Exoplanet Probe to Medium Scale Direct Imaging Mission Requirements and Characteristics - (SAG9)

Rémi Soummer (STScI)
ExoPAG 8 meeting, Denver
October 5, 2013

SAG9 group (37 members, open membership to the community)
Outline

• SAG9 Charter, constitution
• Overview of a few SAG9 activities
  ‣ Complementarity with ground-based imaging (Daniel Apai)
  ‣ Complementarity with JWST coronagraphy (Tom Greene/Bill Danchi)
  ‣ Complementarity RV + Direct Imaging (Nick Cowan)
  ‣ DRM studies for RV planets (Bob Brown)
• Discussion
SAG9 Charter

- The ExoPAG Study Analysis Group 9 (SAG-9) will define metrics by which the science yield of various exoplanet probe-scale to medium-scale direct-imaging mission designs can be compared and evaluated in order to facilitate a well-informed decision process by NASA.

- SAG-9 will focus on mission sizes that can be considered on shorter timescales than a flagship, with a particular emphasis on missions with probe-scale costs (under $1B). The work will build on the methodology developed by SAG-5 (Exoplanet Flagship Requirements and Characteristics), defining science goals, objectives and requirements, further detailed into "Musts" and "Discriminators".

- SAG-9 will establish the minimum science thresholds ("Musts") for such missions, and develop quantitative metrics to evaluate the marginal performance increase beyond the threshold science using "Discriminators".

- Key questions to be studied by this group include:
  - What is the minimum threshold science to justify an exoplanet probe-scale direct imaging mission?
  - What are the additional science goals that can be used as "discriminators" to evaluate science performance beyond the minimum thresholds?
  - What are the possible achievements from the ground by plausible launch date, and overlapping the expected mission lifetime?
  - What quantitative metrics for these "discriminators" can we provide to help define the weighting process to be used in the comparison of mission concepts?
# Near-Future ExAO Instruments and Possible Future Instruments

## Approximate Timescales

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>8m Class</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VLT + SPHERE</td>
<td>Young jovian planets: detection + spectroscopy (1–1.6 μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gemini + GPI</td>
<td>Young jovian planets: detection + spectroscopy (1–1.6 μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LBT/AO</td>
<td>Young + Older Super-jupiters: detection + photometry (1–5 μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subaru/ScExAO</td>
<td>Super-jupiters: detection + photometry (1–2 μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>30m Class</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GMT/ExAO?</td>
<td>No approved concept; Super-earths?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TMT/ExAO?</td>
<td>No approved concept; Super-earths?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EELT/EPIC</td>
<td>HZ low-mass planets, few Earth analogs, old GPs in reflected light (1–1.7 μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EELT/METIS</td>
<td>MIR imaging spectroscopy of disks and planets (3–10 μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Space</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HST</td>
<td>Photometry of exceptionally bright super-jupiters (1-1.7 μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JWST</td>
<td>Young GPs + Few Older Jovian planets (2 M_\text{J} at 4pc): detection + LR/MR spectroscopy, Disk Imaging + MR spectroscopy; IWA 0.5” 10^{-5} (1–5 μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WFIRST-2.4m Coron?</td>
<td>Jupiter analogs and disks, RV planets, Imaging+Spectra, 10^{-9} IWA 0.1” (0.3–1 μm);</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probe-class Off-Axis Mission?</td>
<td>Jupiter analogs; Disks and some RV planets, Imaging+LR Spectra, 10^{-9}–10^{-10} IWA 0.1”–0.3” (0.3–1 μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SPHERE

41x41 actuator DM (180mm)
Shack-Hartmann WFS
90% H-band Strehl

Three sub-instruments:
IRDIS: IR Dual-Beam Imager and Spectrograph (0.95-2.32 micron)
IFS: IR Integral Field Spectograph (0.95-1.7 micron)
ZIMPOL: Visible Differential Imager (0.6-0.9 micron)

Coronagraphs:
1) Achromatic four-quadrant phase mask coronagraph
2) Classical Lyot coronagraph
3) Apodized Pupil Lyot Coronagraph (APLC)
Ongoing work on NIR coronagraphs

