W F I R S T

Preparatory Science Teams

An extraordinary science investigation of new worlds and new horizons

Dr. Margaret Turnbull, SETI Institute
Carl Sagan Center for the Study of Life in the Universe

Pre-Formulation Emphasis

- WFIRST pre-formulation activities have been directed in three key areas from 2008-2015:
  - Developing and iterating a design reference mission in sufficient detail to:
    1. verify critical mission performance parameters;
    2. support a high-degree-of-confidence costing activity.
  - Maturing key technologies;
    1. Detectors
    2. Coronagraph
  - Developing well defined requirements from science

Thanks to Dominic Benford for this slide

WFIRST Preparatory Science

Strategy:

Engage much wider swath of the astronomical community into working on the science of WFIRST-AFTA.

Benefits:

1. Yields richer understanding of WFIRST-AFTA science
2. Provides forecasts of WFIRST-AFTA results
3. Widens community thinking about WFIRST-AFTA science
4. Strengthens understanding of the mission implementation

Thanks to Dominic Benford for this slide

Long-Term Plans

- Expect to enter Phase A (formulation) during CY16
  - Formally, for "concept and technology development"
  - All technologies on track for TRL=5 (validation in simulated environment)
- System Requirements Review notionally June 2017
- Timeline for entering Phase B October 2017
  - Formally for "preliminary design and technology completion"
  - All technologies expect at TRL=6 (full system validation)
- Timeline for entering Phase C December 2018
  - Implementation: final design, fabrication

- Officially, WFIRST could launch in mid-2020s. Project estimate, with significant assumptions of spending authority in excess of PBR, puts launch date (with reserve) approximately August 2024.

Thanks to Dominic Benford for this slide

WFIRST Prep Science Program: Exoplanets

David Bennett, U. Notre Dame

WFIRST Exoplanet Microlensing Survey Simulation

- We propose to update the space-based exoplanet survey simulation code that was responsible for the selection of such a survey as a part of the WFIRST mission. The primary focus of this upgrade will be to include all the effects that can be used to make direct mass measurements and distance estimates of the planetary systems found by the survey. These effects include microlensing parallax and direct measurement of the relative proper motion between the source and planet host star. The simulations will also include fully realistic simulated images with all known noise sources and systematic errors. This will allow the simulation to be used to help develop the WFIRST exoplanet microlensing survey photometry and astrometry pipeline.

WFIRST Prep Science Program: Exoplanets

Geoff Bryden, JPL

Planet Detection and Orbit Tracing by the WFIRST Coronagraph

Specifically, we will calculate:

1) the probability of WFIRST detecting each known RV planet,
2) the expected number of new planet discoveries and the corresponding list of target stars,
3) the number of observations required to constrain each planet's orbital properties and (if it has measured RV signal) its mass,
4) the optimal RV measurements needed to improve the orbit determination and to predict when WFIRST should observe each planet, and
5) the number of post-mission RV observations that will be required to measure the masses of newly discovered planets.

WFIRST Prep Science Program: Exoplanets

Christine Chen, STScI

The Circumstellar Environments of Exoplanet Host Stars

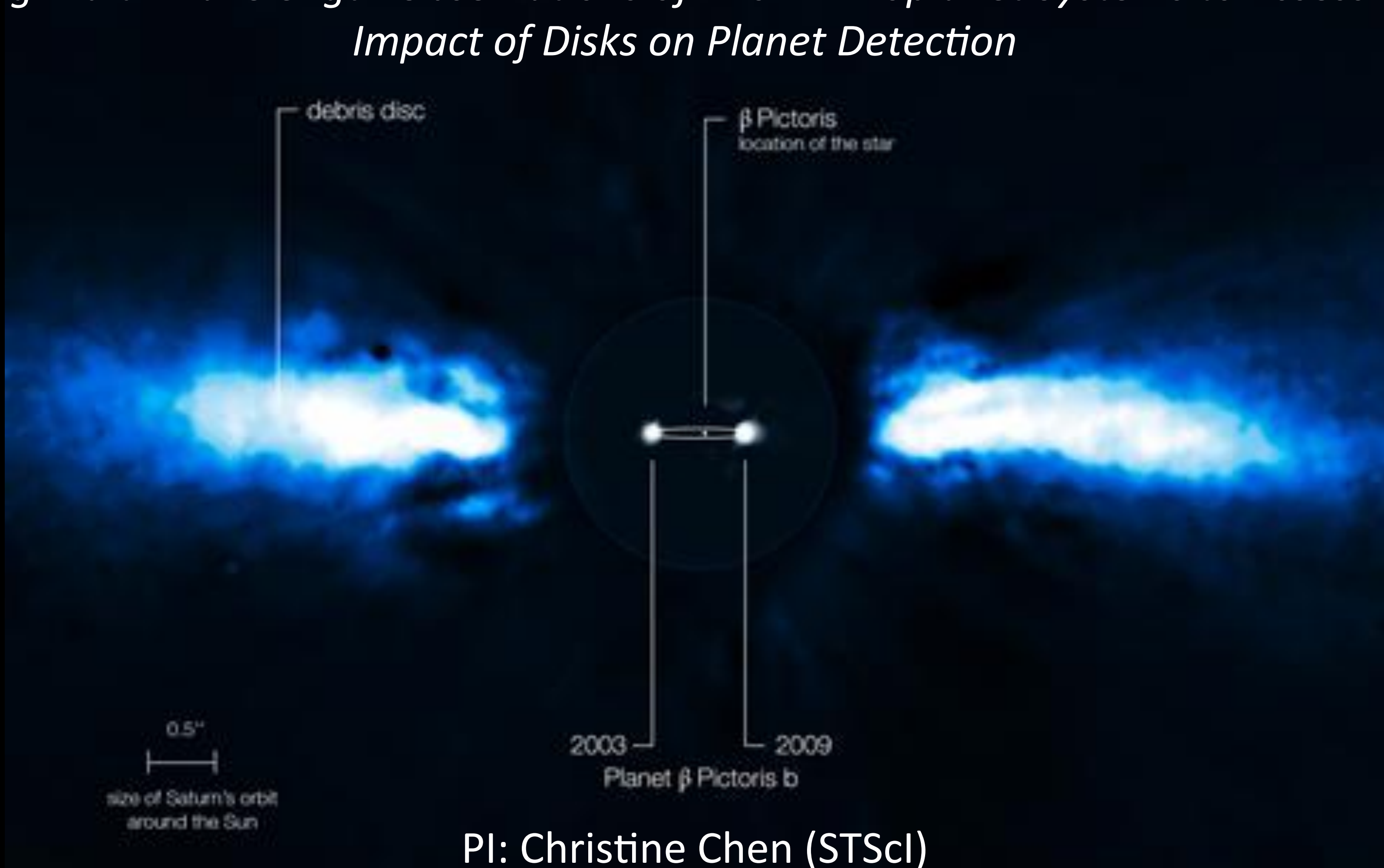
(1) model the dust in exoplanetary systems with well characterized planets and infrared excesses to better constrain the dust geometry and particle properties;

(2) generate synthetic WFIRST-AFTA images of these disks with embedded known and putative planets using point-spread-functions generated by JPL, and run our simulations though a WFIRST- AFTA pipeline

(3) evaluate the sensitivity of WFIRST-AFTA to known and putative planets that have a range of masses and distances from their host stars.

The Circumstellar Environments of Exoplanet Host Stars

Using Multi-Wavelength Observations of Known Exoplanet Systems to Assess the Impact of Disks on Planet Detection



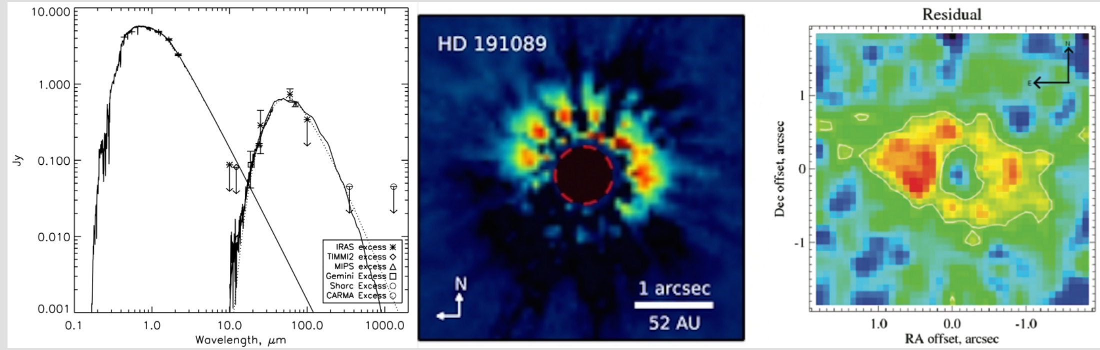
PI: Christine Chen (STScI)

CoIs: Dean Hines, Remi Soummer, Chris Stark (STScI), Colin Norman (JHU), John Krist, Bertrand Mennesson (JPL)

Lagrange et al. (2010)

WPS Program Overview

Representative Observations



HD 191089 SED, HST NICMOS 1.6 μm Scattered Light Image, and Gemini T-ReCS 10 μm image (Churcher et al. 2011, Soummer et al. 2014)

Observations (SEDs, Scattered Light and Thermal Emission Maps)

Dynamical Structure from Hypothetical Planets

Disk Models

Planet + Disk WFIRST Simulation

Planet + Disk PSF Subtraction

MCFOST Model

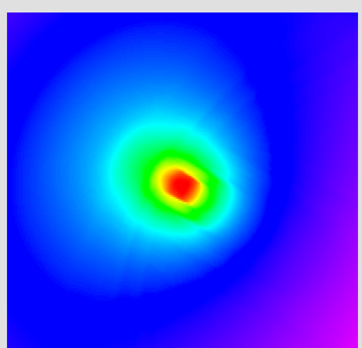


Table 1. Exoplanet Host Stars with *Spitzer* IRS or MIPS 24 μm Excess

Name	Spectral Type	Distance (pc)	Age (Myr)	Planet Mass (M_{Jup})	Semi-Major Axis (AU)
HD 10647	F8V	17.4	2300	0.9	2.1
τ Cet	G8.5V	3.7	5800	0.01, 0.01, 0.01, 0.02	0.2, 0.4, 0.6, 1.4
ϵ Eri	K2V	3.2	850	1.6	1.9
β Pic	A6V	19.1	12	9	8-15
HD 69830	K0V	40.7	5600	0.03, 0.04, 0.06	0.08, 0.2, 0.6
1 RXSJ1609	M3	145	5	8	330
HD 95086	A8III	90.4	17	5	56
HD 106906	F5V	92.1	13	11	650
61 Vir	G7V	8.6	6100	0.02, 0.03, 0.07	0.05, 0.2, 0.5
70 Vir	G4V	18.0	7100	7.5	0.5
HR 8799	F0V	39.4	60	7, 10, 10, 10	15, 24, 38, 68

WFIRST Prep Science Program: Exoplanets

Dmitry Savransky, Cornell U.

