The Habitable Exoplanet (HabEx) Imaging Mission

Bertrand Mennesson, HabEx Study Scientist

Jet Propulsion Laboratory, California Institute of Technology

for the HabEx STDT, with inputs from ExoPAG and COPAG

http://www.jpl.nasa.gov/habex

SPIE Meeting, San Diego, August 6 2017

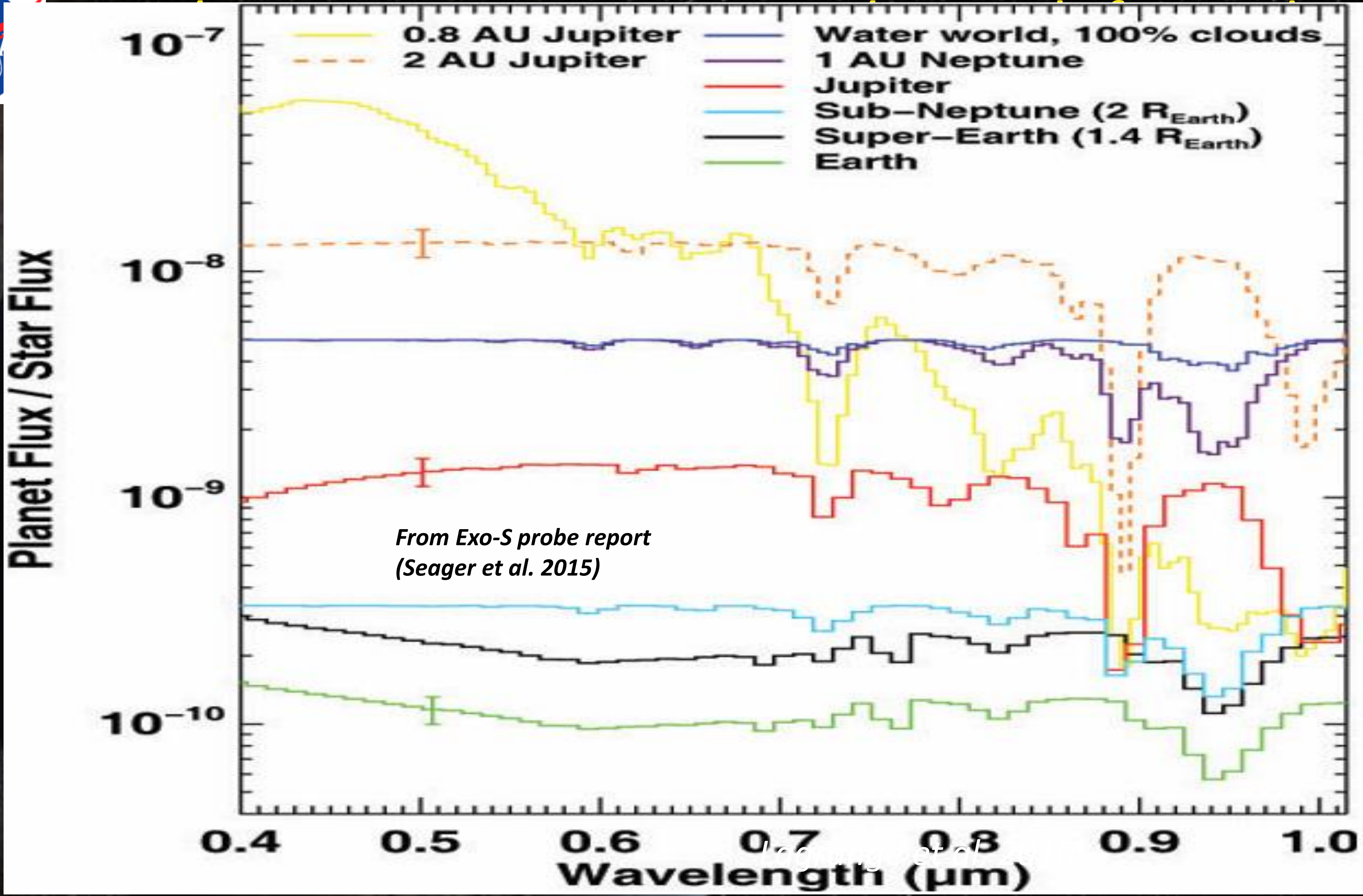
Illustration Credit: NASA Ames/JPL-Caltech

HabEx Primary Science Goal: search for and characterize potentially habitable worlds

- ✓ Characterize Earth-sized planets in the HZ of nearby MS stars via direct detection and spectroscopic analysis of their reflected starlight
- ✓ Understand the atmospheric and surface conditions of those exoplanets
- ✓ Specifically, search for water and bio-signature gases on those exoplanets