<table>
<thead>
<tr>
<th>Requirement</th>
<th>IRDIS</th>
<th>IFS</th>
<th>ZIMPOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Throughput</td>
<td>40% (goal 45%) for each beam</td>
<td>60% (goal 70%)</td>
<td>25% (goal 40%)</td>
</tr>
<tr>
<td>Wavelength coverage</td>
<td>0.95-2.32µm</td>
<td>0.95-1.7µm</td>
<td>0.6 - 0.9µm (goal: 0.5 - 0.9µm)</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>DBI: R ~ 20-30</td>
<td>R ~ 30</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>LS: R ~ 50 (Y-K), 500 (0.95-1.8µm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field of View</td>
<td>&gt;11&quot; diameter</td>
<td>&gt;1.35&quot; square (goal 3&quot; square)</td>
<td>&gt;3&quot; square</td>
</tr>
<tr>
<td>Spatial Sampling</td>
<td>12.25 mas (1/2D at 0.95µm)</td>
<td>12.25 mas (1/2D at 0.95µm)</td>
<td>&lt;7.8 mas (1/2D at 0.6µm)</td>
</tr>
<tr>
<td>Contrast (5s)</td>
<td>at 0.1&quot;: &lt;5e-5 (goal 1e-5) at 0.5&quot;: &lt;5e-6 (goal 5e-7)</td>
<td>at 0.5&quot;: &lt;1e-6 (goal 1e-8)</td>
<td>at 1&quot;: &lt;1e-8 in 4hr (goal 3e-9 in 15 hr) for a 30% polarized planet</td>
</tr>
<tr>
<td>Observing modes</td>
<td>Imaging, dual-band imaging (DBI), dual-polarimetric imaging (DPI), long-slit spectroscopy (LS)</td>
<td>IFS</td>
<td>Visible Imaging, Differential polarimetric imaging</td>
</tr>
</tbody>
</table>

Daniel Apai (U Arizona)
Performance:  
$1.3 \times 10^{-5}$ down to 0.2”

First light: End of 2013

260 nights GTO
~250 nights planned for public surveys

This would in particular fully justify a large effort in an extended observational survey of several hundred nights concentrating on the following classes of targets:

- **Nearby young associations** will offer the best chance of detecting low mass planets, since they will have brighter sub-stellar companions, and therefore the greatest number of planets per star observed.
- **Stars with known planets,** especially any that exhibit long term residuals in their radial velocity curves, indicating the possible presence of a more distant planet.
- **Nearest stars:** measuring these targets will probe the smallest orbits and will thus the only opportunities for detecting planets by directly reflected light.
- **Stars aged from 100 Myr to 1 Gyr:** planets will still be over-luminous as compared to Solar System planets, so mass limit will be lower than for old systems.

With such a prime objective, it is obvious that many other research fields will benefit from the large contrast performance of SPHERE: proto-planetary disks, brown dwarfs, evolved massive stars and marginally, Solar System and extragalactic science. These domains will nicely enrich the scientific impact of the instrument. Their instrumental needs should however not be in conflict with the high-contrast requirement.
Goal: Direct detection and characterization of young, Jovian-mass exoplanets

Young systems:
Detection of >10% of gas giants with $M_p > 0.5$ MJ for $t = 100$ Myr and $d < 75$ pc

Older systems:
Detection of >50% of gas giants with $M_p > 8$ MJ for $t < 1$ Gyr and $a > 15$ AU

---

Photo: Marshall Perrin Oct 3, 2013 GPI on flexure rig at Gemini South
### GPI

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contrast</td>
<td>$1 \times 10^{-7} \text{ @ } 0.5''$</td>
</tr>
<tr>
<td>IWA</td>
<td>0.15''</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>R~45 + pol.</td>
</tr>
<tr>
<td>Wavelength Range</td>
<td>YJHK</td>
</tr>
<tr>
<td>Field of view</td>
<td>2.8'' x 2.8''</td>
</tr>
<tr>
<td>WFS magnitude</td>
<td>$I&lt;8$ mag $I&lt;9$ mag goal</td>
</tr>
<tr>
<td>Coronagraph</td>
<td>Apodized-pupil Lyot (Soummer 2005)</td>
</tr>
<tr>
<td>DM</td>
<td>64x64 MEMS + PZT woofer</td>
</tr>
<tr>
<td>Science instrument</td>
<td>Integral field spectrograph</td>
</tr>
<tr>
<td>WFS</td>
<td>Visible Shack-Hartmann + IR interferometer</td>
</tr>
</tbody>
</table>

20-50 planets discovered in a 900h simulated survey (McBride et al. 2011)
GPI: Simulated HR8799 in actual I&T end to end data

