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

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ExoPAG 8 meeting, Denver
October 5, 2013

SAG9 group (37 members, open membership to the community)
Apai, Belikov, Breckinridge, Brown, Cahoy, Cash, Choquet, Cowan, Danchi, Fortney, Gaudi
Goldman, Greene, Kasting, Lawson, Levine, Lillie, Lo, Lyon, Lipscy, McElwain, N'Diaye,
Mennesson, Noecker, Plavchan, Roberge, Savransky, Serabyn, Shaklan, Solmaz, Unwin,
Stapelfeldt, Thomson, Trauger, Turnbull, Vasicht,

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

		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
8m Class	VLT + SPHERE	Young jovian planets: detection + spectroscopy (1–1.6 μm)															
	Gemini + GPI	Young jovian planets: detection + spectroscopy (1–1.6 μm)															
	LBT/AO	Young + Older Super-jupiters: detection + photometry (1–5 μm)															
	Subaru/ScExAO	Super-jupiters: detection + photometry (1–2 μm)															
30m Class	GMT/ExAO?														No approved concept; Super-earths?		
	TMT/ExAO?														No approved concept; Super-earths?		
	EELT/EPIC												HZ low-mass planets, few Earth analogs, old GPs in reflected light (1–1.7 μm)				
	EELT/METIS												MIR imaging spectroscopy of disks and planets (3–10 μm)				
Space	HST	Photometry of exceptionally bright super-jupiters (1–1.7 μm)															
	JWST				Young GPs + Few Older Jovian planets (2 M_J at 4pc): detection + LR/MR spectroscopy. Disk Imaging + MR spectroscopy; IWA 0.5" 10^{-5} (1–5 μm)												
	WFIRST-2.4m Coron?									Jupiter analogs and disks, RV planets, Imaging+Spectra, 10^{-9} IWA 0.1" (0.3–1 μm);								
	Probe-class Off-Axis Mission?									Jupiter analogs; Disks and some RV planets, Imaging+LR Spectra, 10^{-9}–10^{-10} IWA 0.1"–0.3" (0.3–1 μm)							

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

Baseline Specification

Requirement	IRDIS	IFS	ZIMPOL
Optical Throughput	40% (goal 45%) for each beam	60% (goal 70%)	25% (goal 40%)
Wavelength coverage	0.95-2.320µm	0.95-1.7µm	0.6 - 0.9µm (goal: 0.5 - 0.9µm)
Spectral Resolution	DBI: R ~ 20-30 LS: R ~ 50 (Y-K), 500 (0.95-1.8µm)	R ~ 30	-
Field of View	>11" diameter	>1.35" square (goal 3" square)	>3" square
Spatial Sampling	12.25 mas (l/2D at 0.95µm)	12.25 mas (l/2D at 0.95µm)	<7.8 mas (l/2D at 0.6µm)
Contrast (5s)	at 0.1": <5e-5 (goal 1e-5) at 0.5": <5e-6 (goal 5e-7)	at 0.5": <1e-6 (goal 1e-8)	at 1": <1e-8 in 4hr (goal 3e-9 in 15 hr) for a 30% polarized planet
Observing modes	Imaging, dual-band imaging (DBI), dual-polarimetric imaging (DPI), long-slit spectroscopy (LS)	IFS	Visible Imaging Differential polarimetric Imaging

SPHERE

Performance:
1.3×10^{-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.

GPI

Goal: Direct detection and characterization of young, Jovian-mass exoplanets

Young systems:

Detection of >10% of gas giants with Mp>0.5 MJ for t=100 Myr and d<75 pc

Older systems:

