The Subaru Coronagraphic Extreme-AO (SCExAO) system

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+ HiCIAO team, AO188 team
OUTLINE

INTRODUCTION
High contrast imaging at 1 l/D

SCExAO SYSTEM
Solutions to high contrast imaging at 1 l/D
– coronagraphy
– wavefront control
– calibration

SCExAO schedule and early results

SCExAO as a precursor to imaging habitable planets with ELTs
The Subaru Coronagraphic Extreme-AO (SCExAO) system

High contrast imaging at small angular separation is scientifically extremely valuable:

- allows system to probe **inner parts of young planetary systems** (<10 AU)
- constrain planet formation in the **habitable zone** of stars
- **direct imaging** of reflected light planets may be possible (reflected flux goes as $a^{-2}$)

**Coronagraphy:**
High efficiency $1 \lambda/D$ PIAA coronagraph

**Wavefront control:**
- NIR focal plane WF control/calibration
- ExAO-optimized visible WFS visible channel
- Exquisite pointing control

**Aux. Science modes:**
- Non-redundant masking
- Visible light imaging

Designed as a **highly flexible, evolvable platform**
(reduce time from lab demo to science)
Efficient use of AO188 system & HiCIAO camera
Technology development overlap with space coronagraphy
PIAA lab at Subaru Telescope
High contrast imaging in lab reaches much higher performance than what is currently achieved on-sky: newer technologies, more stable environment, better calibrations

SCExAO's goal is to deploy on the telescope new techniques which have been demonstrated in the lab to offer high performance, and to create the conditions necessary to achieve this high performance.

Log contrast
Coronagraphy testbeds for high contrast (< 1e-8) work need to achieve high stability

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

NASA Ames testing PIAA coronagraph / WFC architectures & MEMs DMs.
SCExAO at Subaru Telescope (Aug 2010)
[note: HiCIAO camera not in this image]
[note: IFS under design, built by Princeton]
The Subaru Coronagraphic Extreme-AO (SCExAO) system
The Subaru Coronagraphic Extreme-AO (SCExAO) system
The Subaru Coronagraphic Extreme-AO (SCExAO) system
Phase-Induced Amplitude Apodization (PIAA) coronagraph

Utilizes lossless beam apodization with aspheric optics (mirrors or lenses) to concentrate starlight in single diffraction peak (no Airy rings).

- high contrast (limited by WF quality)
- Nearly 100% throughput
- IWA $0.64 \lambda/D$ to $2 \lambda/D$
- 100% search area
- no loss in angular resol.
- can remove central obscl. and spiders
- achromatic (with mirrors)

Refs: Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present
Lab demos at NASA Ames, NASA JPL for space coronagraphy
3rd generation refractive PIAA optics

- On-axis lenses
- Lenses are 96 mm apart
- Apodize the beam
- Remove the central obscuration
Spider Removal Plate

- 15 mm thick precision window
- Fused Silica
- Tilt angle: 5 +/- 0.02°
Beam shaping hardware
SCExAO Wavefront Control architecture and speckle calibration

Under development at Subaru, UofA, HIA (currently Pyramid)

AO188

AO188 curvature WFS
Uses photon-counting APDs

 Facility AO sytem AO188 (bimorph curvature DM, 188 elements, 1 kHz update)

32x32 actuators MEMS
Deformable mirror
(600 actuators illuminated, low stroke, fast)

High speed high sensitivity ExAO visible
WFS (non-linear curvature)

Near-IR fast frame Imaging camera

32x32 actuators MEMS
Deformable mirror
(600 actuators illuminated, low stroke, fast)

High speed high sensitivity ExAO visible
WFS (non-linear curvature)

Calibrated Science image

Science image

incoherent light component

Estimate of light due to coronagraph leaks and fast speckles

H-band filter

Science focal plane Camera / WFS

Coronagraph

Focal plane AO loop (measures focal plane coherent and incoherent components)

DM offset shape (initially flat)

Tip-tilt, focus

Coherent light component

High order aberrations, high speed
AO188 Woofer reduces WFE to ~200nm
AO188 is stand alone: no communication with SCExAO

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Uses photon-counting APDs

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Facility AO sytem AO188
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AO188 NGS mode

High speed high
Sensitivity ExAO visible
WFS (non-linear curvature)

32x32 actuators MEMS
Deformable mirror
(600 actuators Illuminated, low stroke, fast)