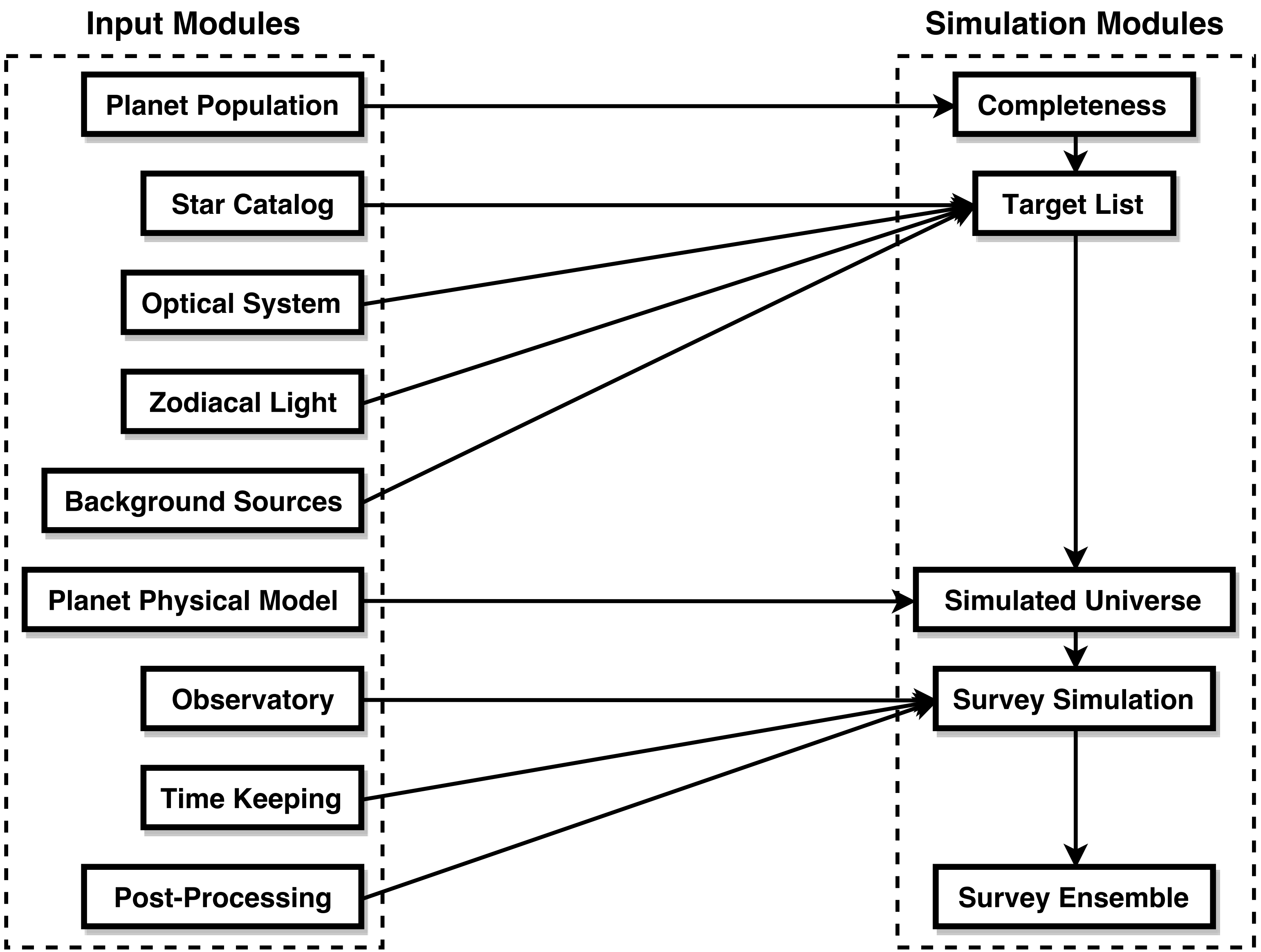
Science Yield Modeling for the WFIRST-AFTA Coronagraph - ExoSIMS

- We will use upgraded modeling capability to evaluate the distributions of the coronagraph's expected science yield and to answer the questions:

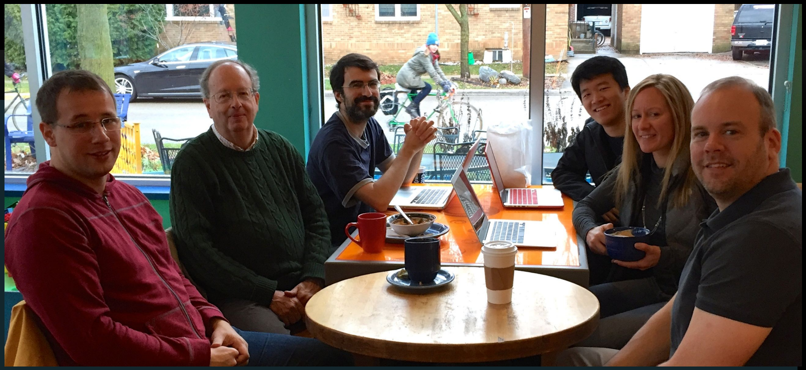
  1) What is the optimal proportion of coronagraph time that should be devoted to searching for new planets versus attempting to image known exoplanets?
  2) What are the best targets and optimal observation times for potential new detections and followup observations?

  3) What are the optimal operating points in terms of detection band and permissible false positive rates and how do these affect the required integration times?

EXOSIMS


Input Modules
Simulation Modules
Planet Population
Star Catalog
Optical System
Zodiacal Light
Background Sources
Planet Physical Model
Observatory
Time Keeping
Post-Processing
Completeness
Target List
Simulated Universe
Survey Simulation
Survey Ensemble

WFIRST Prep Science at SETI/Wisconsin: <u>Colors of Planets and Background Sources</u>



WPS Team Members

PI Margaret Turnbull (SETI)

Co-I Tristan L'Ecuyer (UW Atmospheric Sciences)

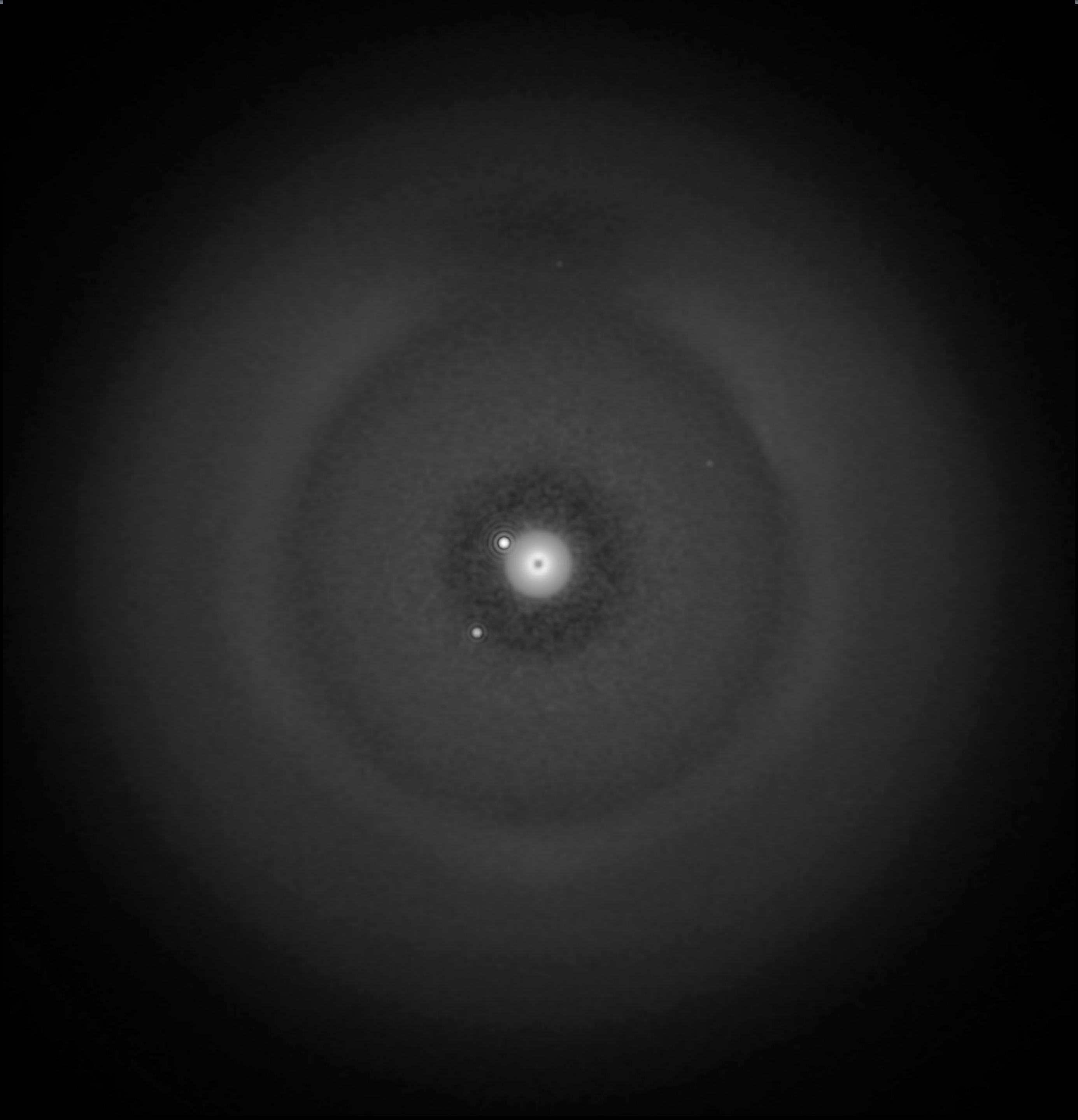
Co-I Renyu Hu (JPL)