Detection of >50% of gas giants with Mp>8 MJ for t<1 Gyr and a>15 AU

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

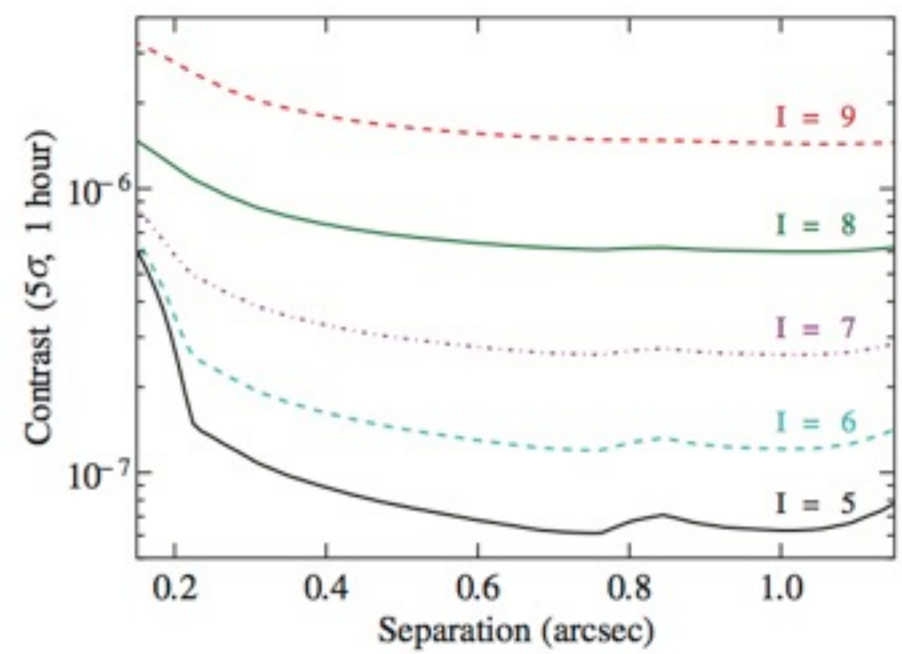
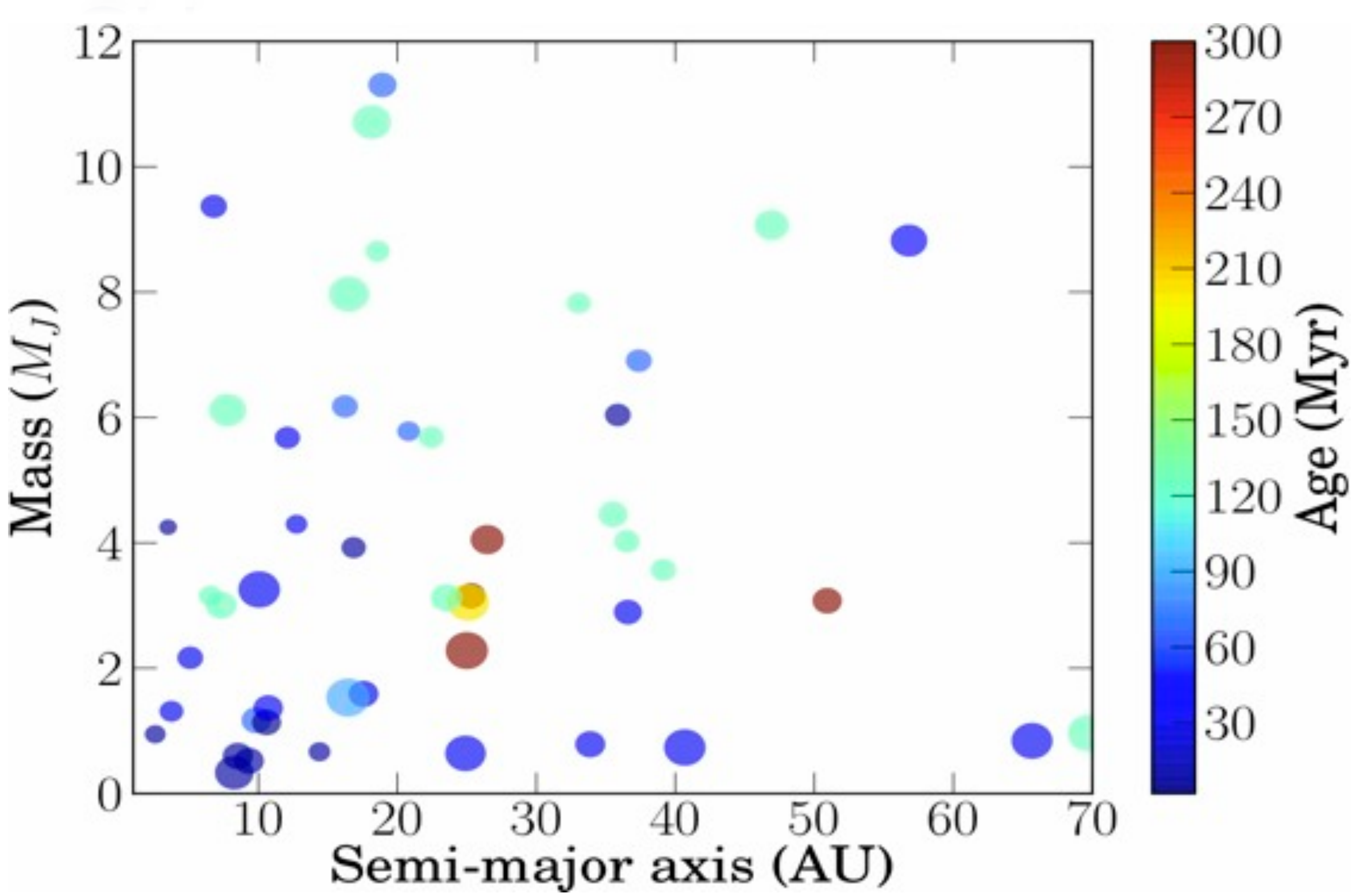


FIG. 1.—Contrast curves (5σ) in the H band as a function of angular separation for five different star I magnitudes, assuming 1 hr on the target and an A0 star. Photon shot noise dominates for stars with $I > 6$ mag, while static speckles dominate for stars with $I > 6$ mag. Visit http://planetimager.org for a tabular version of these data.

