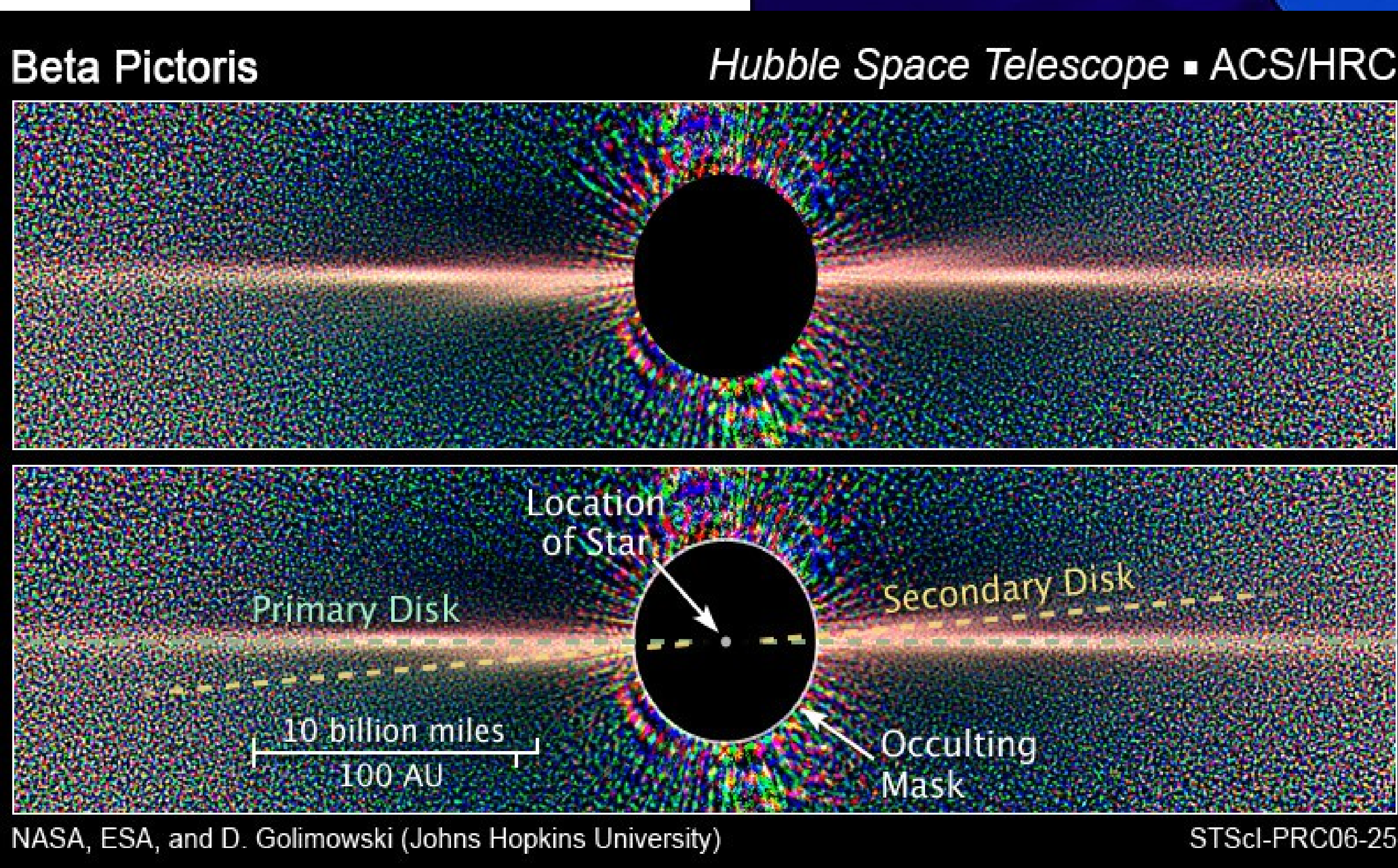
Beta Pictoris

8 Jupiter mass planet

Orbits young massive star in ~20yr

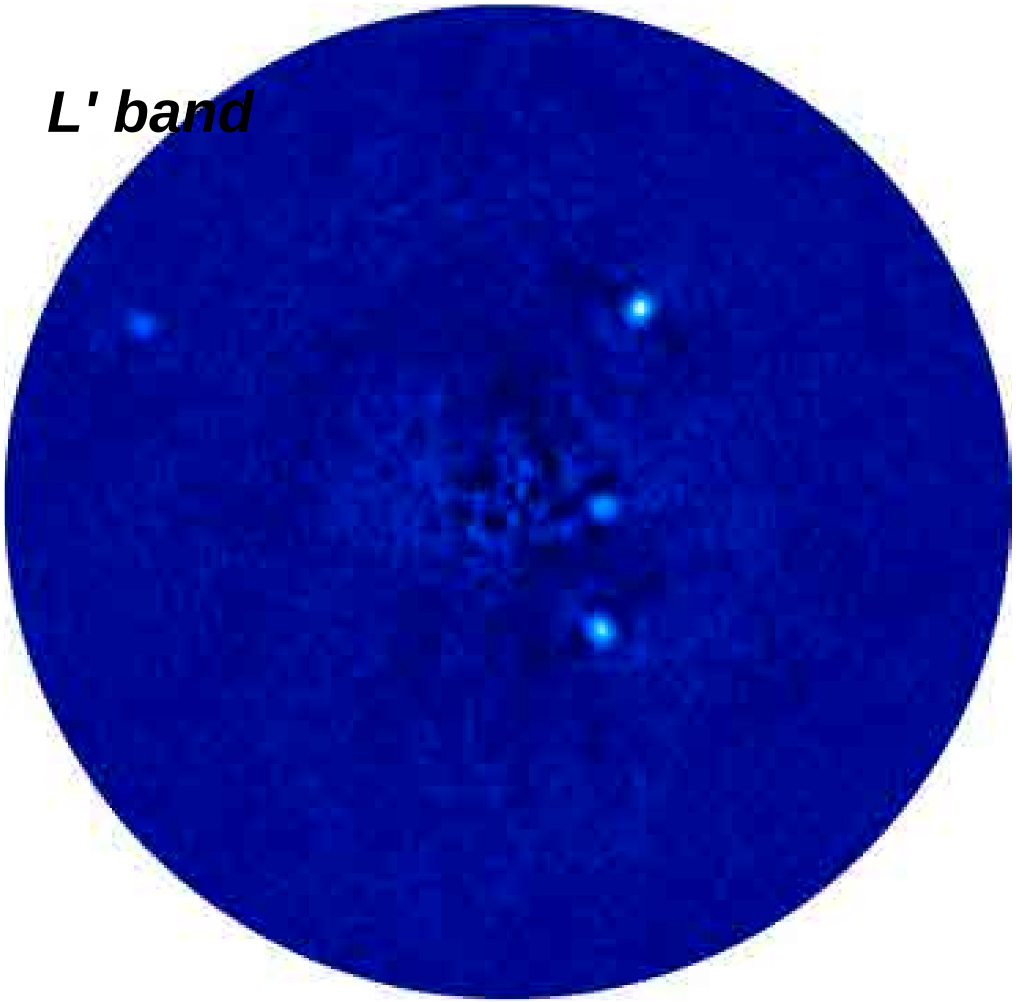


ESO VLT image (Lagrange et al.)

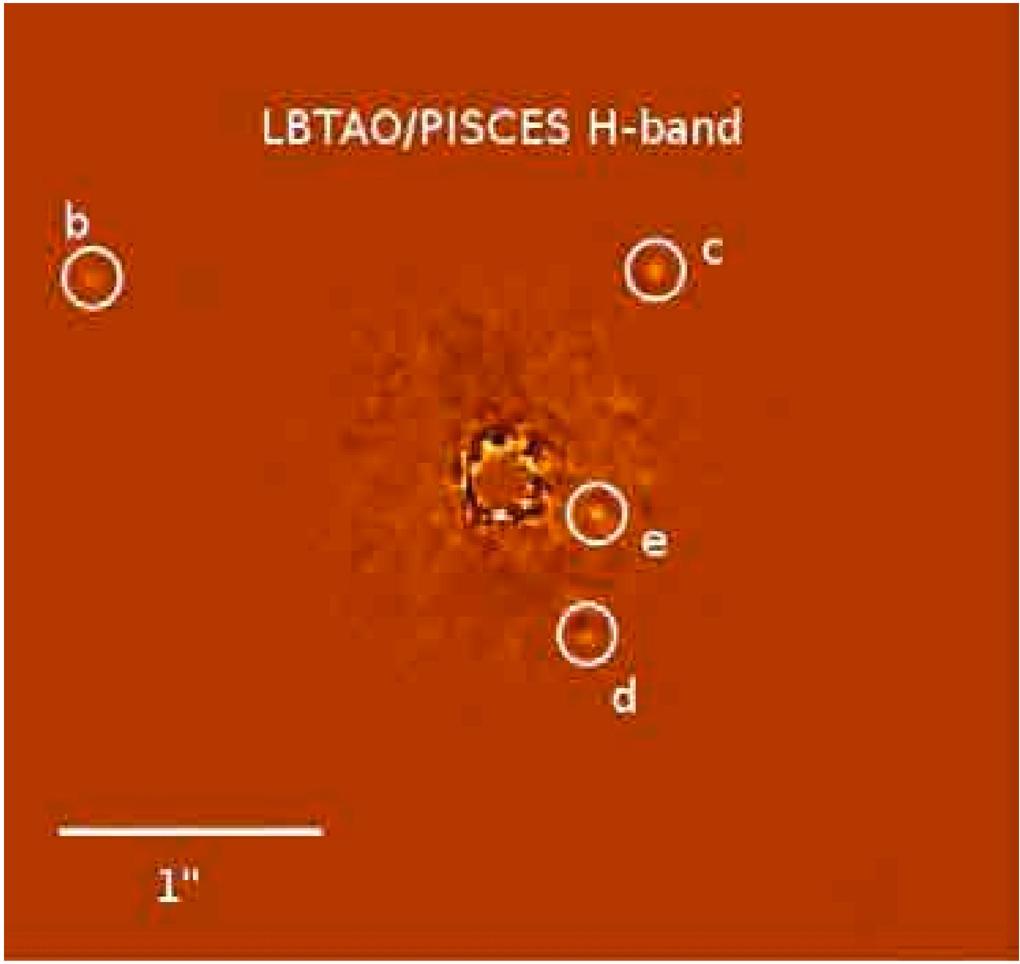


HR8799 imaged with Large Binocular Telescope

Four planets, orbital periods on the order of 100yr
Each planet 5 to 7 Jupiter Mass

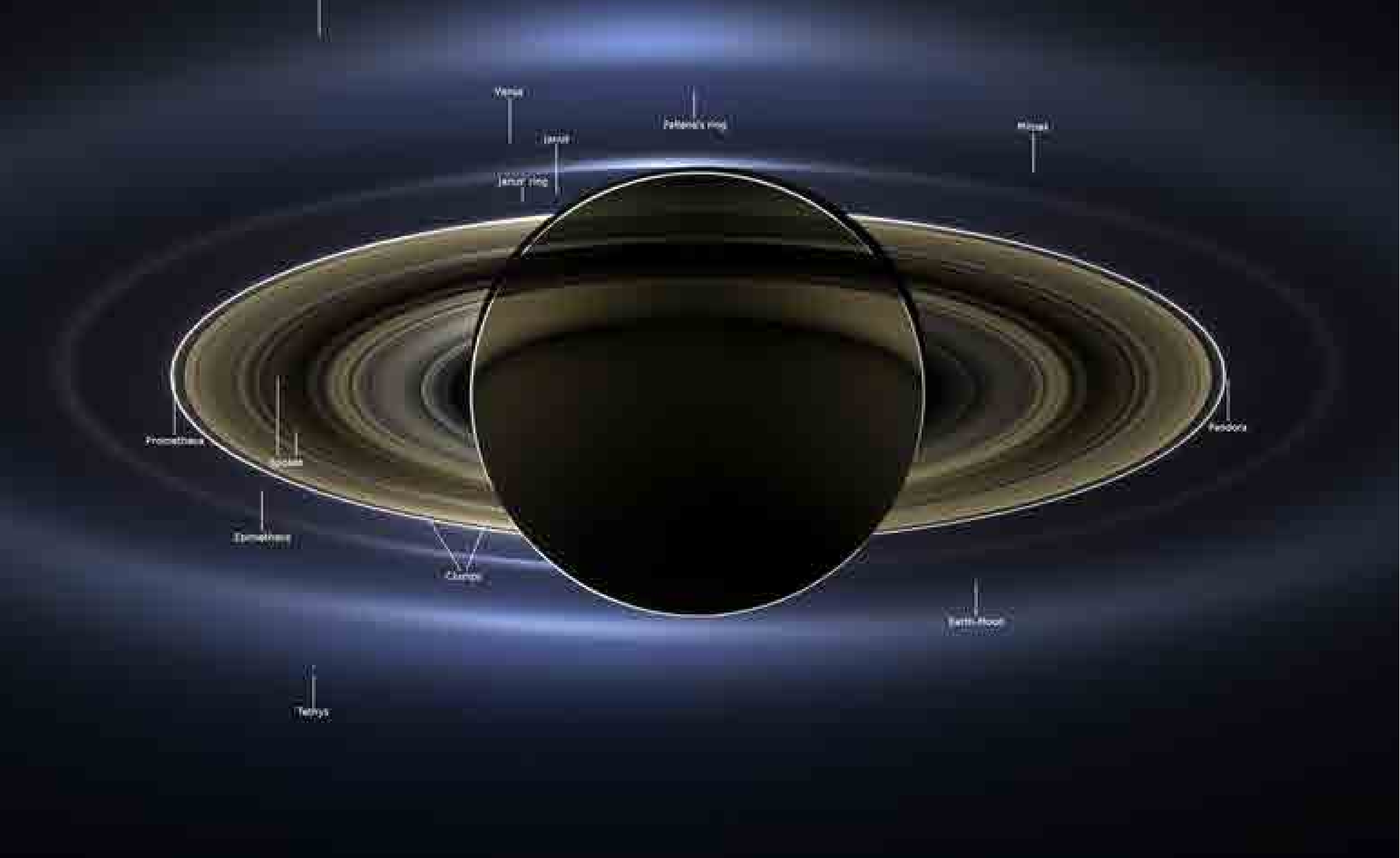


Defrere et al.



Skemer et al.

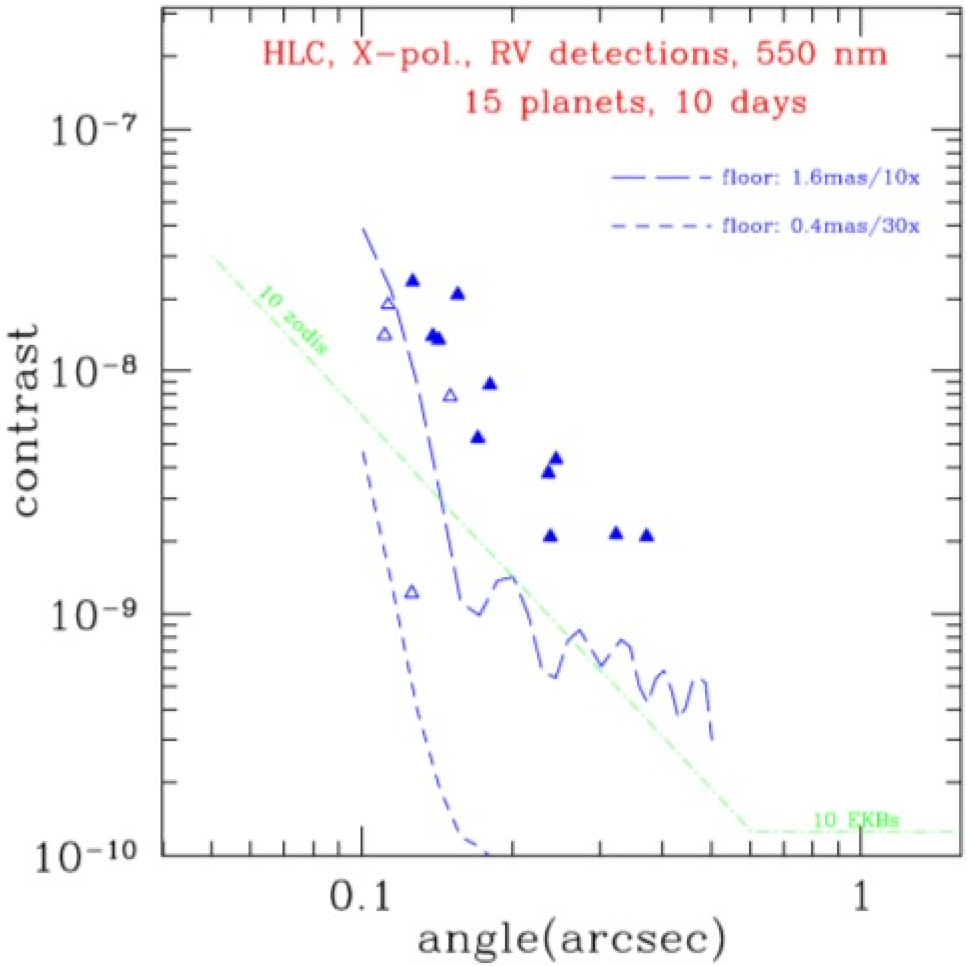
Taking images of habitable exoplanets: Why is it hard ?