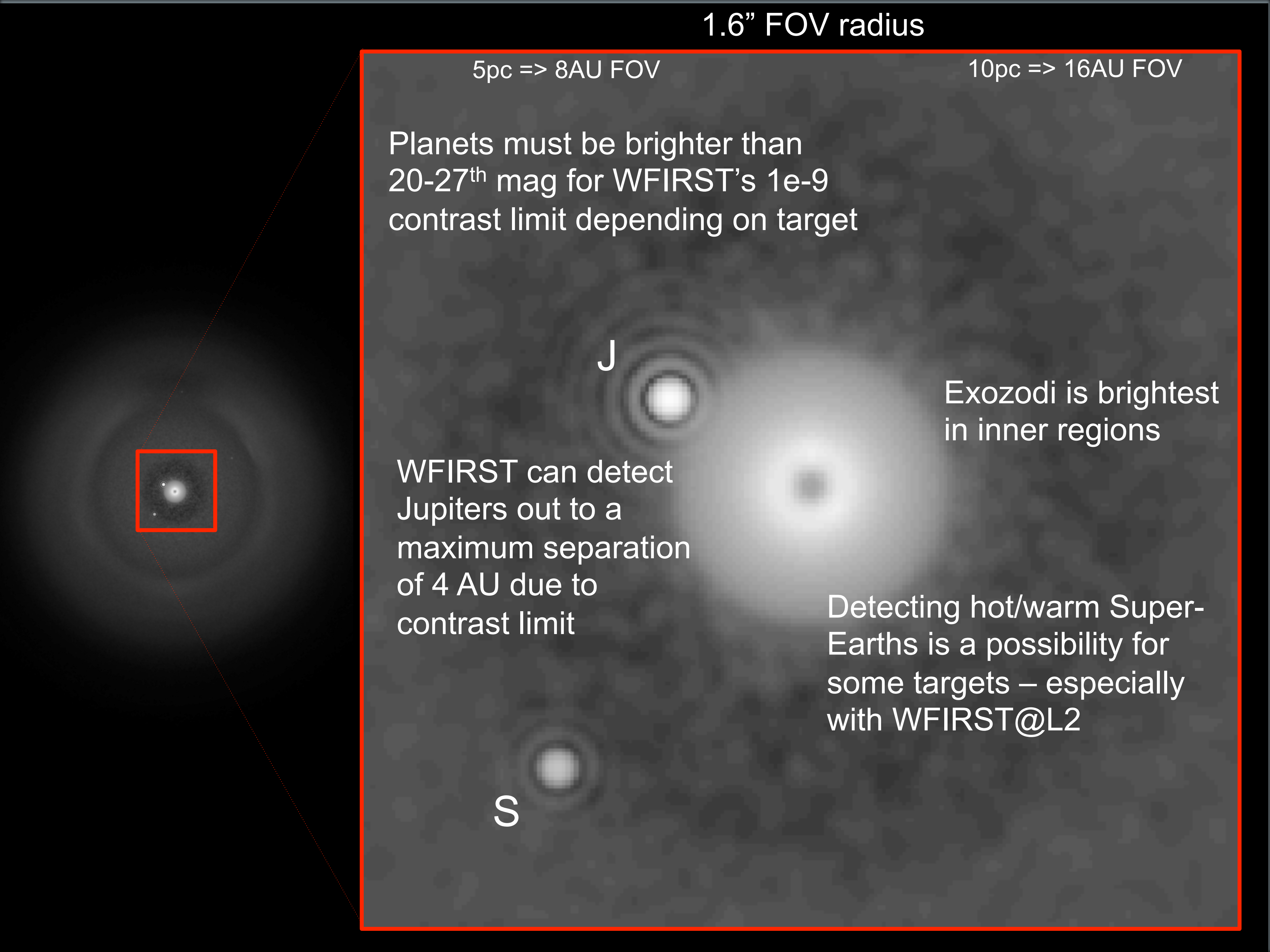
Collaborator Jay Gallagher (UW Astronomy)

Postdoc Aronne Merrelli (UW SSEC)

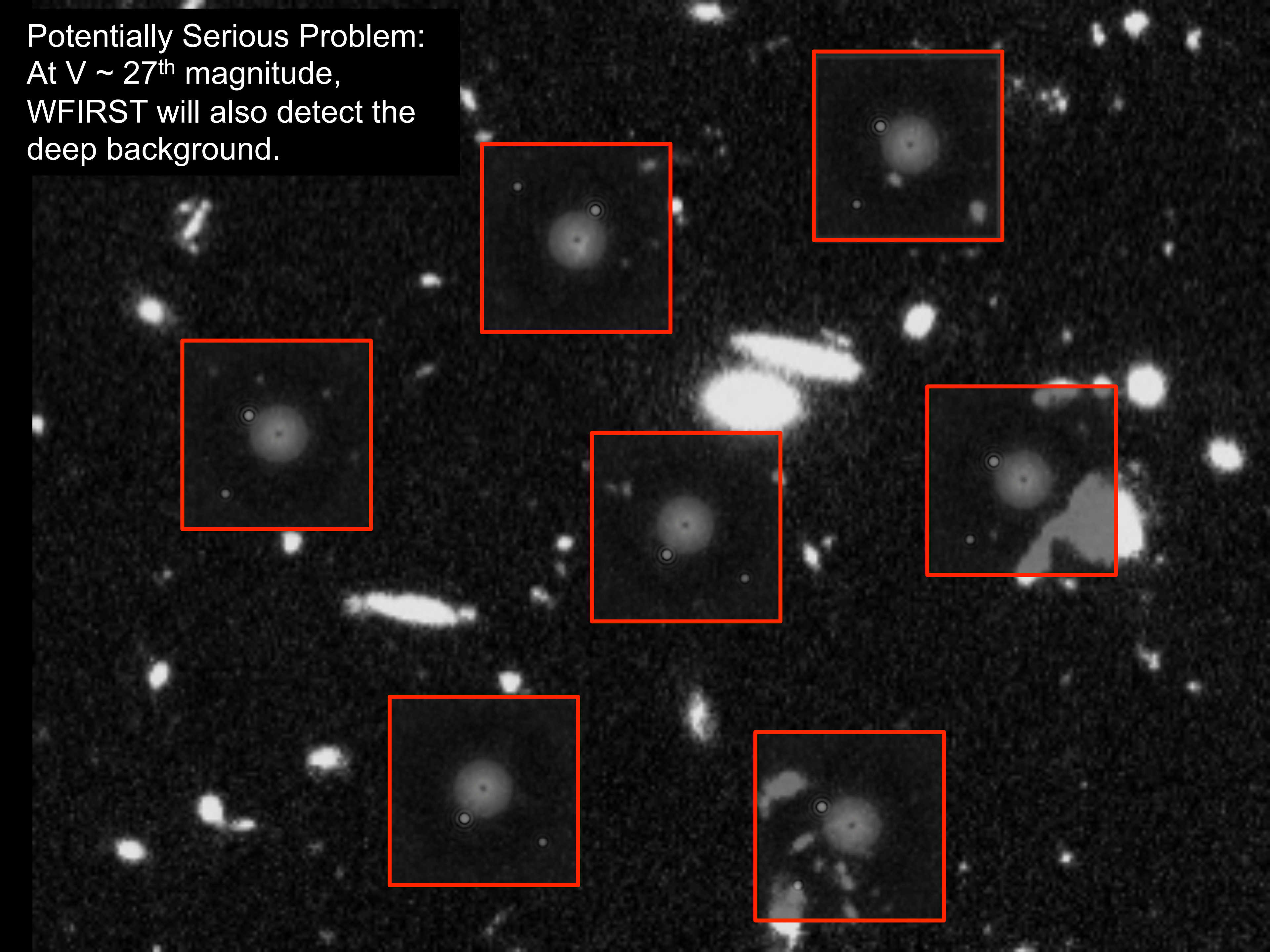
Senior Scientist Ralf Kotulla (UW Astronomy)

Undergraduate Guangwei Fu (UW Astronomy)

