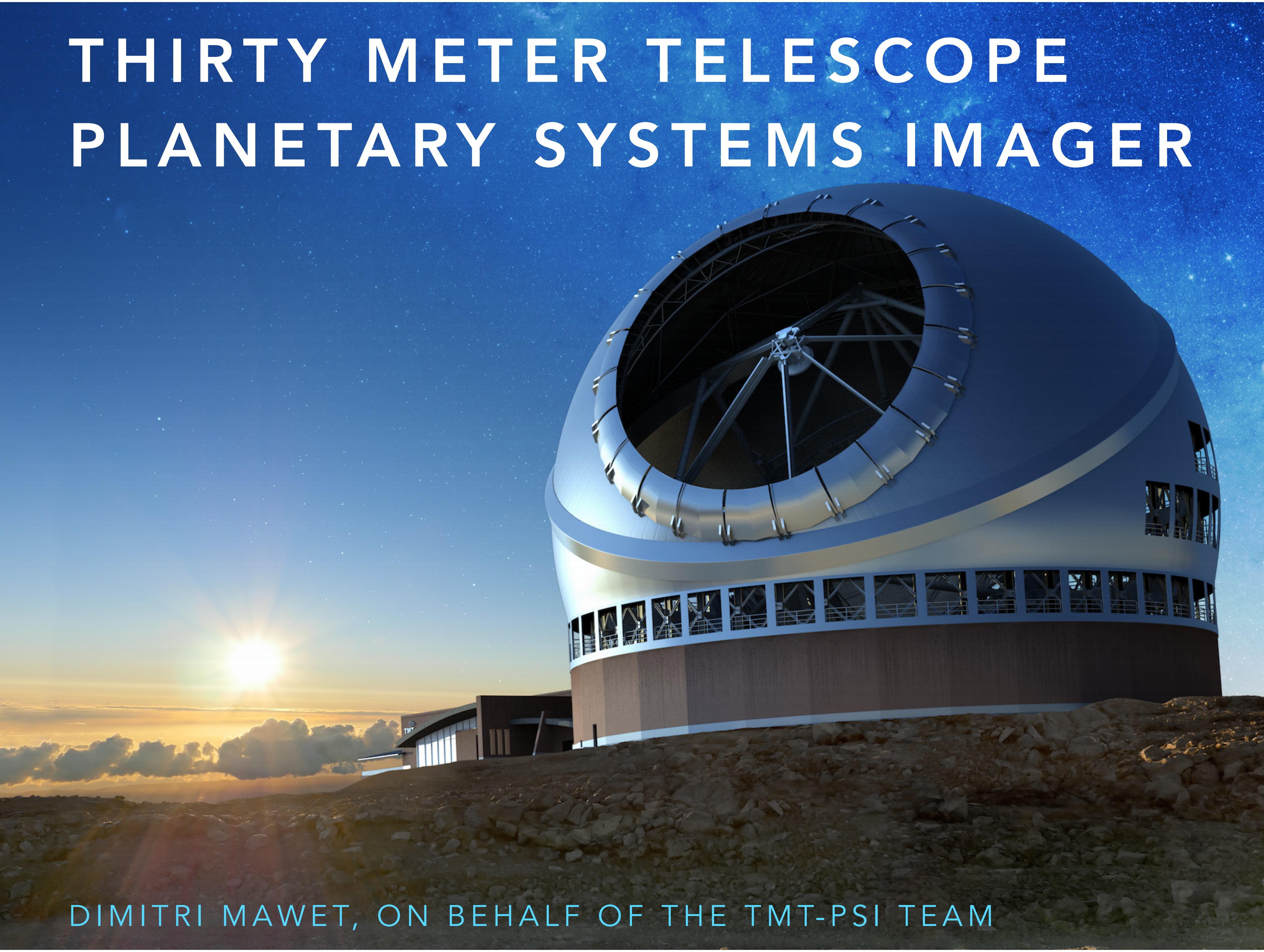
THIRTY METER TELESCOPE PLANETARY SYSTEMS IMAGER



DIMITRI MAWET, ON BEHALF OF THE TMT-PSI TEAM

TMT-PLANETARY SYSTEMS IMAGER

Canada: É. Artigau, B. Benneke, R. Doyon, D. Lafrenière, C. Marois, L. Simard

Caltech/JPL: V. Bailey, C. Beichman, R. Dekany, J.-R. Delorme, L. Hillenbrand, A. Howard, N. Jovanovic, H. Knutson, D. Mawet, M. Millar-Blanchaer, L. Roberts, G. Ruane, G. Serabyn, M. Troy, G. Vasisht, J. K. Wallace, J. Wang

China: S. Dong

Hawaii: C. Baranec, M. Chun, M. Liu

Japan: O. Guyon, J. Hashimoto, H. Kawahara, T. Kotani, J. Lozi, N. Murakami, N. Narita, T.-S. Pyo, M. Tamura

India: S. Mondal

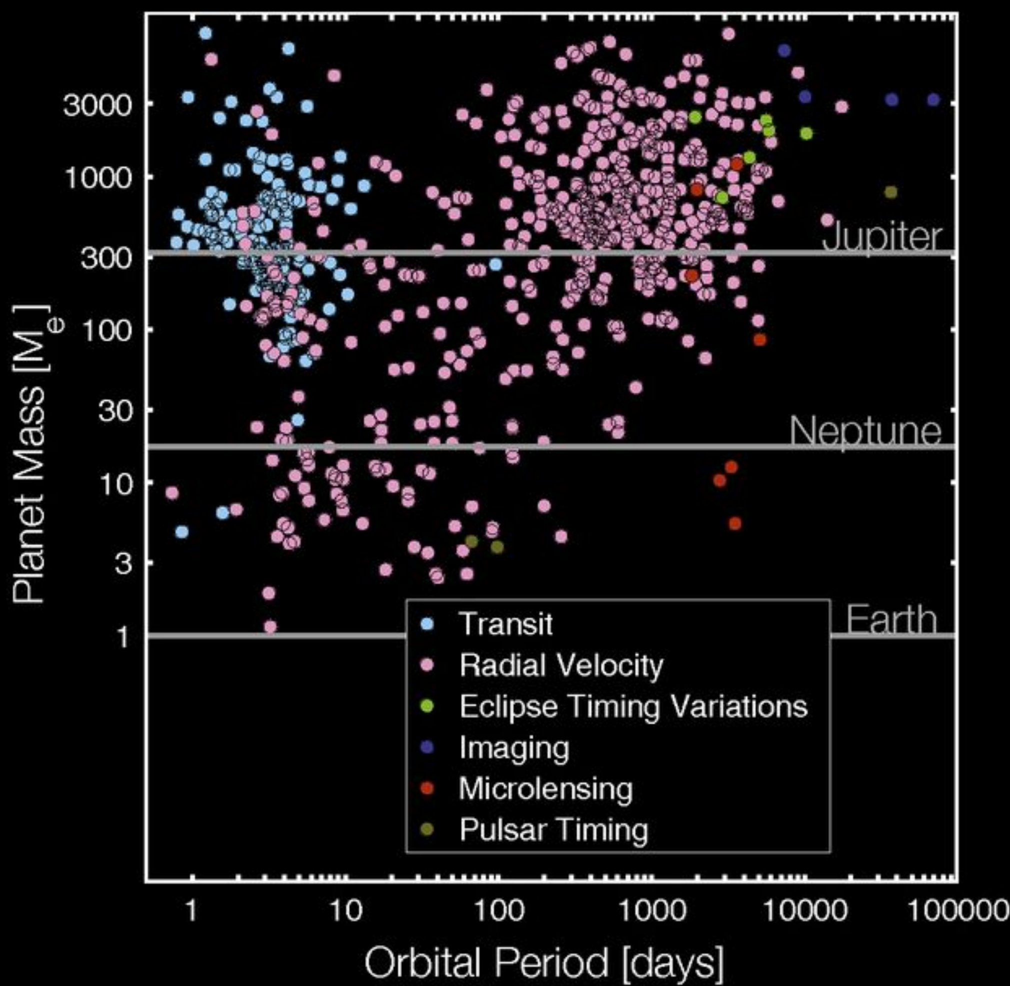
UC: T. Brandt, C. Dressing, M. Fitzgerald,[1] J. Fortney, R. Jensen-Clem, Q. Konopacky, J. Lu, B. Mazin,[2] R. Murray-Clay, A. Shields, A. Skemer, D. Stelter, S. Wright

Other: J. Chilcote, I. Crossfield, R. Dong (soon Canada), R. Frazin, B. Macintosh, J. Males, M. Marley

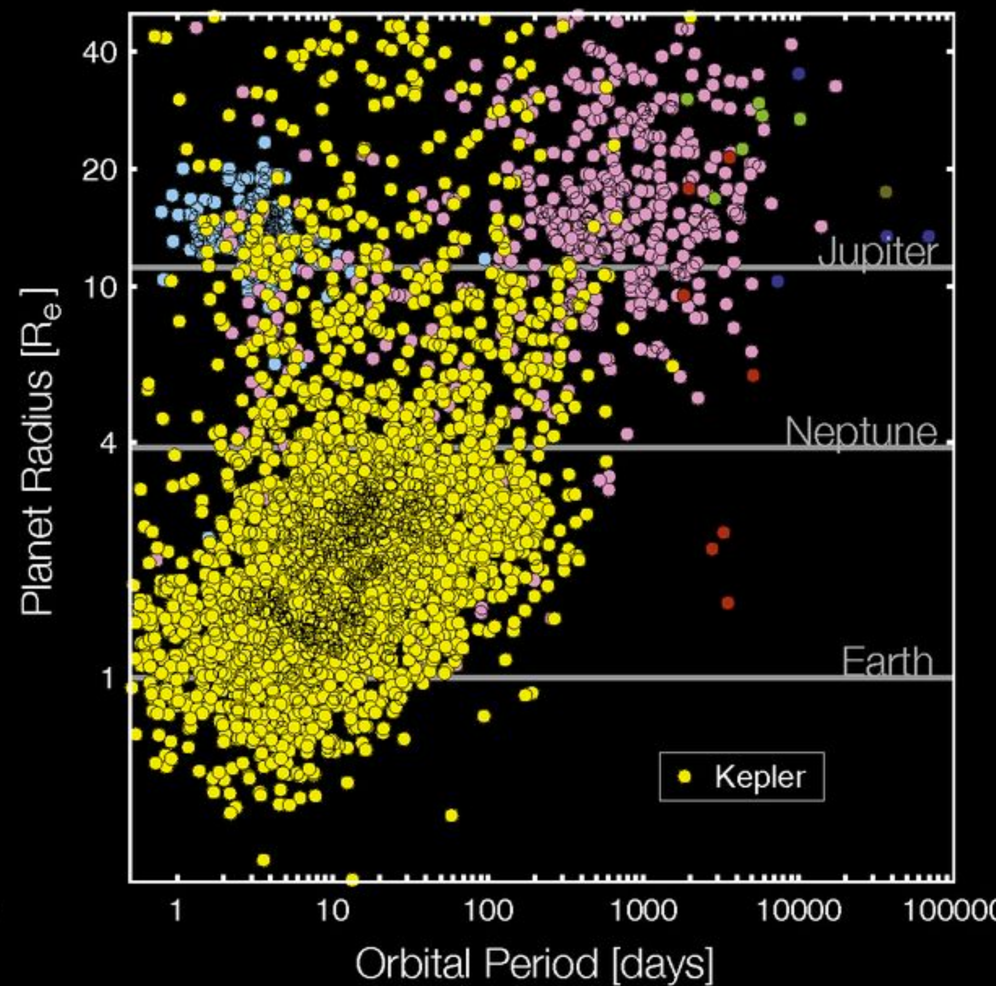
SCIENCE CASES - EXOPLANETS

- Exoplanet demographics on Solar system scales (0.5 AU to >5AU)
- Exoplanet characterization from Earth-like planets, Super-Earths, Mini-Neptunes, Ice and Gas giants
  - Orbital configuration/dynamics
  - Atmosphere composition, clouds/hazes
  - Energy budget, climate
  - Spin, Weather
  - Moons, rings
- Biosignatures on Habitable Earth-size planets around M/K stars
  - H_2O, O_2, CH_4 trifecta