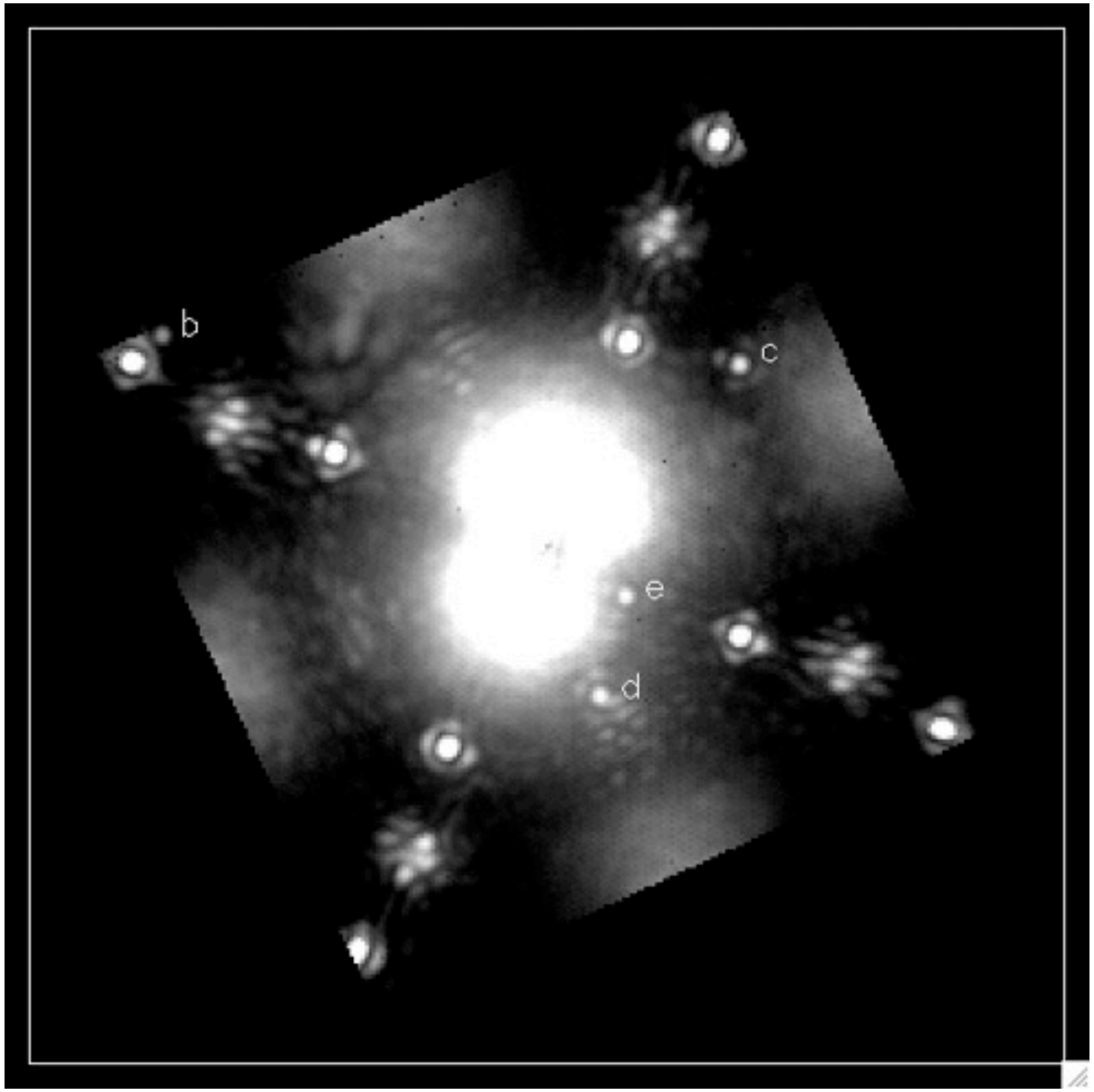
GPI

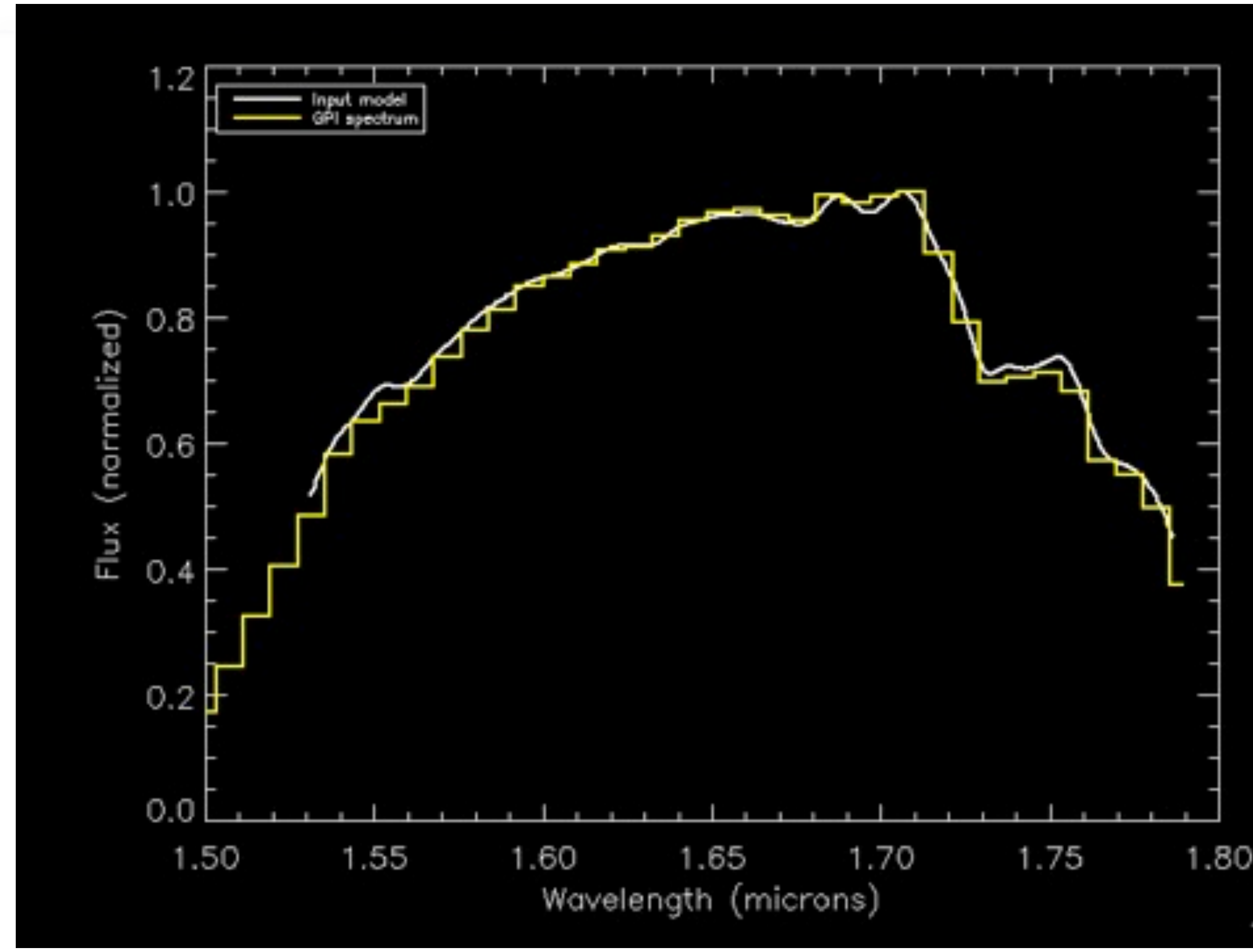
Requirement	Value
Contrast	1x10-7 @ 0.5”
IWA	0.15”
Spectral resolution	R~45 + pol.
Wavelength Range	YJHK
Field of view	2.8” x 2.8”
WFS magnitude	I<8 mag I<9 mag goal
Coronagraph	Apodized-pupil Lyot (Soummer 2005)
DM	64x64 MEMS + PZT woofer
Science instrument	Integral field spectrograph
WFS	Visible Shack-Hartmann + IR inteferometer