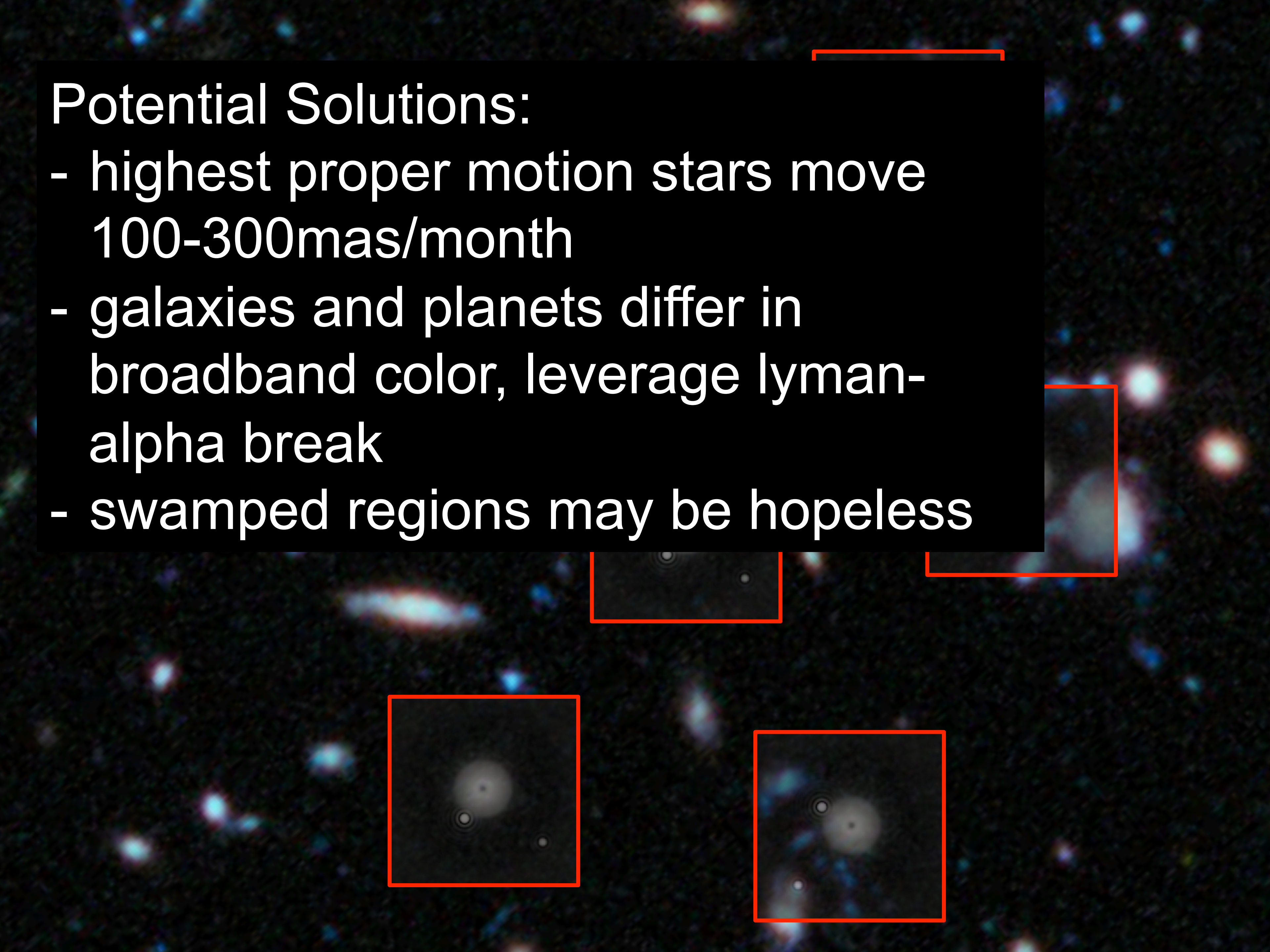



1.6” FOV radius
5pc => 8AU FOV
10pc => 16AU FOV
Planets must be brighter than 20-27th mag for WFIRST’s 1e-9 contrast limit depending on target
J
Exozodi is brightest in inner regions
WFIRST can detect Jupiters out to a maximum separation of 4 AU due to contrast limit
Detecting hot/warm Super-Earths is a possibility for some targets – especially with WFIRST@L2
S

Potentially Serious Problem:
At V ~ 27th magnitude,
WFIRST will also detect the
deep background.



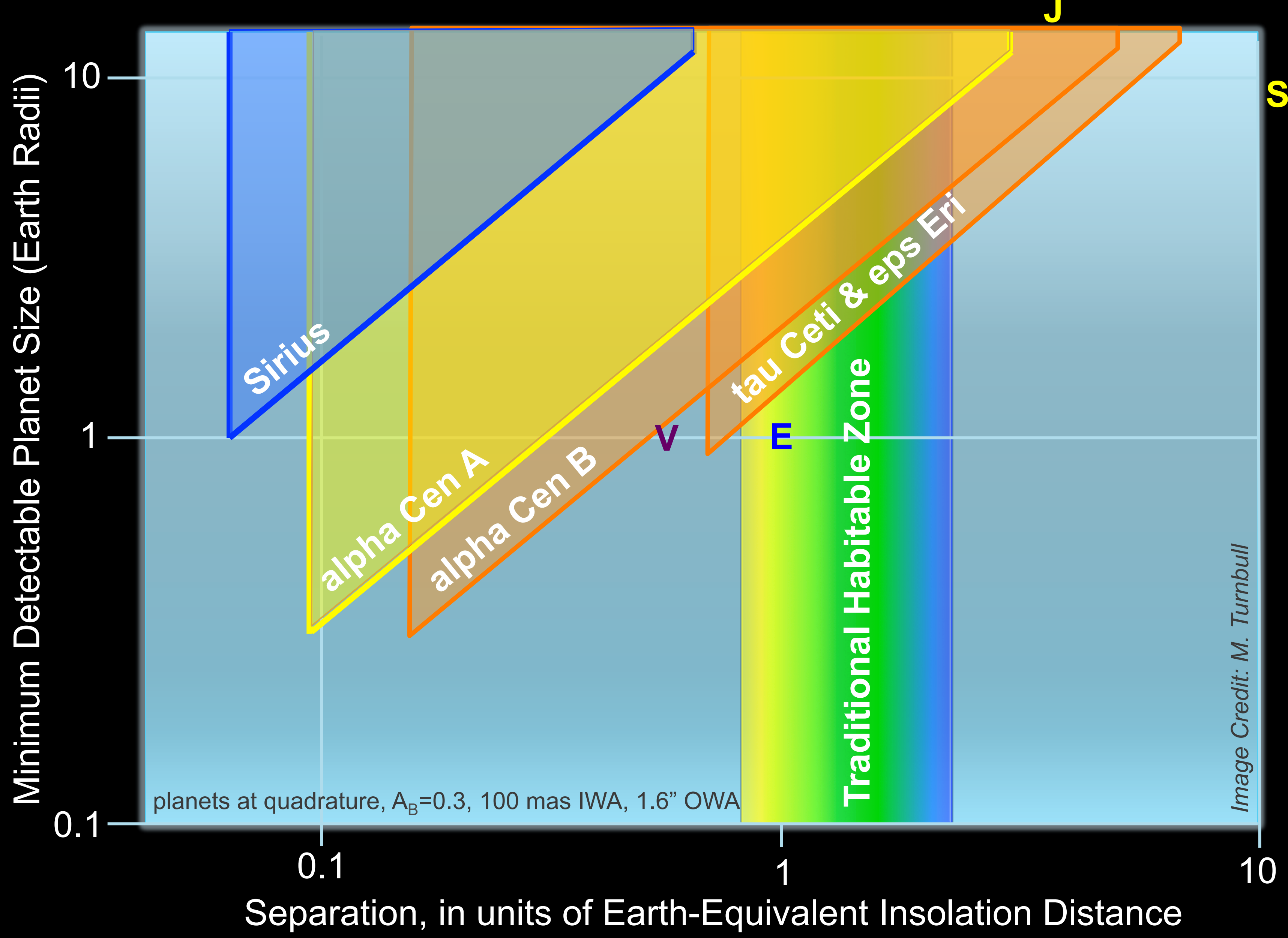
Potentially Serious Problem:
At V ~ 27th magnitude,
WFIRST will also detect the
deep background.