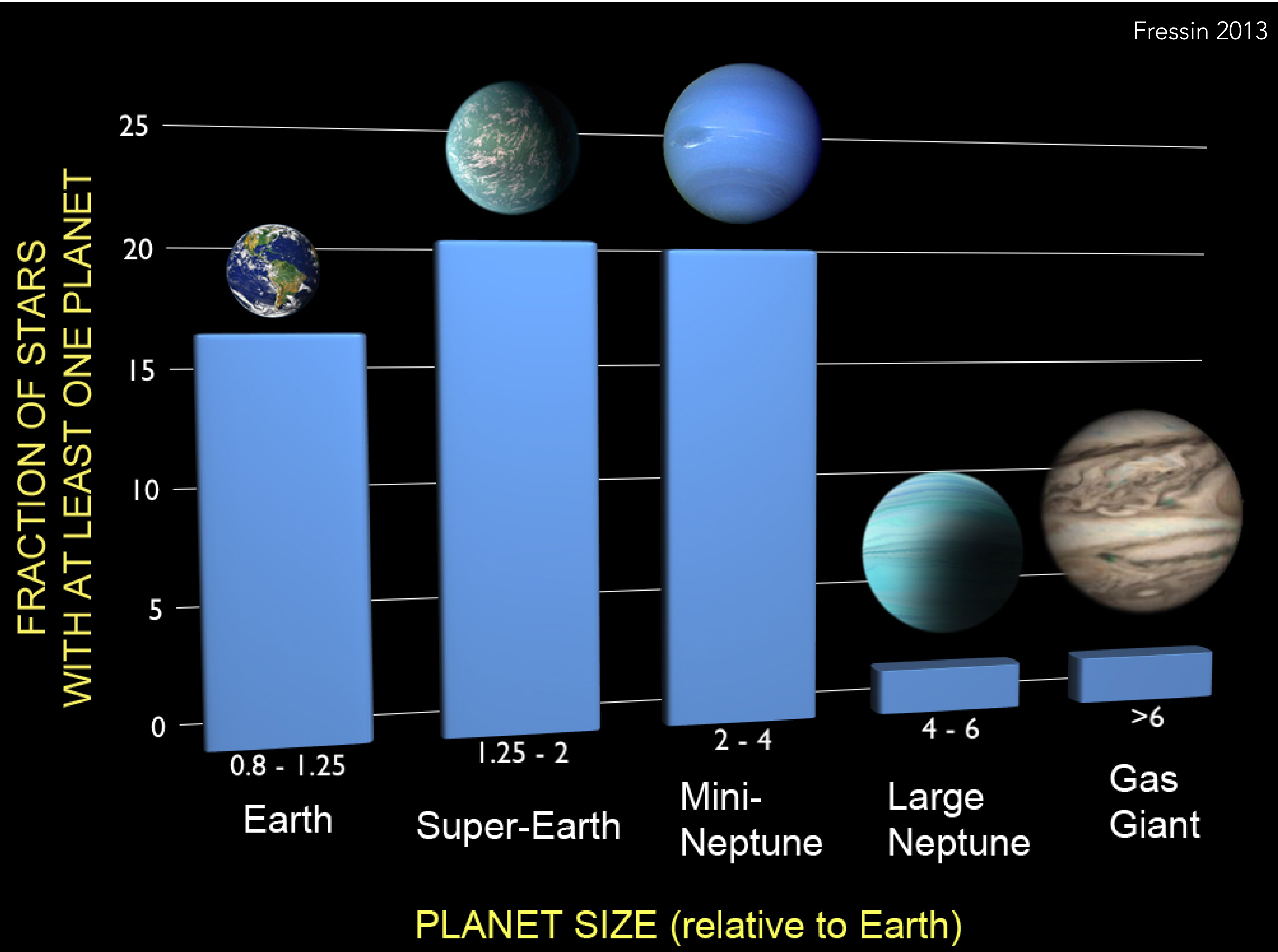
Pre-Kepler



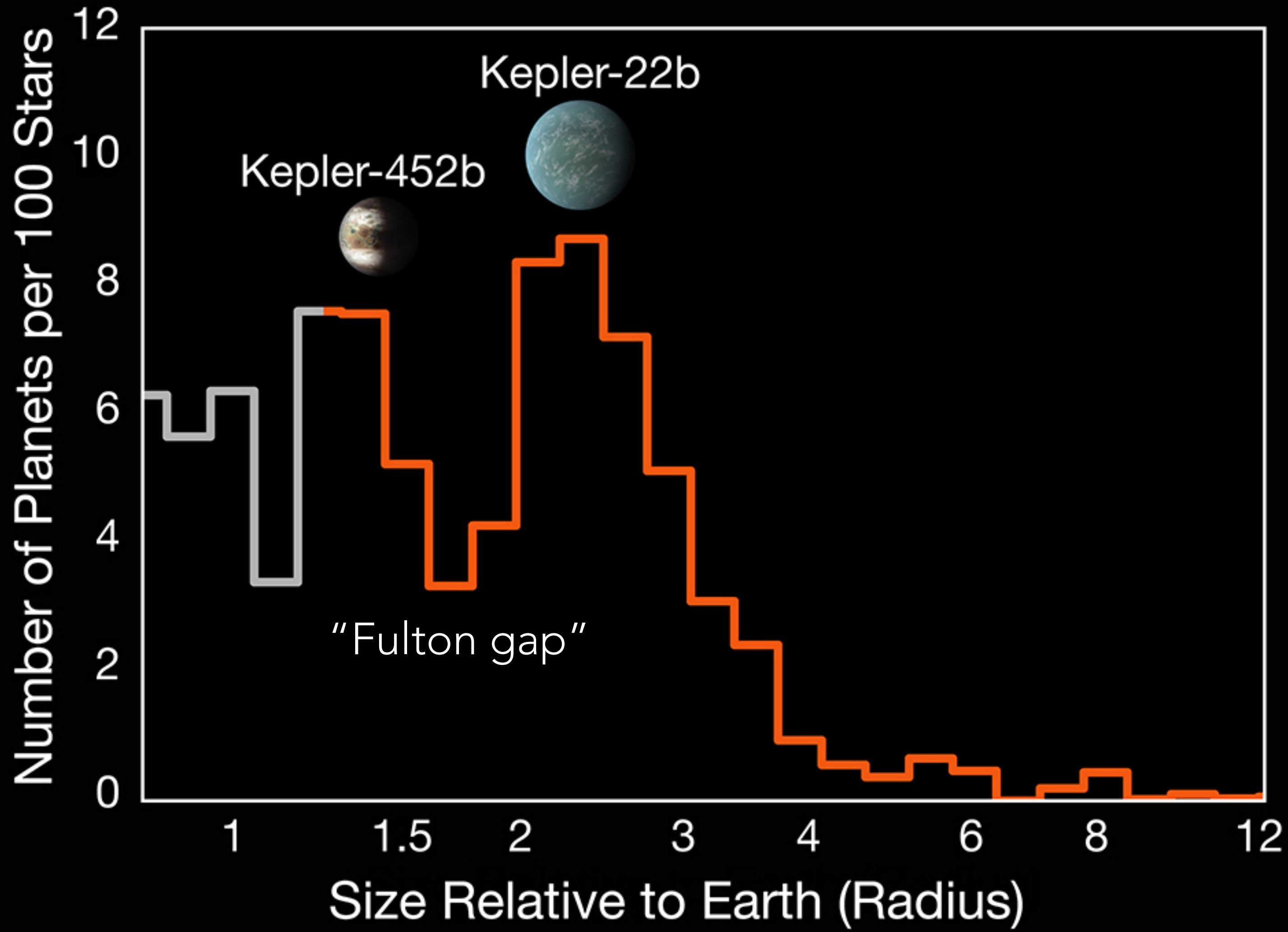
Post-Kepler



N. Batahla


Fressin 2013
FRACTION OF STARS
WITH AT LEAST ONE PLANET
25
20
15
10
5
0
0.8 - 1.25
Earth
1.25 - 2
Super-Earth
2 - 4
Mini-
Neptune
4 - 6
Large
Neptune
>6
Gas
Giant
PLANET SIZE (relative to Earth)

Small Planets Come in Two Sizes



Fulton et al. 2017

1 in 4 M-type stars has a rocky planet in its Habitable zone

Dressing & Charbonneau 2015

Proxima Centauri b

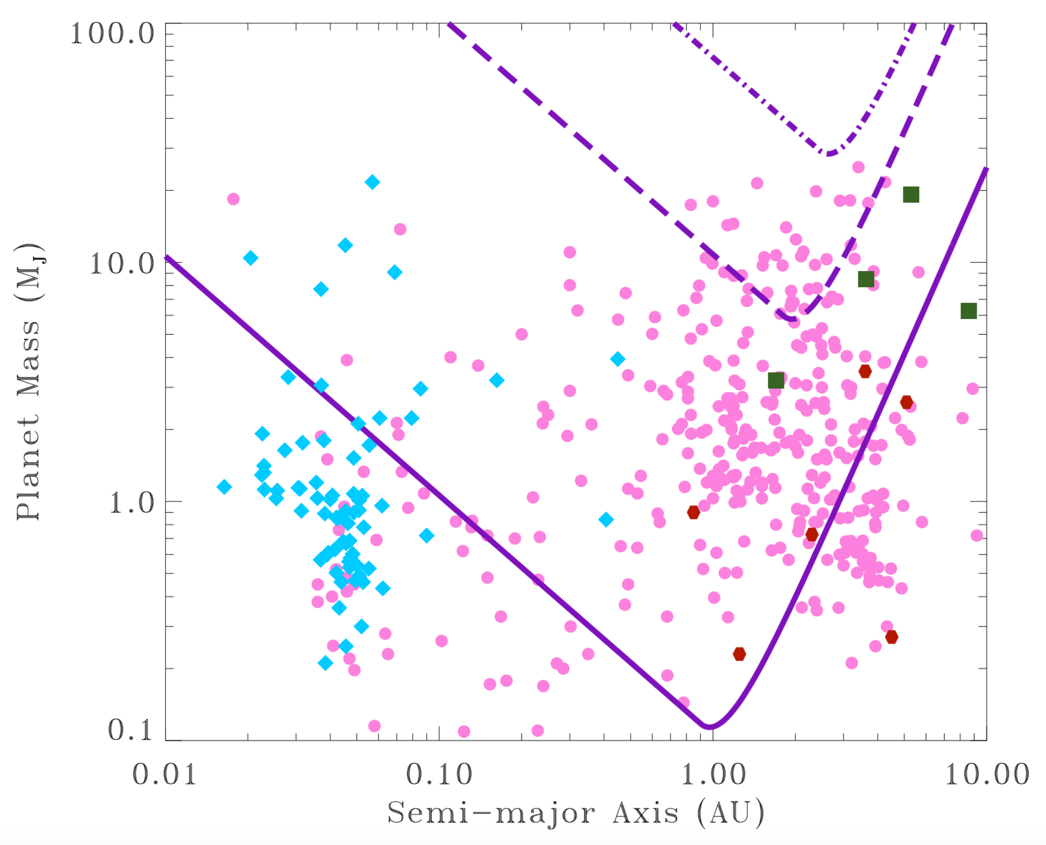
Artist rendition (ESO/M. Kornmesser)

BLIND SEARCH VS TARGETED CAMPAIGN RV, TESS AND GAIA

- Plethora of new RV machines coming online, many now expanding to the near-IR

- TESS Launch imminent (Spring 2018)
- All-sky transit mission
- More exoplanet demographics
- Expected to detect a few super-Earths in 100-day orbits around nearby stars
- Remember single-transits