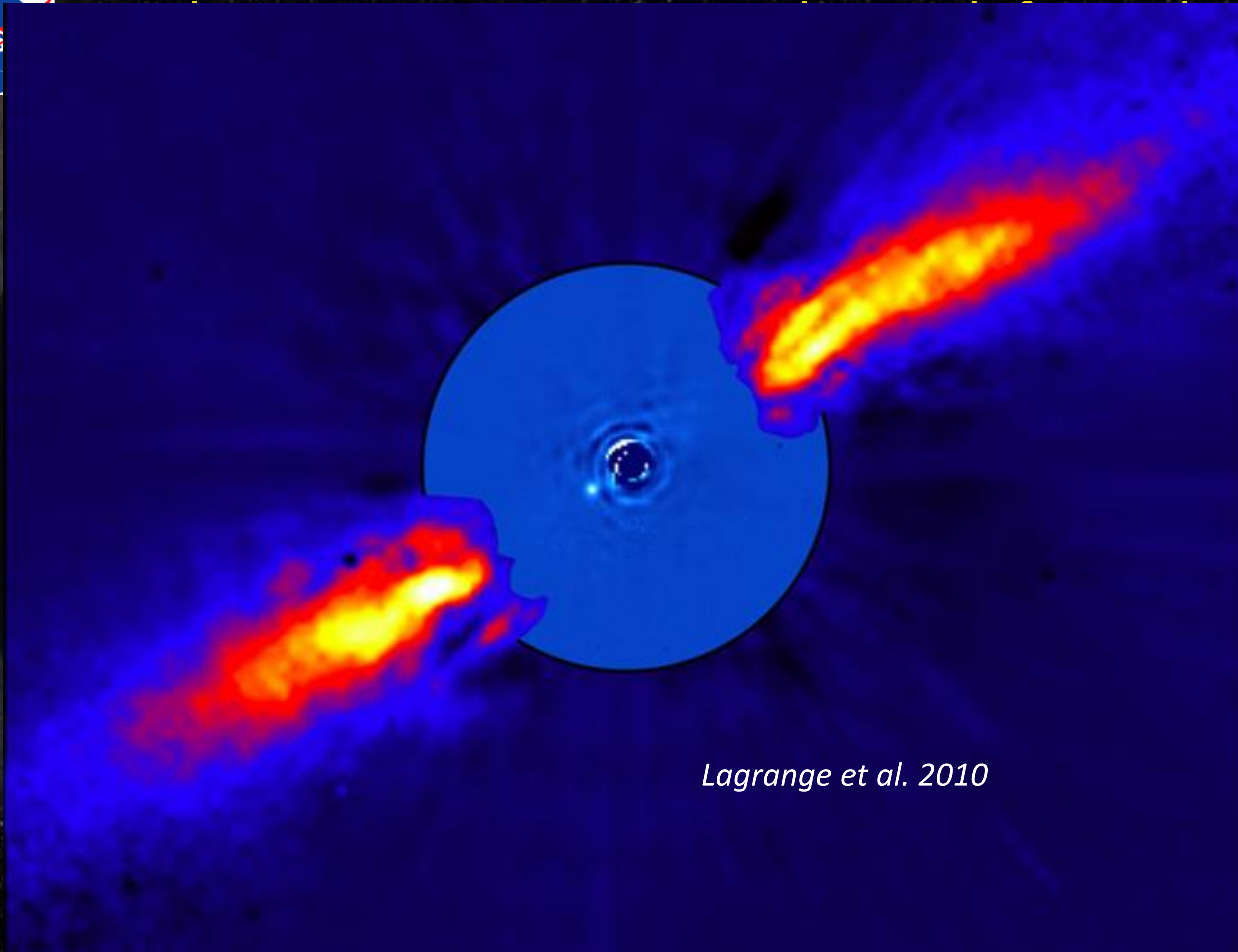
From Exo-S probe report (Seager et al. 2015)

- ✓ Search for signs of habitability and bio activity in Earth-like and non-Earth-like exoplanets
- ✓ Characterize *full* planetary systems, including rocky planets, “water worlds”, gas giants, ice giants, inner and outer dust belts
- ✓ Conduct planet formation and dynamical evolution studies, including planet/disk interactions



From Exo-S probe report (Seager et al. 2015)

- ✓ Conduct planet formation and dynamical evolution studies, including planet/disk interactions


Lagrange et al. 2010

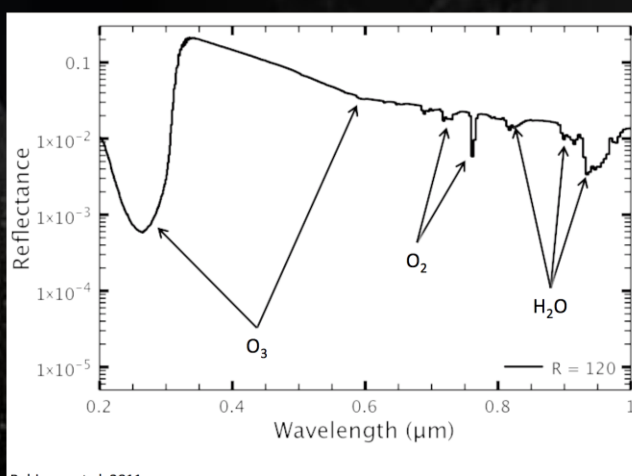
MUSTs and WANTs for biosignatures searches

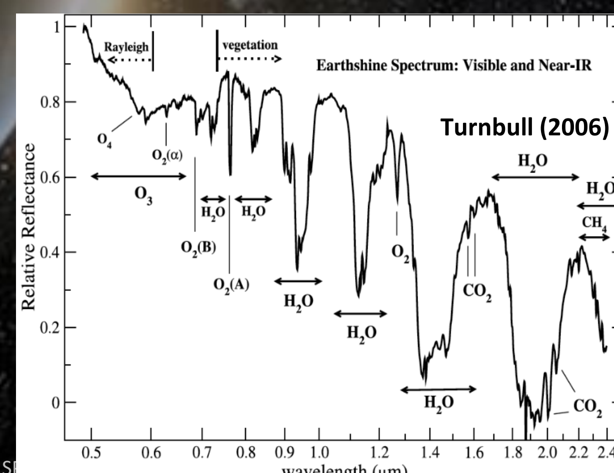
- Minimum continuous spectral coverage from 0.4 to 1.0 μm @ R=70, with possible extension down to ~0.25 μm (UV photometry only)
  "We found the presence of water and biosignature gases (O_2 and O_3) on that planet, but did not search for abiotic sources of those gases."