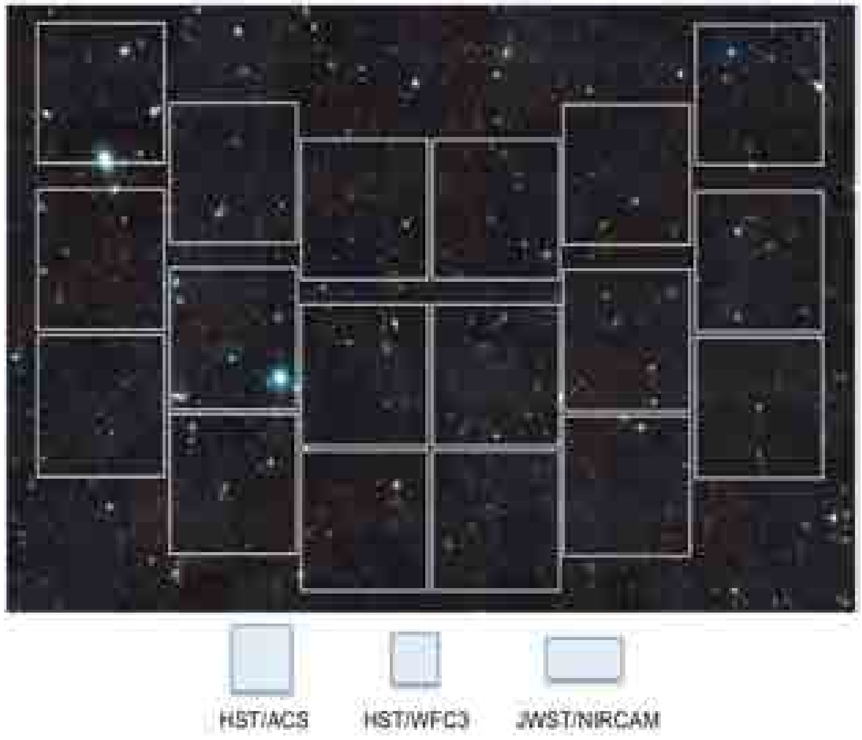



Saturn
Earth

Wide Field InfraRed Survey Telescope (WFIRST)

2.4m telescope:
- 0.28 sq deg nearIR (0.93-2 um) camera
- coronagraphic instrument



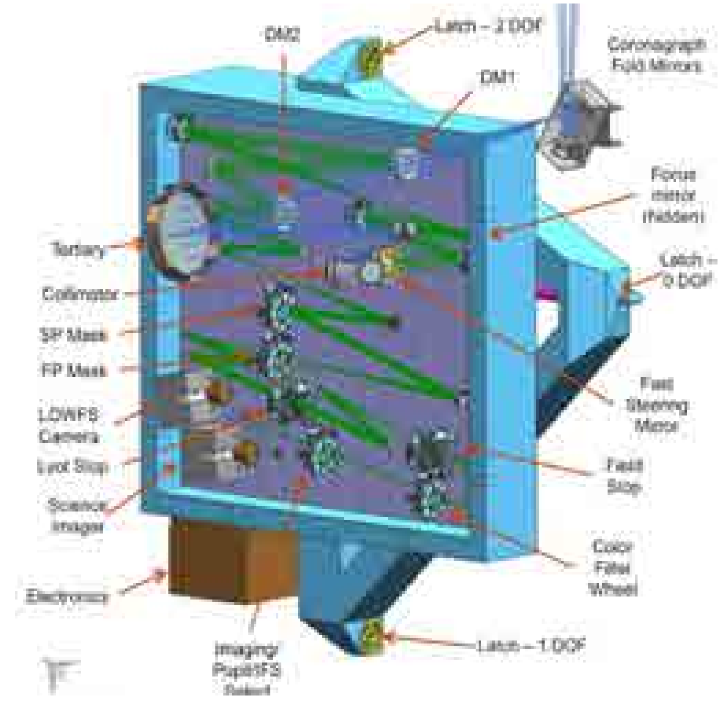


Coronagraph Instrument (CGI)

440 nm – 970 nm
Broadband filter imaging + spectroscopy (IFS)
Prime science goals:

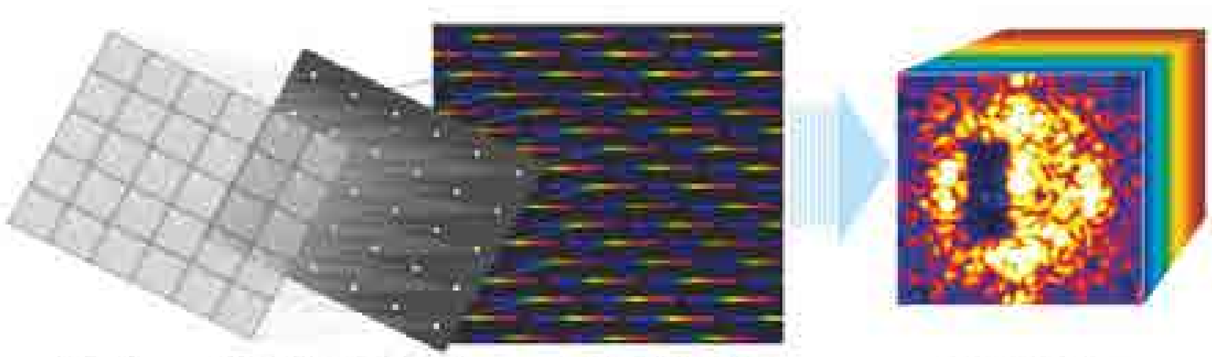
- Spectroscopic characterization of known RV giant planets
- Direct imaging of sub-Neptune mass planets
- Circumstellar disks

May be able to image super-Earths (contingent on instrument performance and target availability)



Baseline: **Occulting Mask Coronagraph (OMC)**
→ Hybrid Lyot Coronagraph (HLC)
→ Shaped Pupil Coronagraph (SPC)

Backup (higher science return):
Phase-Induced Amplitude Apodization Complex Mask Coron. (PIAACMC)



Coronagraph Instrument (CGI): wavefront control

Low-Order Wavefront Sensor (LOWFS) uses starlight rejected by coronagraph for wavefront sensing (pointing, focus...)

Two 48x48 deformable mirrors create a deep coronagraph null for high contrast imaging

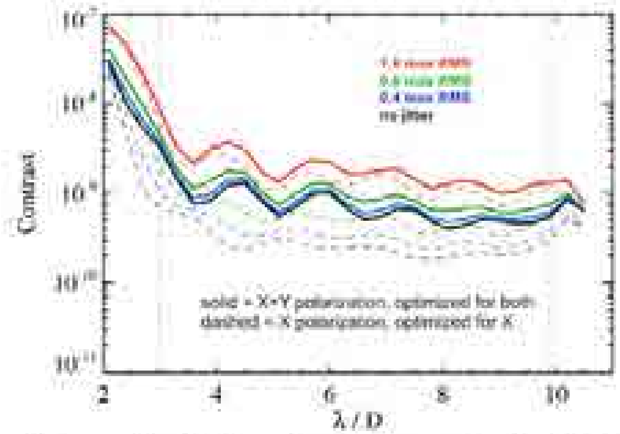


Figure 3-24: Model-predicted contrast for the HLC in the presence of LOS jitter. Jitter values represent the variation after control by the LOWFS, which is expected to reduce rms jitter to a fraction of a milli-arcsecond.

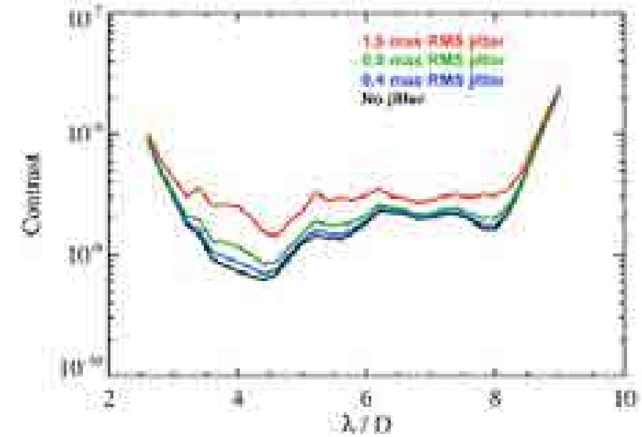
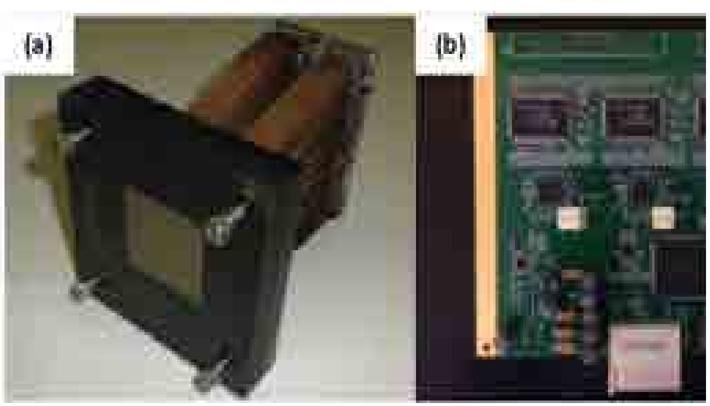


Figure 3-25: Model-predicted contrast for the SPC in the presence of LOS jitter. The LOWFS is expected to reduce jitter seen by the coronagraph to a fraction of a milli-arcsecond.



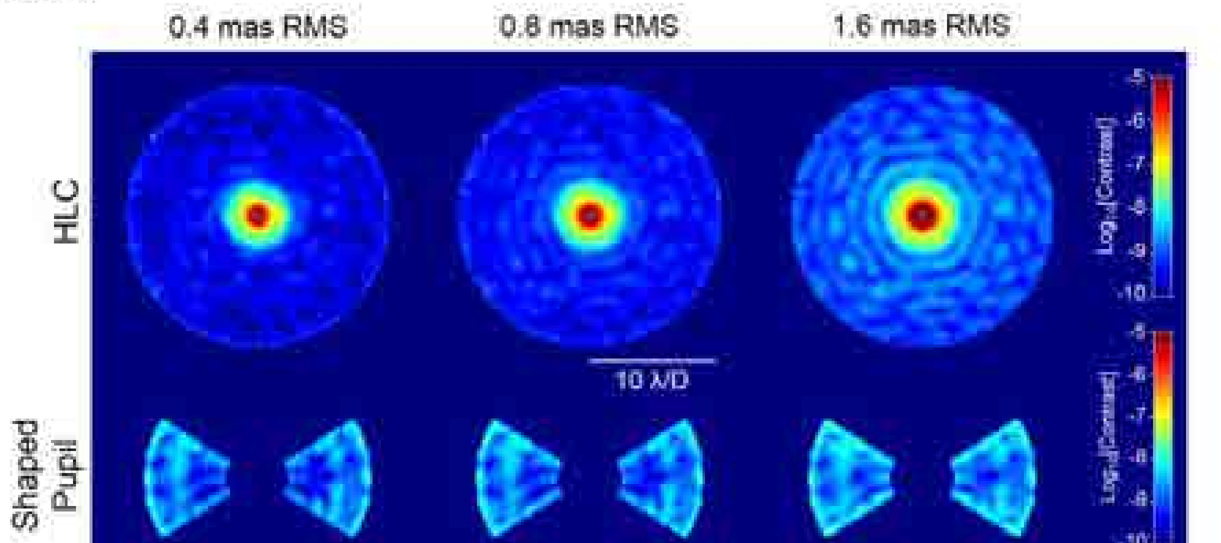
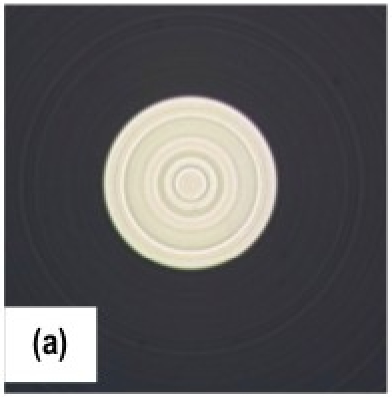
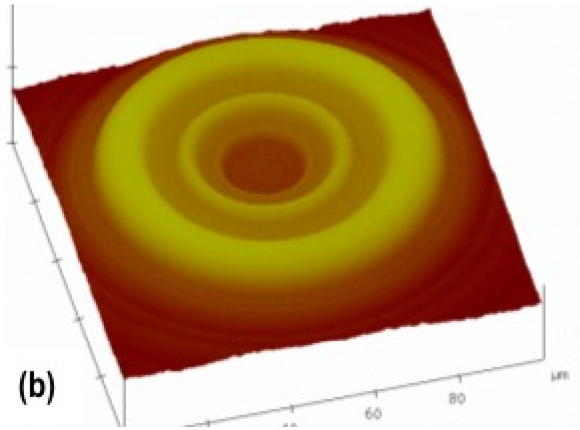


Figure 3-26: Log scale contrast maps for the HLC and SPC, in the presence of different levels of post-LOWFS jitter. Both designs show good tolerance to jitter.

Coronagraph Instrument (CGI): Coronagraph masks

HLC mask

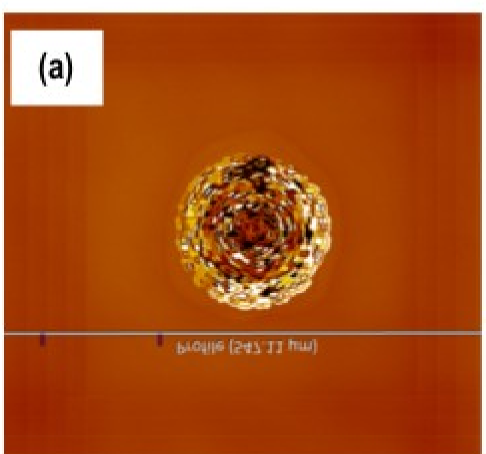


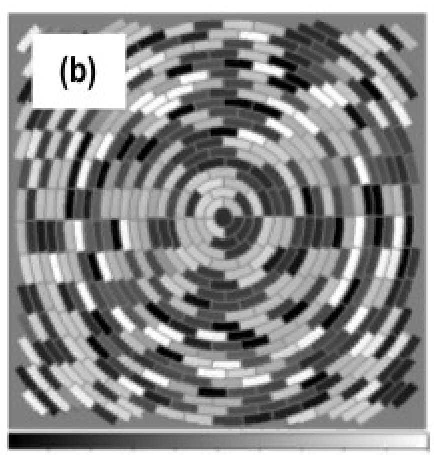


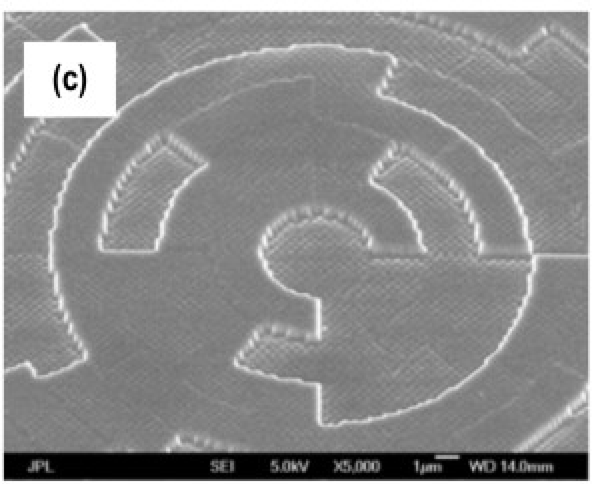
SPC mask

Figure 3-37: Reflective shaped pupil: (a) a processed wafer with 2 discovery and 2 characterization masks, (b) a fabricated characterization mask, (c) design details showing absorbing black silicon and highly reflective aluminum. Colored tints on (a) and (c) are caused by microscope illumination.