Potential Solutions:

- highest proper motion stars move 100-300mas/month
- galaxies and planets differ in broadband color, leverage lyman-alpha break
- swamped regions may be hopeless

Planets of Interest: WFIRST Detection Space



WFIRST Prep Science:
Colors of Planets and Background Sources

GOAL

1. Determine the WFIRST broadband colors for potentially detectable planets:

-> include Venus, Earths/super-Earths and sub-Neptunes through cold giants

-> assess capability of WFIRST to distinguishing planet types in color-color-magnitude space, especially for "discovery" targets where characterization may not always be possible

WFIRST Prep Science:
Colors of Planets and Background Sources

GOAL

2. Publish a library of spectra for planets of interest to WFIRST:

-> include Solar System planets, Earths/super-Earths and sub-Neptunes through cold giants, orbiting stars of various spectral types

-> include Earth/super-Earth spectra of various Earth-”like” planets: ancient Earths, Dunes, waterworlds, ice worlds

-> include variety of phase angles and inclinations

3. Create an online tool for generating spectra and colors for wide variety of objects and bandpasses

WFIRST Prep Science:
Colors of Planets and Background Sources

GOAL

4. Determine the prevalence and WFIRST broadband colors of background sources

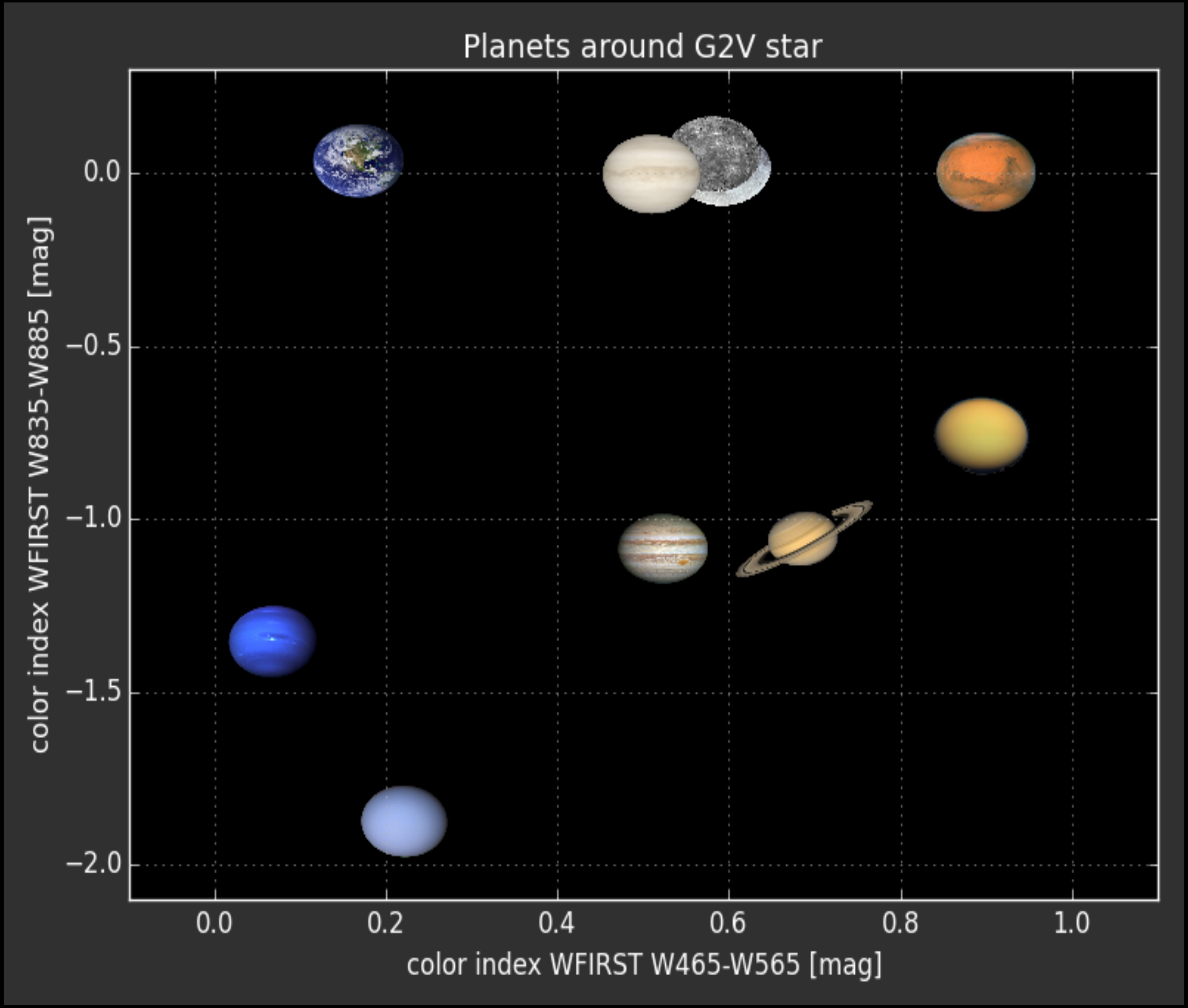
-> assess capability of WFIRST to distinguishing planets from background in color-color-magnitude space

-> assess “background threat” for high priority exoplanet imaging targets: consider proper motion

-> suggest plan for mitigating that threat including possibility of alternative bandpasses, advance observations