  MUST
- For a mission that goes out to 1.7 μm
  "We found the presence of biosignature gases (O_2 and O_3) on that planet, found additional H_2O features, and searched for signs (CO_2, CO, O_4, pressure) that these gases were created by abiotic processes."

  WANT
- For a mission that goes out to ≥ 2.5 μm
  "We found the presence of biosignature gases (O_2 and O_3) on that planet, and secondary features (CH_4(*)) inconsistent with abiotic processes."

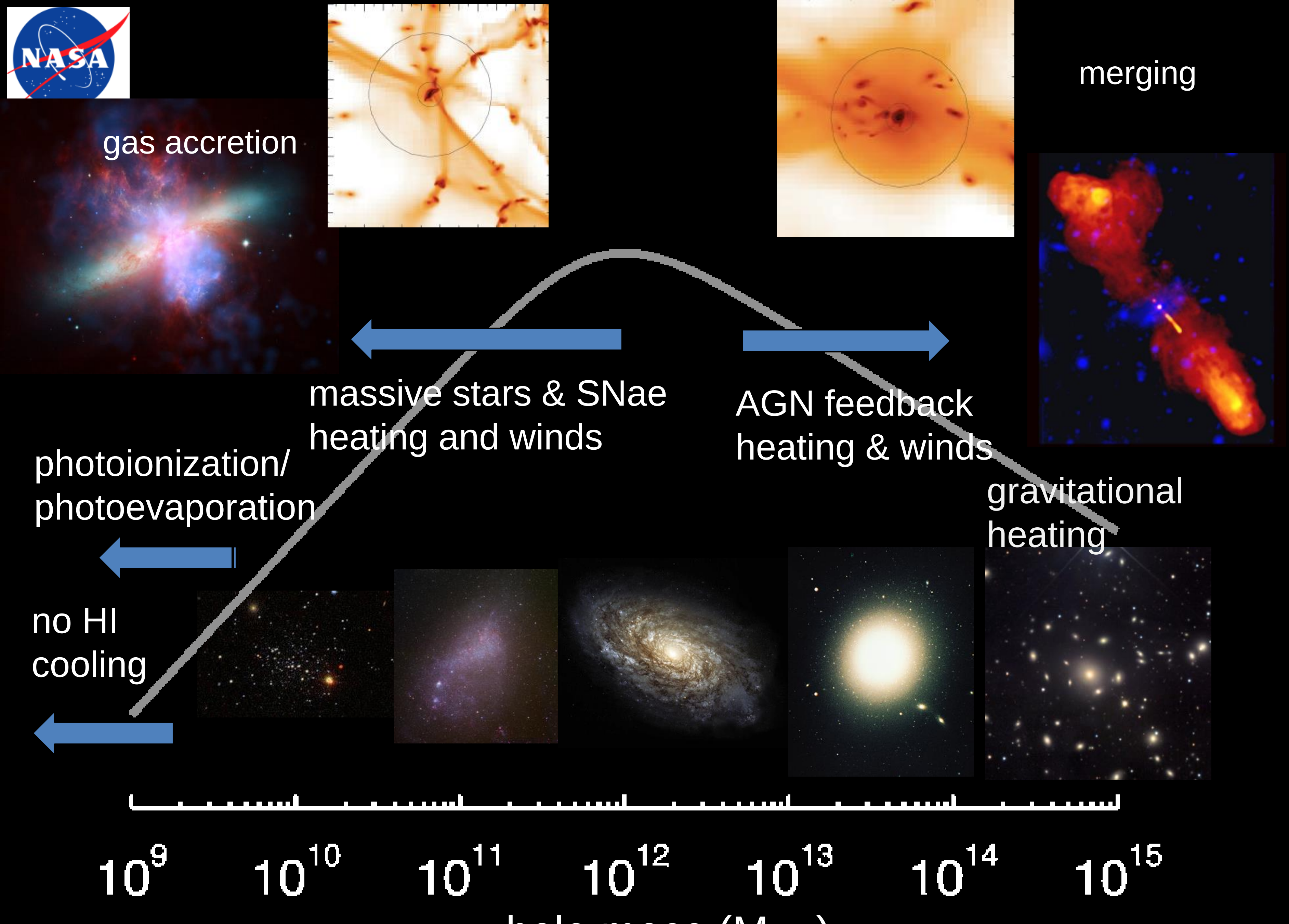
  STRETCH





General Astrophysics with HabEx
(preliminary)

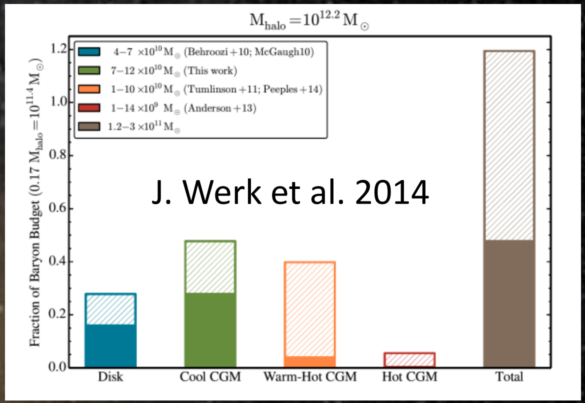
- ✓ *The grand challenge of galaxy formation and evolution*


merging
gas accretion
massive stars & SNae
heating and winds
AGN feedback
heating & winds
photoionization/
photoevaporation
gravitational
heating
no HI
cooling
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
halo mass (M_{sun})