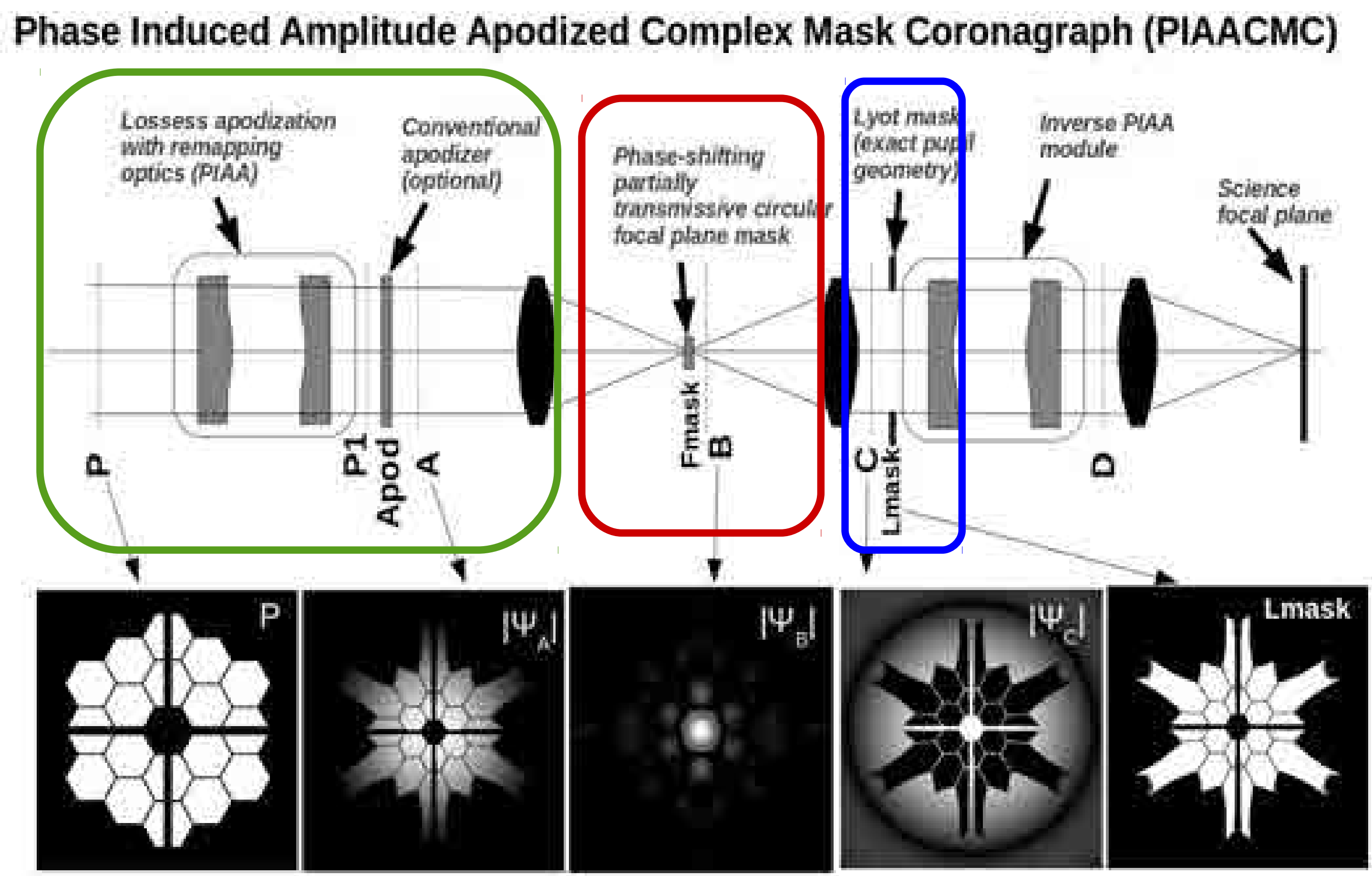
PIAACMC mask







PIAACMC concept

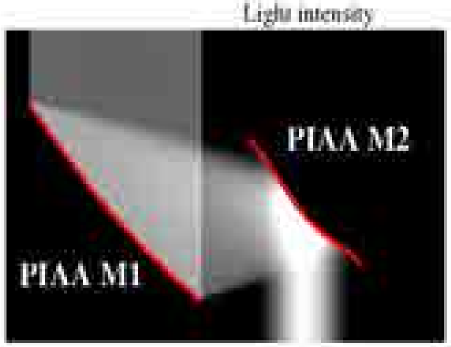


Achieves starlight suppression by combining:

Lossless apodization with aspheric optics (lenses or mirrors)
Creates PSF with weak Airy rings

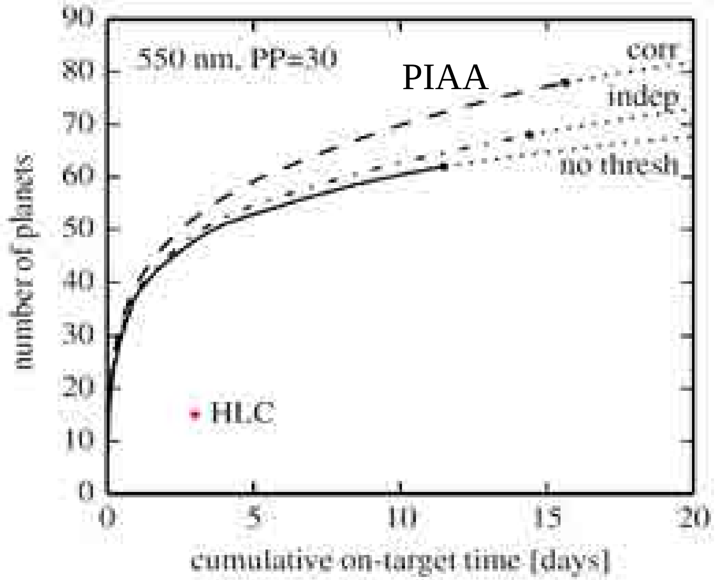
Focal plane mask
complex amplitude -1<t<0
Induces destructive interference inside downstream pupil

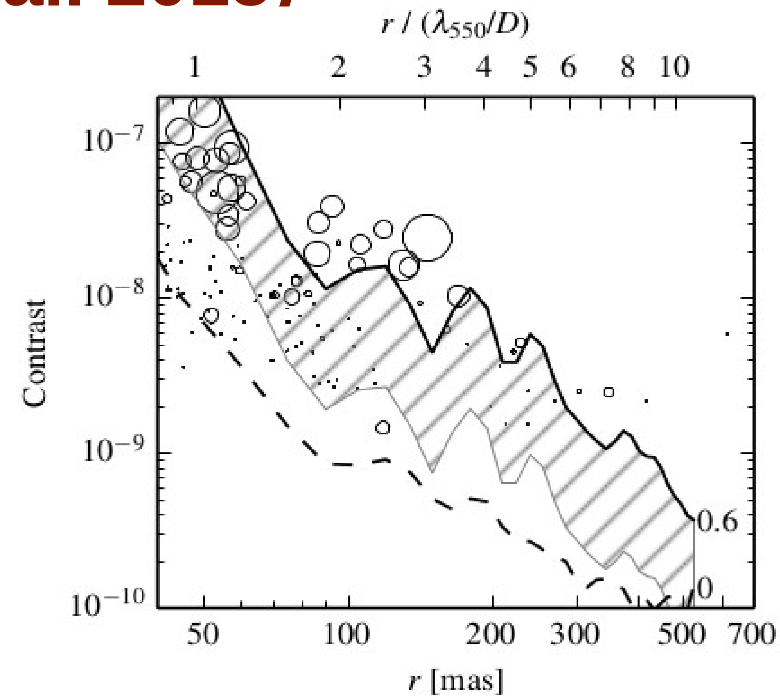
Lyot Stop
Blocks starlight

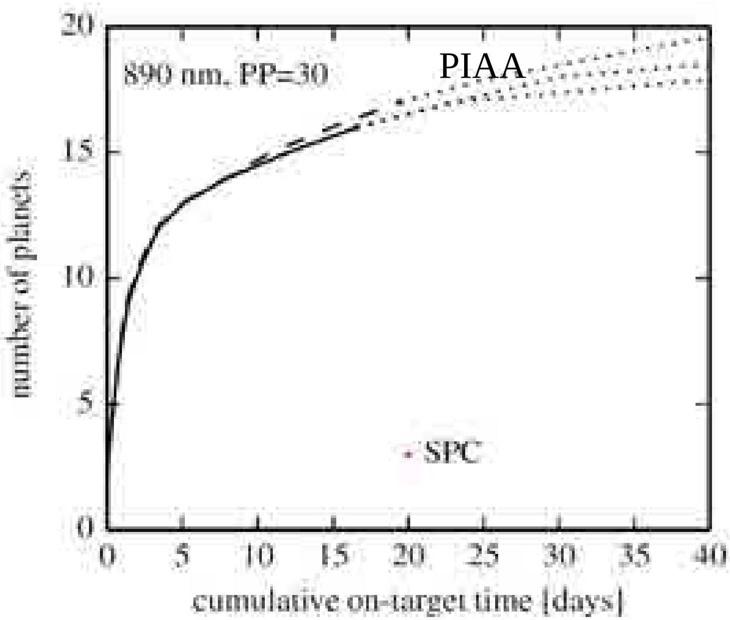


PIAACMC does not care about pupil geometry: segements, spiders, central obstruction OK

PIAACMC → enhanced science return thanks to small IWA (Kern et al. 2015)



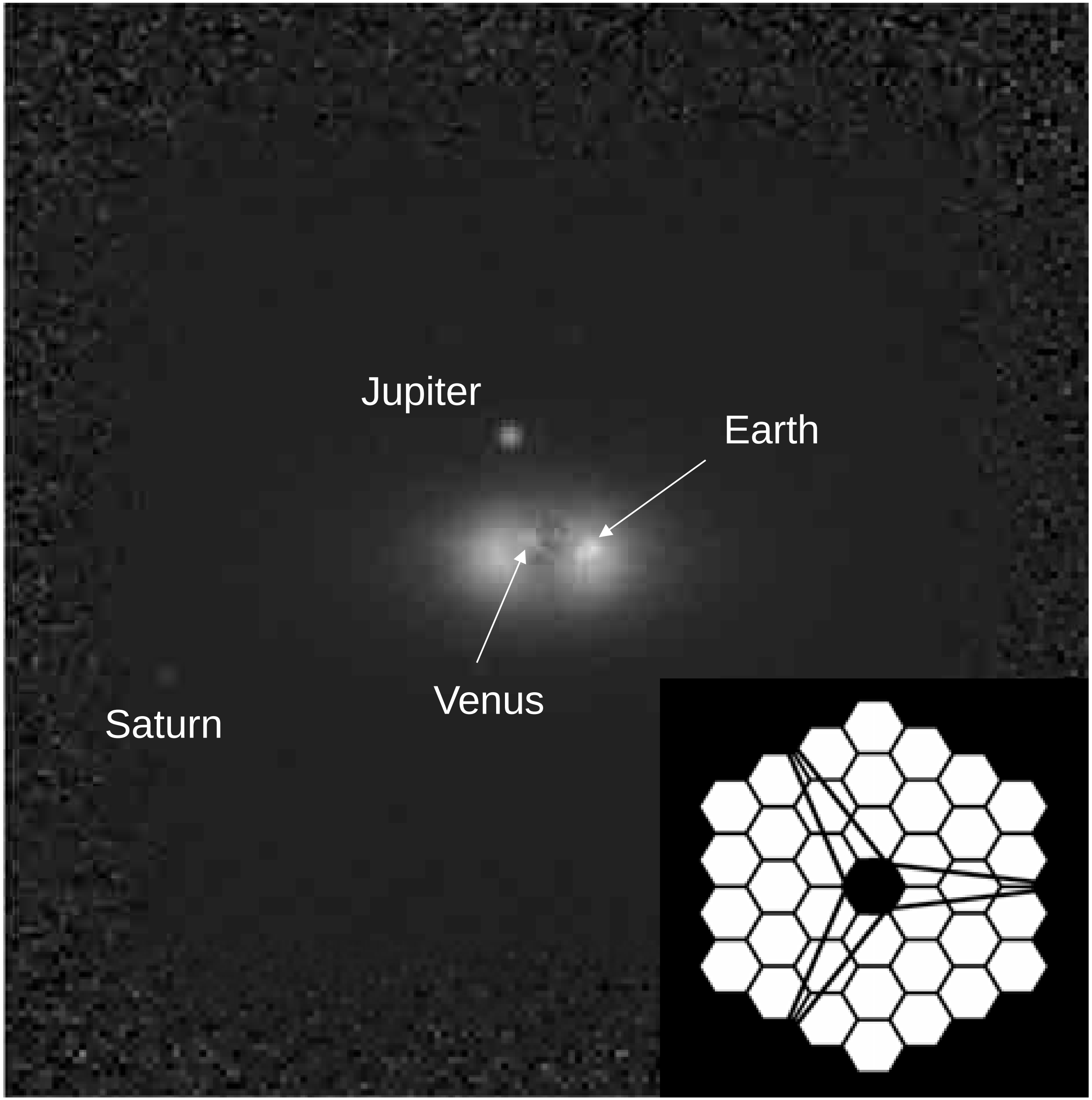




Case	Output channel	wavelength (nm)	band (%)	# pixels	# RV characterizations in less than 1 day each (min, max)		
					HLC	SPC	PIAA
1	imager	465	10	4.9	15	11	76
2	imager	565	10	4.9	15	11	87
3	imager	835	10	4.9	7	5	42
4	imager	670	18	4.9	16	13	85
5	imager	770	18	4.9	10	7	61
6	imager	890	18	4.9	5	5	36
7	IFS	670	1.4	4.9	4	2	39
8	IFS	770	1.4	4.9	2	1	30
9	IFS	890	1.4	4.9	0	0	14

Single polarization for each case, 0.4 mas jitter, post-processing gain = 1/30
Assumes planet location is known

PIAACMC's small IWA enable near-IR spectroscopy of exoEarths with HDST's 12m aperture



Simulated near-IR (1600nm, 20% band) image of a solar system twin at a distance of 13.5pc as seen by a 12m HDST with a 2 day exposure. The pupil geometry adopted for this simulation is shown in the lower right. A Phase-Induced Amplitude Apodization Complex Amplitude Coronagraph (PIAACMC), offering small IWA (1.25 l/D), is used here to overcome the larger angular resolution at longer wavelength. Earth, at 2.65 l/D separation, is largely unattenuated, while Venus, at 1.22 l/D, is partially attenuated by the coronagraph mask. At this wavelength, the wavefront control system (assumed here to use 64x64 actuator deformable mirrors) offers a larger high contrast field of view, allowing Saturn to be imaged in reflected light. This simulation assumes PSF subtraction to photon noise sensitivity. In the stellar image prior to PSF subtraction, the largest light contribution near the coronagraph IWA is due to finite stellar angular size (0.77 mas diameter stellar disk).

Subaru Coronagraphic Extreme-AO (SCExAO)

O. Guyon,
J. Lozi, N. Jovanovic, G. Singh, C. Clergeon, S. Goebel, P. Phatak, J. Males
T. Kudo, D. Doughty, J. Morino and F. Martinache