Near-IR fast frame
Imaging camera

Coronagraph
Deformation

H-band filter

Science image

Calibrated Science image

Science focal plane
Camera / WFS

Focal plane AO loop (measures focal plane coherent and incoherent components)

Tip-tilt, focus

Estimate of light due to coronagraph leaks and fast speckles

Coronagraph
Focal plane mask

DM offset shape (initially flat)

Coherent light component

Tip-tilt, focus

Focal plane AO loop (measures focal plane coherent and incoherent components)
AO188 system at the Nasmyth focus
SCExAO visible high speed WFS

AO188

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AO188 curvature WFS
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HiCIAO

Calibrated Science image

Science image

Near-IR fast frame Imaging camera

Science focal plane Camera / WFS

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H-band filter

Coronagraph

Focal plane mask

600nm<\lambda<900nm

600nm<\lambda<900nm

\lambda>900nm
Wavefront sensing at the sensitivity limit imposed by the telescope diffraction limit

Seeing limited wavefront sensing (what we do now)
   *Example: SH WFS*

Diffraction limited wavefront sensing (what needs to be done for ExAO)
   *Examples: Pyramid (non-modulated), non-linear curvature*

Tip-tilt example (same argument applicable to other modes):
With low coherence seeing-limited WFS, \( \sigma^2 \sim 1/D^2 \) (more photons)
Ideally, one should be able to achieve: \( \sigma^2 \sim 1/D^4 \) (more photons + smaller \( \lambda/D \))

This makes a big difference for Extreme-AO on large telescopes

For Tip-Tilt, SHWFS on ELT is 40000x less sensitive than diffraction-limited WFS (11.5 mag)
Similar gain on other low order modes
Wavefront sensing at the diffraction limit of the telescope

Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After correction, the residual pupil phase aberration (g) is 34.4 nm RMS, allowing high Strehl ratio imaging (h). All images in this figure were obtained at 0.65 μm. The total number of photons available for wavefront sensing in 2e4.
Computer Simulations showing contrast gain with high sensitivity WFS (non-linear curvature)

<table>
<thead>
<tr>
<th>WFS</th>
<th>Loop frequ</th>
<th>RMS</th>
<th>SR @ 0.85 um</th>
<th>SR @ 1.6 um</th>
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<td>101 nm</td>
<td>57%</td>
<td>85%</td>
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<td>SH - D/9</td>
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<td>315 nm</td>
<td>~4%</td>
<td>22%</td>
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<td>195 nm</td>
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<td>SH - D/36</td>
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<td>SH - D/60</td>
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<td>227 nm</td>
<td>~6%</td>
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</tbody>
</table>
Performance gain for ExAO on 8-m telescopes

Large gain at small angular separation: ideal for ExAO

SCExAO visible correction: woofer/tweeter
Optimal use of all visible light

AO188
- AO188 curvature WFS
  - Uses photon-counting APDs
- Facility AO system AO188
  - (bimorph curvature DM, 188 elements, 1 kHz update)

AO188 curvature WFS
- 32x32 actuators MEMS
  - Deformable mirror
  - (600 actuators illuminated, low stroke, fast)

High speed high Sensitivity ExAO visible WFS (non-linear curvature)

Near-IR fast frame Imaging camera
- Coronagraph
- Focal plane mask

Coronagraph
- Estimate of light due to coronagraph leaks and fast speckles
- Science image

Science focal plane Camera / WFS
- Science image

Calibrated Science image
- Coherent light component
- Tip-tilt, focus
- DM offset shape (initially flat)
- High order aberrations, high speed

Focal plane AO loop (measures focal plane coherent and incoherent components)

λ<600nm
- λ>600nm

λ<600nm
- 600nm<λ<900nm
- λ>900nm

H-band filter
- dichroic
Visible vs near-IR WFS

Visible is best for high speed high sensitivity WFS
- detectors are fast and cheap (photon counting APDs, EMCCD)
- optical gain is large: 1 nm is a larger phase in VIS than nearIR
→ SCExAO uses visible photons for fast WF sensing

Visible and near-IR wavefronts are slightly different
- differential atmospheric refraction (tip-tilt)
- chromatic propagation through atmosphere
- non-common path errors due to optics in SCExAO
→ near-IR WF sensing and correction is required
Pointing and coronagraphy

Pointing errors put light in the 1 to 2 $\lambda/D$ 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 $\lambda$ as used for science.
Should be measured at the diffraction limit of telescope.
Should be measured at coronagraph focal plane mask.
SCExAO Low Order WFS