Constraining Galaxy formation and evolution processes with HabEx

- Observational studies of stellar and AGN feedback:
  - HabEx diffraction limited observations will allow unique morphology studies, resolved spectroscopy and high dynamic range studies of galaxies as a function of age and mass
  - Will help understand how "small scale" physics and global galaxy properties are connected
  - E.g. conduct UV observations of massive stars in the local Universe (20Mpc)

  Reqt: R=10^4 UV/optical/NIR spectroscopy with <50 mas resolution



- Probe the CGM and the baryons life cycle
  - How do gas and metals cycle in and out of galaxies?
  - Measure from absorption lines and abundance of H and metals in various ionization states (e.g. Mg II, SiII, CII, SiIII, SiIV, OVI)

  Reqt: R> 10^4 far UV spectroscopy of low z galaxies

- Improve our understanding of galaxy leakiness and reionization
  - How much H-ionizing LyC radiation escapes from SF galaxies as a function of redshift (z< 3.5) and mass?
  - Likely to remain an open question by the end of HST's lifetime
  - Requires high spatial R to mitigate foreground contamination
  - Would exploit HabEx potential for much higher UV throughput and detector QE than HST, and for parallel deep field observations

  Reqt: UV MOS 1000 - 4000 Å, R=200, ~4' FoV

General Astrophysics with Habex (preliminary)

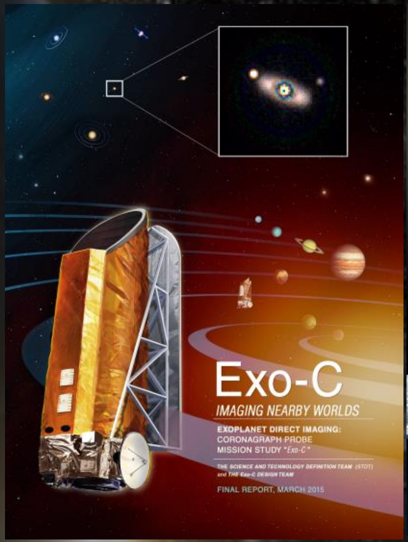
- ✓ *The grand challenge of galaxy formation and evolution*

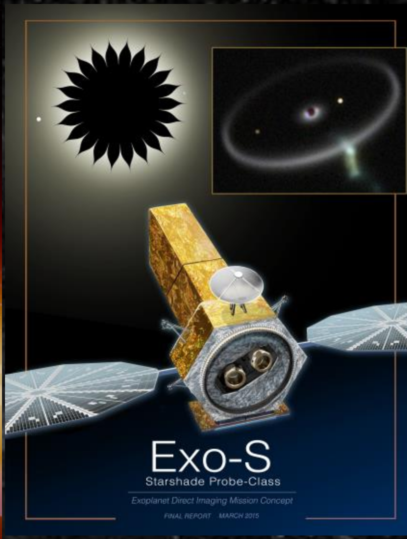
- ✓ *Star and planet formation and evolution*
  - Probing CS environments around young stars and PP disks at high resolution
  - Late stages of stellar evolution
  - Understand the UV environment of host stars to put their planets atmospheres in context

- ✓ *GA may level requirements on the architecture*
  - If justified by killer app and compatible with top exoplanet science goals and preferred architecture

Key Architecture Trades and Open Questions for Exoplanet Science

- High Contrast Imaging and Spectroscopy Concept is open !
  - Many design options a priori possible
  - On or off-axis telescope?
  - Segmented or monolith?
  - Internal coronagraph, external starshade, both?
  - Low R IFS vs high R low SN cross-correlation
  - All to be defined by STDT and science community, with support from JPL study office





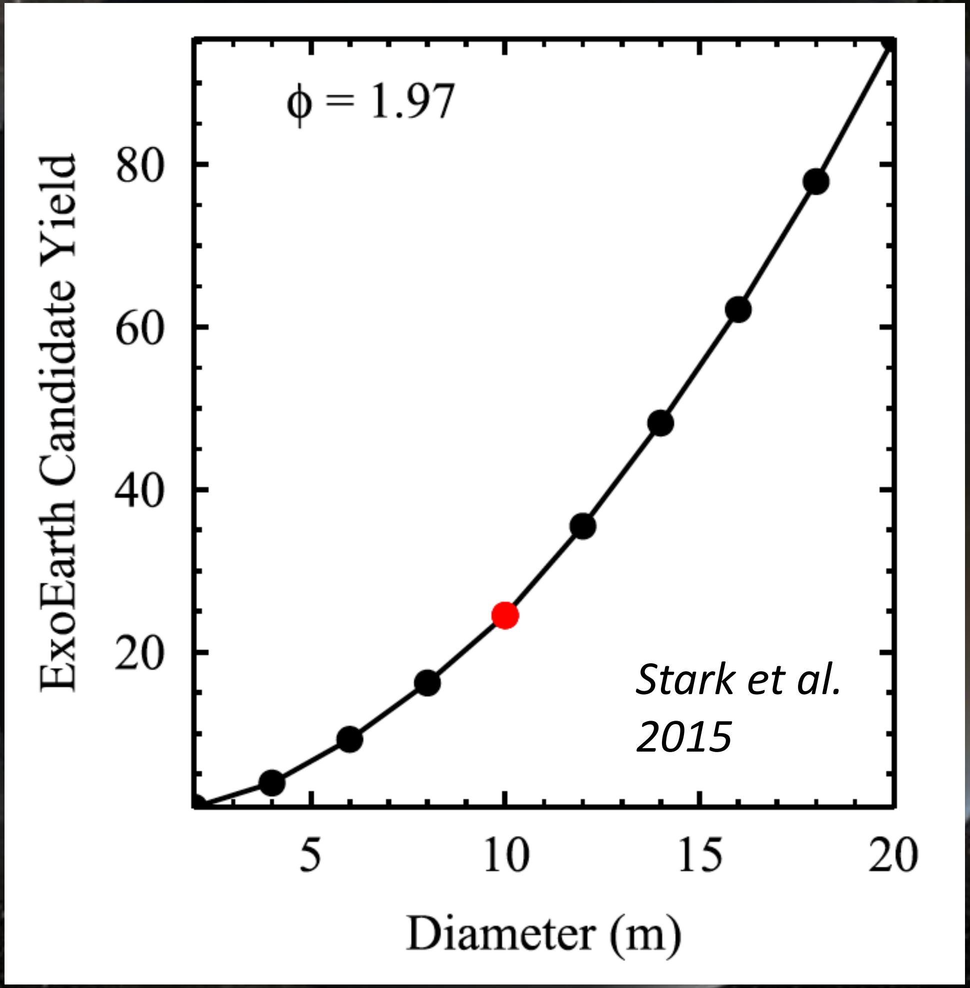
- Possible add-on instrumental capabilities for exoplanet science
  - Should HabEx include transit spectroscopy? till 5 μm or more (Werner et al. 2016)?
  - Should HabEx include a precursor program to detect exo-Earths targets using high precision RV and/or astrometric measurements ?
  - Should such observations be conducted with HabEx or by other facilities/ missions?
  - Should HabEx monitor target star (UV) activity ?