Subaru Telescope, National Astronomical Observatory of Japan

VAMPIRES

P. Tuthill
B. Norris
G. Schworer
P. Stewart

FPM DESIGN

K. Newman

FIRST

E. Huby
G. Perrin
L. Gauchet
S. Lacour
F. Marchis
S. Vievard
O. Lai
G. Duchene
T. Kotani
J. Woillez

AO188

Y. Minowa
Y. Hayano

COCORO

N. Murakami
O. Fumika
N. Baba
T. Matsuo
J. Nishikawa
M. Tamura

VECTOR VORTEX

J. Kuhn
E. Serabyn

CHARIS

J. Kasdin
M. A. Peters
T. Groff
M. Galvin
M. Carr

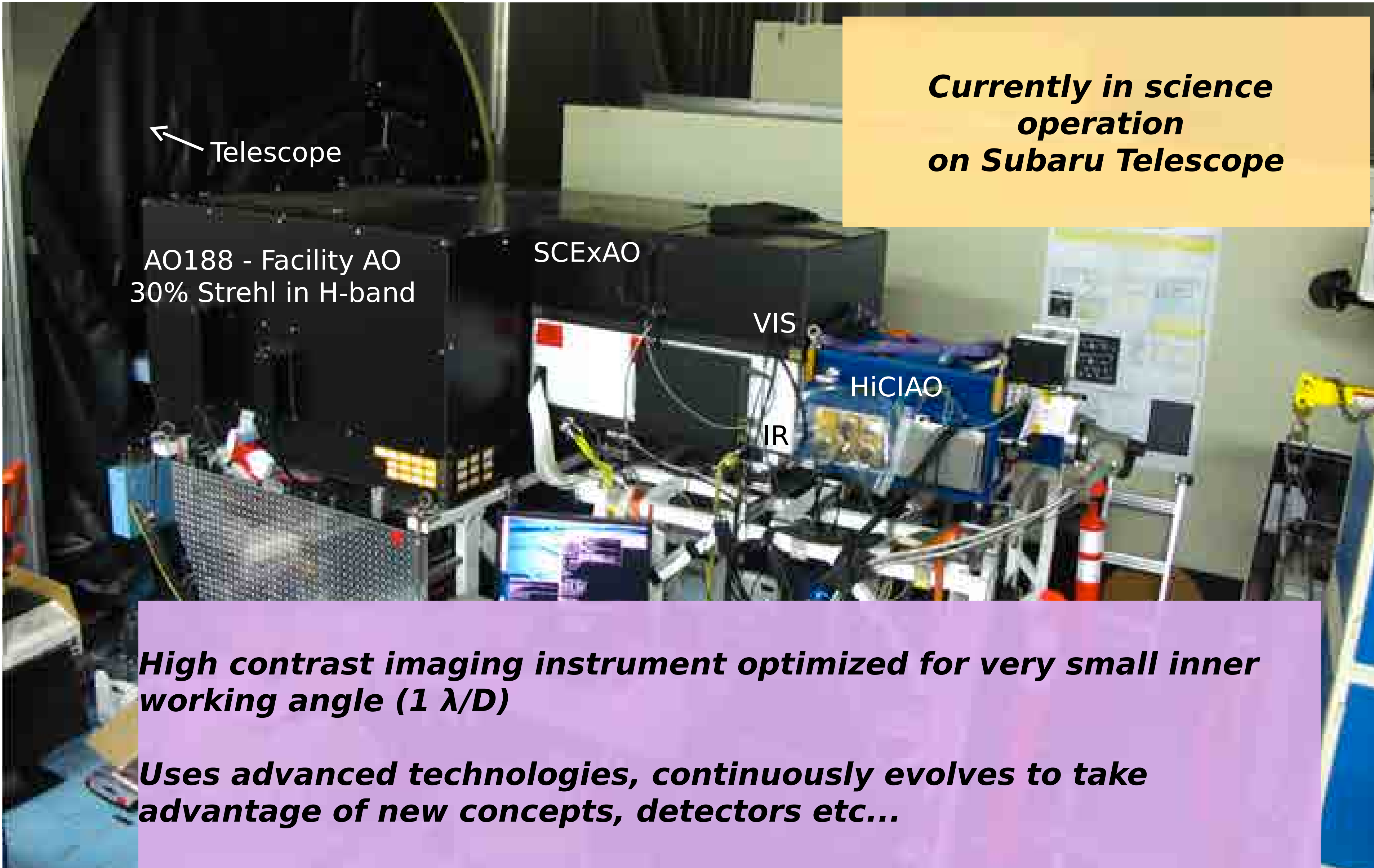
MKIDS

B. Mazin
S. Meeker
M. Strader
J. Van Eyken

FIBER INJECTION

N. Cvetojevic
C. Schwab
J. Lawrence

Subaru Coronagraphic Extreme AO (SCExAO)



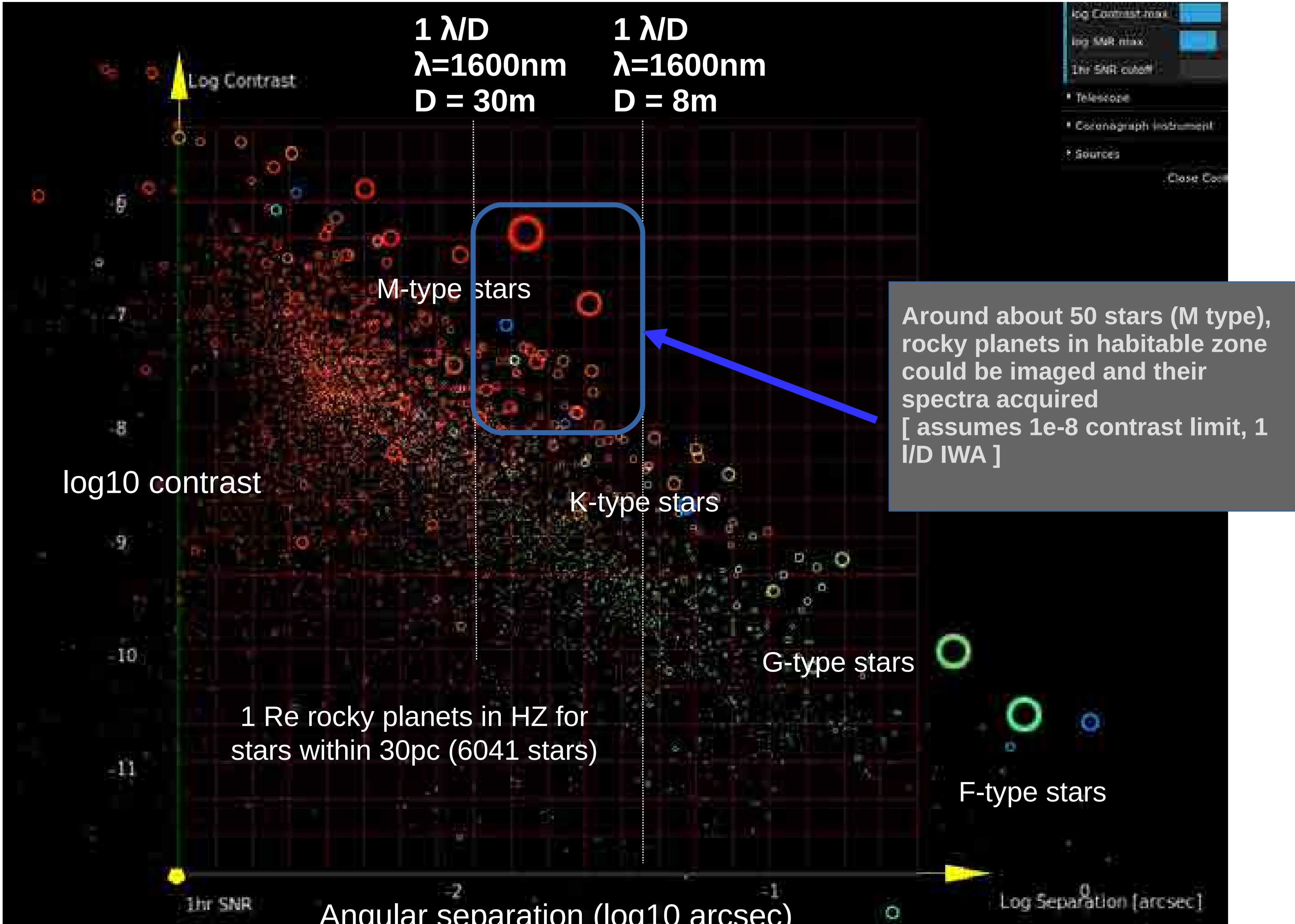
Currently in science operation on Subaru Telescope

High contrast imaging instrument optimized for very small inner working angle (1 λ/D)

Uses advanced technologies, continuously evolves to take advantage of new concepts, detectors etc...

Plans for SCExAO to become visitor instrument on TMT under study → will submit to TMT technical and scientific proposal

Most exciting science case: spectroscopic characterization of Earth-sized planets with TMT



Wavefront sensing:

- Non-modulated pyramid WFS (VIS)
- Coronagraphic low order wavefront sensor (IR) for non-common tip/tilt errors
- Near-IR speckle control

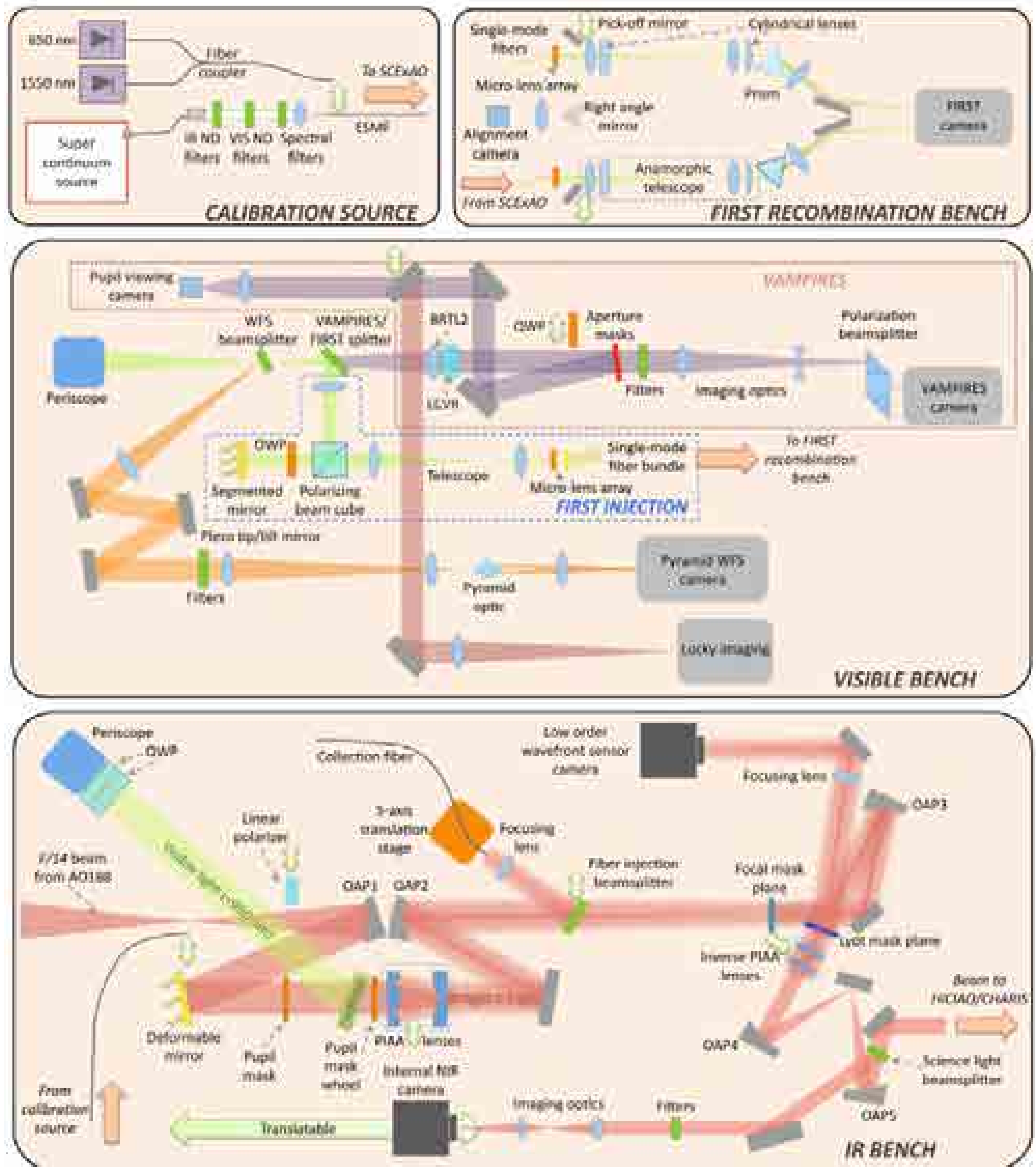
2k MEMS DM

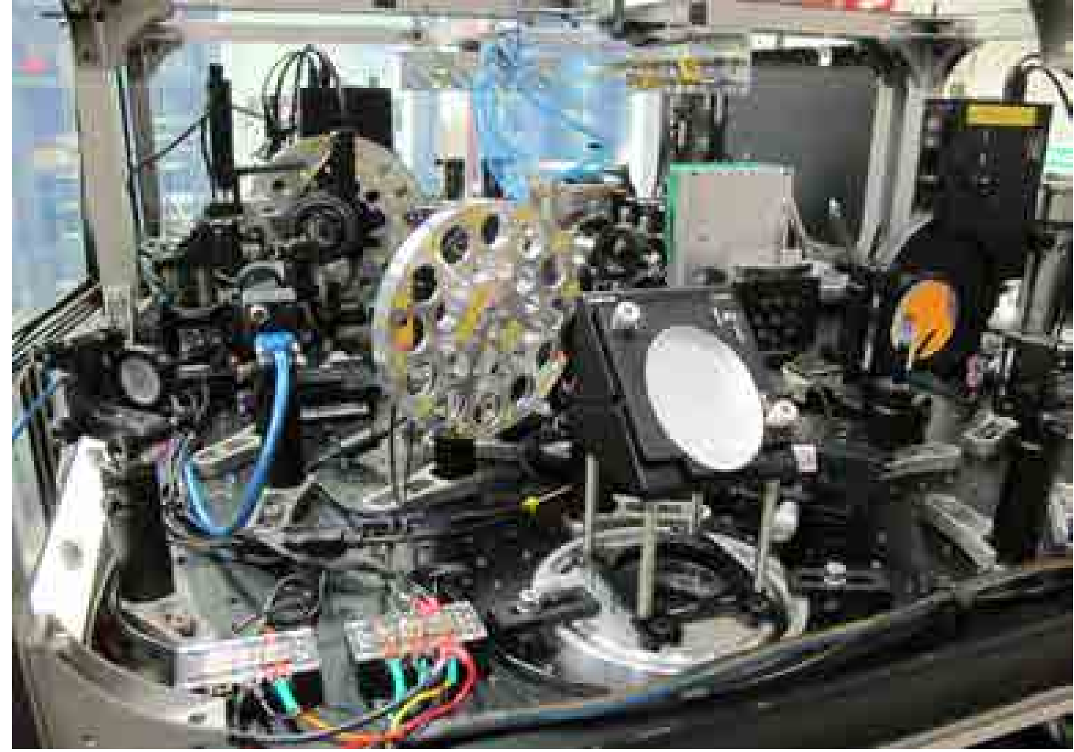
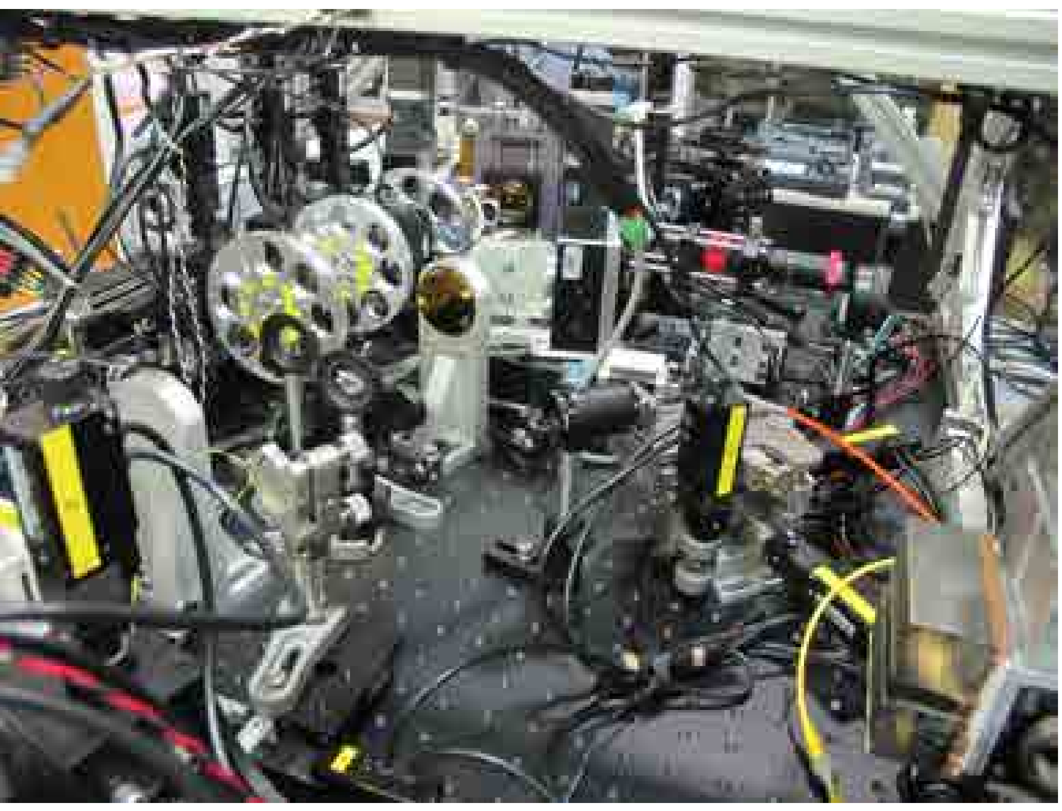
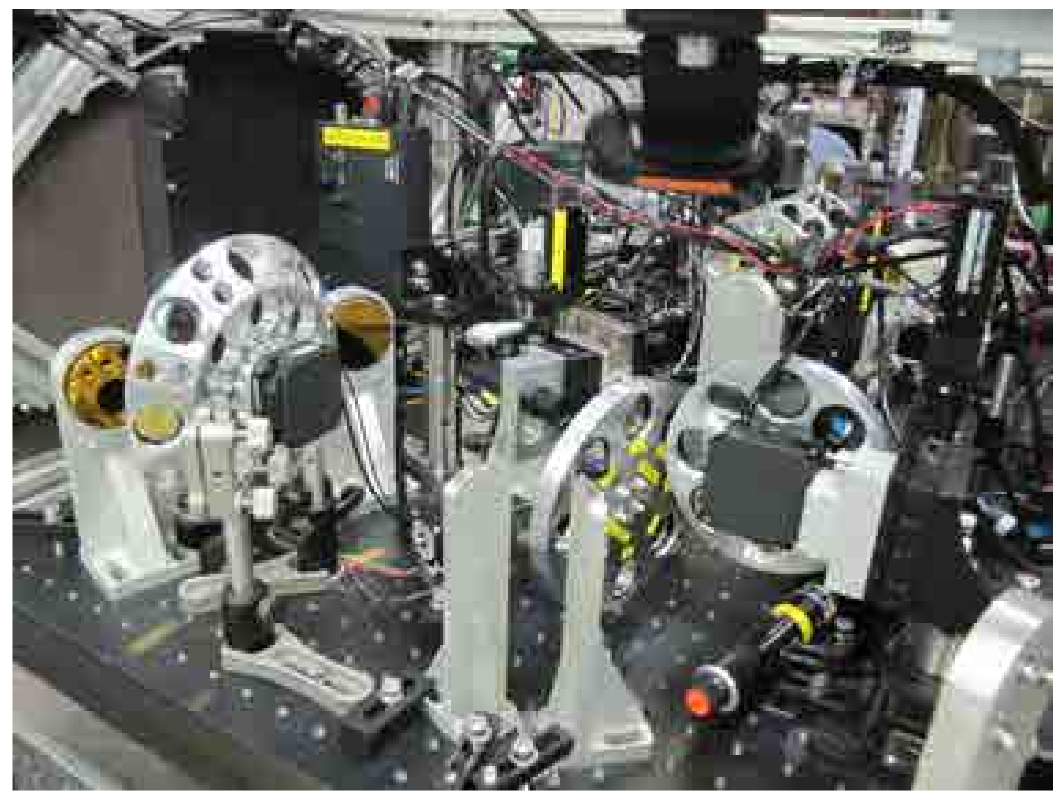
Numerous **coronagraphs** – PIAA, Vector Vortex, 4QPM, 8OPM, shaped pupil (IR)