-> assess scattered light threat due to bright companions

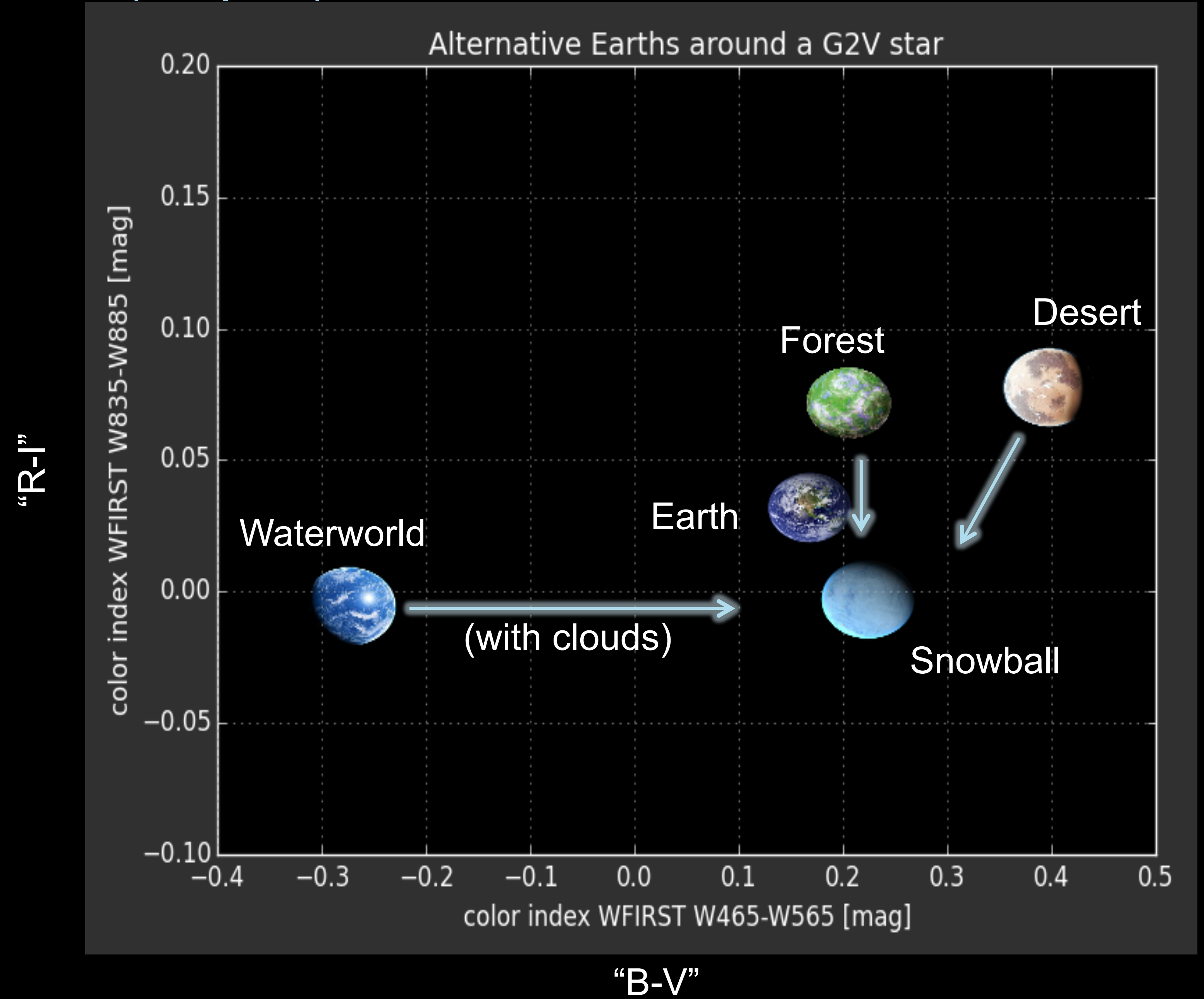
Planets Around the Sun: WFIRST Bands



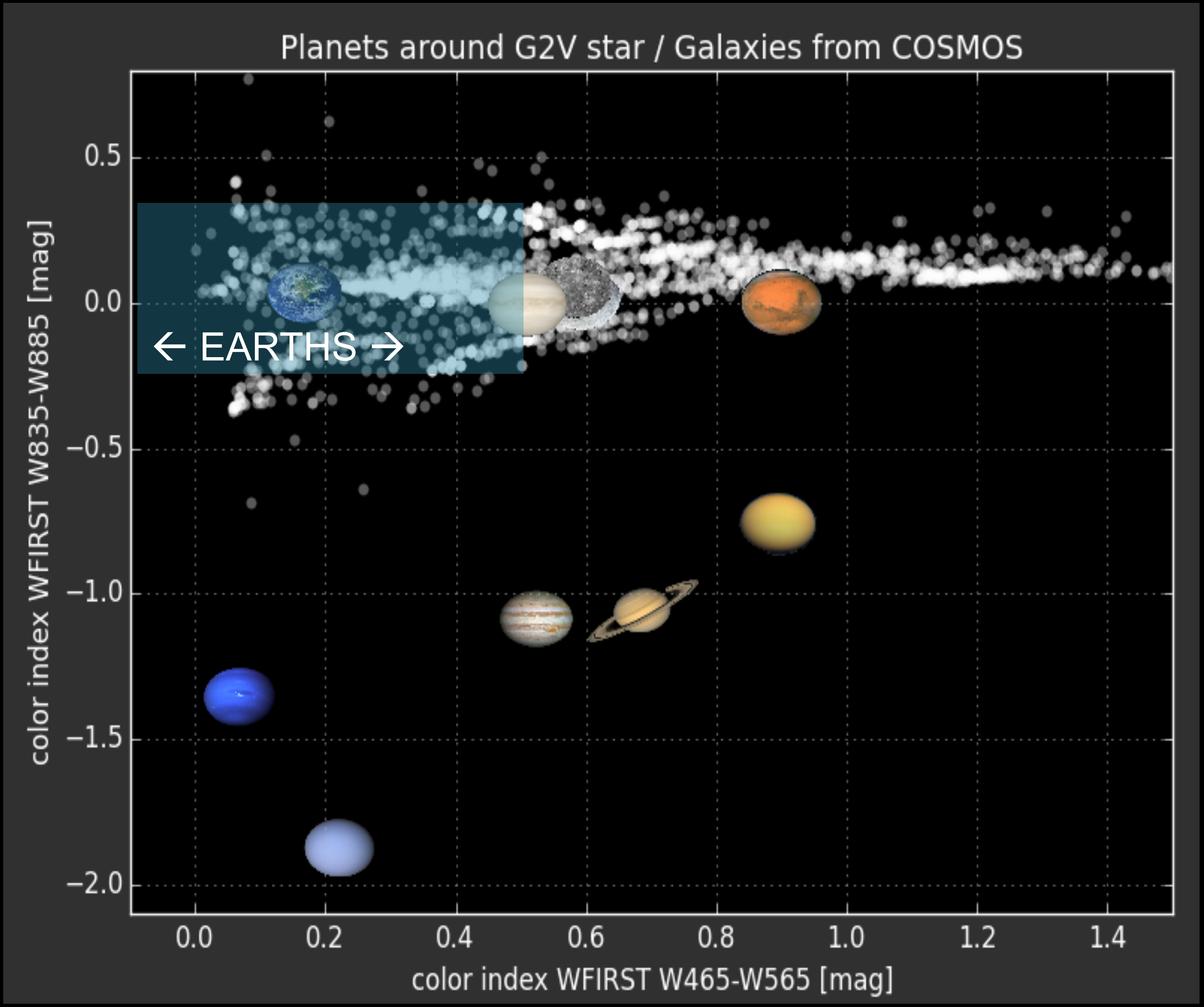
"R-I"

"B-V"

Other (Super)Earth-Like Planets: WFIRST Bands



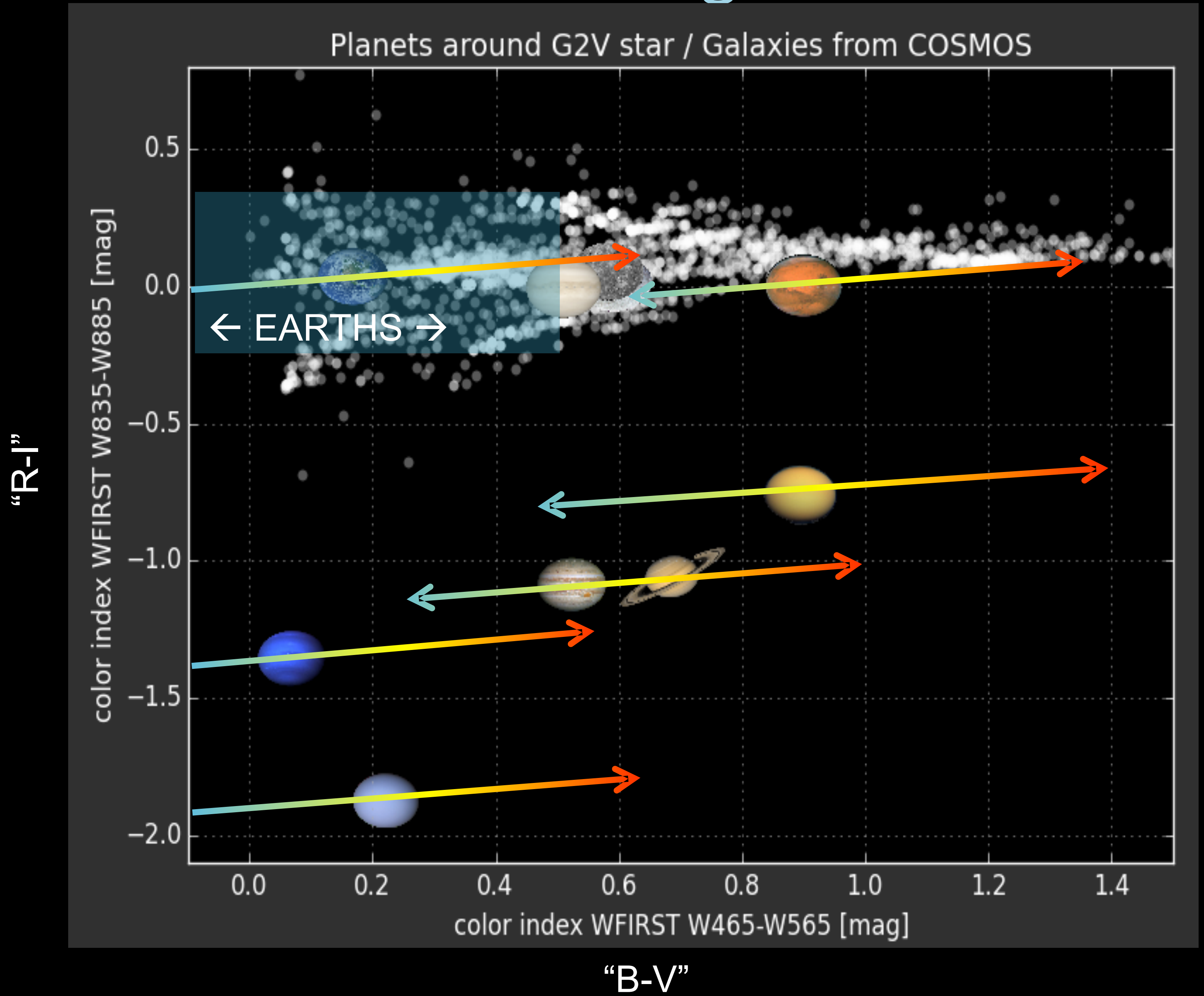
Planets Around the Sun: WFIRST Bands



“R-I”

“B-V”

Planets Around Other Targets: WFIRST Bands



Where We Stand With Planet Spectra

- Have generated crude Earth-like model spectra (desert, ocean, veg., snow) using cloud-free radiative transfer at a single angle
- Plan to use calibrated, spatially resolved spectra from Earth observing instruments to get more accurate surface reflectance
- Exploring tools for generating integrated spectra with polarization
  - Will use polarized, plane parallel RT model to generate pre-computed reflectance tables for various “Earth-like” conditions
  - Compute disk-integrated, polarized, spectral reflectance by integrating over spatially discretized Exo-Earths at a given phase angle
- Goal: RT implementation and verification: spring 2016; initial full polarized disk integrations: summer/fall 2016

Where We Stand With Planet Spectra

- Have begun building a small library of spectra including Solar System planets, models from Hu, Cahoy et al.
  - includes planets orbiting different kinds of stars at various separations, various C/O ratios
  - Goal is to make this publicly available in some organized way
- Plan to collaborate between teams (Lewis, Turnbull) to share models/agree on a subset for calculations
- Interest in obtaining spatially resolved spectra with MaNGA for Jupiter, Saturn, Venus

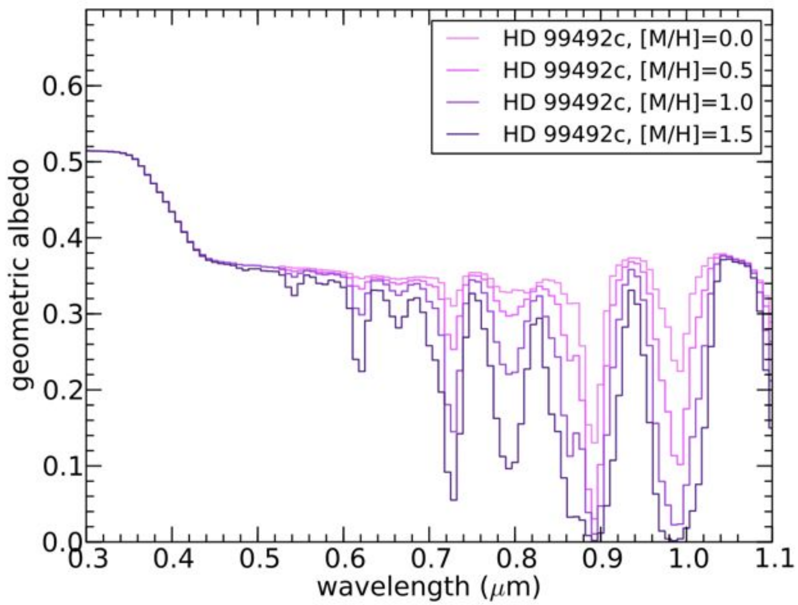
Where We Stand With Galaxies and Stars

- Have a code to calculate broadband magnitudes and colors
  - Next step will be to look at colors for Cahoy, Hu planets
- Will build a GUI tool that will allow users to upload spectra, bandpasses, or use ours
- Probability of finding background sources in the field:
  - Galaxies: High probability, > 50% for most targets down to contrast limit
  - Stars: Low probability, <10% for all targets down to contrast limit
- Will explore fastest PM follow-up times for scheduling codes
- Currently waiting on ODI observations with WIYN, HLA program in hopes of deep imaging along future PM paths

Where We Stand With The Targets

- Most targets have “bright” companions and/or high probability of off-axis background stars - Need off-axis response to estimate background light and potential impact on exposure time, planet harvest
- We find that most targets have physical companions – consider dynamics?
- Currently logging stray light, background worries for all targets
- Wish List: JHK for high priority targets (all of which are saturated in 2MASS) in order to accurately determine luminosities
  - this could be done in one year with minimal time on a small telescope north and south - need a near-IR camera
- Plan to collaborate with Savranksy team on database, starting with known RVs

Spectral and Polarimetric Signatures of WFIRST-AFTA Exoplanet Coronagraphy Targets



Nikole Lewis
STScI
nlewis@stsci.edu

Overview of Program

Main Goal: Provide constraints on the giant exoplanet science achievable with WFIRST-AFTA under the current (evolving) mission design.