Key Requirements and Challenges for exo-Earths imaging and characterization

- Required no matter what architecture selected:
  - Very high contrast observations: $>10^{10}$ dynamic range (after post-processing)
  - At very high spatial resolution (~50 mas) : that is $2*\lambda/D$ at $0.5\mu m$ for a 4m telescope
  - Over a broad wavelength range: At least from 400nm (250nm) to 1000nm (1700nm)
  - With very low noise/ high QE detectors over that range

- Large aperture: 3.5m to 8m, diffraction limited at ~300nm
  - Exo-C ES (2.4m) still produces marginal number of exo-Earth detections
  - Recent Science yield estimates

Yield vs diameter (Coronagraph)



- Assumes blind search
- Likely much higher if prior knowledge of where & when to look
- Believe functional dependency more than absolute yield numbers
- Ignores possible break-point at monolith / segmented telescope diameter transition

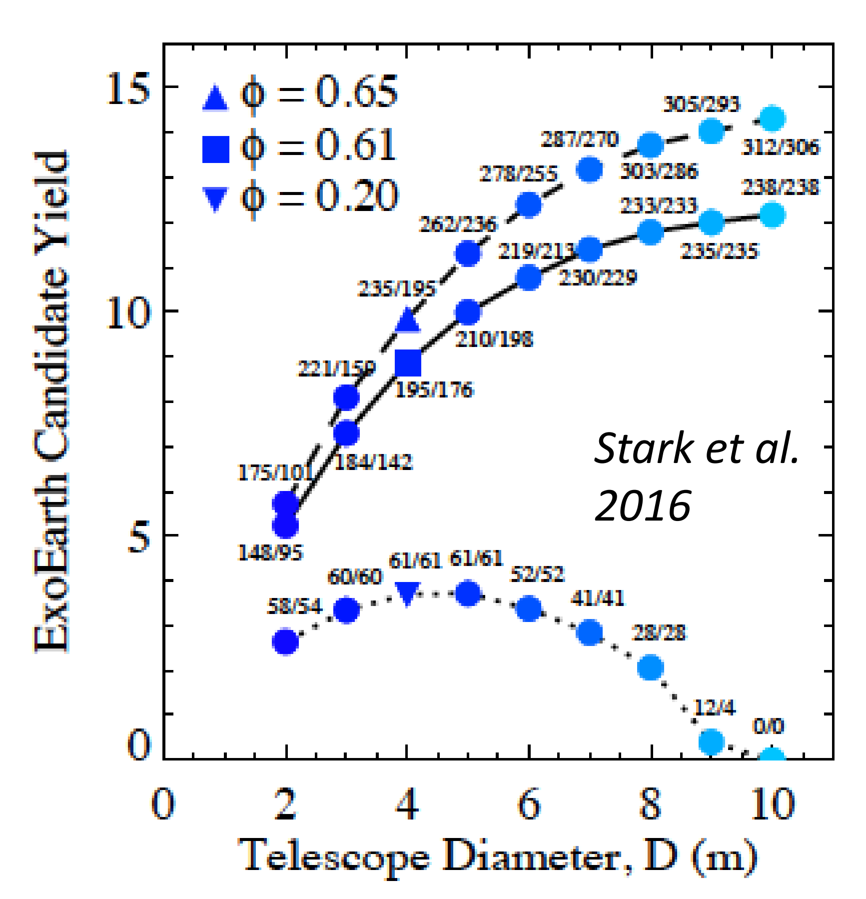
Yield vs diameter (Starshade)

Launch mass limits:

25T

9.8T

3.6T

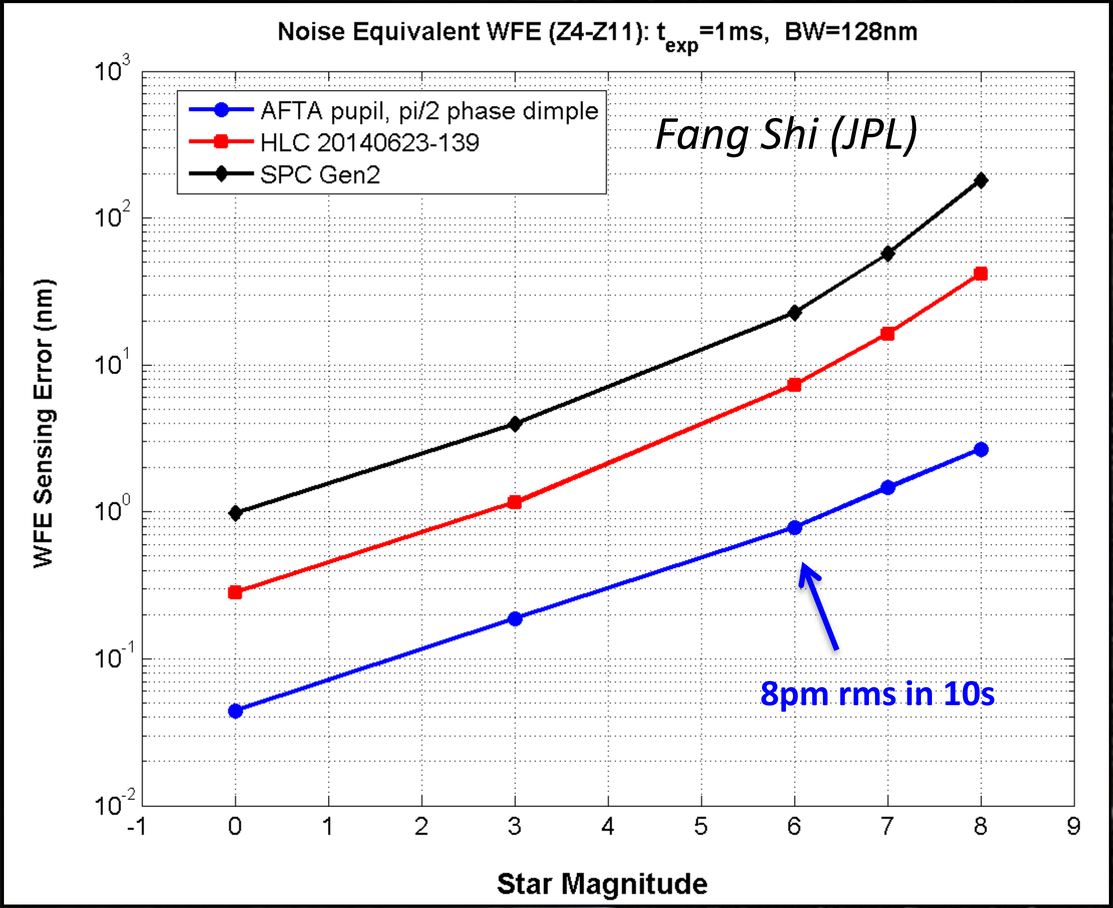


- Assumes blind search
- Likely higher if prior knowledge of where & when to look
- Believe functional dependency more than absolute yield numbers
- Ignores possible break-point at monolith / segmented telescope diameter transition

Key Requirements and Challenges for exo-Earths imaging and characterization

- Required no matter what architecture:
  - Very high contrast observations: >10 [10] dynamic range (after post-processing)
  - At very high spatial resolution (~50 mas) : that is 2*λ/D at 0.5μm for a 4m telescope
  - Over a broad wavelength range: At least from 400nm (250nm) to 1000nm (1700nm)
  - With very low noise/ high QE detectors over that range
- Large aperture: 3.5 to 8m, diffraction limited at ~300nm
- Light weight, high throughput telescope with fast primary
- If internal coronagraph: exquisite wavefront stability
  - Slow LOW drifts (<1Hz) need to be kept <10 pm rms (after correction)