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

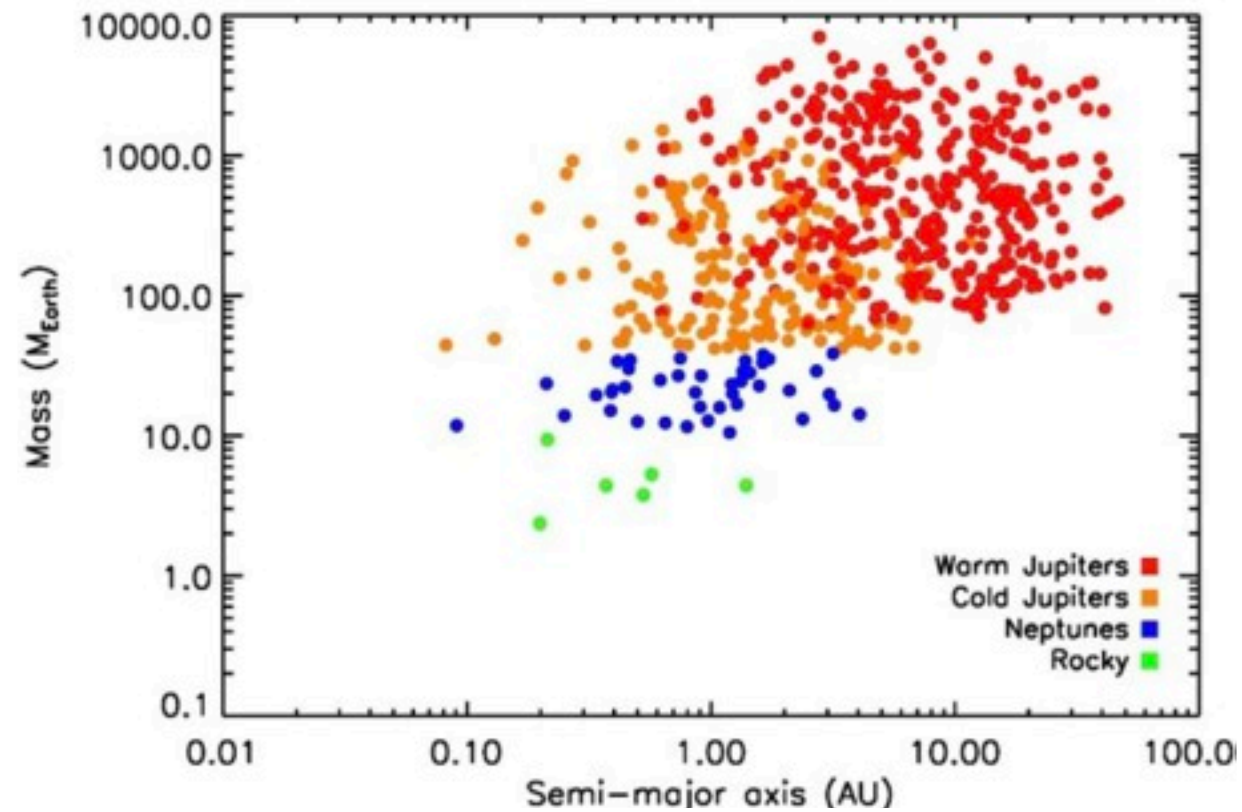
Overview:

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 ~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 ➔ 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 (λ>3μm) range

Mid-infrared E-ELT Imager and Spectrograph

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

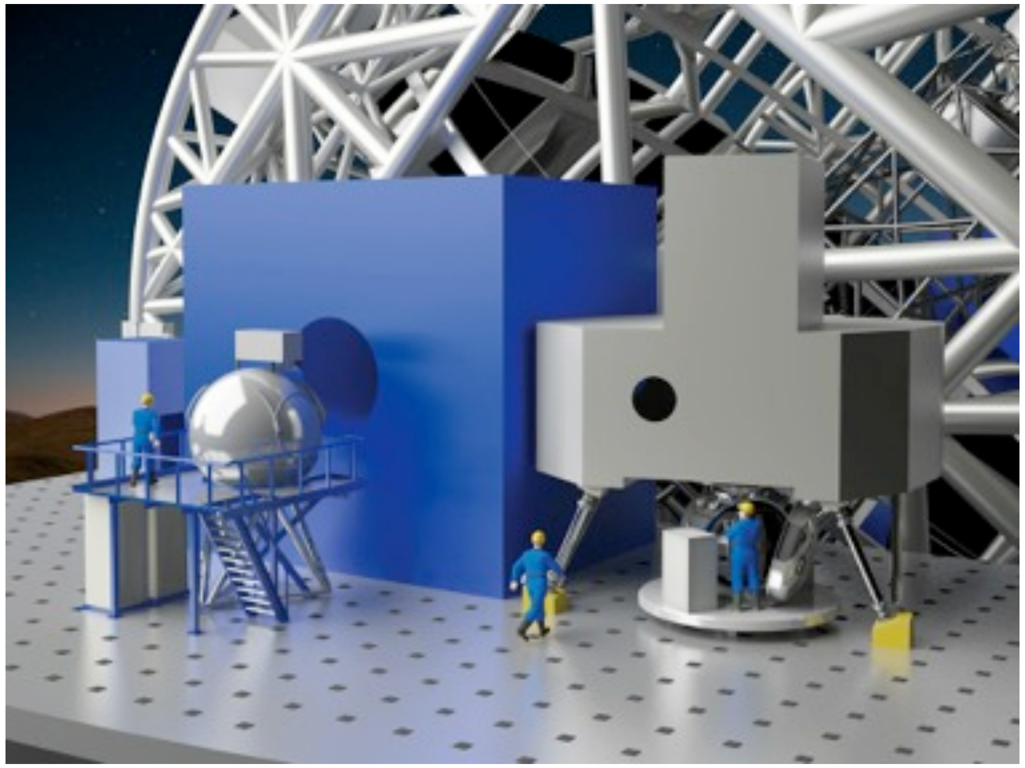
Science goals:
Formation history of the solar system
Proto-planetary disks and planet formation
Physical and chemical properties of Exoplanets
Growth of super-massive Black Holes
Morphologies, Dynamics and Evolution of high-z Galaxies
Galactic center, Evolved stars, Martian atm., Massive young clusters, 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 [2.9-5.3μm] with IFU FoV of 0.4"x1.5" amdd a spectral resolution of R ~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, browns 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