Science Questions:

- How does the composition of gas and ice giant planets vary with mass, orbit, and stellar mass and metallicity?
- Do planets formed inside and outside of the nebular 'snow line' have different composition or C/O ratios?
- How do clouds affect giant planet atmospheres and vary with atmospheric temperature and other planetary parameters?

Deliverables:

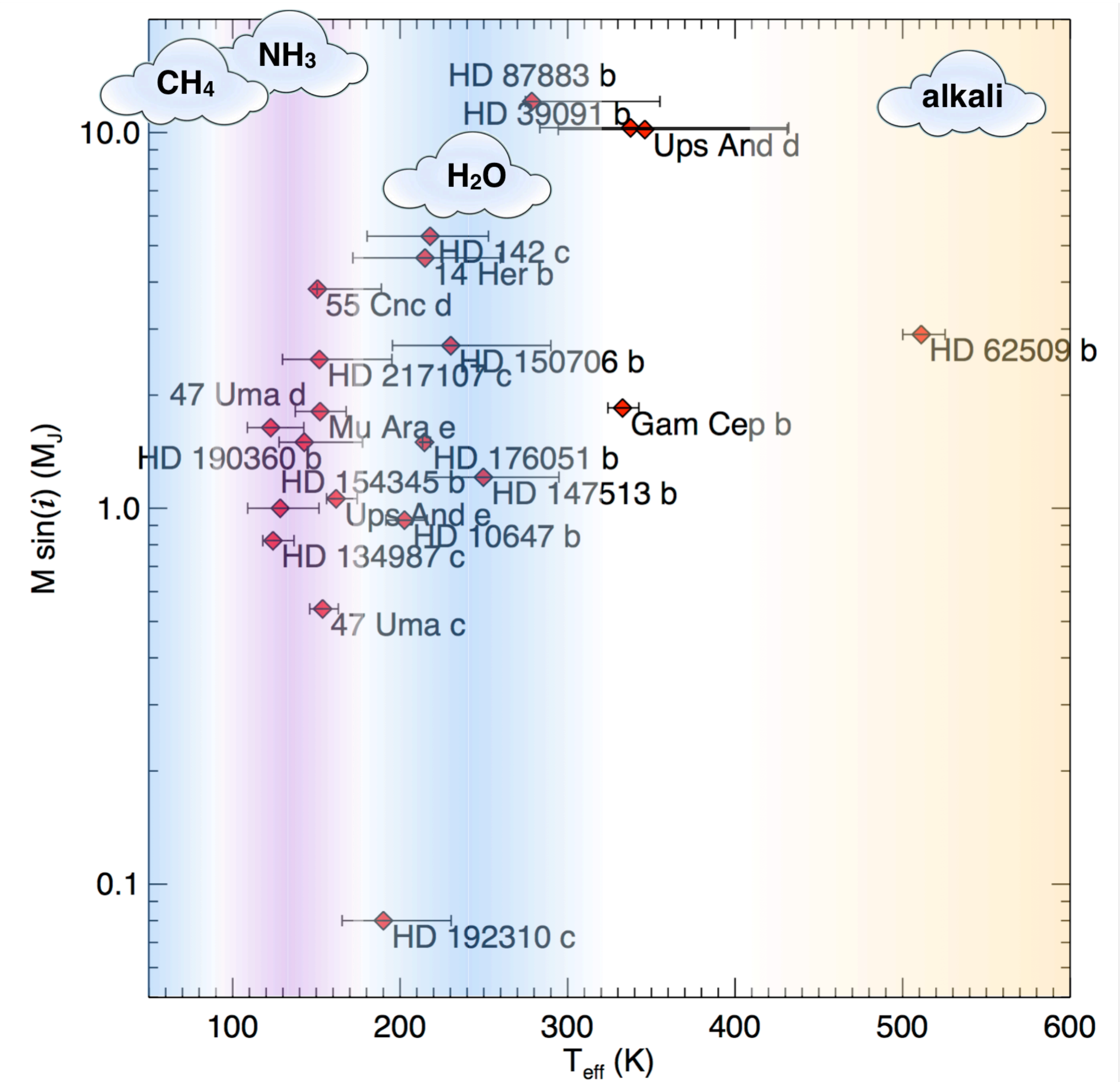
- Theoretical albedo spectra for the prime RV targets and theoretical smaller mass planets observable with the WFIRST-AFTA mission (currently a list of 21 RV planets plus a dozen theoretical planets) over a range of 'appropriate' parameter space (~120 atmospheric models in total).
- Estimates of the polarimetric signals expected for the WFIRST-AFTA coronographic targets.
- Retrieval analysis using spectra generated from the theoretical models and the WFIRST-AFTA simulator.

WPS Program Targets

Table 1. Prime RV Targets

Planet	Msin(i) (M_J)	a AU	Θ ($''$)	V (mag)	SpL	CR	Fe/H	Age (Gyr)	T_{eq} (K)	T_{int} (K)
HD 62509 b	2.9	1.7	0.16	1.15	K0IIIb	2.1e-8	0.19	0.72	500	277
Gam Cep b	1.9	2.1	0.14	3.22	K1III	1.4e-8	0.18	6.60	331	126
Ups And d	10.2	2.6	0.18	4.10	F8V	8.7e-9	0.09	3.80	217	332
Ups And e	1.1	5.3	0.14	4.10	F8V	1.3e-8	0.09	3.80	151	113
47 Uma c	0.5	3.6	0.37	5.04	G0V	2.1e-9	0.00	7.40	152	73
47 Uma d	1.6	11.6	0.24	5.04	G0V	4.3e-9	0.00	7.40	85	115
HD 192310 c	0.1	1.2	0.13	5.72	K3V	2.4e-8	-0.04	7.81	190	42
HD 39091 b	10.3	3.3	0.17	5.67	G1V	5.3e-9	0.09	3.83	156	334
HD 190360 b	1.5	3.9	0.24	5.71	G6IV	3.8e-9	0.24	12.11	134	97
Mu Ara e	1.8	5.2	0.32	5.15	G3IV	2.1e-9	0.28	6.41	130	126
HD 176051 b	1.5	1.8	0.11	5.25	G0V	1.9e-8	-0.11	8.10	211	108
HD 147513 b	1.2	1.3	0.10	5.38	G5V	3.3e-8	-0.03	0.65	220	198
14 Her b	4.6	2.8	0.15	6.67	K0V	7.8e-9	0.43	5.10	140	205
HD 10647 b	0.9	2.0	0.11	5.52	F9V	1.4e-8	-0.08	4.80	199	103
55 Cnc d	3.8	5.8	0.45	5.95	K0IV	1.8e-9	0.31	10.20	93	145
HD 217107 c	2.5	5.3	0.25	6.18	G8IV	2.1e-9	0.37	7.32	116	137
HD 142 c	5.3	6.8	0.25	5.70	G1V	1.3e-9	0.04	5.93	127	211
HD 154345 b	1.0	4.3	0.22	6.74	G8V	3.1e-9	-0.10	4.92	110	105
HD 134987 c	0.8	5.8	0.21	6.46	G5V	1.7e-9	0.25	9.70	119	77
HD 87883 b	12.1	3.6	0.19	7.55	K0V	4.3e-9	0.09	9.80	104	277
HD 150706 b	2.7	6.7	0.23	7.03	G3V	1.3e-9	-0.13	1.17	99	228