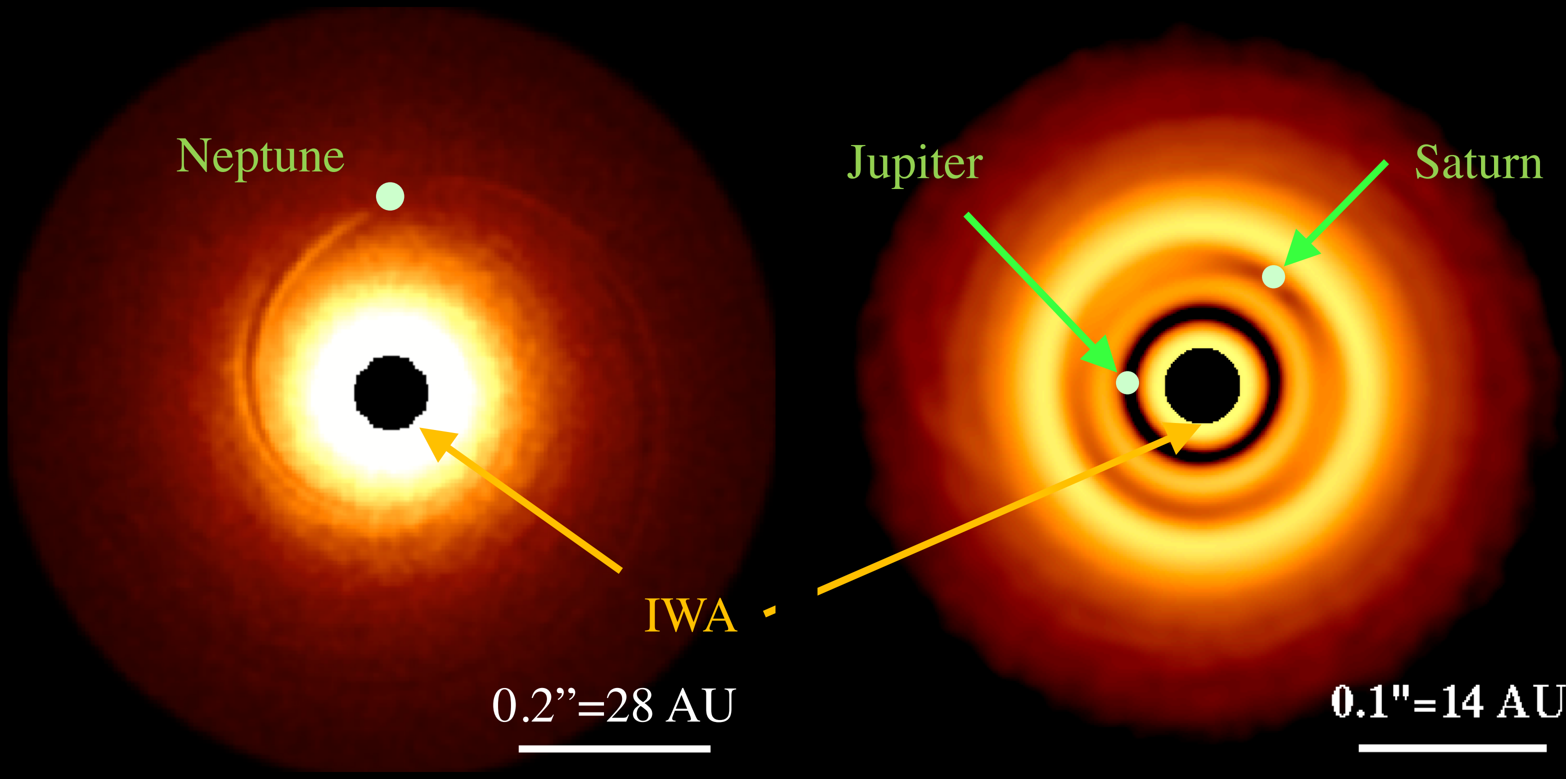
- GAIA expects to find >>10,000 Jupiters orbiting FGKM and WDs <100 pc, many with orbits (and masses!)
- ~2,600 detections of Jupiter mass planets incl. ~500 accurate orbits (assuming ηJup~3% from RV)
- Some detectable with ELTs @ 1e-8 contrast
- Astrometric trends from 1-70 MJup companions. BDs detectable with current ExAO



Sozzetti 2015

SCIENCE CASES - PLANET FORMATION

- Planet formation and systems architectures
  - [Fe/H] and C/O ratios vs distance, migration history
  - Disk substructures: rings, gaps, spirals
  - Complementarity to ALMA

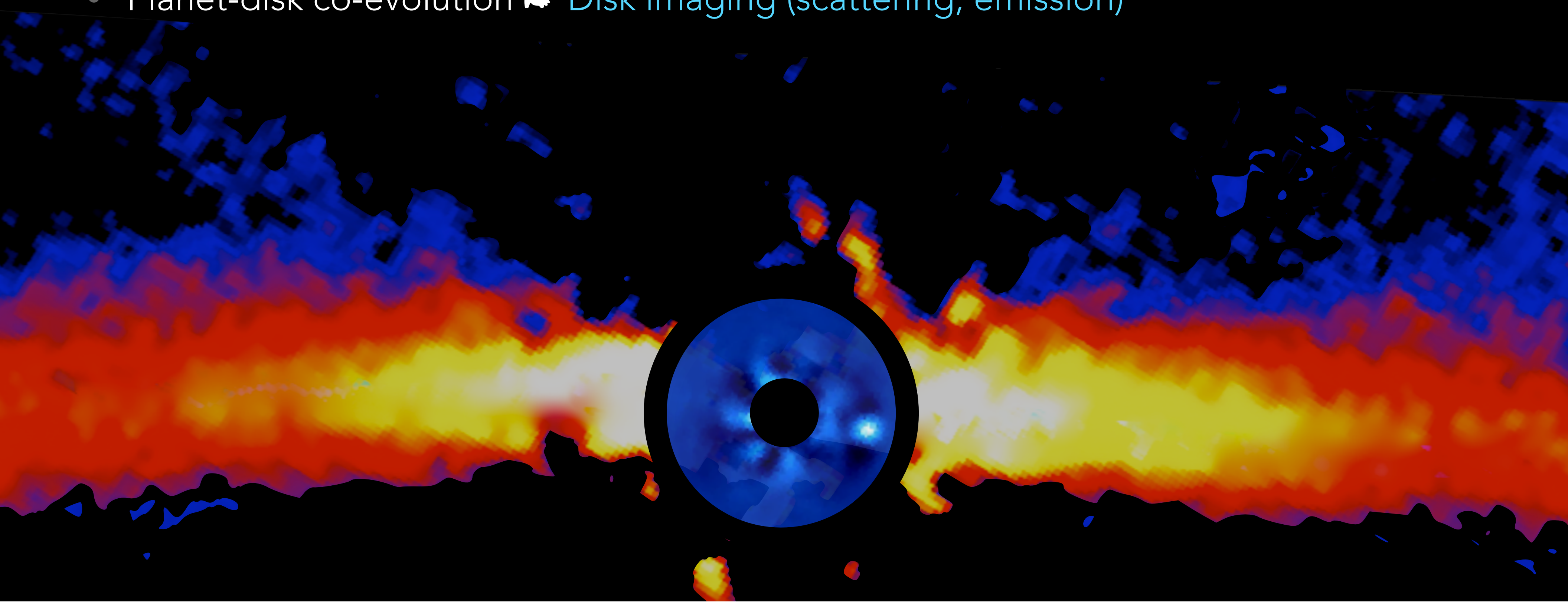


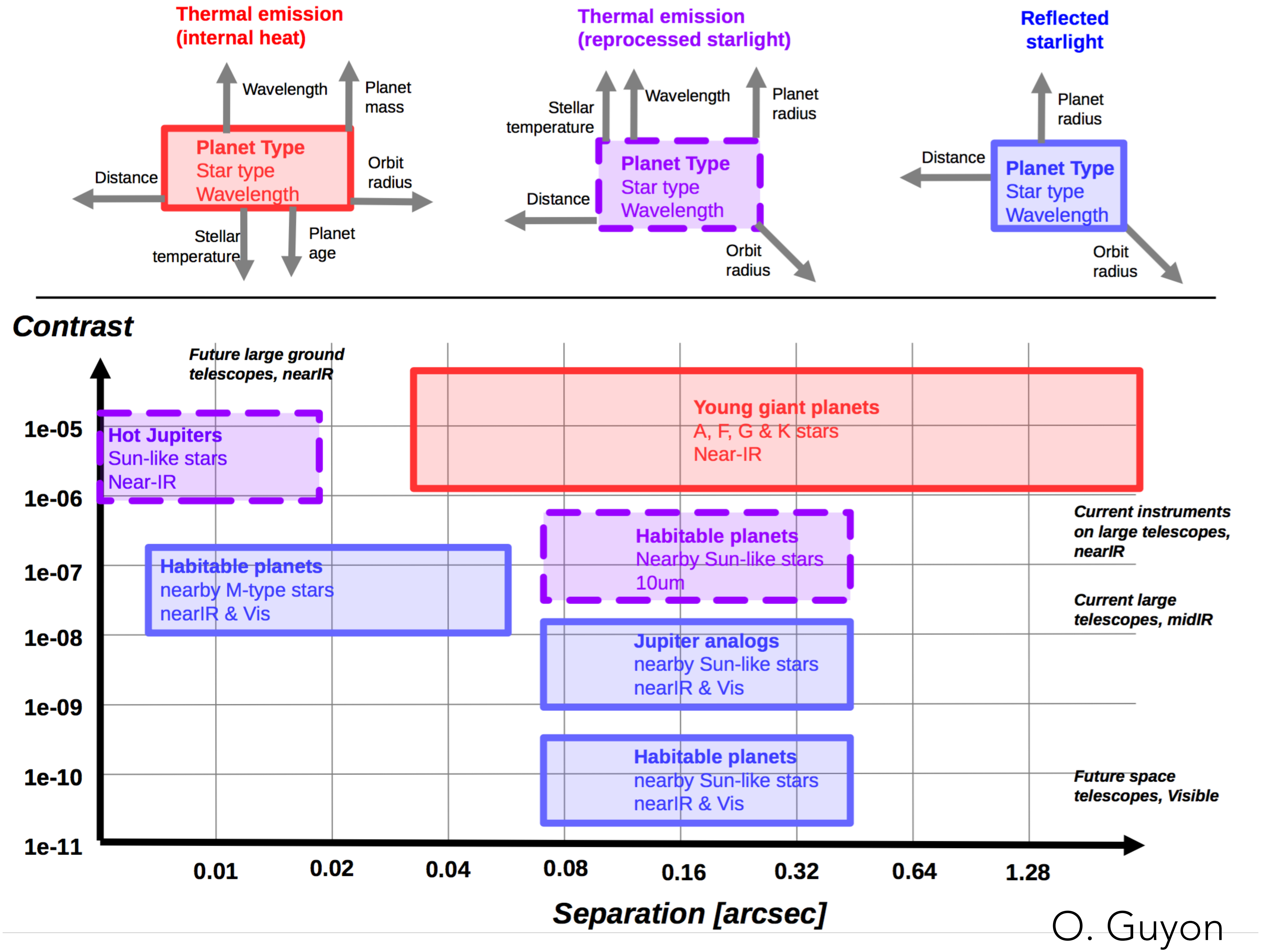
OTHER SCIENCES

- Solar system science:
  - Volcanic Eruptions on Io
  - Organics in Comets
  - Asteroid Multiples
  - Planetary Atmospheres
- Galactic Astrophysics:
  - Stellar Multiplicity
  - Stellar Evolution
  - Inner Regions of Circumstellar Disks
  - Ice Lines in Disks
  - Dust streamers in Interacting Binaries
  - Compact Objects
- Extragalactic Astrophysics:
  - Inner Regions of Quasar-Host Galaxies
  - Spatially Resolved Spectra of Nearby Galaxies