SCExAO

DM offset shape (initially flat)

Coherent light component

Tip-tilt, focus

High order aberrations, high speed

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Coronagraph

Focal plane mask

Focal plane AO loop (measures focal plane coherent and incoherent components)

Coronagraph

Estimate of light due to coronagraph leaks and fast speckles

Calibrated Science image

Science image

incoherent light component

Science focal plane Camera / WFS

λ<600nm

λ>600nm

λ>900nm

H-band filter
Fig. 9.— CLOWFS focal plane mask used in the PIAlA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmitting light to the science camera, extends from 200 micron to 550 micron radius.
Pointing control demonstrated to $1e-3 \lambda/D$ in visible (this would be 0.02 mas on Subaru !!)
SCExAO focal plane WFS

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SCExAO

- DM offset shape (initially flat)
- Coherent light component
- Tip-tilt, focus
- High order aberrations, high speed
- High speed high sensitivity ExAO visible WFS (non-linear curvature)

Near-IR fast frame imaging camera
- 600nm < λ < 900nm

Coronagraph

- Estimate of light due to coronagraph leaks and fast speckles
- H-band filter
- Calibrated Science image

Science image

Focal plane AO loop (measures focal plane coherent and incoherent components)

HiCIAO

- Science focal plane camera / WFS

λ < 600nm

λ > 600nm

λ > 900nm
Focal plane AO and speckle calibration

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”
Initial problem

Complex amplitude of speckle

Take a frame -> measured speckle intensity = I0

DM offset chosen to be ~ equal to speckle amplitude
Lab results with PIAA coronagraph + FPAO with 32x32 MEMs DM

- No conventional AO system has achieved >1e-7 contrast
- Focal plane AO has allowed 1e-9 to 1e-10 contrast in visible light, with ~lambda/10 optics
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
Focal plane WFS based correction and speckle calibration

Fig. 8.— High order wavefront control loop, showing both the main loop and the system response matrix optimization loop (light shaded area). The two dark shaded boxes indicate image acquisition, which in the simulation mode, can be replaced with a simulated image acquisition using a model of the experiment and DM response.
SCExAO residual light calibration

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SCExAO

DM offset shape
(initially flat)

Coherent light component

Tip-tilt, focus

High order aberrations,
high speed

High speed high Sensitivity ExAO visible WFS (non-linear curvature)

32x32 actuators MEMS
Deformable mirror
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Near-IR fast frame Imaging camera

Estimate of light
due to coronagraph leaks and fast speckles

Calibrated Science image

Science image

Focal plane AO loop (measures focal plane coherent and incoherent components)

Coronagraph

Science focal plane Camera / WFS

HiCIAO

Coronagraph Focal plane mask

H-band filter

λ<600nm

600nm<λ<900nm

λ>900nm

600nm<λ<900nm

λ>900nm
LOWFS post-processing: Principle

Use LOWFS data to estimate coronagraphic leaks in science image, and subtract them in post-processing
Challenge: how to model / link CLOWFS data with coronagraph leaks?

Solution:
Acquire and use a dictionary which stores the correspondance between LOWFS and science images
Coronagraph leaks calibrated to 1% in SCExAO (Vogt et al. 2011)
PSF calibration strategies

- “classical” PSF subtraction
- Angular Differential Imaging
  - works well at large angular separations, where aberrations have large static component
  - poor performance close in to the star
- Spectral / Polarimetric differential imaging
  - works great IF source has expected spectral signature or is polarized
- Coherent differential imaging
  - highly flexible, does not make any assumption about source
  - combined wavefront sensing / PSF calibration
  - works within control radius of DM
What sets the contrast limit?

- **Purely random atmospheric speckles average with time**
  - AO correction removes slow atmospheric speckles, leaving fast component that averages down into a smooth halo fairly rapidly

- **Static and slow speckles are removed (or greatly attenuated) by focal plane WFC loop**
  - by design, there is **NO NON COMMON PATH ERROR**
  - coherence time of residual slow speckles is approximately equal to the focal plane WFC loop bandwidth → strong incentive to make focal plane WFC loop as fast and efficient as possible

- **Fast speckles (faster than focal plane WFC loop bandwidth) that have slowly varying statistics are not addressed → they set the contrast limit**
  - example: vibration creates a speckle at 2 l/d that varies in complex amplitude on ~ms timescale. As vibration comes and goes, so does the speckle → this speckle will look exactly like a planet!
  - Similar problem can be created by other effects creating loss in coherence (polarization, spectral effects)