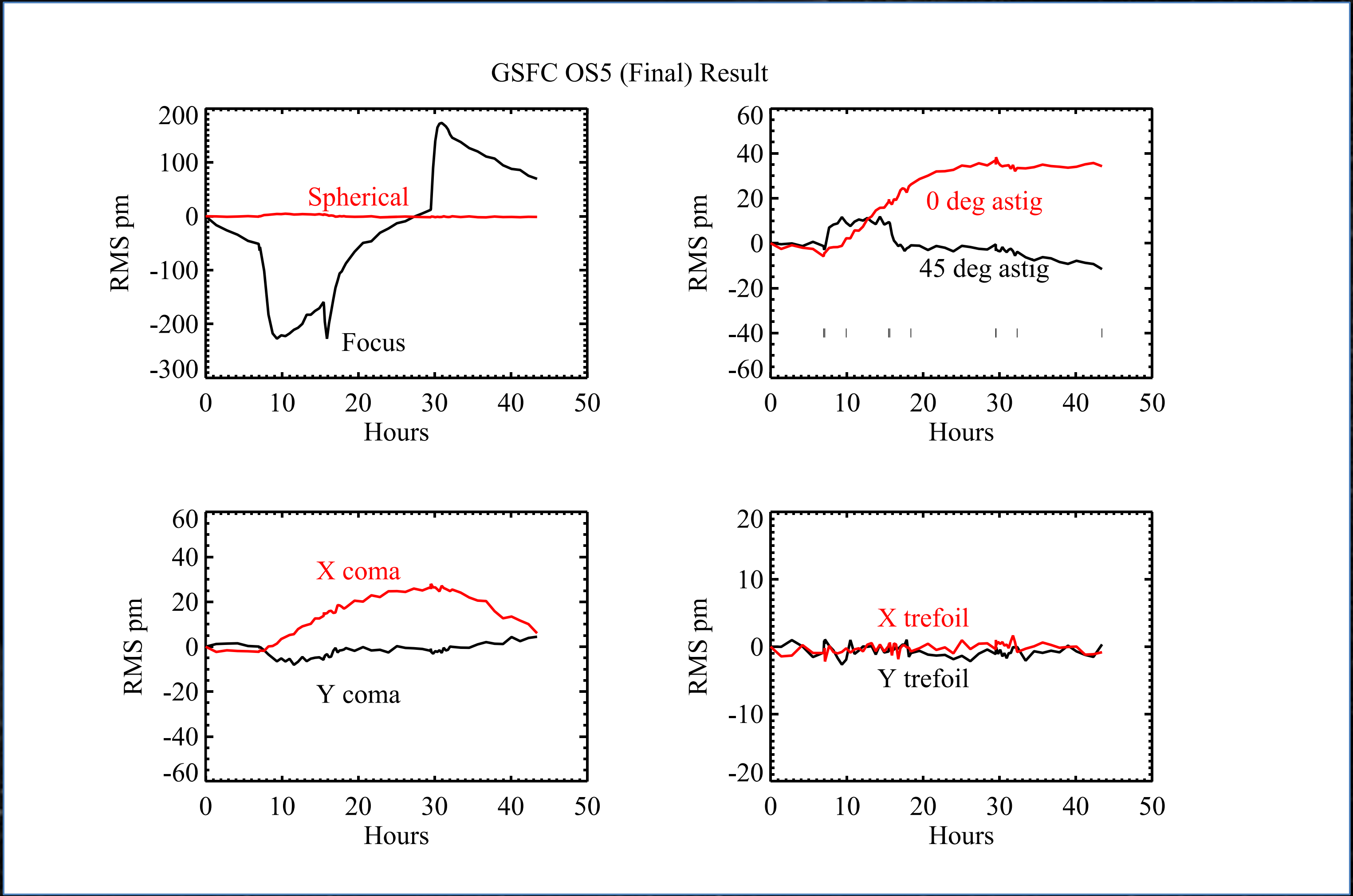
WFIRST LOWFE Sensing



In theory you can get <10 pm rms residual LOWF (Z4-Z11 total rms) estimation error in 10s on V=6 star, providing telescope wavefront drifts allow it, i.e are not faster (or use laser metrology)

Minimizing Thermally induced wavefront drifts

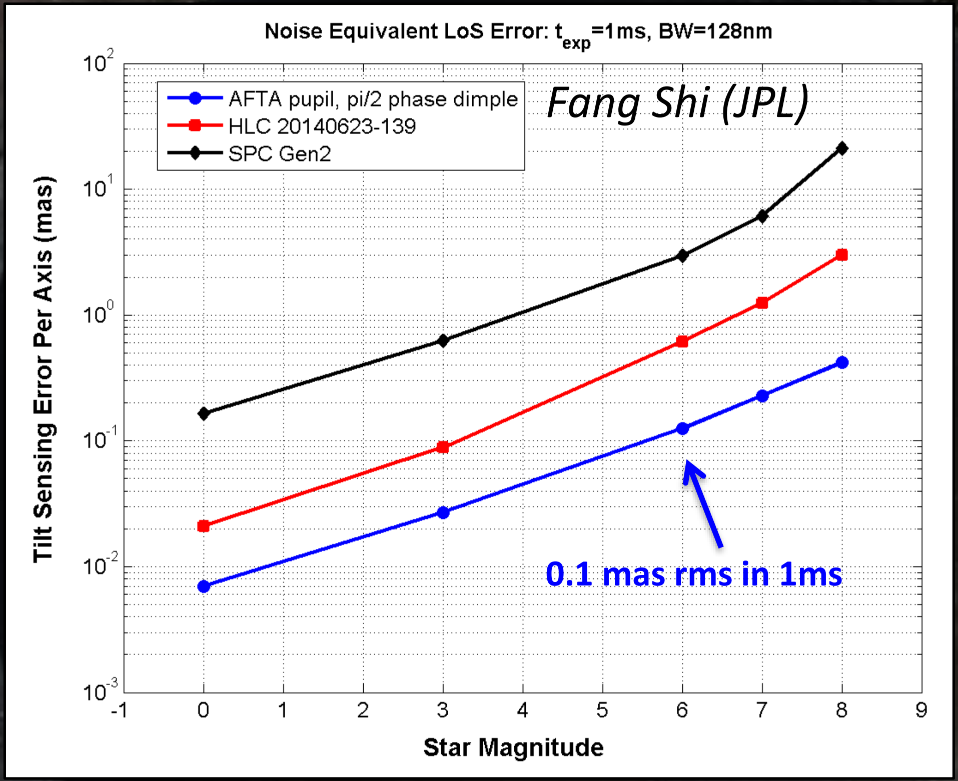
- E.g WFIRST: this is what we think we can live with for detecting jovian planets at 10^{-9} contrast *(after post-processing, and assuming perfect focus correction)* :