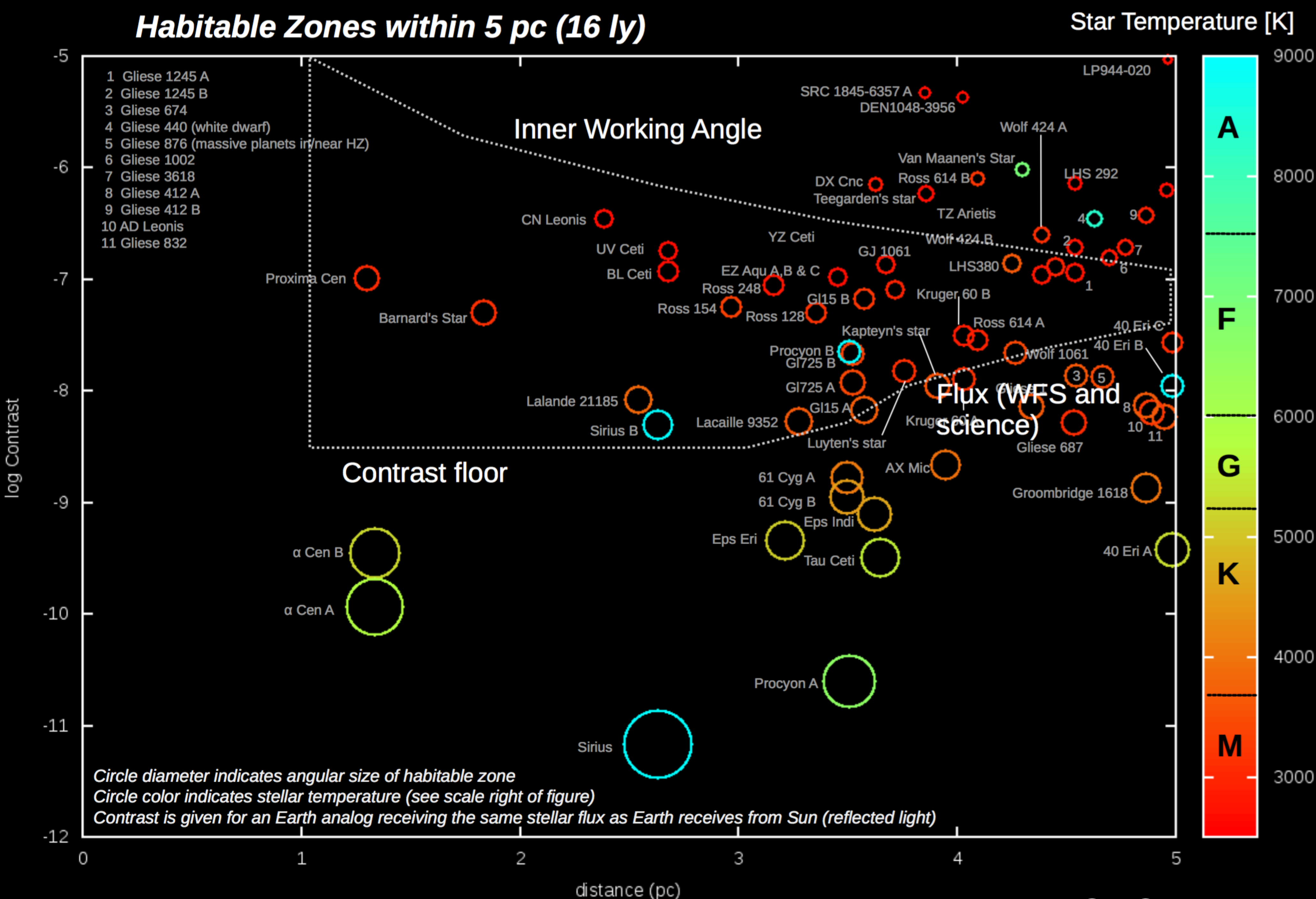
HOW-TO: DIRECT REMOTE SENSING

- Fill out parameter space not probed by indirect techniques ☛ Direct imaging
- Orbital properties (SMA, e, i) ☛ Astrometry
- Bulk properties (Mass, T_{eff}, log g) ☛ Multi-λ Photometry
- Atmosphere's composition, spin, inhomogeneities ☛ Spectroscopy (LRS, HRS)
- *Cloud morphology, particle sizes and composition* ☛ Polarimetry
- Planet-disk co-evolution ☛ Disk imaging (scattering, emission)





Thermal emission
(internal heat)
Wavelength
Planet mass
Planet Type
Star type
Wavelength
Distance
Orbit radius
Stellar temperature
Planet age
Thermal emission
(reprocessed starlight)
Stellar temperature
Wavelength
Planet radius
Planet Type
Star type
Wavelength
Distance
Orbit radius
Reflected
starlight
Planet radius
Distance
Planet Type
Star type
Wavelength
Orbit radius
Contrast
Future large ground telescopes, nearIR
Young giant planets
A, F, G & K stars
Near-IR
Hot Jupiters
Sun-like stars
Near-IR
Current instruments on large telescopes, nearIR
Habitable planets
Nearby Sun-like stars
10um
Habitable planets
nearby M-type stars
nearIR & Vis
Current large telescopes, midIR
Jupiter analogs
nearby Sun-like stars
nearIR & Vis
Habitable planets
nearby Sun-like stars
nearIR & Vis
Future space telescopes, Visible
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
0.01
0.02
0.04
0.08
0.16
0.32
0.64
1.28
Separation [arcsec]
O. Guyon

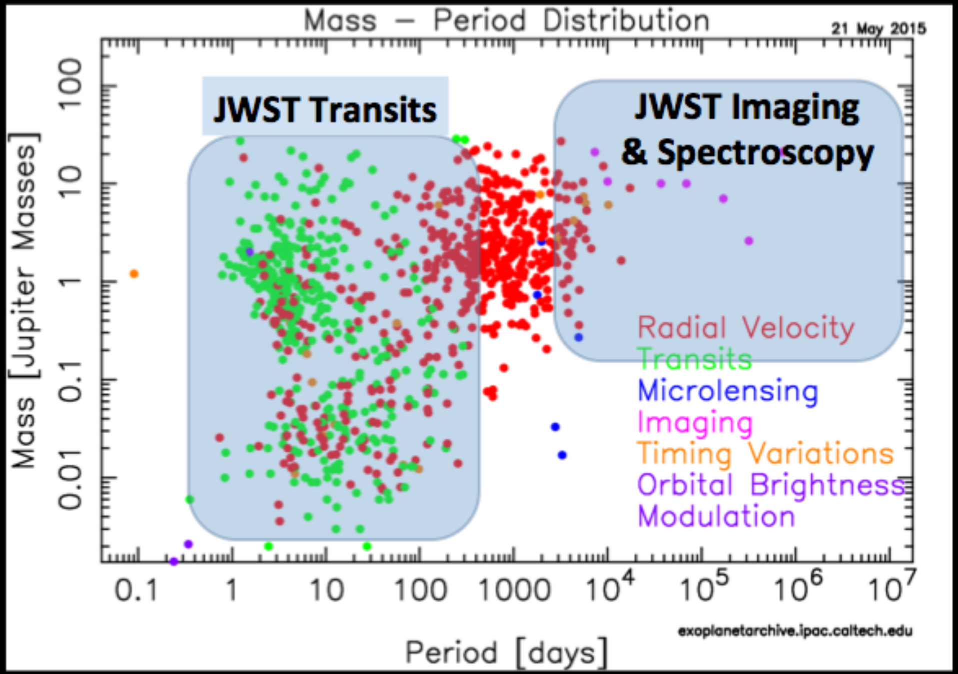


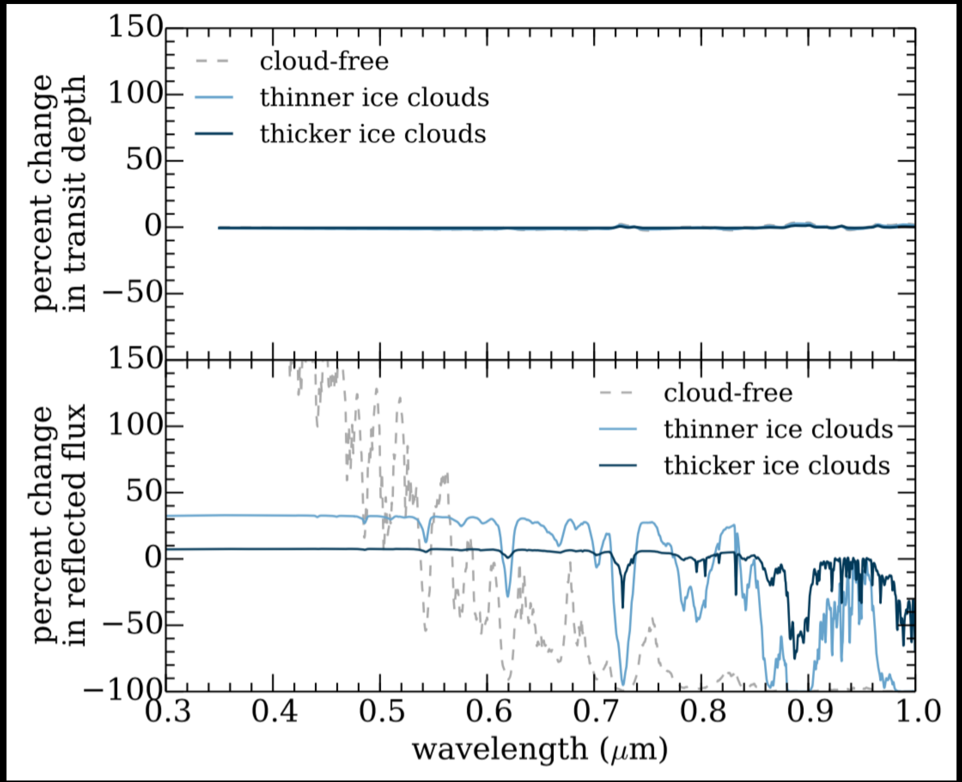
Habitable Zones within 5 pc (16 ly)
Star Temperature [K]
1 Gliese 1245 A
2 Gliese 1245 B
3 Gliese 674
4 Gliese 440 (white dwarf)
5 Gliese 876 (massive planets in/near HZ)
6 Gliese 1002
7 Gliese 3618
8 Gliese 412 A
9 Gliese 412 B
10 AD Leonis
11 Gliese 832
Inner Working Angle
Contrast floor
Flux (WFS and science)
LP944-020
SRC 1845-6357 A
DEN1048-3956
Wolf 424 A
Van Maanen's Star
LHS 292
DX Cnc
Ross 614 B
Teegarden's star
TZ Arietis
CN Leonis
YZ Ceti
Wolf 424 B
UV Ceti
GJ 1061
LHS380
BL Ceti
EZ Aqu A,B & C
Proxima Cen
Ross 248
Gl15 B
Kruger 60 B
Ross 154
Ross 128
Barnard's Star
Ross 614 A
Kapteyn's star
40 Eri C
40 Eri B
Procyon B
Gl725 B
Wolf 1061
Gl725 A
Lalande 21185
Gl15 A
Sirius B
Lacaille 9352
Luyten's star
Gliese 687
AX Mic
61 Cyg A
61 Cyg B
Groombridge 1618
Eps Indi
Eps Eri
α Cen B
Tau Ceti
40 Eri A
α Cen A
Procyon A
Sirius
Circle diameter indicates angular size of habitable zone
Circle color indicates stellar temperature (see scale right of figure)
Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)
log Contrast
distance (pc)
-5
-6
-7
-8
-9
-10
-11
-12
0
1
2
3
4
5
9000
8000
7000
6000
5000
4000
3000
A
F
G
K
M

O. Guyon

COMPLEMENTARITY WITH JWST

- Major impact in transit spectroscopy of short-period planets
- High-contrast imaging of self-luminous planets at larger separations
- Limited low-resolution spectroscopy