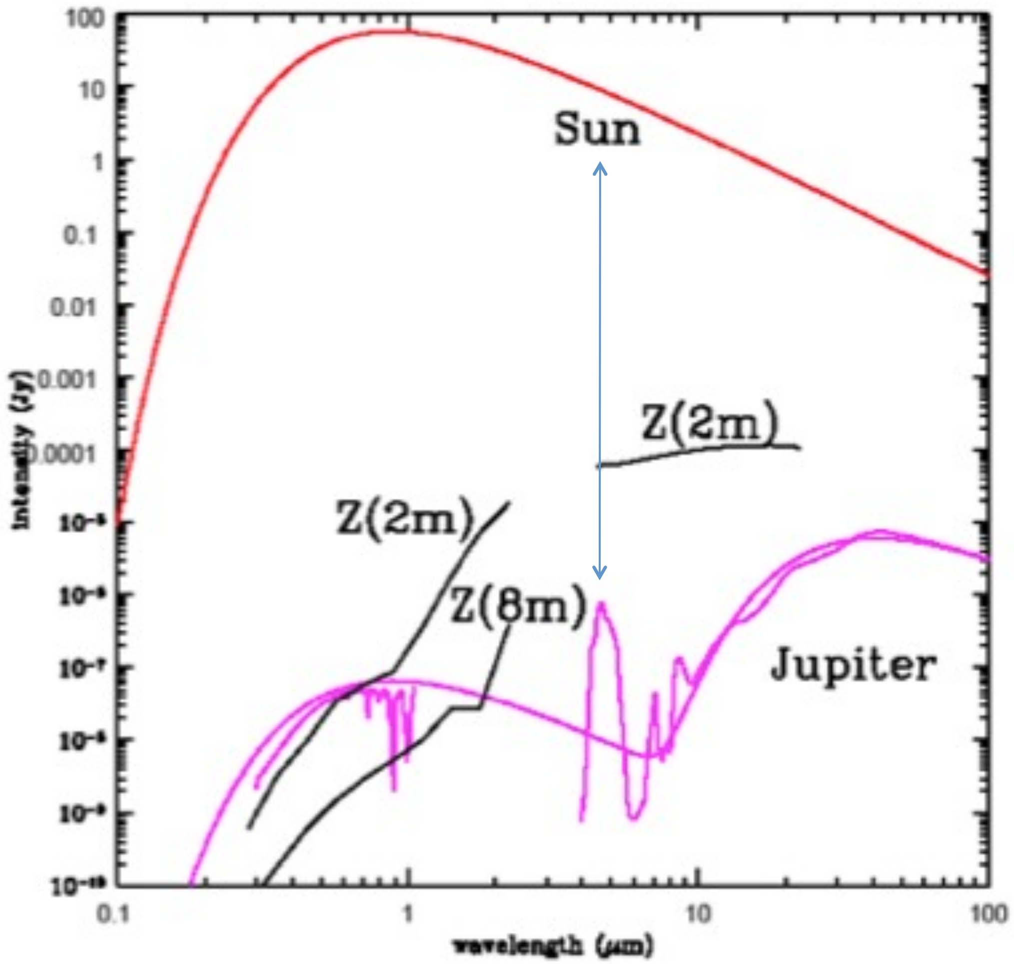
- D = 6.5-m primary mirror
  - 18 segments, ~130 nm WFE
- 5 – 10 year mission lifetime
- Coronagraphic Imaging with modest contrast (C~1E-5):
  - 2.1 – 4.6 microns with NIRCam (IWA ~ 400 – 700 mas)
  - 11 – 16 micron 4QPMs with MIRI (IWA ~500 mas),
    23 micron Classical Lyot coronagraph with MIRI
- 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

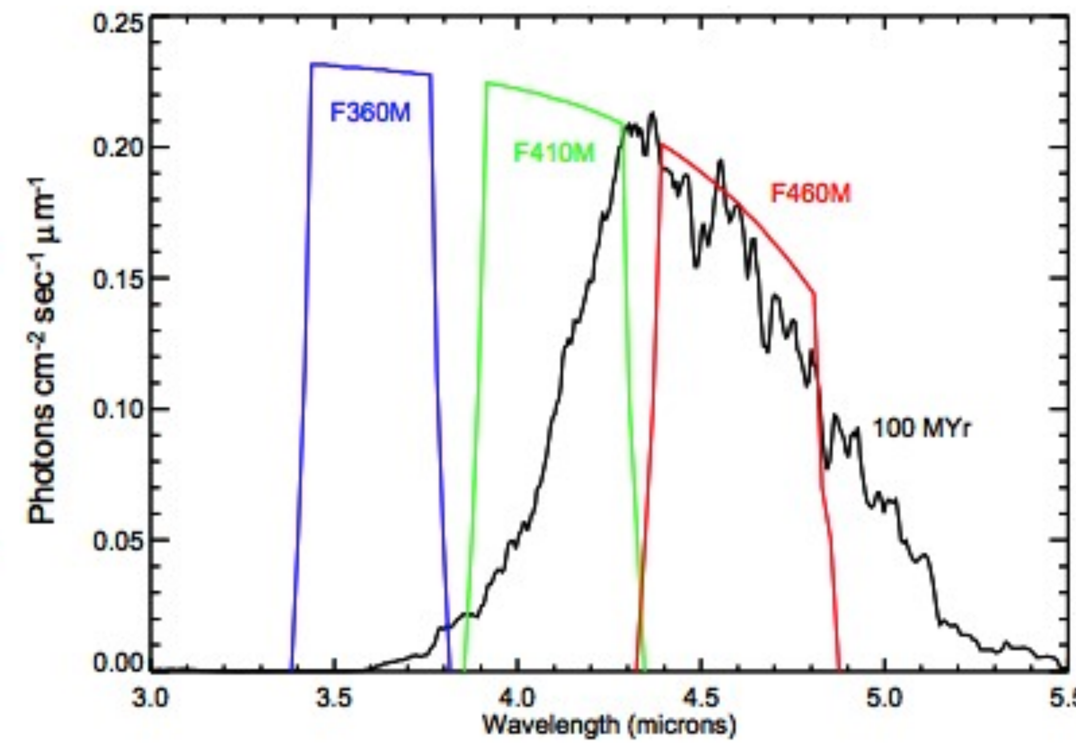
- Lower contrast but longer wavelengths than Probe
- Sensitive to thermal emission from gas giant planets
    - Good planet / star contrast in ~4.8 micron window
    - Most sensitive to planets < 1 Gyr old
- Can detect and resolve < ~1000 zodi disks with coronagraph
    - PSF subtraction is critical; 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