GPI: 1 minute
EPICS: high-contrast imaging of exoplanets with the E-ELT

Overview:
Collaborators: M. Kasper (PI), C. Vérinaud, & EPICS consortium
Consortium: ESO, IPAG, Padova Obs., ASTRON, Univ. Oxford, LESIA, NOVA, ETH Zürich, FIZEAU, LAM

Science goals:
- Detection of low-mass and wide orbit exoplanets to explore mass-orbit function
- Characterization of exoplanet down to the size of rocky planets by direct imaging, spectroscopy and polarimetry
- Detection of disks and very young planets (<10MYr) close to the ice-line to test planet formation and evolution models

Description:
Concept
- NIR Imaging: 950-1650nm, 0.8” FoV, 2.33 mas/px
- NIR IFS: R=125, 1400 & 20,000
- Vis Imaging: 600-900nm, 2” FoV, 1.5 mas/px
- Vis polarimetry (EPOL)

Concept highlights
1. XAO and wavefront control
   - turbulence residual halo \( \sim 10^{-5} \) at 30mas, \( 10^{-6} \) further out
   - quasi-static speckles < \( 10^{-7} \) (goal \( 10^{-8} \)) at \( 5\lambda/D \)

2. good temporal stability
   - All moving or rotating optics in the common path
   - cover providing thermal inertia and dust protection

3. very efficient calibration of PSF residuals
   - small and known chromaticity for spectral deconvolution
   - small instrumental polarization and efficient calibration for differential polarimetry

EPICS goal \( \rightarrow \) Photon-noise limited

Status:
- EPICS phase-A study for E-ELT concluded in 2010
- New instrument name: PCS (Planet Imager and Spectrograph) for the E-ELT

Schedule for E-ELT/PCS:
2013: Preliminary R&D
2015: Conceptual design, R&D
2018: Project start, preliminary design start
2020: Final design start
2022: MAIT start
2026: 1st light

Adapted from M. Kasper, AO4ELT2 Victoria (11/2012)
NearestNeighbrs, Leiden (10/2012)
Slide Mamadou N'Diaye / Daniel Apai
**METIS: E-ELT instrument**

for the thermal/mid-infrared ($\lambda > 3\mu m$) range

**Overview:**

Collaborators: B. Brandl (PI), R. Lenzen, E. Pantin, A. Glasse, J. Blommaert, M. Meyer, M. Guedel

Phase A Consortium: NOVA Leiden & ASTRON, MPIA, CEA Saclay, KU-Leuven, UK ATC

**Science goals:**
- Formation history of the solar system
- Proto-planetary disks and planet formation
- Physical and chemical properties of Exoplanets
- Growth of super-massive Black Holes
- Morphologies, Dynamics and Evolution of high-z Galaxies
- Galactic center, Evolved stars, Martian atm., Massive young clusters, Brown dwarfs, etc.

**Description:**

1. An **imager** at L/M and N band with 18”x18” wide FoV
   - coronagraphy at L/M and N band
   - low-resolution ($R < 5,000$) long slit spectroscopy at L/M & N
   - polarimetry at N-band (TBD)

2. An IFU fed **high resolution spectrograph** at L/M band [2.9-5.3$\mu m$]
   with IFU FoV of 0.4”x1.5” amdd a spectral resolution of $R \sim 100,000$.

All subsystems work at the diffraction limit (AO!)

**AO concept**

METIS requires two AO modes:

1. An **internal, near infrared WFS** for self-referencing targets and highest Strehl ratios (e.g., exoplanets, bright PP-disks, Galactic center)

2. A **LGS LTAO system** to provide full sky coverage, mainly outside the Galactic plane and for intrinsically faint targets (high-z galaxies, faint PP disks, brown dwarfs, solar system targets)

**Status:**
- Phase-A study ➔ clear instrument baseline
- identified as 3rd E-ELT instrument on roadmap ➔ 2023

Adapted from B. Brandl, MOS on the E-ELT Amsterdam (10/2012)
References

Beuzit et al. 2008 ESO Messenger
Kasper et al. 2011 Proc. AO42ELT2, Text
Krist et al. 2007 SPIE 6693
McBride 2011 PASP 123, 692
Stapelfeldt 2006 Proc. IAU Symp 232

SPHERE Consortium

METIS website
Complementarity of Exoplanet Probe and JWST Observations

ExoPAG SAG 9

T. Greene, W. Danchi
September 26, 2013
Probe Architecture Assumptions

• D ~ 1–m primary mirror
• 3+ year mission lifetime
• Broadband (~20% BW) filters 450 – 800+ nm
• Low resolution spectroscopy (R~30–50)
• High contrast imaging, C < 1E–9
• Inner Working Angles
  • IWA ~ 2 – 3 l/D (~300 mas) for internal coronagraphs
  • IWA < 300 mas for starshades
• Outer Working Angles
  • OWA < 24 l/D (~2.7 arcsec) for internal coronagraphs
  • OWA nearly unlimited for starshades
Probe Science Niches / Goals