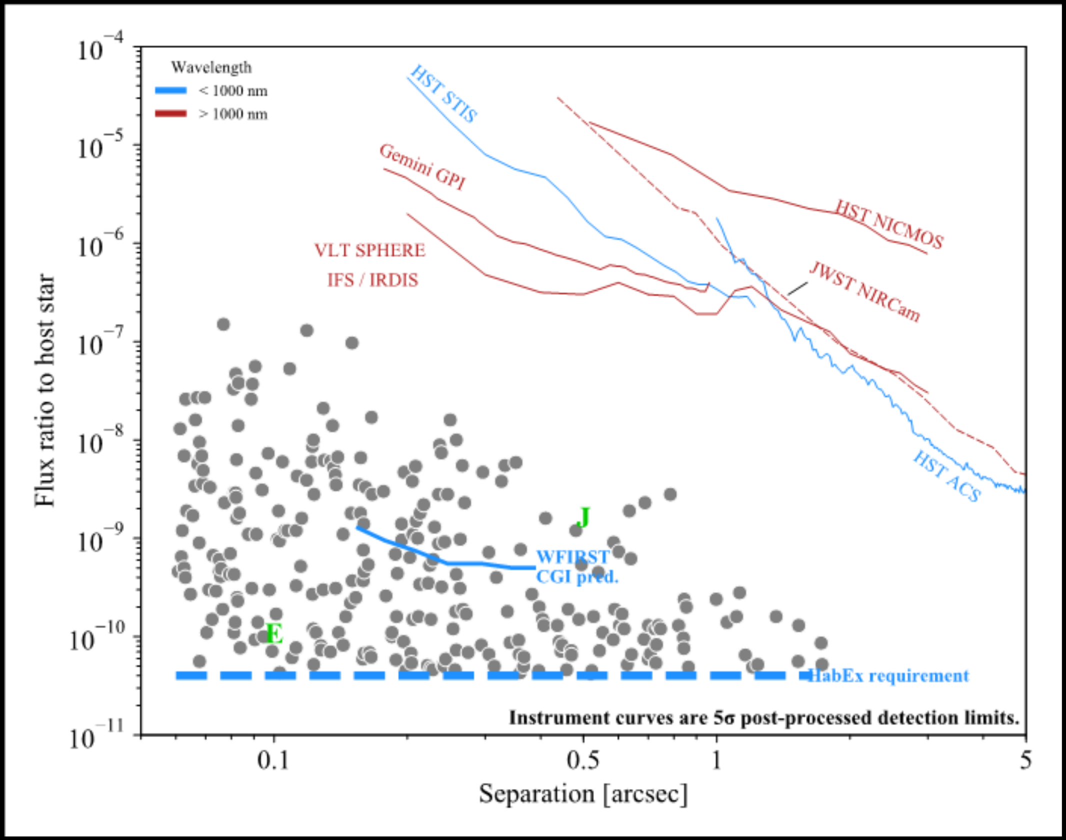




Morley et al. 2015

COMPLEMENTARITY WITH WFIRST CGI, HABEX/LUVOIR

- Launch >2024
- 0.4-1.0 um, R~70 spectroscopy
- Inner working angle 0.2”
- Discovery and characterization of nearby giant planets, several Neptunes
- Coronagraph may or may not have significant science program
- An opportunity for TMT for Reflected-light spectroscopic follow-ups of Jupiters/ Neptunes at 100-500K Teff.
- Technological synergies
- **And HabEx and LUVOIR**

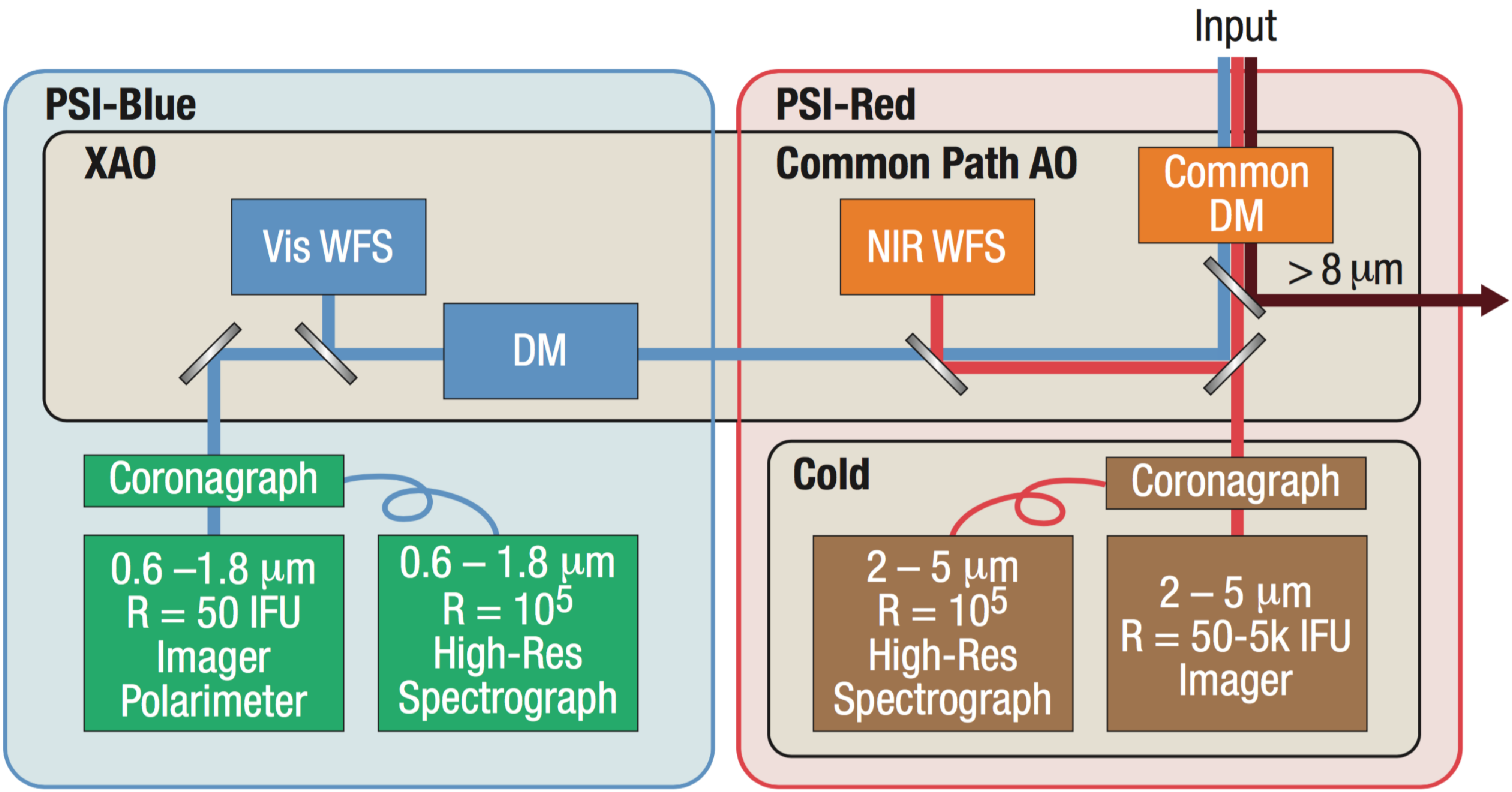


[redacted]

FEATURES OF THE PSI CONCEPT

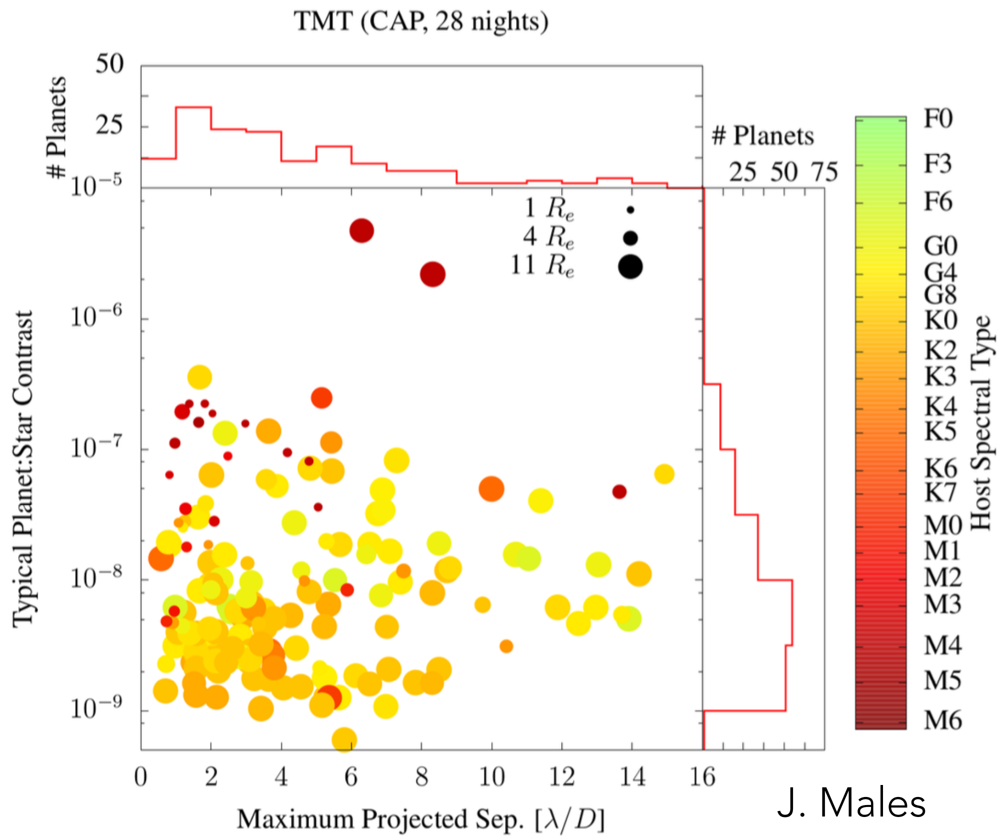
- Ability to address a wide range of science goals
  - Including non-exoplanet science
- Modularity
  - Core capabilities support different science instruments
  - Upgrade paths to accommodate new technology
  - Fiber feeds allow straightforward use of instruments deployed and tested on smaller telescopes
- Relatively compact
  - Diffraction-limited, narrow field-of-view optics
  - Allows for phased development and deployment