Visible Aperture Masking Polarimetric Interferometer for Resolving Exoplanetory Signatures (VAMPIRES) (VIS)

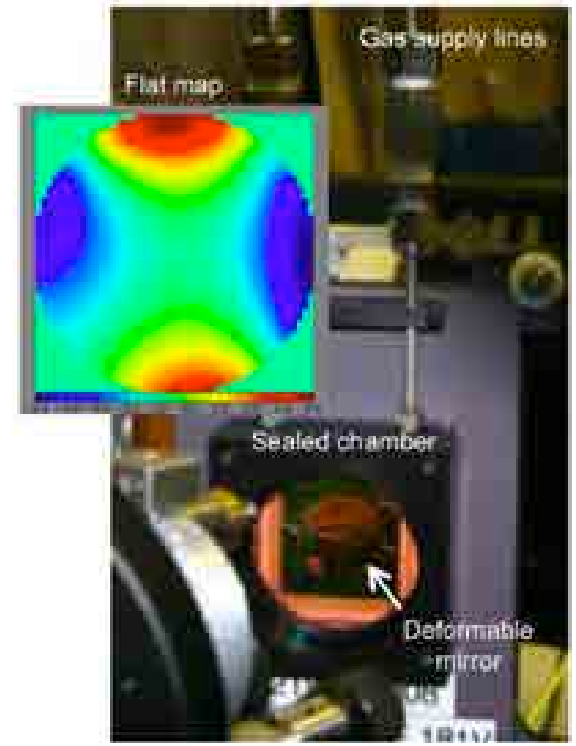
Fibered Imager for a Single Telescope (FIRST) (VIS)
Fourier Lucky imaging (VIS)

Broadband diffraction limited internal cal. Source + phase turbulence simulator



How SCExAO achieves high contrast

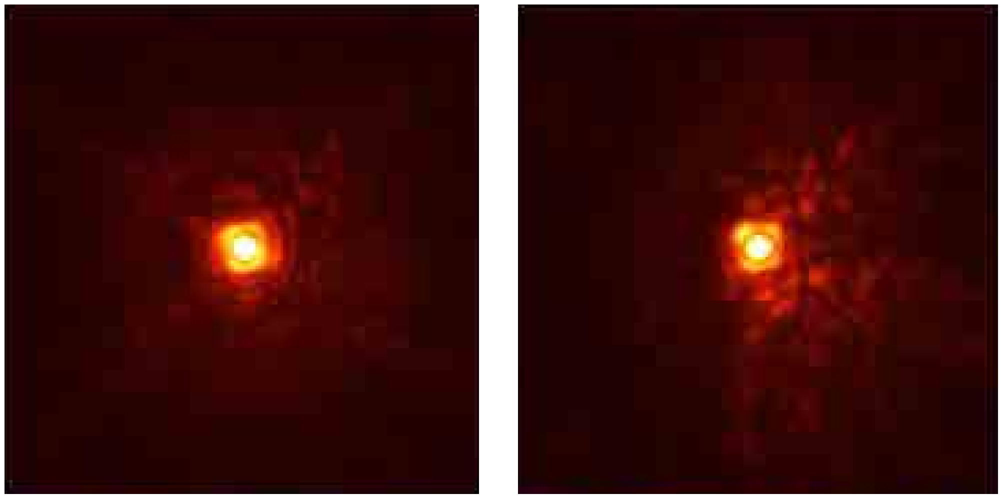


(1) Small IWA, high throughput Coronagraphy
→ removes diffraction (Airy rings), transmits r>1 l/D region

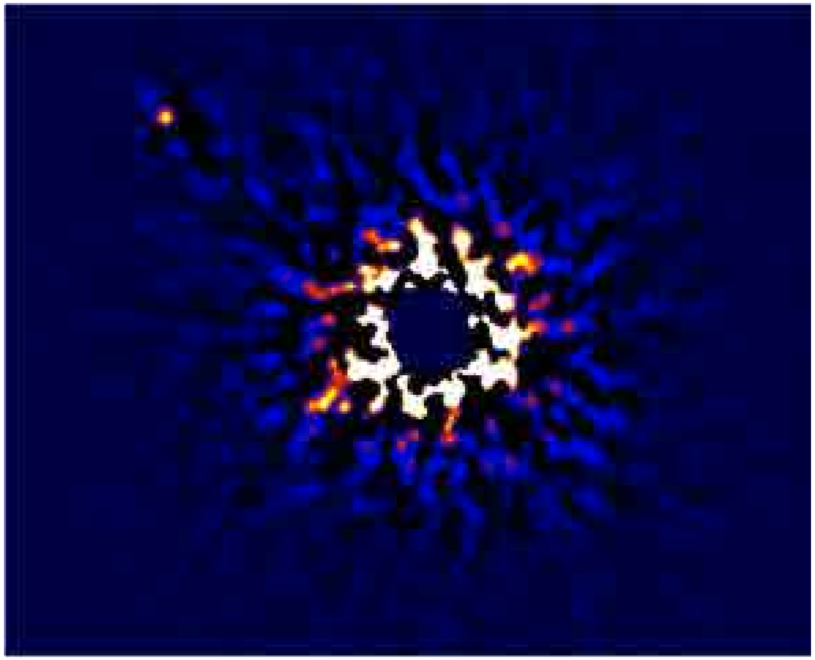
(2) Extreme-AO with fast diffraction-limited WFS
→ removes wavefront errors

(3) Near-IR LOWFS
→ keeps star centered on coronagraph and controls Focus, Astig, etc..
→ records residual WF errors to help process data

(4) Fast Near-IR Speckle control
→ modulates, removes and calibrates residual speckles

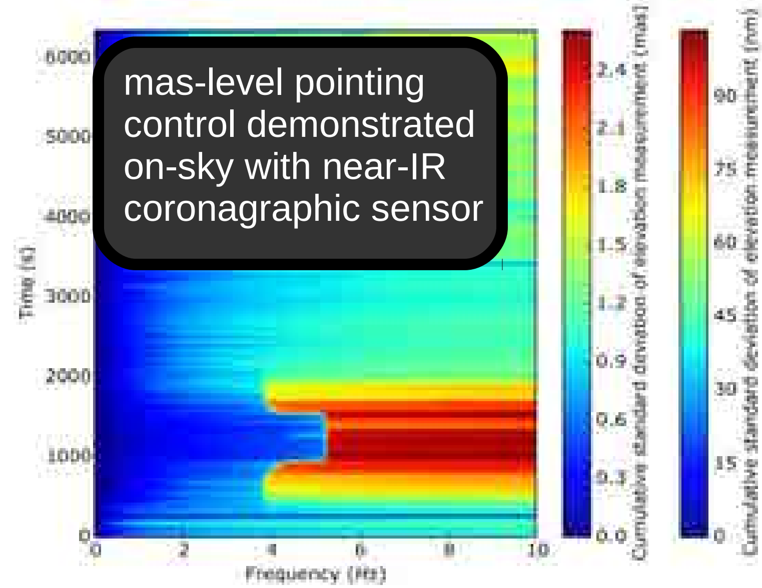


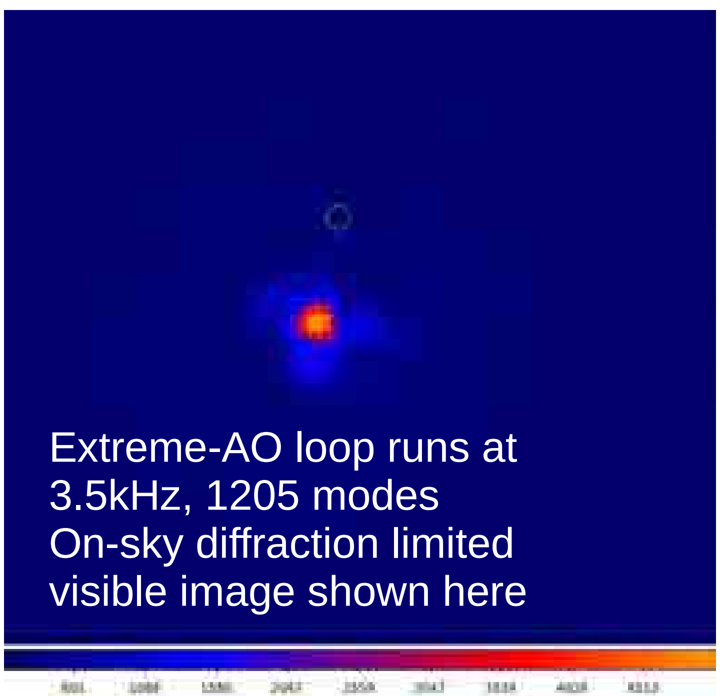
Speckle nulling on-sky

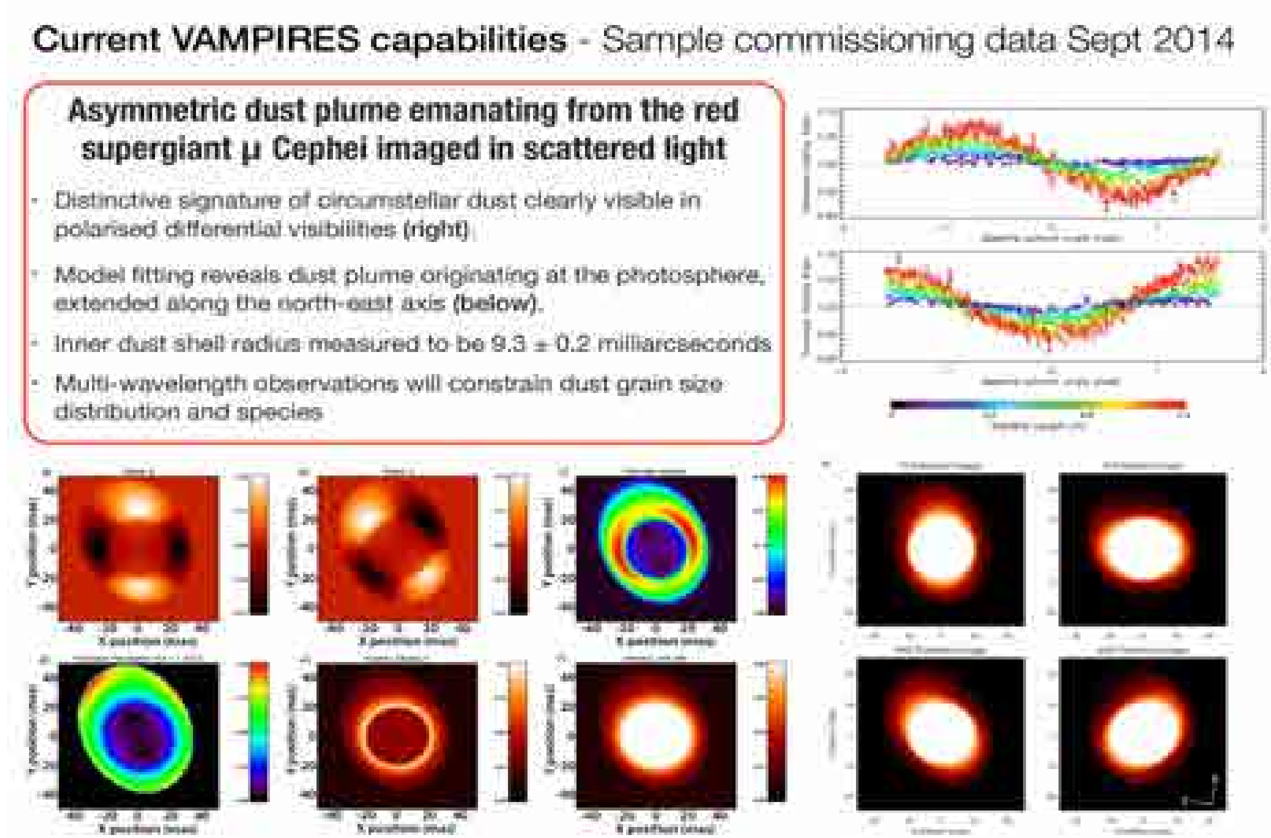


Kappa And (data reduction: T. Currie)