• High contrast C < 1E–9 visible light imaging:
• Search for gas and ice giant planets around nearby stars
• Measure albedo colors of giant planets over large (> 1 octave) spectral range
• Low Resolution (R≈ 30 – 50) Spectroscopy:
  A few known RV planets (R ~ 20–50)
  Some newly discovered gas giants
• Search for super–earths / mini–Neptunes around very nearby stars
• Survey of exozodi disks around nearby stars
• Measure exozodi dust in HZ around very nearby stars
• High contrast general astrophysics, particularly for late stages of stellar evolution, and for protoplanetary disk, and planet formation studies
JWST Mission Architecture

• D = 6.5–m primary mirror
  18 segments, ~130 nm WFE
• 5 – 10 year mission lifetime
• Coronagraphic Imaging with modest contrast (C~1E–5):
  2.1 – 4.6 microns with NIRCam (IWA ~ 400 – 700 mas)
  11 – 16 micron 4QPMs with MIRI (IWA ~500 mas),
    23 micron Classical Lyot coronagraph with MIRI
• High resolution FGS/NIRISS Non–Redundant Mask Imaging
  35 – 70 mas resolution at 2.2 – 4.4 microns, OWA~400 mas
    Modest contrast – no starlight suppression – 10E–4
• No coronagraphic spectroscopy
• Numerous non–coronagraphic spectroscopy modes for 0.7 – 12+ micron transit and eclipse spectroscopy
JWST Exoplanet Niches

• Lower contrast but longer wavelengths than Probe
• Sensitive to thermal emission from gas giant planets
  ◦ Good planet / star contrast in ~4.8 micron window
  ◦ Most sensitive to planets < 1 Gyr old
• Can detect and resolve < ~1000 zodi disks with coronagraph
  ◦ PSF subtraction is critical; coronagraph mostly prevents saturation of star
• Measure exozodi dust in HZ around very nearby stars
• High contrast general astrophysics, particularly for late stages of stellar evolution, and for protoplanetary disk, and planet formation studies
JWST gas giant sensitivity

• Contrast of 1 Gyr old Jupiter is 1E–6, 1E8 yr old contrast is 1E–4 at 4.5 μm
• See Beichman et al. 2010 PASP 122, 162 for JWST sample and planet yield estimates
Comparison of Ground and Space Capabilities

- TFI/NRM 4.4 um
- MIRI 11 um
- NIRCam 4.4 um Spot
- P1640/GPI/SPHERE 1.65um
- TMT 1.65 um
- 1 m class probe
# JWST / Probe complementarity

<table>
<thead>
<tr>
<th></th>
<th>Probe</th>
<th>JWST</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Planet sensitivity</strong></td>
<td>Reflected vis. light from giants close to stars (near IWA)</td>
<td>• Emitted light from planets (far from stars)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Known transiting planets</td>
</tr>
<tr>
<td><strong>Best host stars</strong></td>
<td>Nearby F/G/K mature stars</td>
<td>Young stars, M stars, A stars &lt; 1 Gyr (imaging)</td>
</tr>
<tr>
<td><strong>Atmospheric spectra</strong></td>
<td>Samples bulk atmosphere above clouds</td>
<td>• Emission from large depths (images, eclipses)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Outer atmospheres with transits</td>
</tr>
<tr>
<td><strong>Circumstellar disks</strong></td>
<td>Reflected light from nearby exozodi disks &gt; ~10 zodi &lt; 3 arcsec</td>
<td>Emitted light from large, massive (~1000 zodi) disks</td>
</tr>
</tbody>
</table>
Science Metric for Probe/Medium missions

- Criterion #1: Permitted pointing (observing window)
- Criterion #2: systematic limit ($s > IWA$ & $Dmag < Dmag0$)
- Criterion #3: wavelength (true at all wavelengths)
- Criterion #3: time (observations can fit in observing window and mission duration)

Starshade probe
coronagraph probe
### Coronagraph Probe Times

Max observable time vs. Exposure times (days)