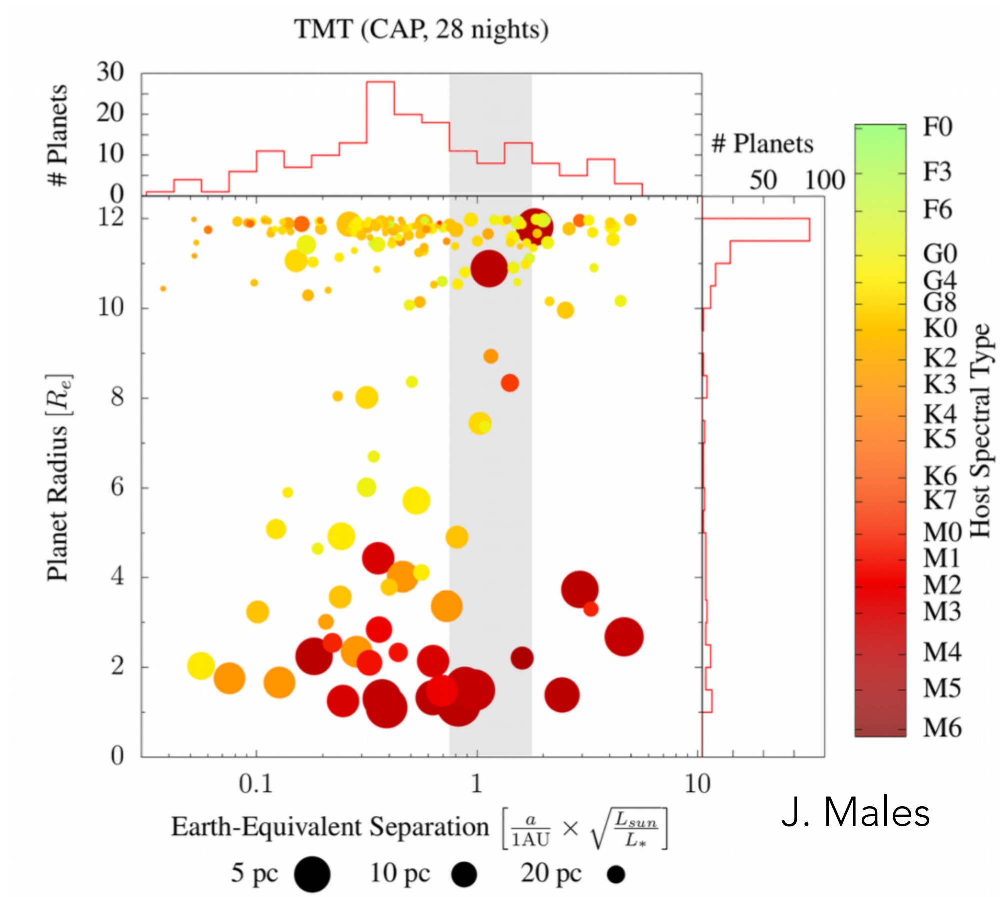
TMT-PLANETARY SYSTEMS IMAGER



Science case requires broad wavelength coverage

IMAGING GAS GIANTS, MINI-NEPTUNES AND ROCKY PLANETS



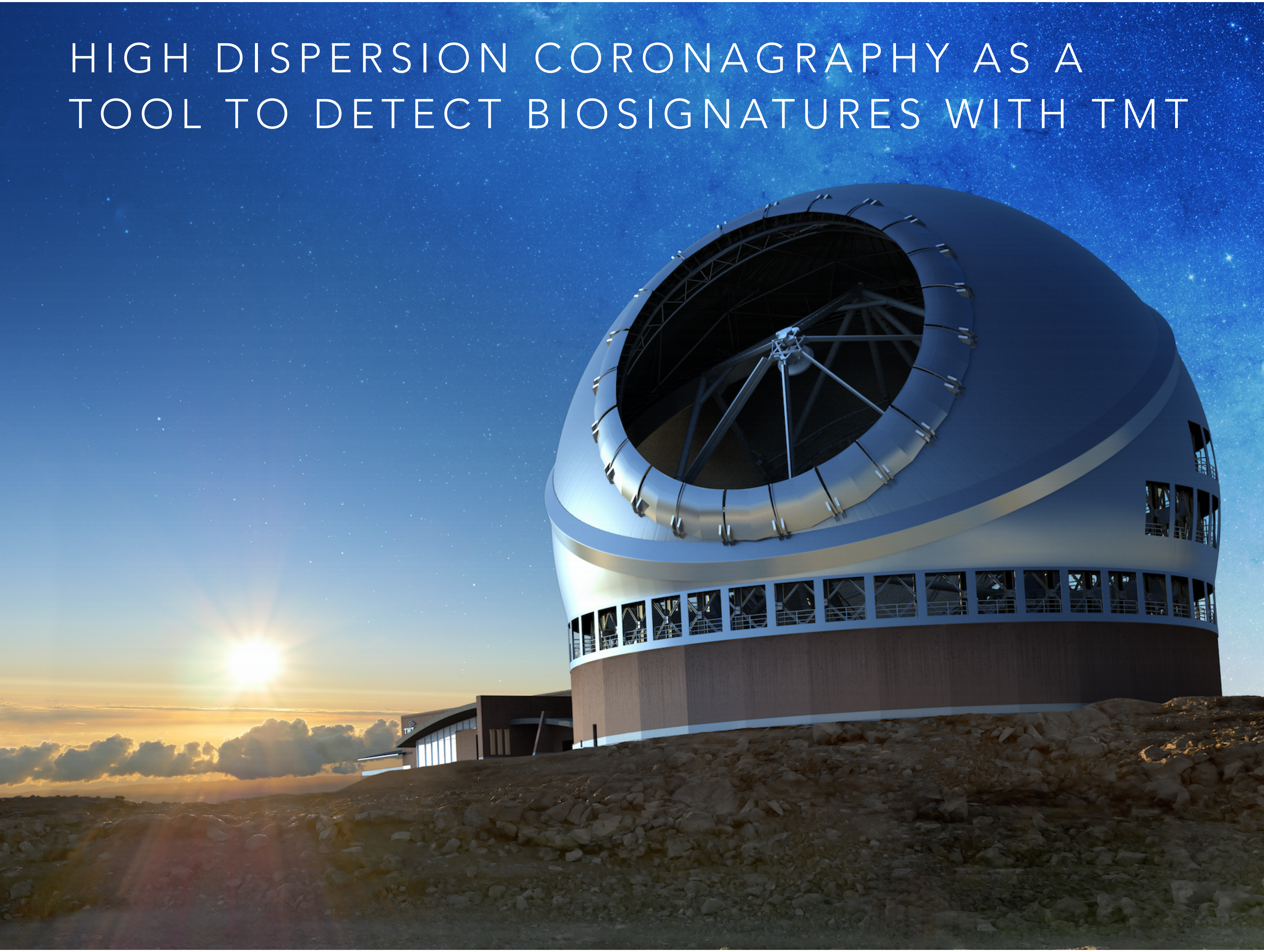


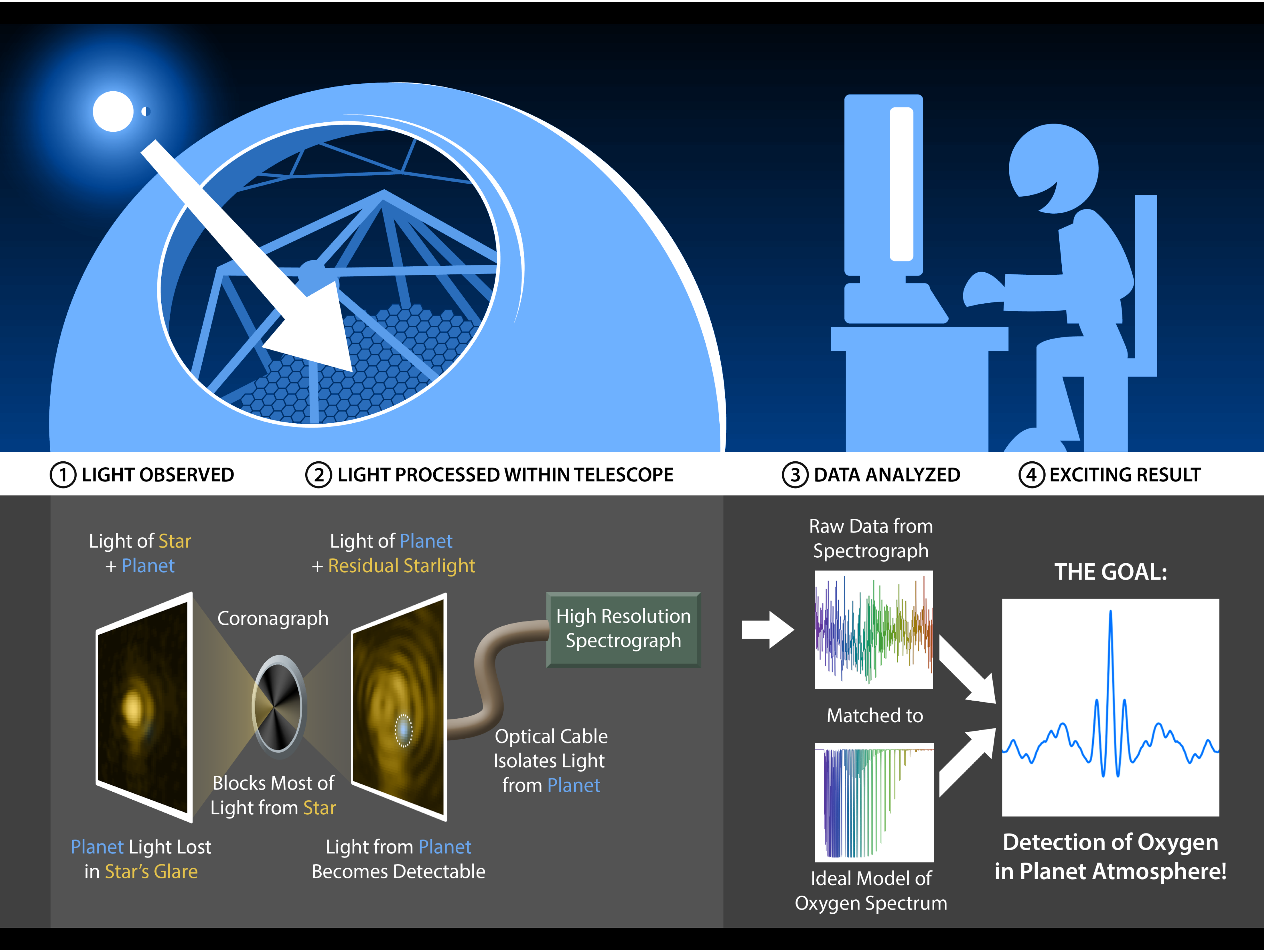
1 l/D IWA coronagraph, SNR=5 in broadband (400nm) @ 800nm

Speckle-noise limited with predictive control

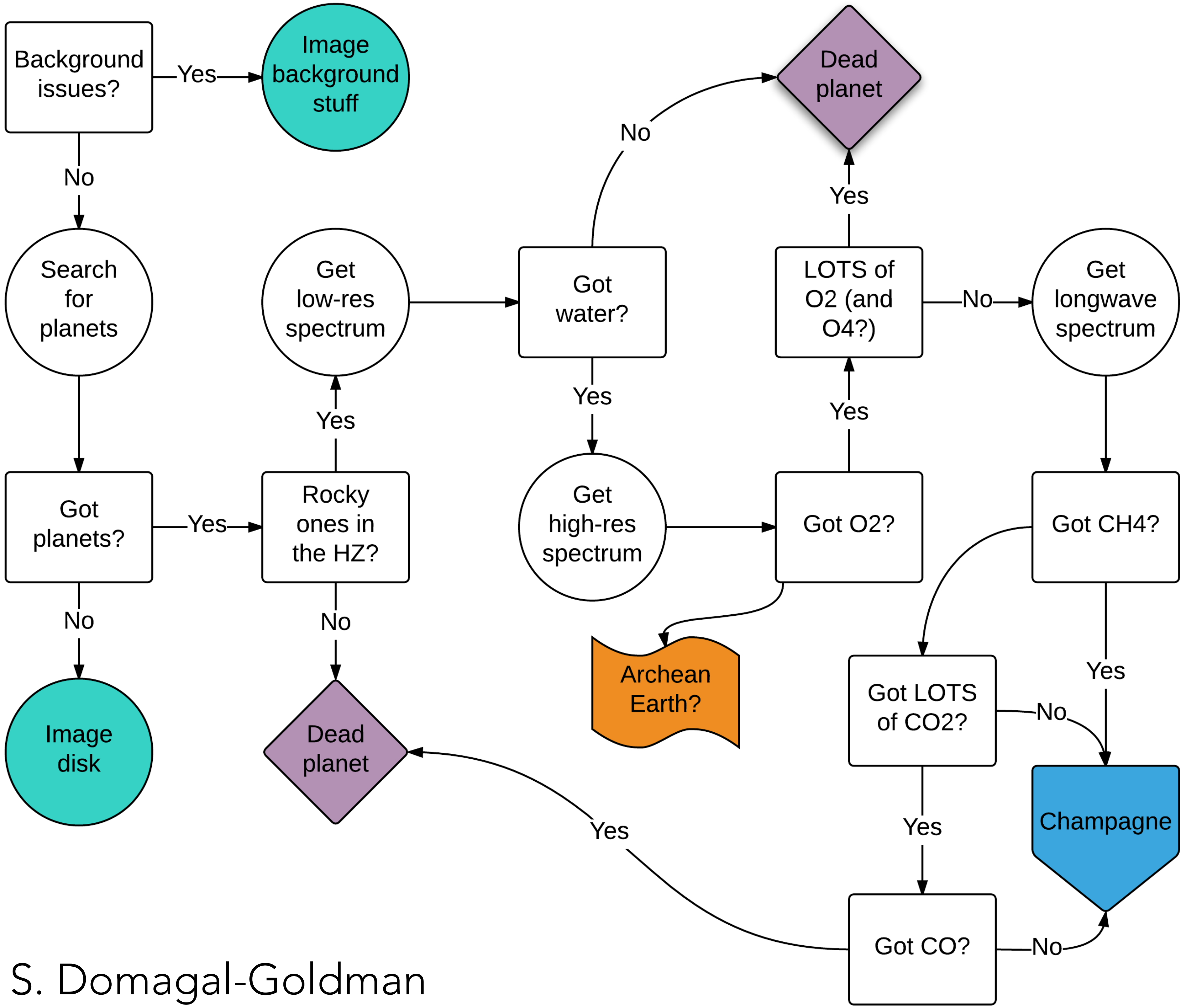
No chromatic effects (WFS and science at 800nm)