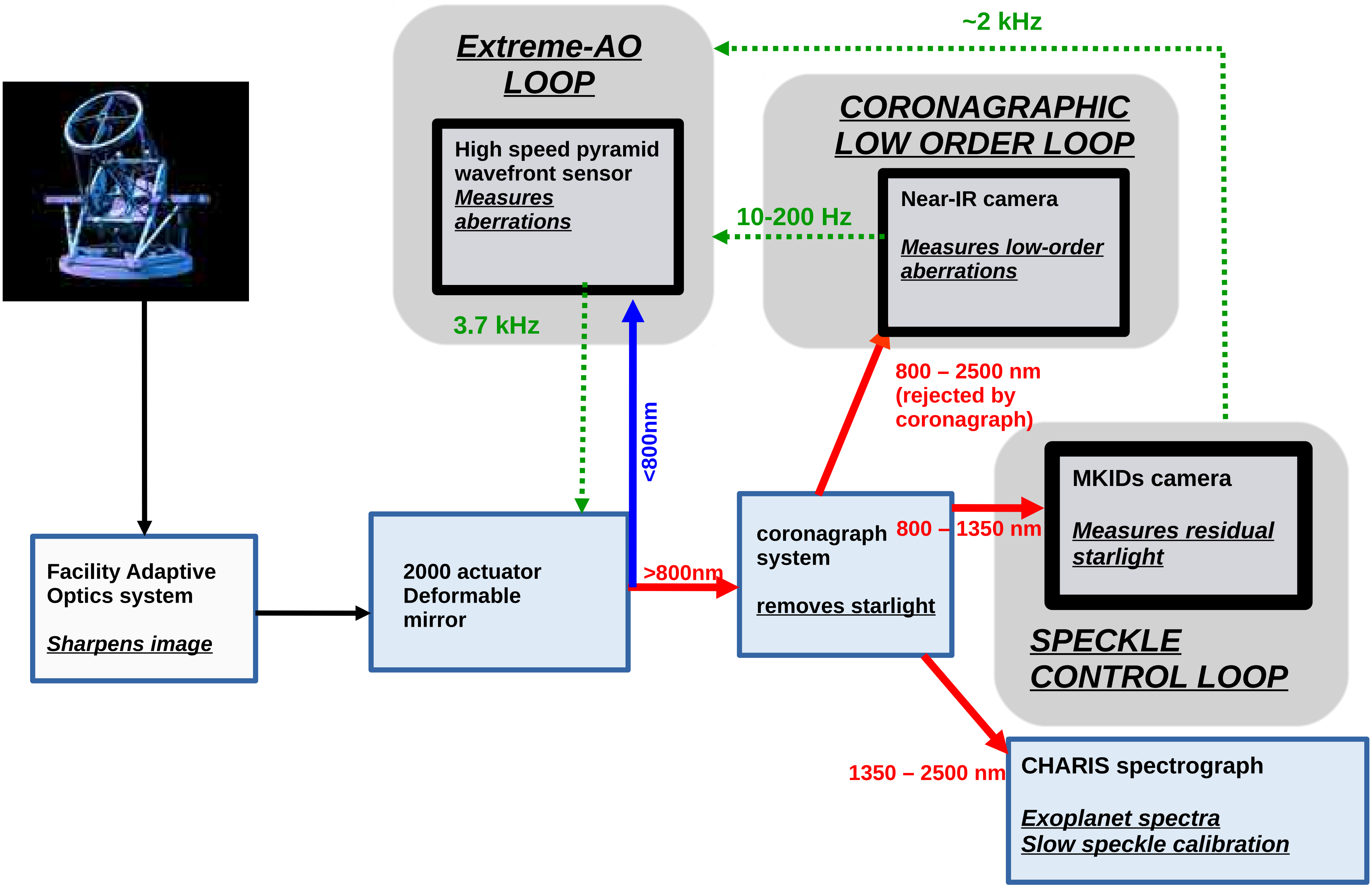
Early results





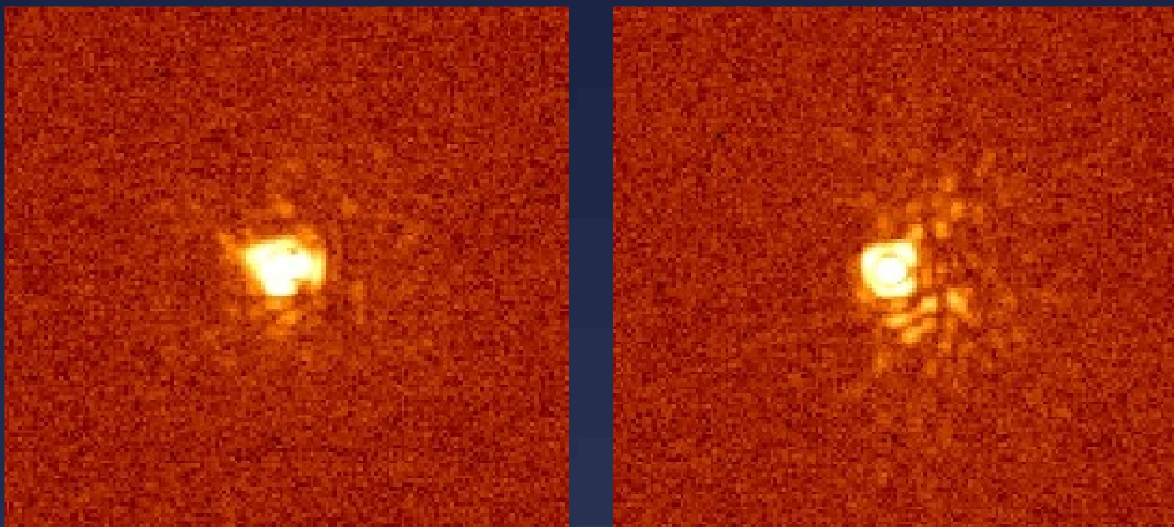


SCExAO: wavefront control loop



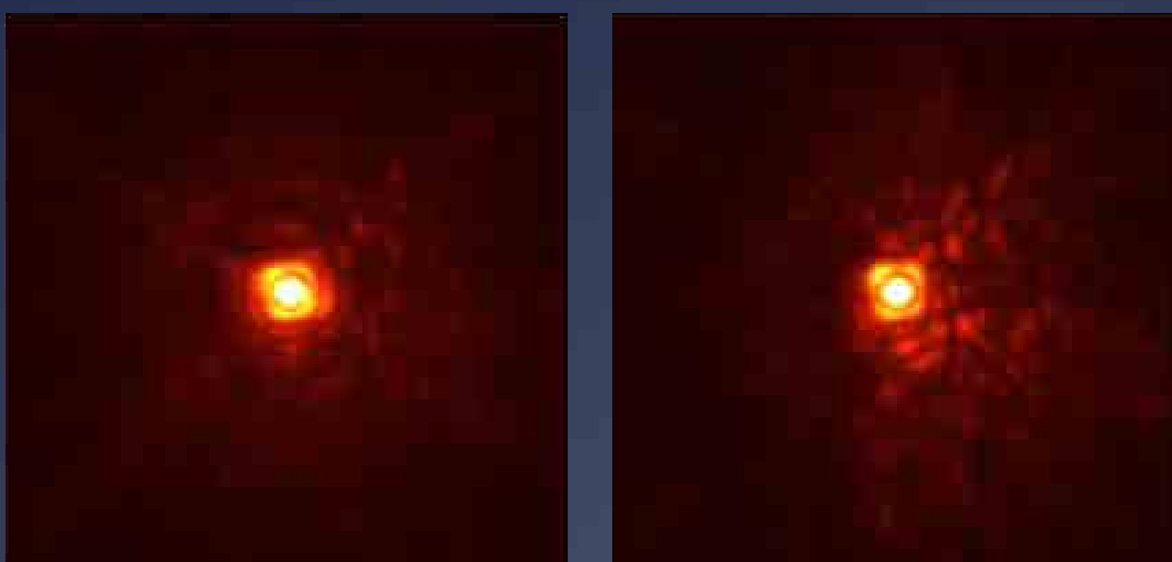
speckle nulling results on-sky (June 2014)

Single frames: 50 us



Meta data:

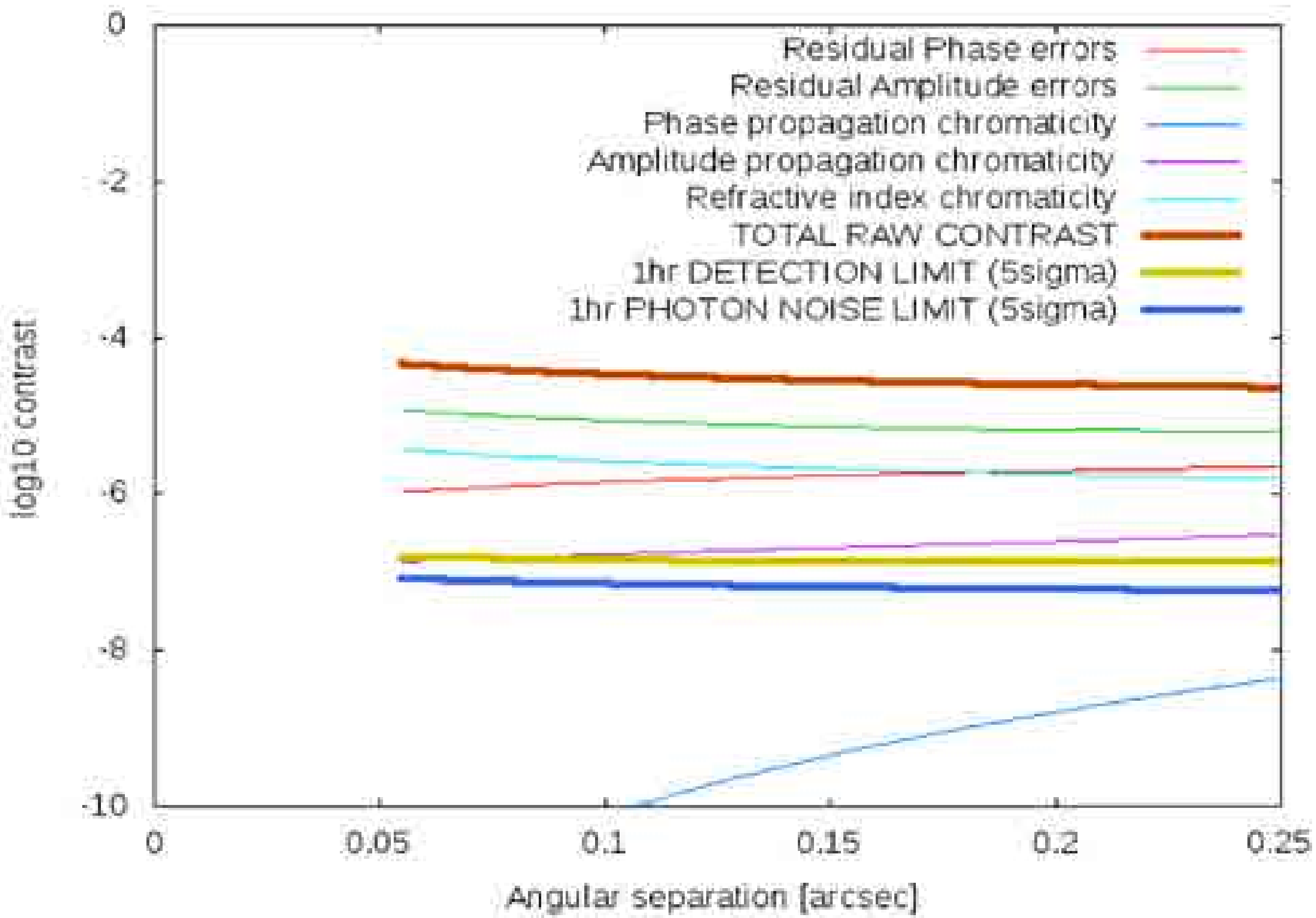
Date: 2^{nd} or June
Target: RX Boo (also repeated on Vega)
Seeing: <0.6”
AO correction: 0.06” post-AO corrected in H- band (0.04” is diffraction-limit)
Coronagraph: None (used Vortex on Vega)

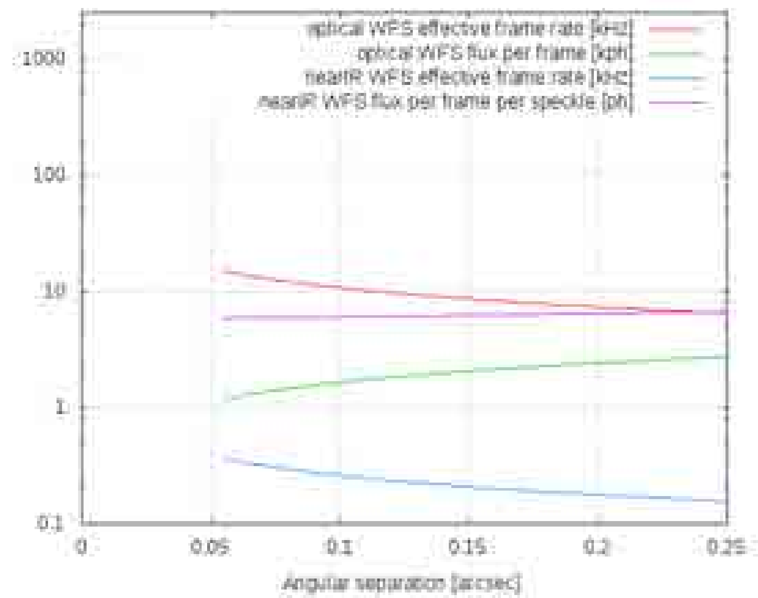


Sum of 5000 frames: shift and add

Martinache, F. et. al.

8m: Pyramid-based system + nearIR Speckle Control → 100x contrast gain





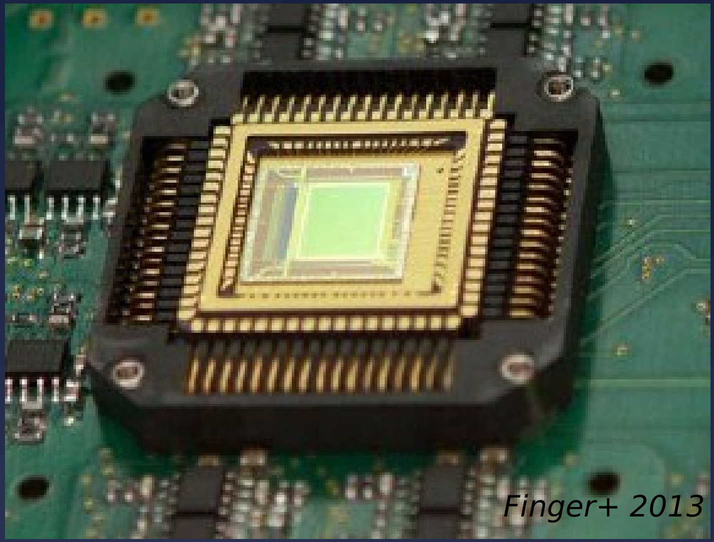
300Hz speckle control loop (~1kHz frame rate) is optimal

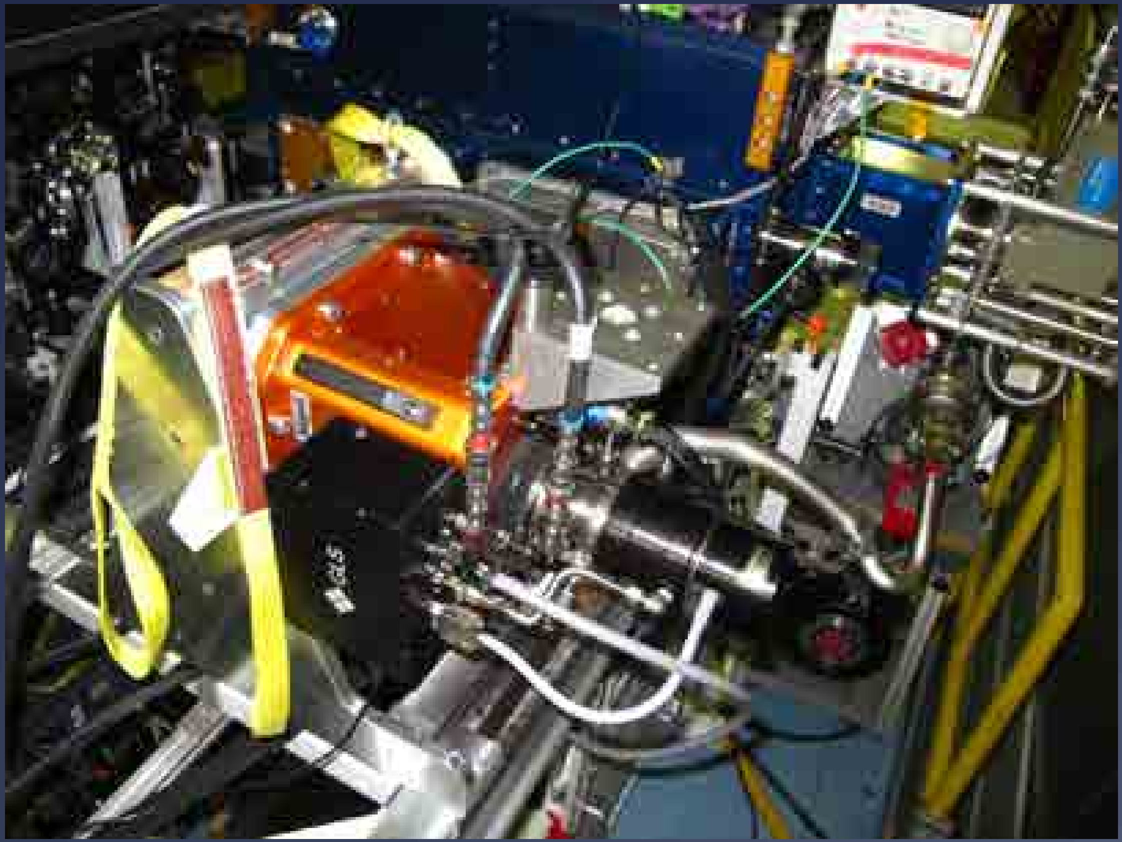
Residual speckle at ~5e-5 contrast and fast → good averaging to detection limit at few `1e-7

SAPHIRA Infrared APD array

HgCdTe avalanche photodiode manufactured by Selex

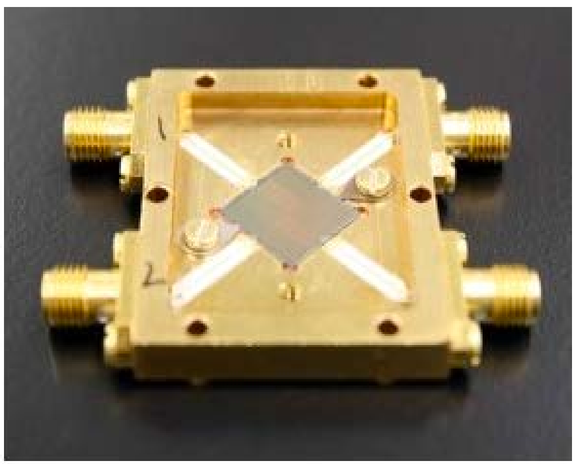
<u>Specifications</u>
320 x 256 x 24µm
32 outputs
5 MHz/Pix

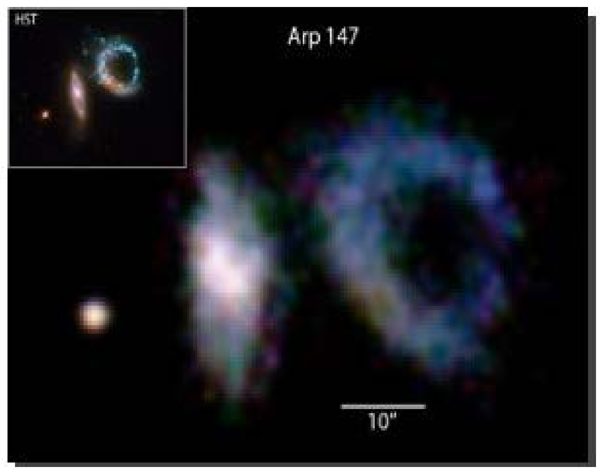




MKIDS camera (built by UCSB for SCExAO)

