Direct Imaging and spectroscopic Characterization of habitable Exoplanets with ELTs

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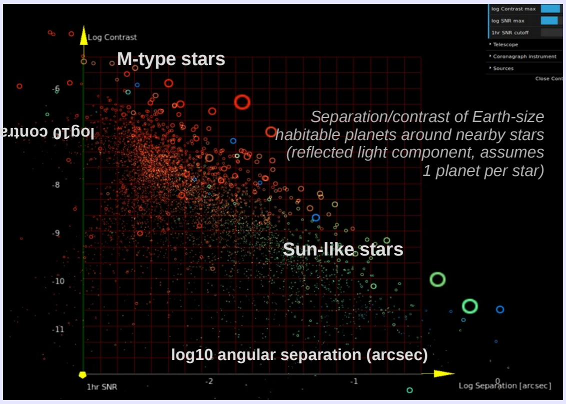
Extremely Large Telescopes (ELTs), will offer the angular resolution to resolve the habitable zone of nearby M-type stars (~20mas) in the near-IR. Reflected light contrast for Earth-size planets in the habitable zone of these stars is ~1e-7. Such planets can be imaged and characterized with ELTs in the near-IR, likely providing the first opportunity for detection of biosignatures outside our solar system.
Technologies supporting this goal are under development and validation on the Subaru Coronagraphic Extreme-AO (SCExAO) instrument, with a goal to be ready for deployment soon after TMT first light.



Separation/contrast of Earth-size habitable planets around nearby stars (reflected light component, assumes 1 planet per star)

Targets

For approximately 50 stars, high contrast imaging-optimized instrument can image (reflected light) Earth-size planet in habitable zone with 30m telescope.

Selection criteria are based on angular separation (> 1 l/D), contrast (> 1e-8, function of stellar flux), planet apparent brightness (sensitivity for spectroscopy), star brightness (wavefront sensing sensitivity).

Most favorable targets

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

Key technologies & expected performance

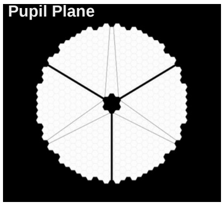
1. High performance Coronagraphy enables efficient access to habitable zones of nearby M-type stars
Small inner working angle (~1 l/D), at <1e-6 raw contrast in 20% wide spectral band achievable on segmented TMT pupil (example: PIAACMC design)

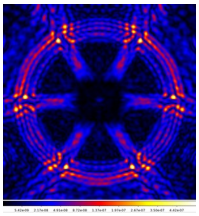
2. Extreme-AO correction is required to reduce speckle noise and deliver stable high quality PSF
New generation of wavefront sensors operate at diffraction-limited sensitivity → on TMT, **40,000x gain in sensitivity** compared to seeing-limited sensors (such as Shack-Hartmann)
This sensitivity gain + new near-IR photon-counting detectors allow ExtremeAO correction to deliver high performance on nearby M stars.

3. Coronagraphic Low-order Wavefront sensing & control operating at the science wavelength measures and corrects residual low-order modes (due mostly to atmosphere chromaticity) that would otherwise be confused for exoplanet detections near the coronagraph's IWA

4. Focal plane speckle control actively cancels coherent light (speckles) in the science image

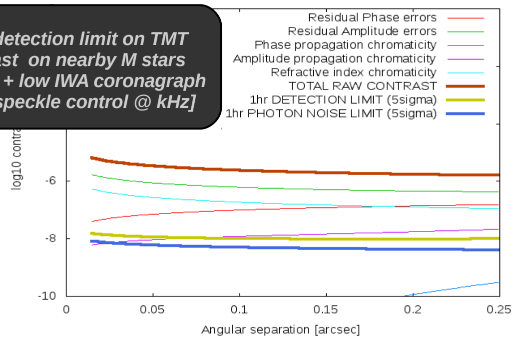
5. Coherence differential imaging (CDI) isolates incoherent exoplanet light from coherent starlight
CDI is a powerful alternative to passive post-processing approaches such as angular differential imaging (ADI), which does not perform well at small angular separation





TMT PIAACMC design

Coronagraphic PSF@ 1600nm
3e-9 contrast in 1.2 to 8 l/D
80% off-axis throughput
1.2 l/D IWA
CaF2 lenses
SiO2 mask



Predicted detection limit on TMT 1e-8 contrast on nearby M stars [fast ExAO + low IWA coronagraph + near-IR speckle control @ kHz]

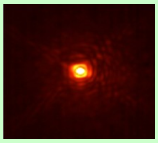
Path forward: from SCExAO on Subaru to TMT instrument

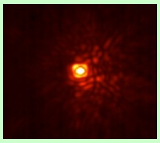
Develop/demonstrate system on 8-m telescope

SCExAO on Subaru Telescope combines key technologies 1-5
Next few years: understand system-level operation, develop algorithm, measure and understand on-sky performance

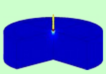
SCExAO's high-speed DM

SCExAO works closely with near-IR detector development teams to enable kHz speckle control



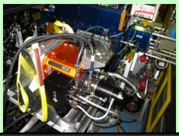


on-sky speckle control with SCExAO (H band, InGas camera)
Performance currently limited by near-IR detector



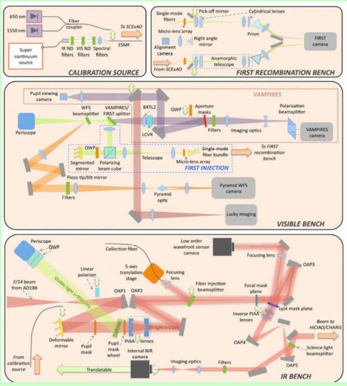
Electron injection (EI) near-IR detector development (Northwestern Univ & Keck foundation)

Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB
Delivery to SCExAO in CY2016



Low-noise fast near-IR SAPHIRA camera currently in use with SCExAO (Univ, of Hawaii)

SCExAO architecture



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

SCExAO is evolving toward a TMT-ready instrument in ~10yr

Goal: deployment on TMT soon after first light
→ Early detection and (some) characterization of habitable planets around M-type stars
→ Scientific and technology precursor to more capable 2nd or 3rd generation ExAO instrument(s) on TMT and other ELTs.

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SCExAO instrument webpage on www.naoj.org