HIGH DISPERSION CORONAGRAPHY AS A TOOL TO DETECT BIOSIGNATURES WITH TMT



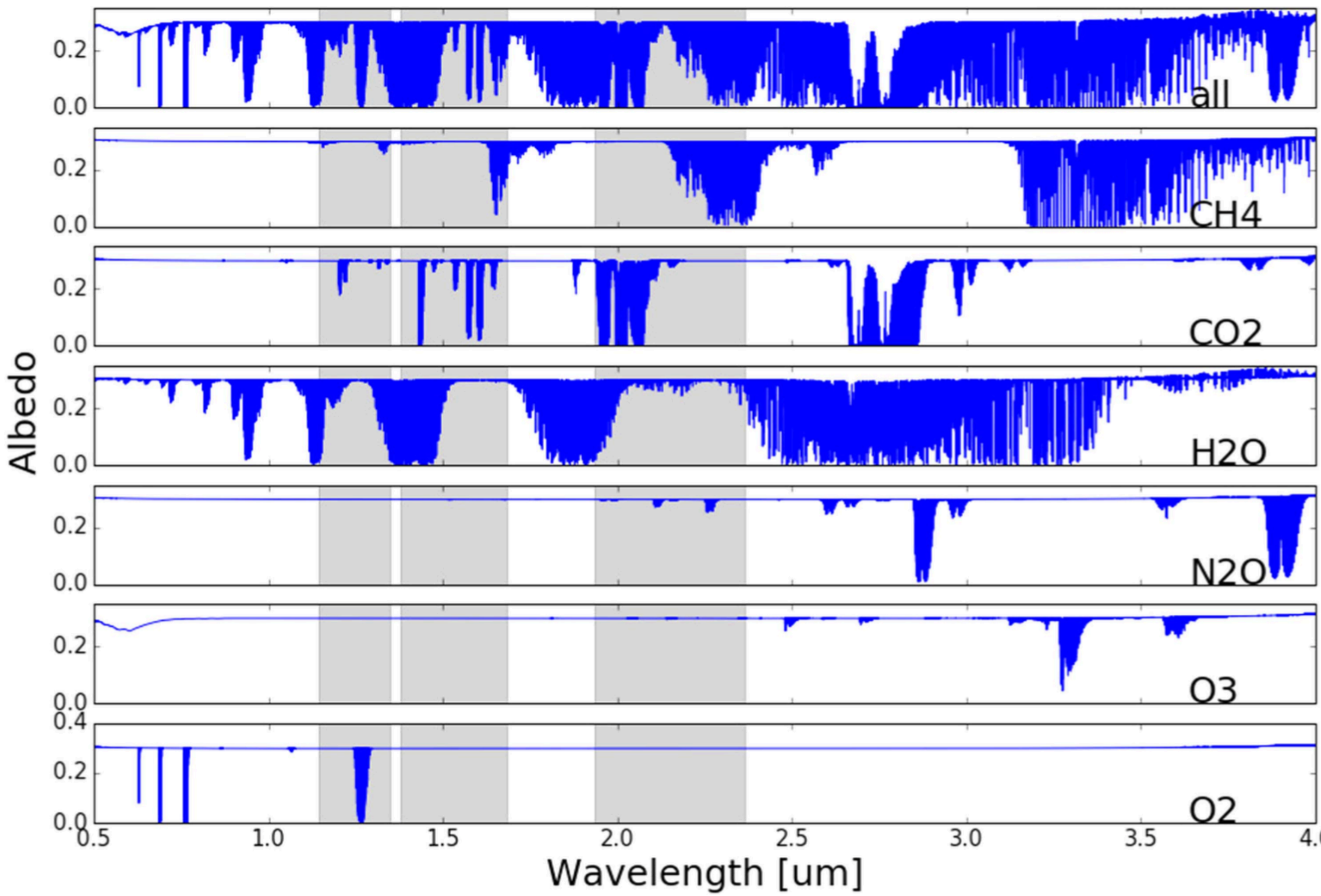


1 LIGHT OBSERVED
2 LIGHT PROCESSED WITHIN TELESCOPE
3 DATA ANALYZED
4 EXCITING RESULT
Light of Star + Planet
Light of Planet + Residual Starlight
Coronagraph
High Resolution Spectrograph
Blocks Most of Light from Star
Optical Cable Isolates Light from Planet
Planet Light Lost in Star's Glare
Light from Planet Becomes Detectable
Raw Data from Spectrograph
Matched to
Ideal Model of Oxygen Spectrum
THE GOAL:
Detection of Oxygen in Planet Atmosphere!



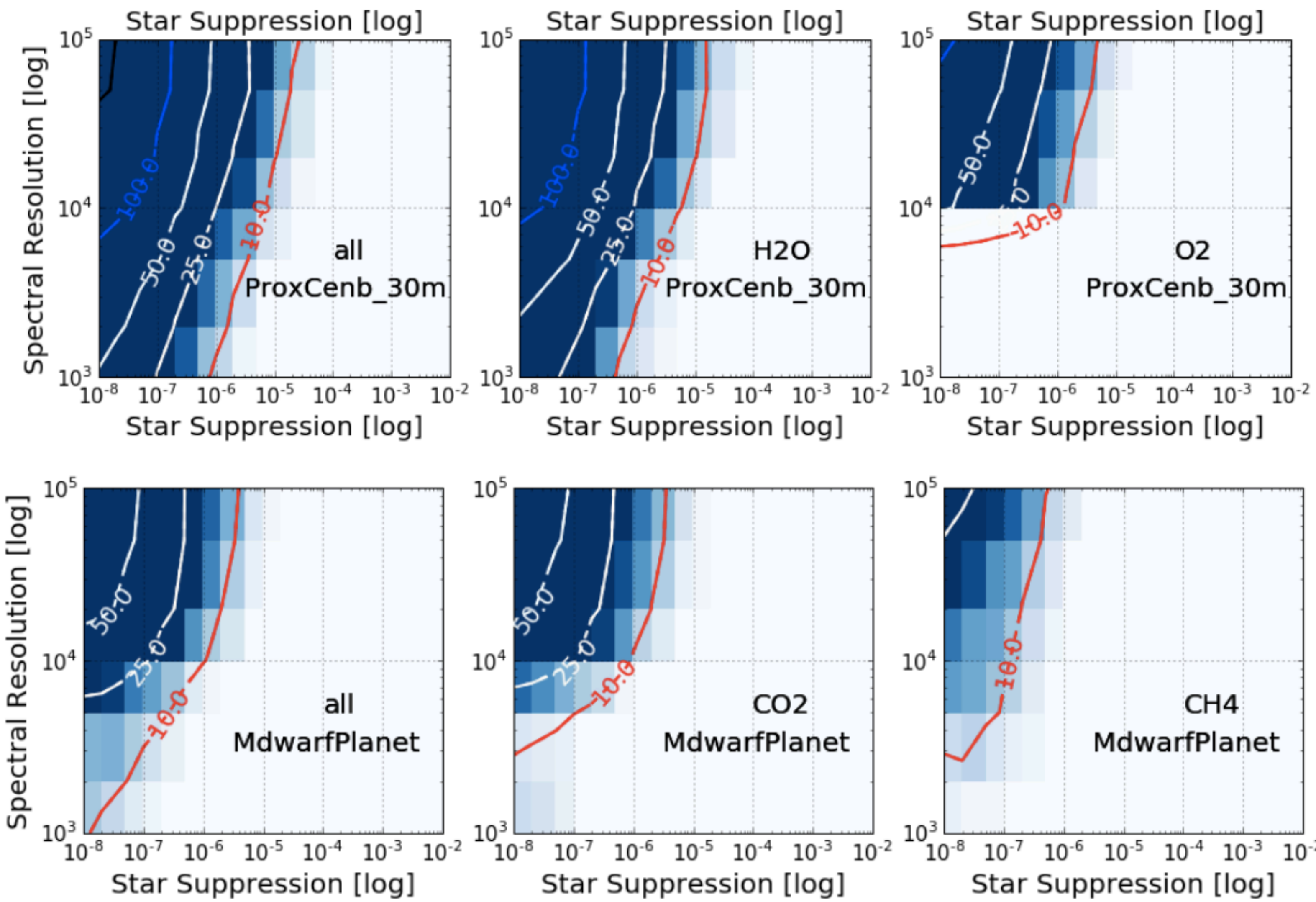
S. Domagal-Goldman

HDC SIMULATIONS FOR GSMTS



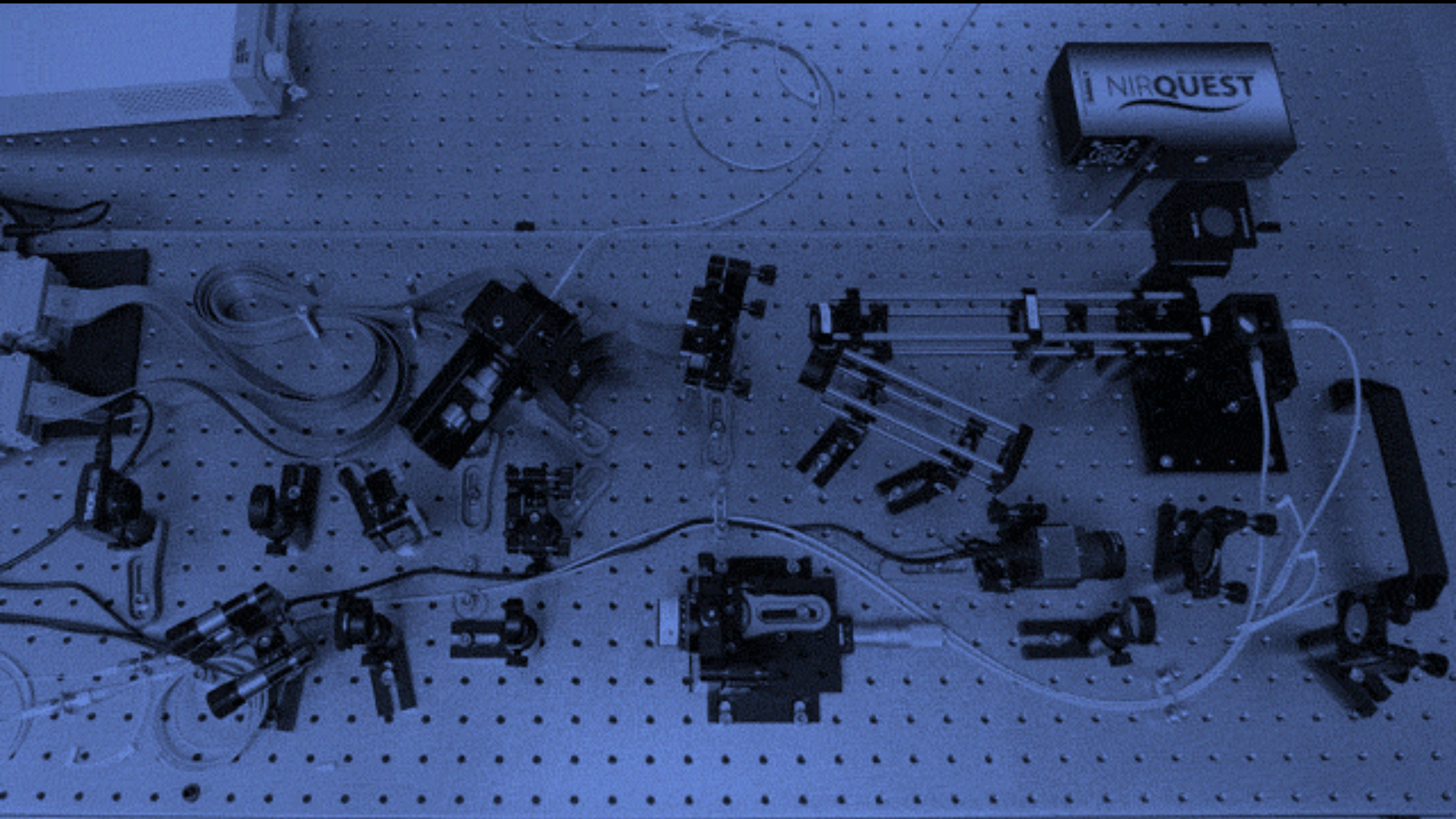
Observing exoplanets with high dispersion coronagraphy. I. The scientific potential of current and next-generation large ground-based telescopes, J. Wang , D. Mawet, G. Ruane, R. Hu, B. Benneke, AJ 2017