Photon-counting, wavelength resolving 100x200 pixel camera

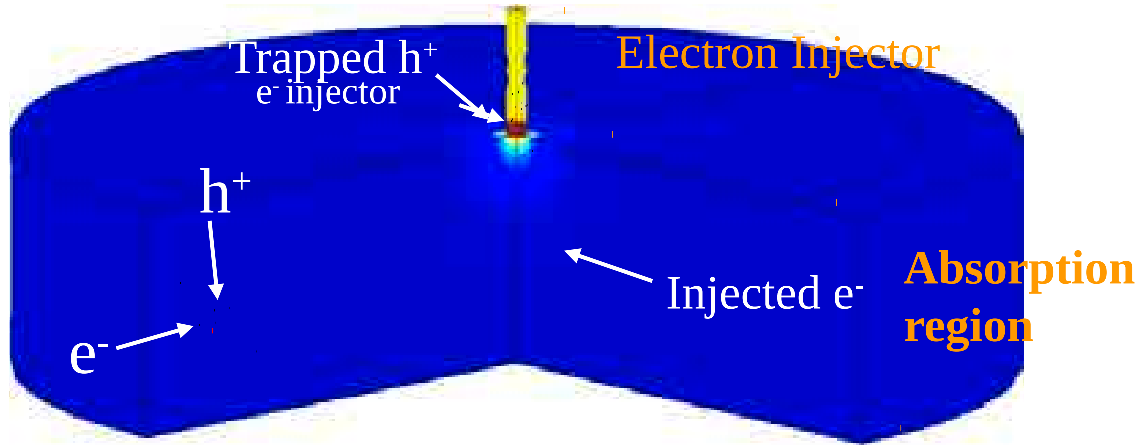


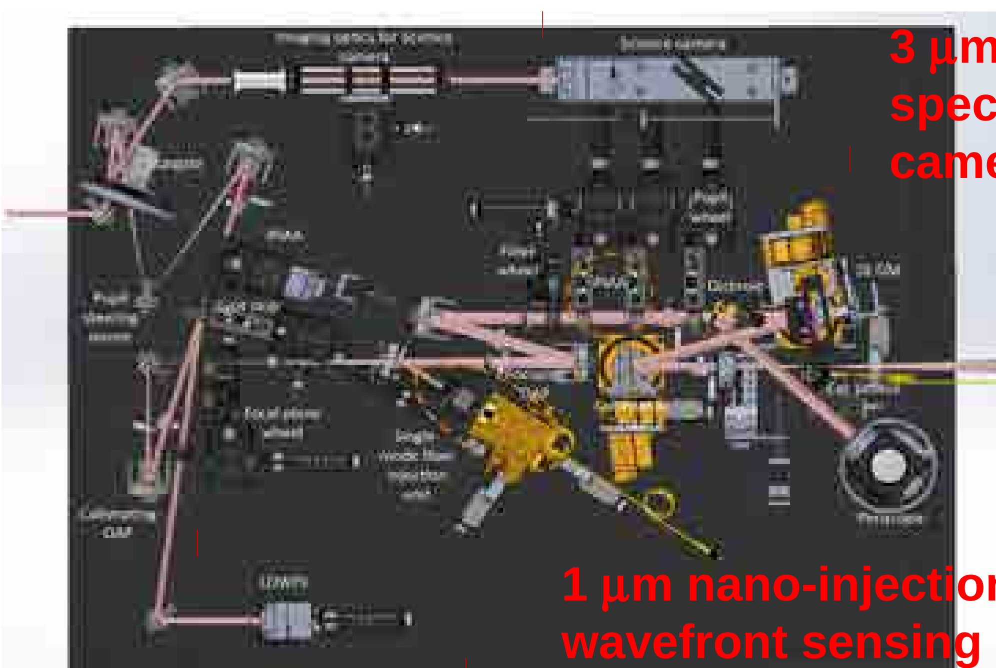


Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB

Delivery to SCExAO in CY2016

Nano-injector nearIR camera (Northwestern Univ / Keck foundation)





3 µm nano-injection speckle imaging camera

1 µm nano-injection low-order wavefront sensing (pointing) camera

SCExAO high contrast imaging capabilities: expected schedule for capabilities offered to observers

NearIR planet detection at moderate contrast

→ **NearIR planet imaging at high contrast**
Visible light interferometry, polarimetry
(disks, stellar physics)

→ **Near-IR spectroscopic characterization**
Ultra-High contrast → reflected light
strong visible light capabilities

2014 | 2015 | 2016 | 2017

VAMPIRES **PyWFS** **SAPHIRA** **FIRST** **CHARIS** **MKIDs** **Nano-injector cams**

Phase 1 operation

LOWFS + slow speckle control →
Moderate contrast improvement over HiCIAO

Small IWA (~2 l/D) coronagraphy

Phase 2 operation

Significant contrast improvement over HiCIAO thanks to ExAO
High SR (~0.9)
→ more robust performance for coronagraph and LOWFS systems

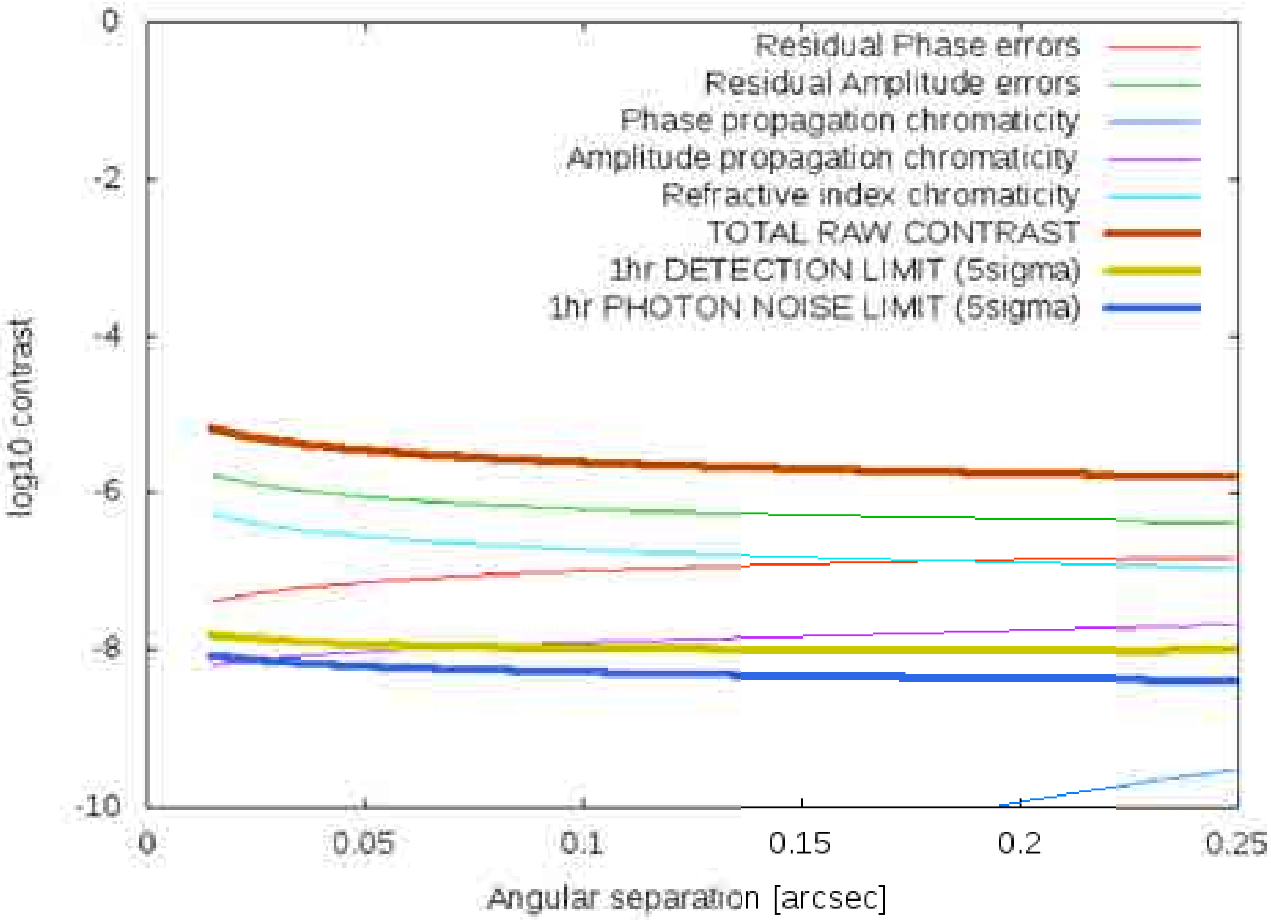
Smaller IWA (~1 l/D)

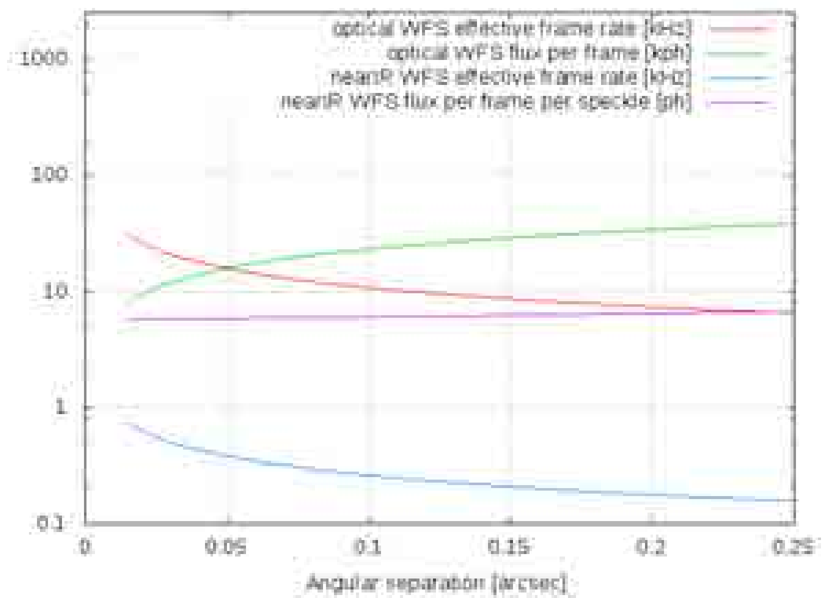
Full system (CHARIS+MKIDS)

MKIDs camera → faster speckle control and better calibration → significantly higher contrast at small separation (~1e-8)

Spectroscopy:
CHARIS + MKIDS provide spectroscopy from ~0.8 um to 2.7um

30m: Pyramid-based system + speckle control

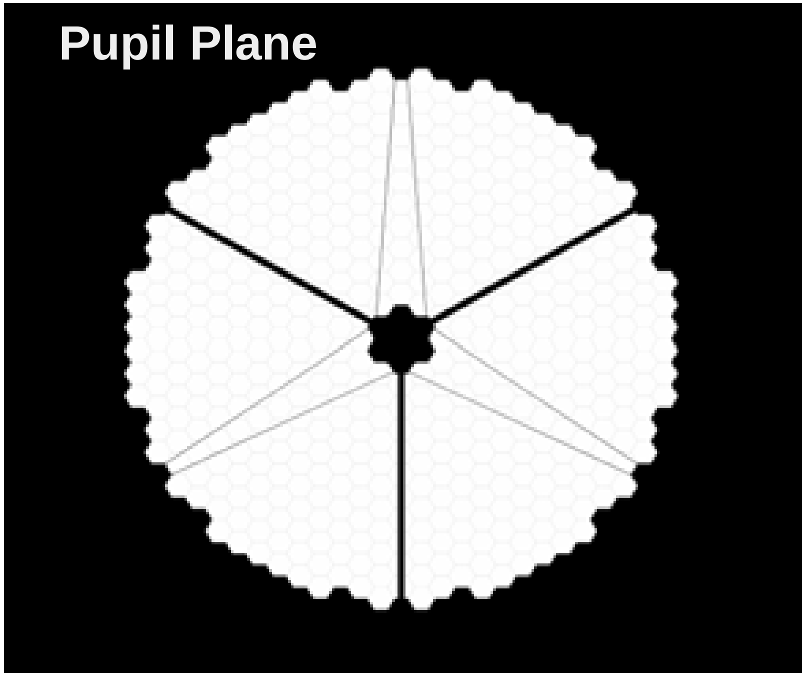


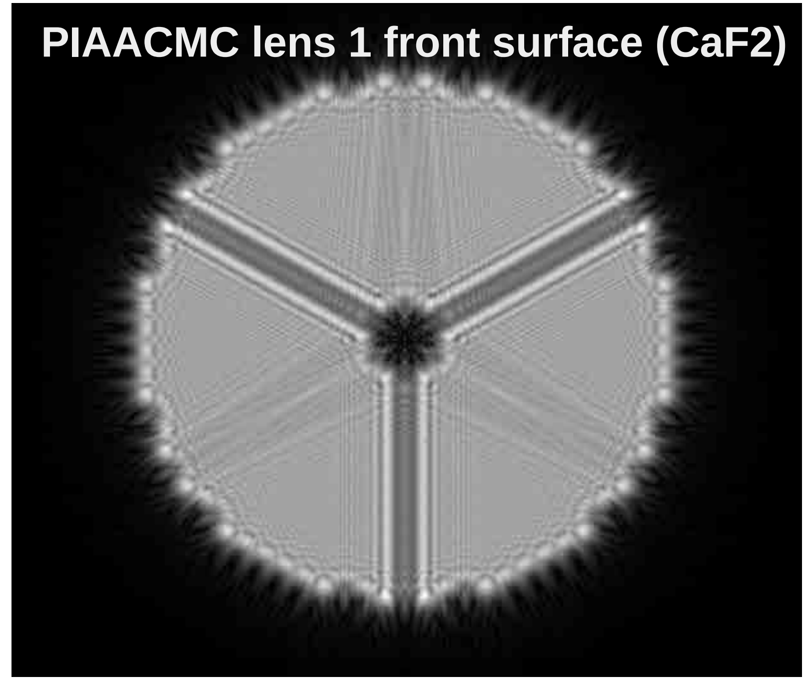


300Hz speckle control loop (~1kHz frame rate) is optimal

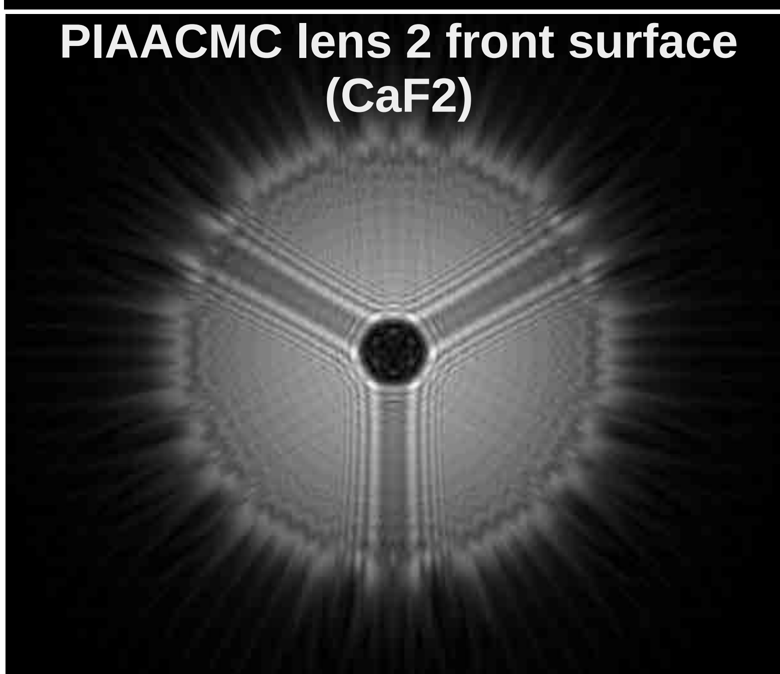
Residual speckle at ~1e-6 contrast and fast → good averaging to detection limit at ~1e-8