<table>
<thead>
<tr>
<th>star</th>
<th>( \log_{10} t_{\text{max}} )</th>
<th>( \log_{10} t_{0,\text{LSO},1\text{ m}} )</th>
<th>( \log_{10} t_{0,\text{LSO},1.5\text{ m}} )</th>
<th>( \log_{10} t_{0,\text{LSO},2.4\text{ m}} )</th>
<th>( \log_{10} t_{0,\text{LCO},1\text{ m}} )</th>
<th>( \log_{10} t_{0,\text{LCO},1.5\text{ m}} )</th>
<th>( \log_{10} t_{0,\text{LCO},2.4\text{ m}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.44</td>
<td>-0.432</td>
<td>-0.807</td>
<td>-1.23</td>
<td>0.517</td>
<td>0.144</td>
<td>-0.274</td>
</tr>
<tr>
<td>2</td>
<td>2.56</td>
<td>0.574</td>
<td>0.112</td>
<td>-0.362</td>
<td>1.49</td>
<td>1.04</td>
<td>0.572</td>
</tr>
<tr>
<td>3</td>
<td>2.47</td>
<td>0.872</td>
<td>0.372</td>
<td>-0.131</td>
<td>1.86</td>
<td>1.36</td>
<td>0.861</td>
</tr>
<tr>
<td>4</td>
<td>2.47</td>
<td>1.11</td>
<td>0.580</td>
<td>0.0483</td>
<td>2.32</td>
<td>1.76</td>
<td>1.21</td>
</tr>
<tr>
<td>5</td>
<td>2.47</td>
<td>1.74</td>
<td>1.14</td>
<td>0.529</td>
<td>2.90</td>
<td>2.28</td>
<td>1.65</td>
</tr>
<tr>
<td>6</td>
<td>2.47</td>
<td>1.81</td>
<td>1.20</td>
<td>0.579</td>
<td>2.91</td>
<td>2.29</td>
<td>1.66</td>
</tr>
<tr>
<td>7</td>
<td>2.56</td>
<td>2.10</td>
<td>1.47</td>
<td>0.811</td>
<td>3.32</td>
<td>2.68</td>
<td>2.00</td>
</tr>
<tr>
<td>8</td>
<td>2.56</td>
<td>2.19</td>
<td>1.56</td>
<td>0.890</td>
<td>3.38</td>
<td>2.73</td>
<td>2.04</td>
</tr>
<tr>
<td>9</td>
<td>2.44</td>
<td>2.25</td>
<td>1.61</td>
<td>0.939</td>
<td>3.23</td>
<td>2.60</td>
<td>1.93</td>
</tr>
<tr>
<td>10</td>
<td>2.56</td>
<td>2.25</td>
<td>1.61</td>
<td>0.939</td>
<td>3.23</td>
<td>2.60</td>
<td>1.93</td>
</tr>
<tr>
<td>11</td>
<td>2.47</td>
<td>2.28</td>
<td>1.64</td>
<td>0.964</td>
<td>3.44</td>
<td>2.79</td>
<td>2.10</td>
</tr>
<tr>
<td>12</td>
<td>2.44</td>
<td>2.43</td>
<td>1.78</td>
<td>1.08</td>
<td>3.41</td>
<td>2.76</td>
<td>2.07</td>
</tr>
<tr>
<td>13</td>
<td>2.44</td>
<td>2.59</td>
<td>1.93</td>
<td>1.22</td>
<td>3.66</td>
<td>3.00</td>
<td>2.28</td>
</tr>
<tr>
<td>14</td>
<td>2.44</td>
<td>2.82</td>
<td>2.15</td>
<td>1.42</td>
<td>3.93</td>
<td>3.26</td>
<td>2.52</td>
</tr>
<tr>
<td>15</td>
<td>2.56</td>
<td>2.93</td>
<td>2.25</td>
<td>1.52</td>
<td>3.91</td>
<td>3.24</td>
<td>2.50</td>
</tr>
<tr>
<td>16</td>
<td>2.56</td>
<td>3.04</td>
<td>2.37</td>
<td>1.62</td>
<td>4.13</td>
<td>3.45</td>
<td>2.70</td>
</tr>
<tr>
<td>17</td>
<td>2.45</td>
<td>3.23</td>
<td>2.55</td>
<td>1.79</td>
<td>4.43</td>
<td>3.74</td>
<td>2.98</td>
</tr>
<tr>
<td>18</td>
<td>2.44</td>
<td>3.28</td>
<td>2.59</td>
<td>1.83</td>
<td>4.41</td>
<td>3.73</td>
<td>2.96</td>
</tr>
<tr>
<td>19</td>
<td>2.45</td>
<td>3.68</td>
<td>2.99</td>
<td>2.21</td>
<td>4.60</td>
<td>3.91</td>
<td>3.14</td>
</tr>
<tr>
<td>20</td>
<td>2.54</td>
<td>4.32</td>
<td>3.62</td>
<td>2.82</td>
<td>5.21</td>
<td>4.51</td>
<td>3.71</td>
</tr>
<tr>
<td>21</td>
<td>2.48</td>
<td>4.54</td>
<td>3.84</td>
<td>3.04</td>
<td>4.49</td>
<td>3.81</td>
<td>3.03</td>
</tr>
<tr>
<td>22</td>
<td>2.47</td>
<td>5.28</td>
<td>4.58</td>
<td>3.77</td>
<td>5.47</td>
<td>4.78</td>
<td>3.98</td>
</tr>
<tr>
<td>23</td>
<td>2.56</td>
<td>5.39</td>
<td>4.68</td>
<td>3.87</td>
<td>5.32</td>
<td>4.63</td>
<td>3.82</td>
</tr>
<tr>
<td>24</td>
<td>2.44</td>
<td>5.05</td>
<td>5.24</td>
<td>4.43</td>
<td>5.89</td>
<td>5.19</td>
<td>4.38</td>
</tr>
</tbody>
</table>