Spectra of Jupiter and the Sun at 10 pc (Kasting et al. 2009). Note significant emission from Jupiter at 4.5 microns



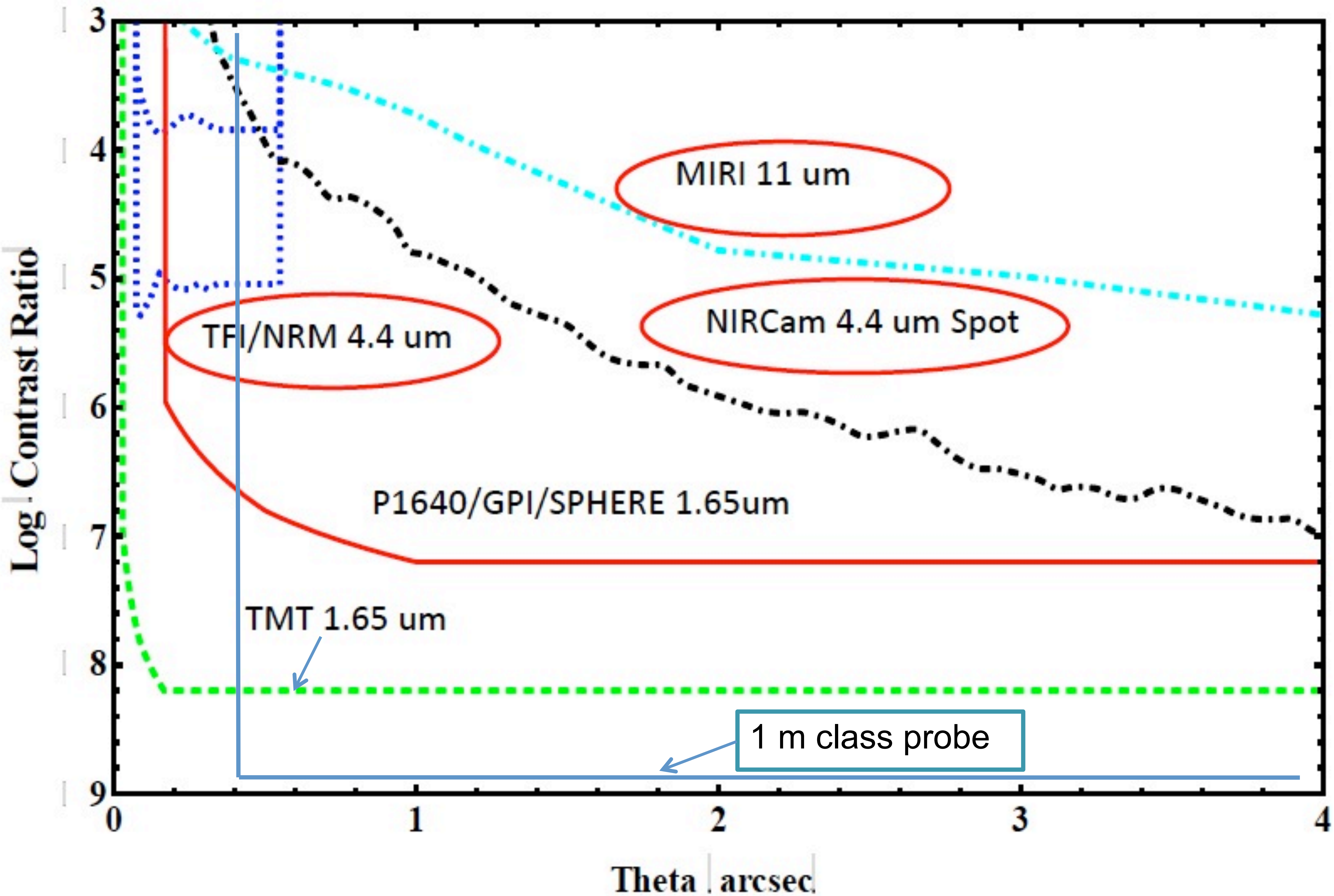
Krist et al. 2007 SPIE



Burrows et al. (2003) model spectrum of 1E8 yr, 2 Mjup planet with JWST NIRCam filters