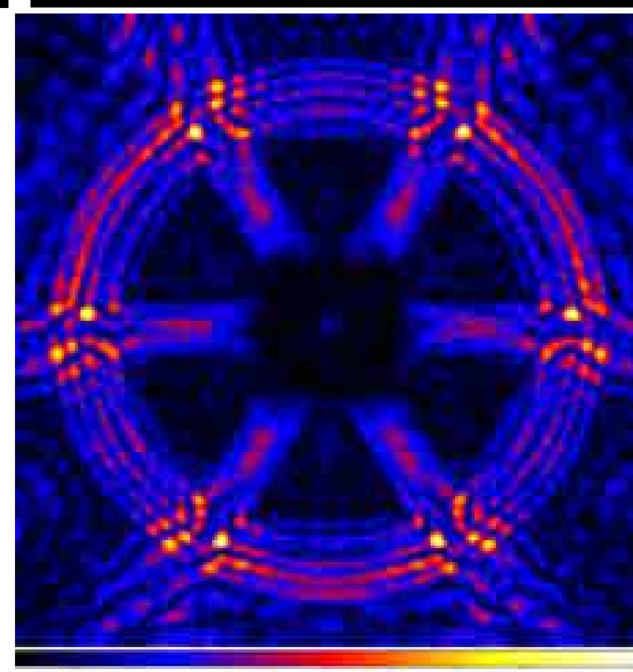
TMT coronagraph design for 1 l/D IWA





To be updated with new pupil shape





PSF at 1600nm

3e-9 contrast in 1.2 to 8 l/D

80% off-axis throughput

1.2 l/D IWA

CaF2 lenses
SiO2 mask

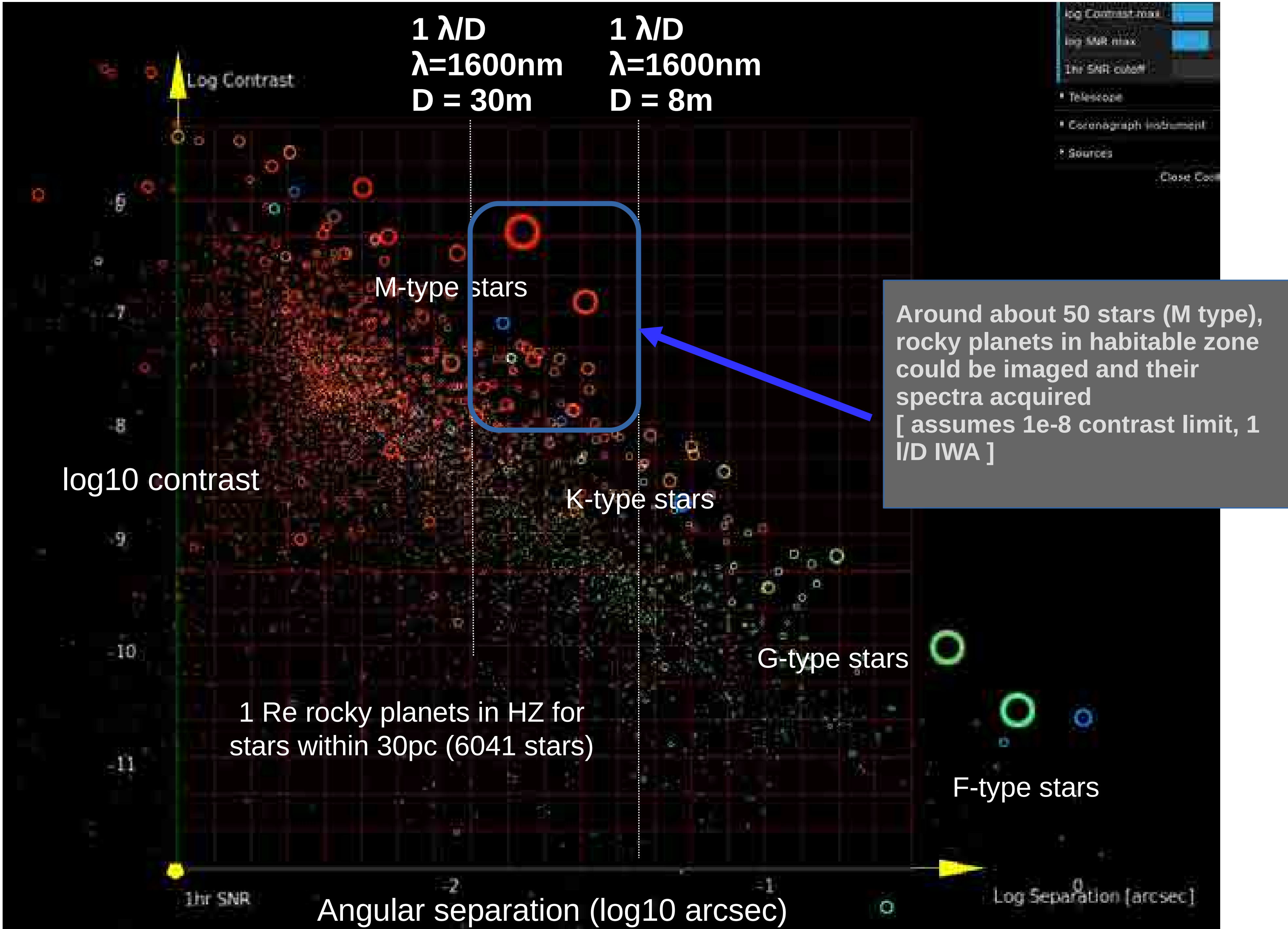
From Subaru to habitable planets characterization on TMT

Much of the system would be unchanged, but input beam feed to SCExAO would be re-built. Two options under consideration:
- Add “Woofer” stage + ADC in front of current system (currently favored)
- Feed SCExAO from NFIRAOS

Demonstrate and validate performance on Subaru prior to deployment on TMT
→system ready to go as first light visitor instrument, with well understood science performance
→mitigates risks and minimizes need for engineering/commissioning time on TMT
→ benefits from yrs of practice and experience on Subaru (loop control, data reduction algorithms, observing strategy)

Open international effort engaging TMT partners. Expected overlap with development team of 2nd generation, more capable ExAO system.

Spectroscopic characterization of Earth-sized planets with TMT



PANOPTES **P**anoptic **A**stronomical **N**etworked **OP**tical observatory for **T**ransiting **E**xoplanets **S**urvey

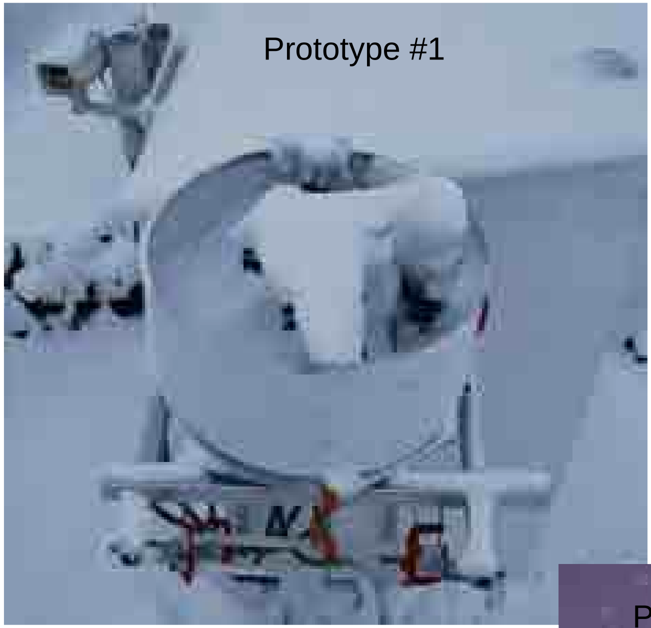
Discovering transiting exoplanets requires monitoring large parts of the sky for long periods of time

The most efficient way to do this is to use inexpensive digital cameras

PANOPTES is a citizen science project aimed at discovering a large number of exoplanets

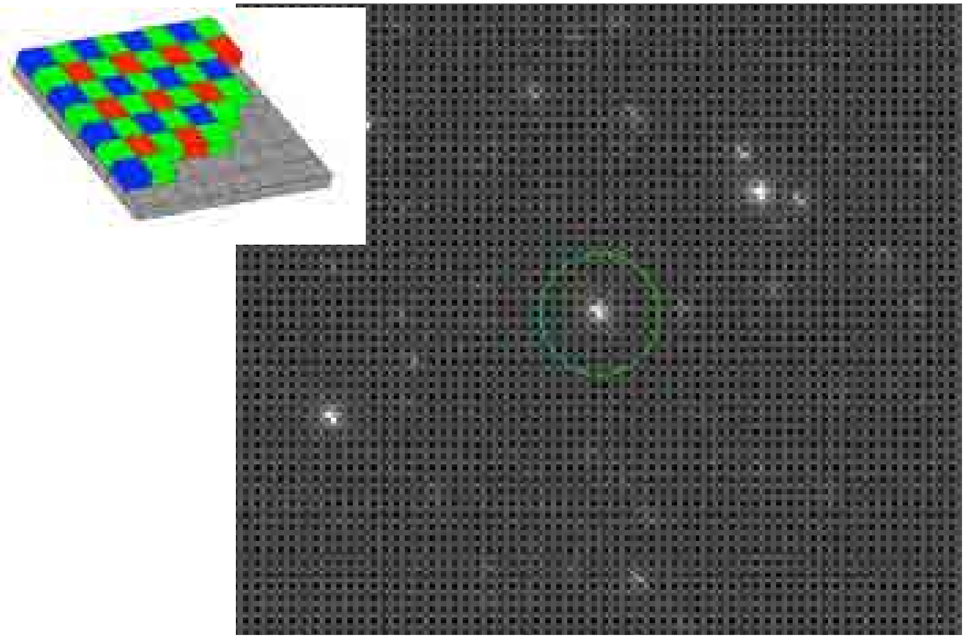
Cameras: Canon EOS SL1 (x2), Lenses: Rokinon 85mm F1.4 (x2)
Mount: iOptron IEQ30
Weather and cloud sensor
12V computer. All system runs on 12V battery charged by 120V AC (resilient to short power failures)
Python-based software

PANOPTES prototypes (2010-2014)



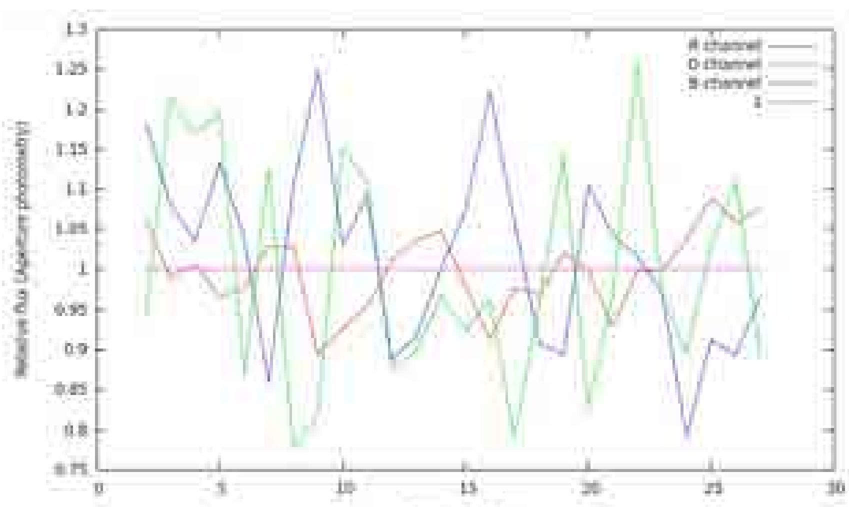
Project started in 2010 with deployment of prototype #1 at the Mauna Loa observatory (Hawaii, USA).
2013: prototype #3 deployed at Mauna Loa observatory
Quasi-continuous robotic operation of prototypes since early 2011

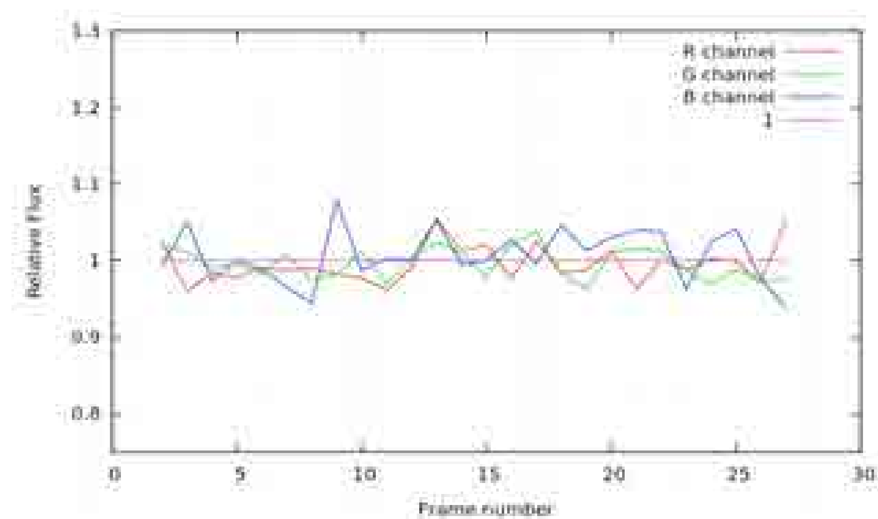
Precision flux measurement



Color DSLR cameras have “colored” pixels → we can't simply add pixel values to measure star brightness

We use comparisons between ~100,000 star images available in each field to calibrate flux

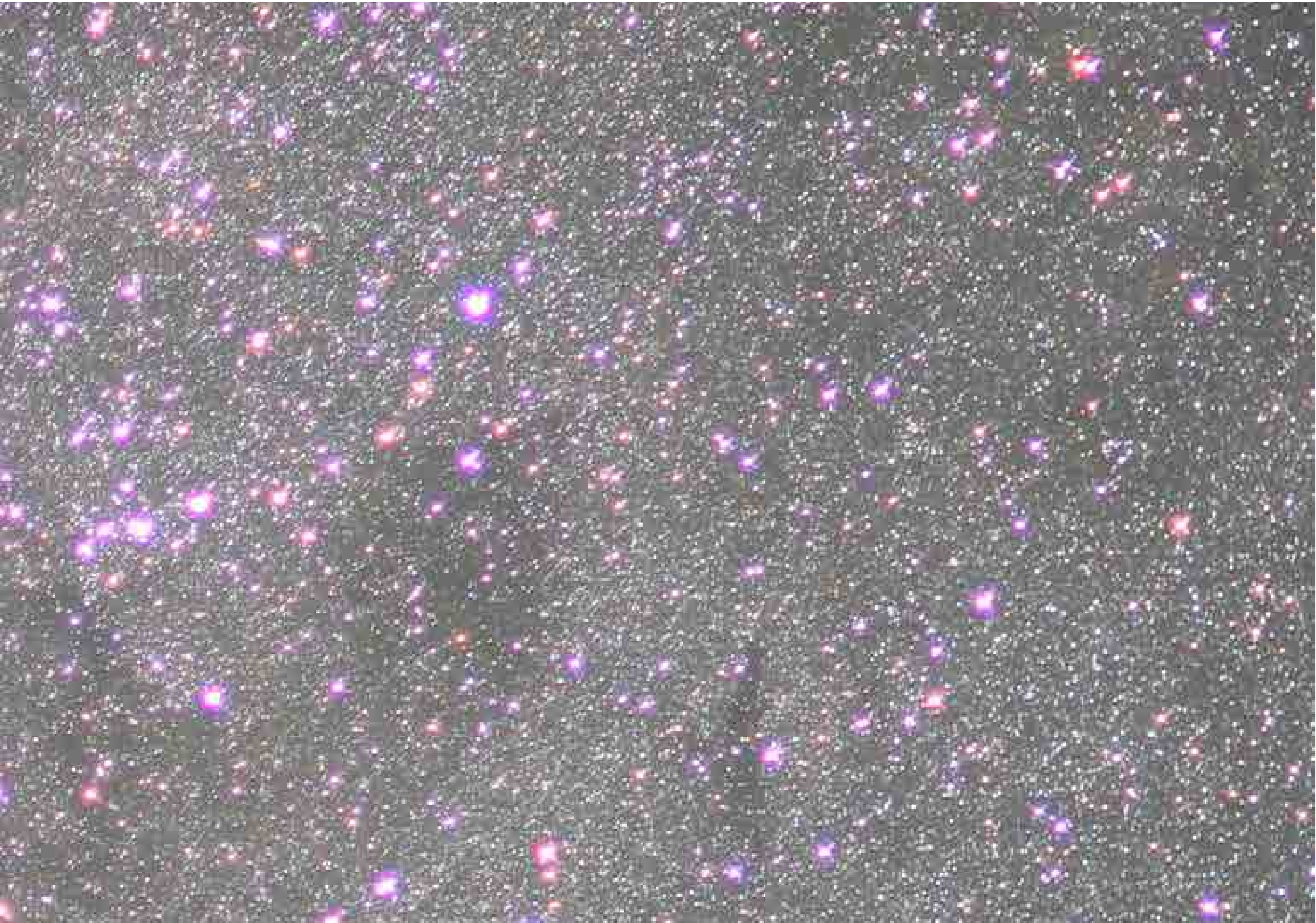




Orion field (image processed by Jon Talbot)

Comet Lovejoy (image processed by Jon Talbot)

Example image (Cygnus field): >100,000 stars in a single image



More info, how to join PANOPTES

Project website: www.projectpanoptes.org
Software: https://github.com/panoptes
Joining request: info@projectpanoptes.org