WPS Program Targets



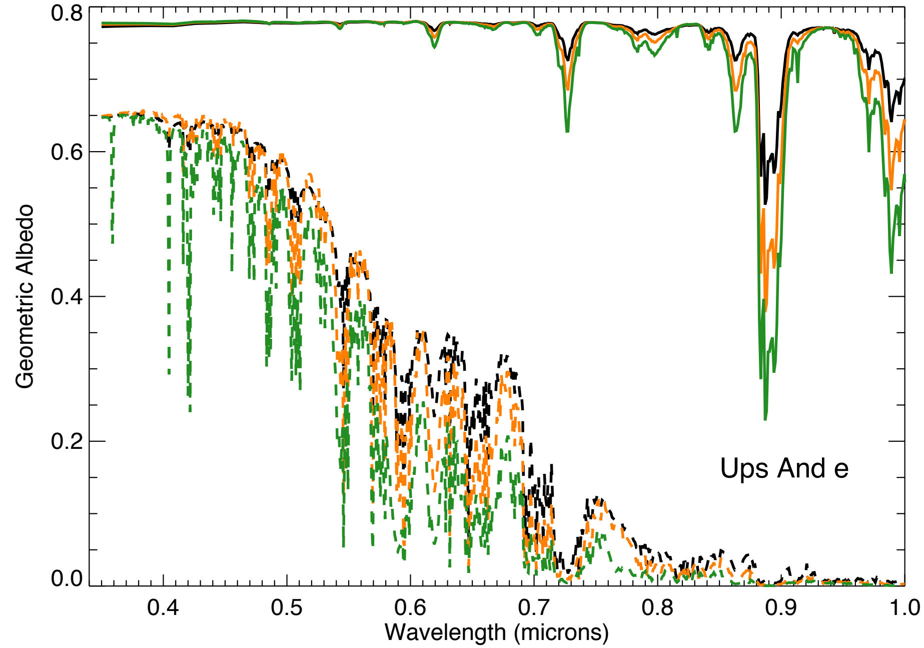
WPS Forward Models

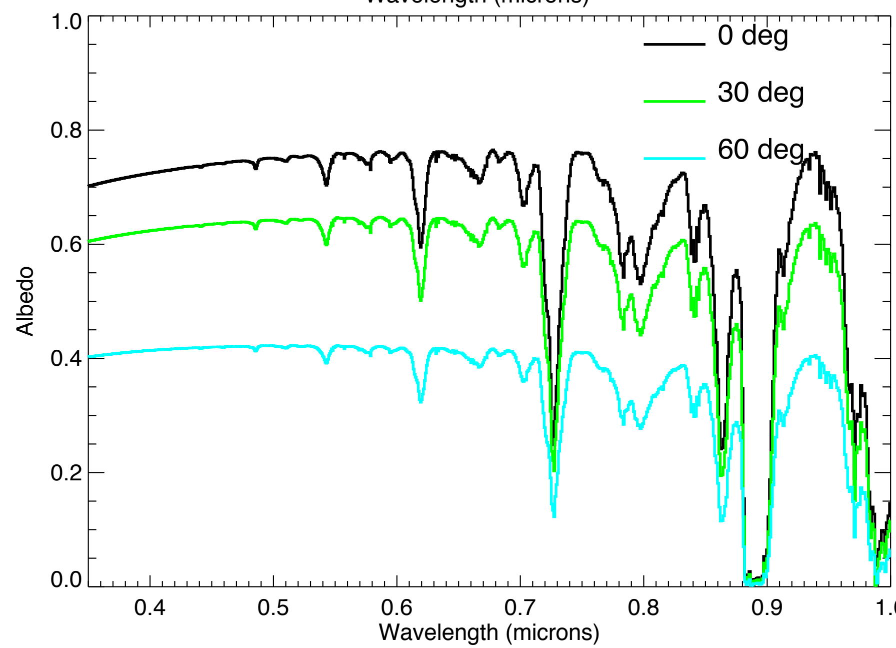
- Forward models include variations in following
  - Cloudy vs. Cloud-free
  - Assumed gravity
  - Metallicity (-0.3 to 2.0 dex)
  - C/O ratio (0.25 to 2.5 of Solar Value
  - Cloud sedimentation efficiency
  - Effective temperature (T_int)

- Albedo as a function of orbital phase calculated rigorously (see Cahoy et al. 2010)

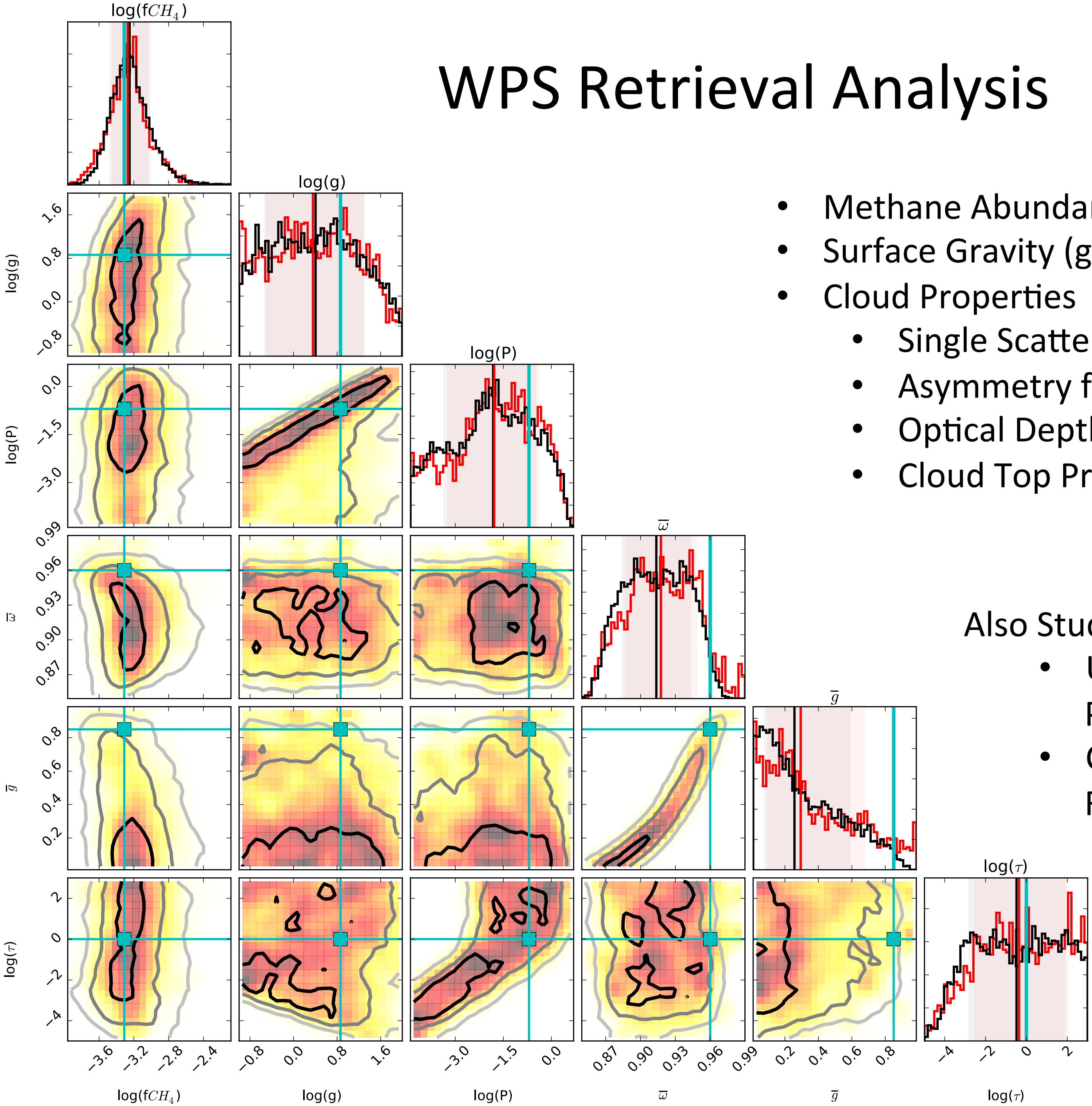
- Polarimetry Code will ingest output from forward models and can consider inhomogeneous clouds

- Theoretical targets will explore Super-Earth to Neptune regime as informed by other WPS programs.





WPS Retrieval Analysis



- Methane Abundance (fCH4)
- Surface Gravity (g)
- Cloud Properties
  - Single Scattering Albedo (ϖ)
  - Asymmetry factor (ğ)
  - Optical Depth (τ)
  - Cloud Top Pressure (P)

Also Studying Effects of

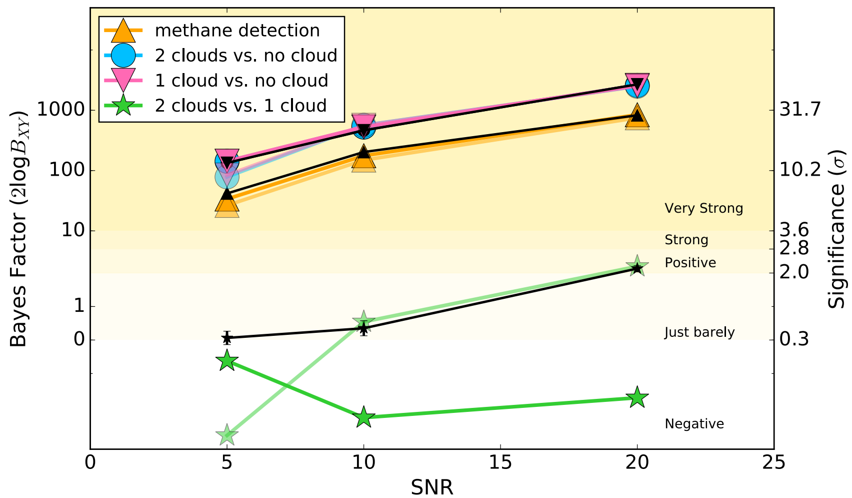
- Unknown Orbital Phase
- Constraints on Mass/ Radius

WPS Program Overview

Albedo Spectra from Forward Models → WFIRST Instrument Model/Simulator → Retrieval Analysis

Albedo Spectra from Forward Models ↓ Spectral Library

Retrieval Analysis ↓ Atmospheric Characterization with WFIRST



- See Talks at AGU (Lupu) and AAS (Lewis) meetings
- Stay tuned for RV target results in the Spring.

Team Members

Nikole Lewis (STScI) -> Program Management, Forward Models, Spectra, Result Synthesis

Mark Marley (NASA Ames) -> Retrievals, Polarimetry
Roxana Lupu (NASA Ames) -> Retrievals, Atmospheric Opacities
Laura Mayorga (NMSU) -> Polarimetry

Jonathan Fortney (UCSC) -> Forward Models, Retrievals
Caroline Morley (UCSC) -> Forward Models
Mikey Nayak (UCSC) -> Retrievals
Tyler Robinson (UCSC) -> Instrument Noise Model

Tom Greene (NASA Ames) -> Instrument Noise Model
Wes Traub (JPL) -> Instrument Noise Model
Channon Visscher (Dordt College) -> Atmospheric Chemistry
Richard Freedman (NASA Ames) -> Atmospheric Opacities
Mike Line (UCSC/ASU) -> Retrievals