EARTH-LIKE PLANET CHARACTERIZATION



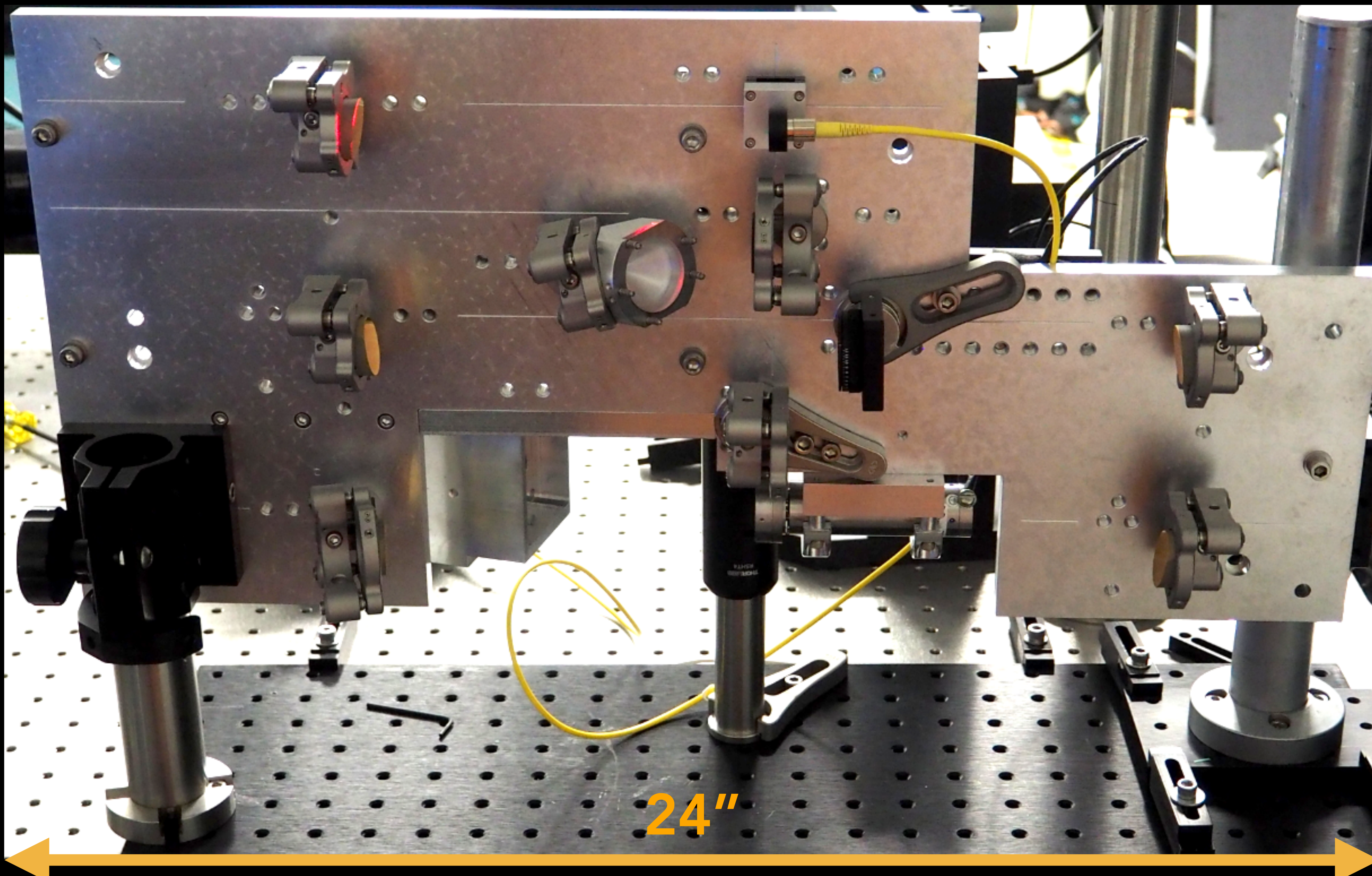
Wang et al. 2017

HIGH DISPERSION CORONAGRAPHY



Mawet et al. 2017

FIBER INJECTION UNIT FOR THE KECK PLANET IMAGER AND CHARACTERIZER



Design: J. K. Wallace (JPL). I&T: N. Jovanovic (Caltech), J.-R. Delorme (Caltech), D. Echeverri (Caltech).

TECHNOLOGY GAPS - HARDWARE

Items	Requirements	Actors/Partners	Notes
High-Density Deformable Mirror	120×120, fast, large stroke (6 μm), low defective actuator count	BMC, NG, ALPAO, IRIS AO, TNO, Phys Inst, Xinetics, Northrop Gruman	R&D initiated by ALPAO, ESO, BMC, synergies with space, Could be realized with woofer + tweeter setup
Low-noise detectors	<1 e^- ron, energy resolving, fast (ms), both for optical and IR	E2V (EMCCD), FLI, Nüvü, Leonardo/UH (IR-APD), UCSB/JPL (optical/NIR MKIDs)	Synergies with WFIRST-CGI, HabEx/LUVOIR
Coronagraph for segmented, obscured apertures	$>$20%BW, small IWA, high throughput	UoA/Subaru, NASA AMES, Princeton, Caltech, JPL, Leiden, ABC/NAOJ, Hokkaido U	Solutions exist, need lab/on-sky demos
Low order wavefront sensor (LOWFS)	Fast, out of band, sensitive, sensor fusion	UoA/Subaru, NASA AMES, UCSC, HIA, U of T	Now in operation, telemetry management not unified
Real Time Controller	Fast, large scale SVD (predictive control)	UoA/Subaru, MicroGate, GreenFlash, JPL, KAUST, Osaka Univ.	Requirements TB refined
Fibers (single/multi-mode, bundles)	Low-loss, cryogenic, feedthroughs, photonic lanterns, high-density high fill factor bundles	LVF, Corning, Caltech, JPL, fiberguide, ABC/NAOJ, U Tokyo	Synergies with RV and highly multiplexed spectro
Polarimetric devices	Fast switching high efficiency modulators, achromatic waveplates	Leiden, Caltech/JPL, Subaru	New tech. Available: e.g. polarization gratings
Dichroics/ADC	High efficiency, large bandwidth, cryogenic	Asahi Spectra	Microstructures promising

Table 1. Key technologies for TMT PSI — high priority HARDWARE needs. Actors/Partners will expand with our collaboration.

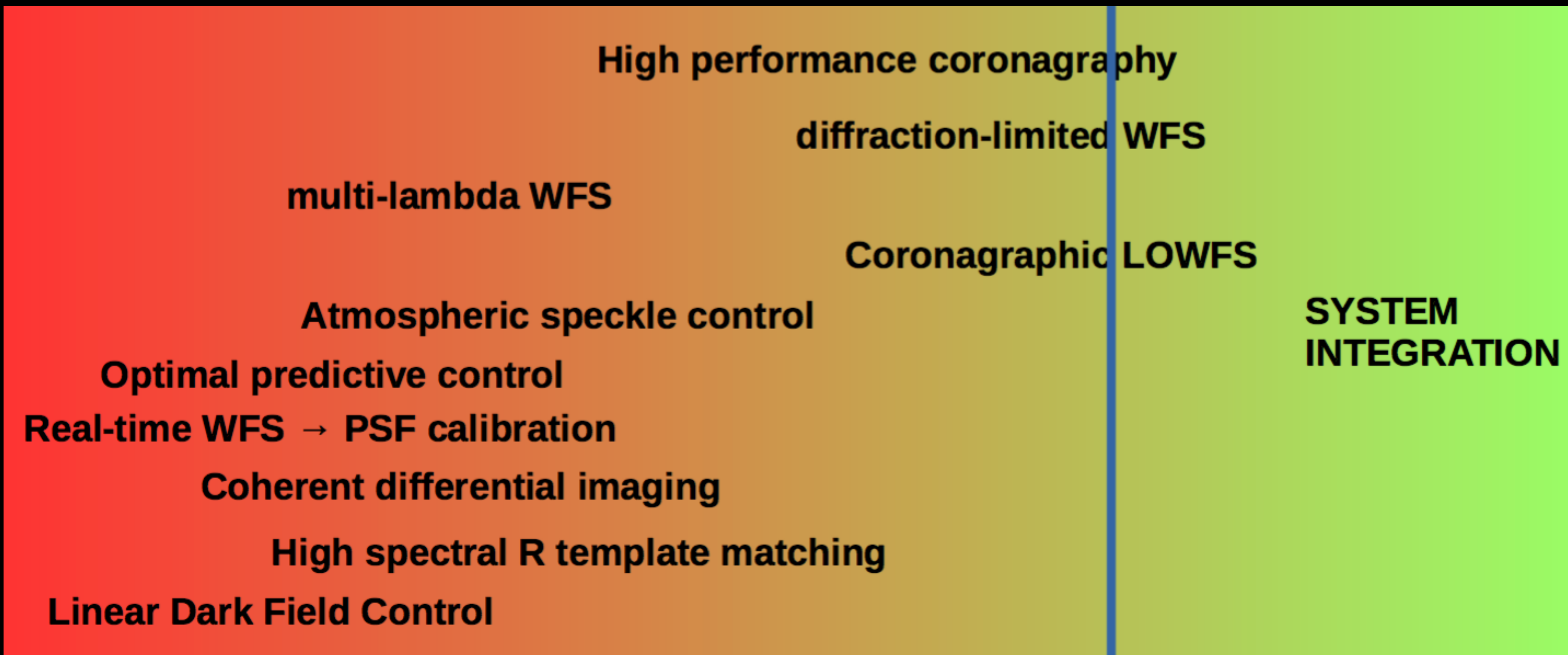
TECHNOLOGY GAPS - SOFTWARE

Items	Requirements	Actors/Partners	Notes
Extreme AO	2 kHz, 100 μs lag for $I = 9$, 120×120 elements	UoA/Subaru, LLNL, Stanford, JPL, NRC	$\sim$2 kHz loop frequency, assuming predictive control
Focal plane WFS/C	Control amplitude speckles, NCPAs	JPL/Caltech, NRC	Eliminates non-common paths from control
Predictive AO control	Achieve 100 μs-level temporal lag on $I = 9$ sources	LLNL, Victoria, Stanford, UoA/Subaru	Improves sensitivity, critical for M dwarfs
Sensor fusion	Integrated control algorithms making use of all sensors/telemetry	Princeton, JPL/Caltech, UoA/Subaru	Improves sensitivity, addresses WF chromaticity
Post-processing	Bridge the gap between raw contrast and astrophysical contrast, work at the photon noise limit	LAOG, Berkeley, Caltech, Stanford, STScI, UCLA, NRC	Machine learning techniques (supervised learning), coherent differential imaging

Table 2. Key technologies for TMT PSI — high priority SOFTWARE needs. Actors/Partners will expand with our collaboration.

KEY TECHNOLOGIES NEED RAPID MATURATION FROM PAPER CONCEPTS TO SYSTEM INTEGRATION

Paper concept (TRL 1)   Lab demo (TRL 3)   On-sky demo (TRL 5)



Return on investment for ground-based instruments is more rapid.
But we need more investments!

TENTATIVE TIMELINE