- 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



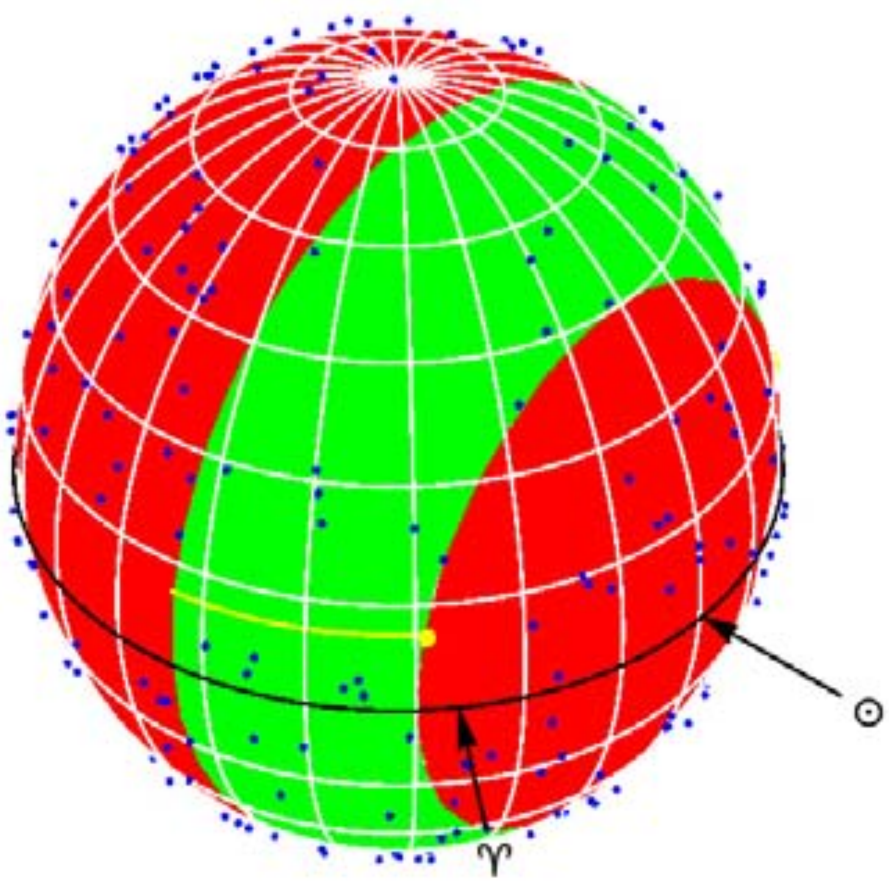
Greene / Danchi, ExoPAG SAG9

JWST / Probe complementarity

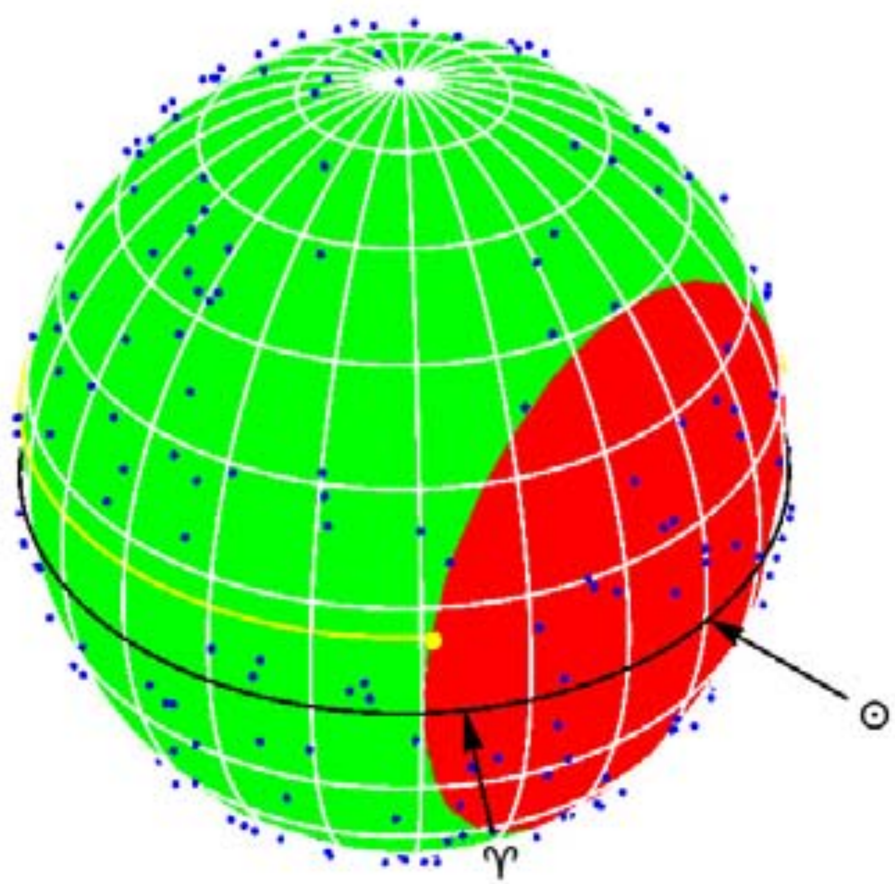
	Probe	JWST
Planet sensitivity	Reflected vis. light from giants close to stars (near IWA)	• Emitted light from planets (far from stars) • Known transiting planets
Best host stars	Nearby F/G/K mature stars	Young stars, M stars, A stars < 1 Gyr (imaging)
Atmospheric spectra	Samples bulk atmosphere above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

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

adapted from Bob Brown

Coronagraph Probe Times

Max observable time vs. Exposure times (days)

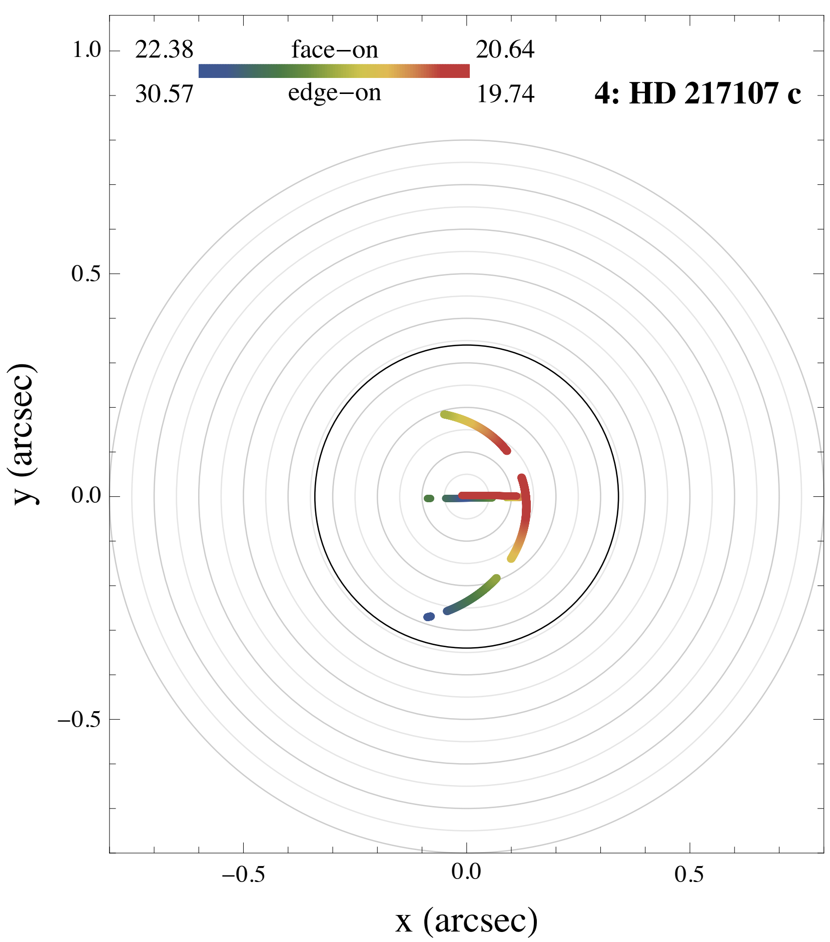
	star	log t_{max}	log $t_{0,LSO,1\,m}$	log $t_{0,LSO,1.5\,m}$	log $t_{0,LSO,2.4\,m}$	log $t_{0,LCO,1\,m}$	log $t_{0,LCO,1.5\,m}$	log $t_{0,LCO,2.4\,m}$
1	beta Gem	2.44	−0.432	−0.807	−1.23	0.517	0.144	−0.274
2	gamma Cep	2.56	0.574	0.112	−0.362	1.49	1.04	0.572
3	epsilon Eri	2.47	0.872	0.372	−0.131	1.86	1.36	0.861
4	upsilon And	2.47	1.11	0.580	0.0483	2.32	1.76	1.21
5	47 UMa	2.47	1.74	1.14	0.529	2.90	2.28	1.65
6	mu Ara	2.47	1.81	1.20	0.579	2.91	2.29	1.66
7	HD 10647	2.56	2.10	1.47	0.811	3.32	2.68	2.00
8	HD 39091	2.56	2.19	1.56	0.890	3.38	2.73	2.04
9	HD 192310	2.44	2.25	1.61	0.939	3.23	2.60	1.93
10	HD 190360	2.56	2.25	1.61	0.939	3.32	2.68	1.99
11	HD 30562	2.47	2.28	1.64	0.964	3.44	2.79	2.10
12	55 Cnc	2.44	2.43	1.78	1.08	3.41	2.76	2.07
13	HD 217107	2.44	2.59	1.93	1.22	3.66	3.00	2.28
14	HD 134987	2.44	2.82	2.15	1.42	3.93	3.26	2.52
15	14 Her	2.56	2.93	2.25	1.52	3.91	3.24	2.50
16	HD 154345	2.56	3.04	2.37	1.62	4.13	3.45	2.70
17	HD 33636	2.45	3.23	2.55	1.79	4.43	3.74	2.98
18	HD 220773	2.44	3.28	2.59	1.83	4.41	3.73	2.96
19	HD 87883	2.45	3.68	2.99	2.21	4.60	3.91	3.14
20	HD 181433	2.54	4.32	3.62	2.82	5.21	4.51	3.71
21	GJ 832	2.48	4.54	3.84	3.04	4.49	3.81	3.03
22	GJ 676 A	2.47	5.28	4.58	3.77	5.47	4.78	3.98
23	GJ 649	2.56	5.39	4.68	3.87	5.32	4.63	3.82
24	GJ 849	2.44	5.95	5.24	4.43	5.89	5.10	4.38