**Fundamental problem : wavefront cannot be accurately described by static/slowly varying term + fast zero-mean term with constant statistical properties**
SCExAO schedule

SCExAO is currently in engineering, for phase 1

1\textsuperscript{st} nighttime engineering Feb 2011 (2 nights): demonstrated coupling with AO188 system + basic functions (no science IR camera – using internal SCExAO video IR camera)

2\textsuperscript{nd} nighttime engineering Sep 2011 (1 night): PIAA coronagraph, on-sky wavefront control: LOWFS, coupling with HiCIAO

May-June 2012: daytime engineering (2 weeks) to test and validate focal plane wavefront control + LOWFS

3\textsuperscript{rd} nighttime engineering summer/early fall 2012 (1 night ?): on-sky wavefront control (focal plane WFC + LOWFS)+ HiCIAO
→ start of science observation with phase 1 system (no fast visible extreme AO WFS)

Phase 2: integrate ExAO visible WFS
SCExAO Results

LOWFS validated on sky
– robust performance at low gain (~0.1) in difficult conditions
– calibration can be time consuming

PIAA coronagraphy at 1.2 lambda/D validated
– Inverse PIAA image sharpening validated
SCExAO first visible images (V. Garrel PhD)

SCExAO acquired first visible light diffraction limited on Subaru in Feb and Sept 2011

Despite moderate AO performance (seeing 1” to 2” + clouds in Feb, poor AO perf in Sept) selection + new Fourier-based reconstruction allowed diffraction-limited imaging.
Achieving high contrast at 1 lambda/D: challenges & approaches

**Coronagraphy**
Requires a coronagraph with 1 lambda/D IWA, while maintaining nearly full sensitivity and angular resolution

**Wavefront control**
Exquisite control of low order aberrations, including tip-tilt
High sensitivity wavefront sensing for low order aberrations
Wavefront control loop should be bias-free (no static or slow speckles)

**Calibration**
Need robust scheme to separate speckles from planet(s)
SDI, ADI will not work at 1 lambda/D

→ **Solutions to these problems have been developed in the last ~10 yrs in several labs**
Some of these techniques are part of the SCExAO instrument on Subaru, which is a precursor to an ELT ExAO system
Is coronagraphy at < 1 lambda/D possible on ELTs?

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)
PIAACMC performance on various pupils
PIAACMC performance on various pupils

**Subaru pupil**

![Graph showing Subaru PIAACMC design performance](image)

**GMT pupil**

![Graph showing GMT PIAACMC design performance](image)

**TMT pupil**

![Graph showing TMT PIAACMC design performance](image)

**E-ELT pupil**

![Graph showing E-ELT PIAACMC design performance](image)
Science goals

ExAO instrument on ELT timescale for science return
~ 2030

Detection of Jupiter-like giants
Good science (statistics), but not Earth-shattering
Competition from indirect techniques and space (JWST?)

Spectroscopy of Jupiter-like giants

Planet formation
ELT well suited for this science goal

Imaging and low resolution spectroscopy of rocky planets
In habitable zones

Unique to ELTs for low-mass stars
May also be first opportunity to image
Habitable planets (timing of space mission ?)
Fundamental limits of ExAO system:
(1) Raw contrast
   - Expected to be 14x better than on 8-m telescope
   - 1e-5 on 8-m telescope → 7e-7 on 30-m telescope
(2) Detection contrast
   - Expected to be 14x better than on 8-m telescope
   - 1e-7 on 8-m telescope → 7e-9 on 30-m telescope
(3) IWA ~ 1 lambda/D
   - Scales as 1/D: 40mas on 8-m, 10mas on 30-m
(4) Background-limited sensitivity (1hr, SNR=5)
   - mH: 23.5 on 8-m telescope → mH = 26.5 on 30-m

Assuming Super-Earths (~2x Earth diameter)
   - Still potentially habitable
   - Easier than Earths: 1e9 contrast at 1 AU separation (Earth ~ 2e10)
   - Abundant (HARPS results: ~30% occurrence)

Detection, colors: mH = 26.5 limit on planet
Spectroscopy (R=200, SNR = 5): mH = 21.5 limit on planet
   → ability to analyze atmosphere composition, biological activity
Challenges and strategy

Earth twin at 10pc (nominal system for space-based mission studies)
**NOT DETECTABLE WITH ELTs**
Too faint, contrast too extreme (~1e10)