(adapted from Bob Brown)
Impact of time criterion

Simple max separation argument is incomplete because mission time much smaller than period of considered large-separation RV planet periods.

<table>
<thead>
<tr>
<th>RV exoplanet</th>
<th>d (pc)</th>
<th>$m \sin i$ ($m_\oplus$)</th>
<th>$a$ (au)</th>
<th>$e$</th>
<th>$\omega_p$</th>
<th>period (days)</th>
<th>periapsis (JD -2450000)</th>
<th>$a(1+e)/d$ (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>epsilon Eri b</td>
<td>3.22</td>
<td>0.82</td>
<td>1.05</td>
<td>3.38</td>
<td>0.25</td>
<td>186.00</td>
<td>-1060.00</td>
<td>1.31</td>
</tr>
<tr>
<td>GJ 832 b</td>
<td>4.95</td>
<td>0.45</td>
<td>0.64</td>
<td>3.40</td>
<td>0.12</td>
<td>124.00</td>
<td>1211.00</td>
<td>0.77</td>
</tr>
<tr>
<td>55 Cnc d</td>
<td>12.34</td>
<td>0.91</td>
<td>3.54</td>
<td>5.47</td>
<td>0.02</td>
<td>74.00</td>
<td>3490.00</td>
<td>0.45</td>
</tr>
<tr>
<td>HD 217107 c</td>
<td>19.86</td>
<td>1.11</td>
<td>2.62</td>
<td>5.33</td>
<td>0.52</td>
<td>18.60</td>
<td>1106.32</td>
<td>0.41</td>
</tr>
<tr>
<td>mu Ara c</td>
<td>15.51</td>
<td>1.15</td>
<td>1.89</td>
<td>5.34</td>
<td>0.10</td>
<td>237.60</td>
<td>2955.20</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Five RV planets satisfy the max separation criterion $a(1+e)/d>IWA$

With 3-year mission, expected value from DRM is respectively 1, 1.45, and 2.45 planet for 1.0, 1.5 and 2.4m missions

adapted from Bob Brown
### DRM science metric

Science metric (expected value of the number of planets detected and characterized for these missions)

<table>
<thead>
<tr>
<th></th>
<th>Coronagraph</th>
<th>Star Shade</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$ (m)</td>
<td>Total exposure time (days)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>183</td>
<td>365</td>
</tr>
<tr>
<td>1.0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.4</td>
<td>2</td>
<td>3.15</td>
</tr>
<tr>
<td>1.0</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>1.5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>2.4</td>
<td>6</td>
<td>8.23</td>
</tr>
</tbody>
</table>

DRM estimates of $N_{RV}$ for 1LSO ($R=5$, $SNR=5$) +3LCO ($R=20$, $SNR=10$)
Discussion

1- DRM /ETC still work in progress
   ETC, assumptions, observing scenario and parameters, e.g. better detectors
   IFU vs. three consecutive narrow band observations
   Sharpness for complex shaped Lyot stops/shaped pupil
   Detection threshold traditional SNR vs. probabilistic approach Kasdin in prep
   RV catalog increase by launch date

2- Complementarity with other missions / ground-based project
   JWST
   ELTs
   second generation 8m high-contrast?