adapted from Bob Brown

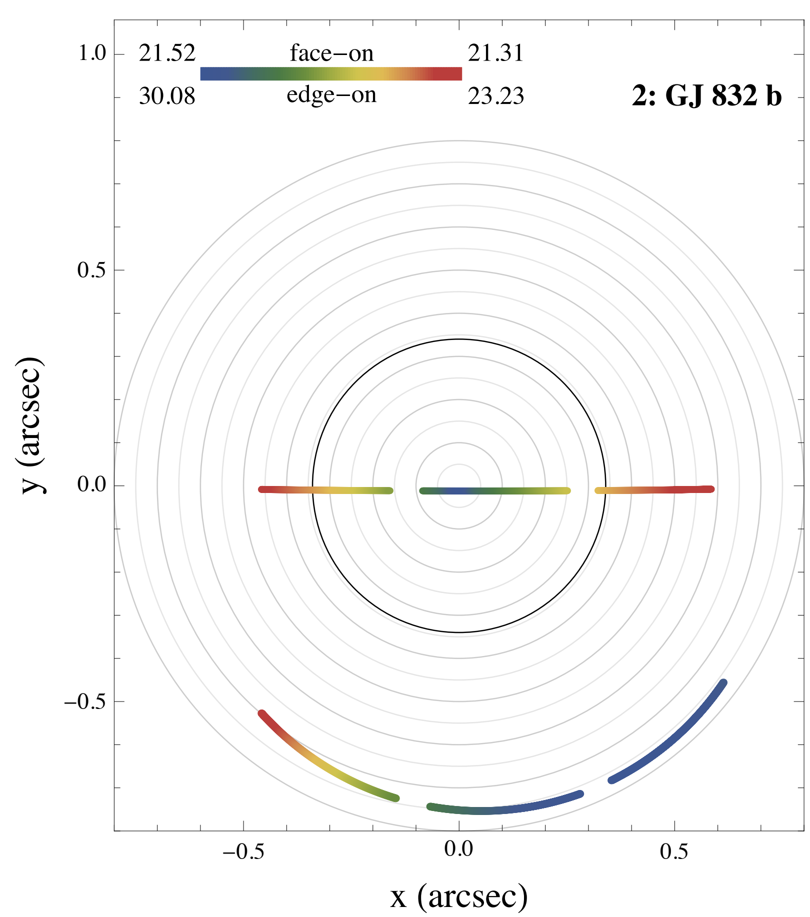
Impact of time criterion

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

	RV exoplanet	d(pc)	m_s ($m_\odot$)	$m_p \sin i$ ($m_{♃}$)	a(au)	ϵ	ω_p	period (days)	periapsis (JD -2450000)	$a(1+\epsilon)/d$ (arcsec)
1	epsilon Eri b	3.22	0.82	1.05	3.38	0.25	186.00	2500.	-1060.00	1.31
2	GJ 832 b	4.95	0.45	0.64	3.40	0.12	124.00	3416.	1211.00	0.77
3	55 Cnc d	12.34	0.91	3.54	5.47	0.02	74.00	4909.	3490.00	0.45
4	HD 217107 c	19.86	1.11	2.62	5.33	0.52	18.60	4270.	1106.32	0.41
5	mu Ara c	15.51	1.15	1.89	5.34	0.10	237.60	4206.	2955.20	0.38



HD127107c never comes out of IWA during the 3 year mission



GJ832b comes out of IWA but too faint and ruled out for time constraints

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)

		Total exposure time (days)		
	D (m)	183	365	730
Coronagraph	1.0	1	1	1
	1.5	1	1	2
	2.4	2	3.15	4.15
Star Shade	1.0	2	3	4.23
	1.5	3	5	6.34
	2.4	6	8.23	11.3

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

adapted from Bob Brown

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?