*Thermal emission from young planets*
Young = not habitable ...
**NOT DETECTABLE WITH ELTs**
Strategy works well for massive young planets, but:
1. luminosity drops rapidly with lower mass
2. young systems are not very close to us (~50 - 100 pc ?)
   → Rocky planets too faint

**OPTIMAL STRATEGY:**
**Reflected light imaging around nearby low mass stars**
Key advantage of ELTs is IWA
   Reduced contrast challenge
   Nearby stars → apparent luminosity is more favorable
Reflected light imaging
Science vs instrument performance

**Thermal emission:**
Flux is steep function of planet mass
0.5 MJ is much harder than 1 MJ
Increased science return (lower mass) requires significant instrument performance improvement

**Reflected light:**
Flux is shallow function of planet mass
0.5 MJ is about as hard as 1 MJ
Large increase in science return (lower mass) obtained by moderate instrument performance improvement

**Prediction:**
Once the first planets are imaged in reflected light, steady and fast progress expected
Reflected light imaging: Contrast vs separation

Gliese catalog of nearby stars
Kept only main sequence
→ 2347 stars within 25 pc

Each star characterized by:
- Distance (pc)
- Temperature (K)
- Absolute V magnitude

→ computed bolometric luminosity
→ computed location of habitable zone (1 AU equivalent)
→ placed a 2x Earth size planet, Earth albedo, at max elongation
→ Used main sequence colors (V-H) to compute apparent luminosity of star and planet at H band
Reflected light imaging: Contrast vs separation

8-m telescope, 4 lambda/D
Reflected light imaging: Contrast vs separation

8-m telescope, 1 lambda/D
Reflected light imaging: Contrast vs separation

30-m telescope, 1 lambda/D

Diagram showing contrast vs separation for different temperatures (5000 K).

The x-axis represents separation (arcsec), and the y-axis represents contrast.
Reflected light imaging: ELT targets

30-m telescope, 1 lambda/D: 365 targets within IWA and detection contrast limits
All are M-type stars, (T~3400K), nearby (d~10pc)

Fainter than conventional ExAO targets (mV ~ 10 to 11)
What kind of ExAO system is required?

**GPI-like system on ELT**
- Detection contrast: $7 \times 10^{-9}$ (equivalent to $1 \times 10^{-7}$ on 8-m)
- Wavefront sensing: $mV = 8$ limit
- Coronagraphy: $4 \lambda/D$
- Sensitivity: $mH = 26.5$

$\rightarrow$ **3 targets** *(0 for $R=200$ spectroscopy)*

**Increased WFS sensitivity**
- Same as above, but with $mV = 12$ limit for WFS

$\rightarrow$ **23 targets** *(0 for $R=200$ spectroscopy)*

**Improved IWA**
- Same as above, but with $1 \lambda/D$ coronagraph

$\rightarrow$ **287 targets** *(7 for $R=200$ spectroscopy)*
R=200 spectroscopy targets

287 targets suitable for detection

7 prime targets on 30-m ELT, for which R=200 spectroscopy in near-IR can be done at SNR=5 in <1hr
Distance: 1.8 – 5.4 pc
Teff : 2900 K – 3200 K
Contrast: 3e-7 - 5e-8
Separation: 14 mas – 30 mas
Star V mag: 9.8 – 11.3
Star H mag: 3.0 – 4.9
Planet H mag: 20.8 – 21.4

→ The targets are challenging because of their angular separation (& star V mag)
Habitable planets spectroscopy

Space (~4m telescope): F-G-K type stars, visible light

Ground (ELT): M type stars, nearIR
Conclusions

SCExAO WFC architecture combines several innovative technologies to provide both efficient wavefront control and high level of residual light calibration. These technologies have been and are developed in lab testbeds. SCExAO will be first system to test and combine several of these new concepts on sky.

→ much will be learned in the next year

SCExAO's flexible platform allows adaptive architecture, which can be quickly modified if required

SCExAO calibrated contrast limit will be set by incoherent speckles (due to polarization, fast temporal behavior or chromaticity) which “come and go”. It is a present difficult to estimate where this limit is.

PSF ≠ static slow speckles + random halo which averages to a smooth halo in long exposures

SCExAO is a precursor to an experiment that could image habitable planets around nearby M-type stars with ELTs

In ~15 yrs, we may have an opportunity to acquire spectra of habitable planets - we should think hard about this problem in the next decade.