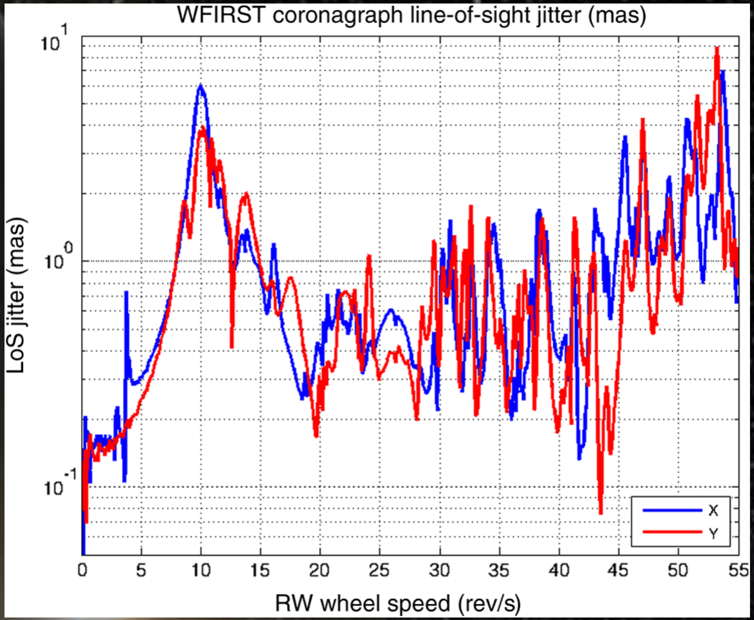


Key Requirements and Challenges for exo-Earths imaging and characterization

- Required no matter what architecture:
  - Very high contrast observations: >10 [10] dynamic range (after post-processing)
  - At very high spatial resolution (~50 mas) : that is 2*λ/D at 0.5µm for a 4m telescope
  - Over a broad wavelength range: At least from 400nm (250nm) to 1000nm (1700nm)
  - With very low noise/ high QE detectors over that range
- Large aperture: 3.5 to 8m, diffraction limited at ~300nm
- Light weight, high throughput telescope with fast primary
- If internal coronagraph: exquisite wavefront stability
  - Slow LOW drifts (<1Hz) need to be kept <10 pm rms (after correction)
  - Pointing jitter (>1Hz) need to be <0.1 mas rms per axis after correction at a few 100Hz

Pointing Jitter Sensing error

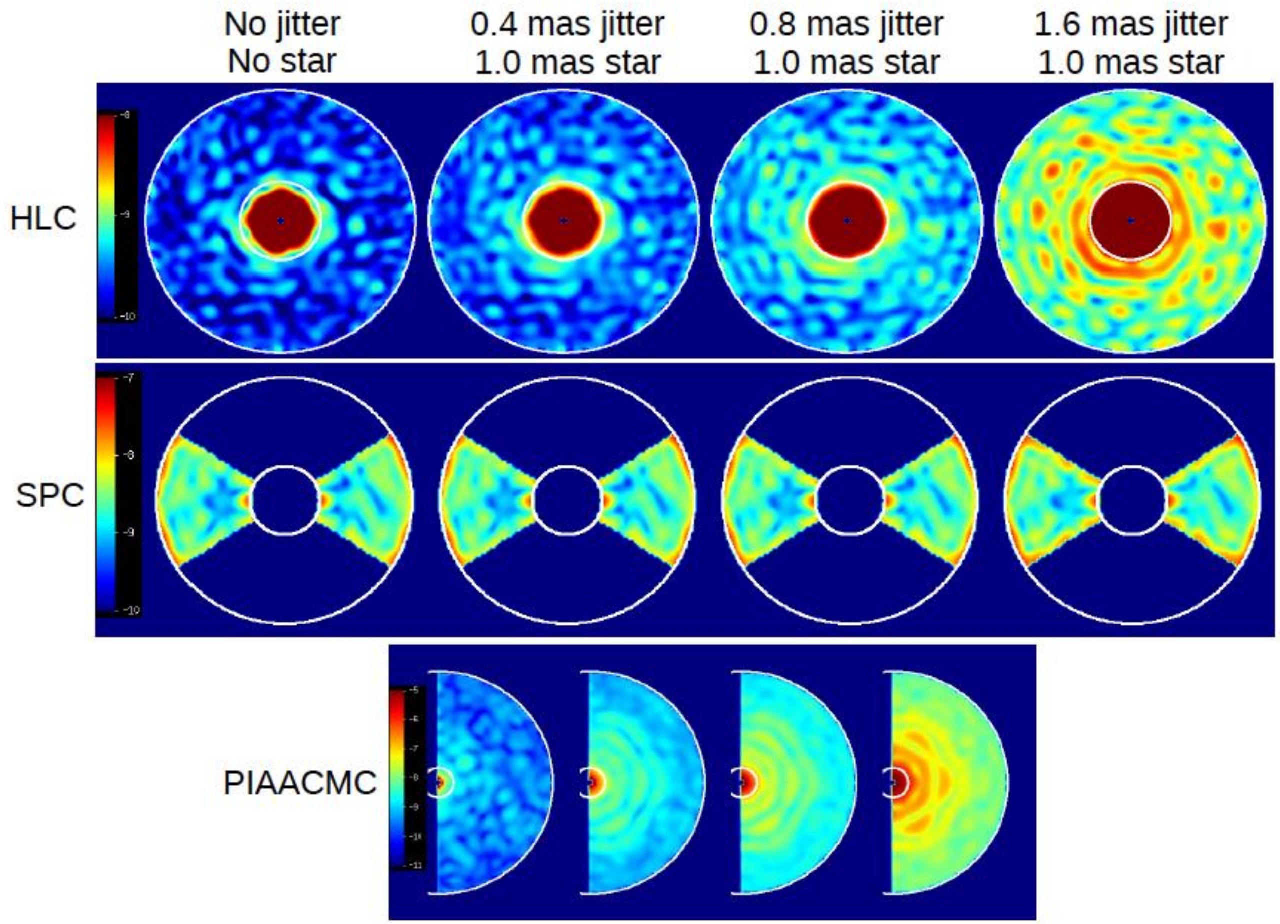




In theory, you can get 0.1 mas rms pointing estimation error in 1ms on V=6 star,
providing telescope pointing jitter allows it.
(WFIRST native telescope pointing jitter is expected to be 4mas rms per axis for RW speeds below 50Hz)

Impact of Pointing Jitter

Dark Holes with Pointing Jitter & Finite Star

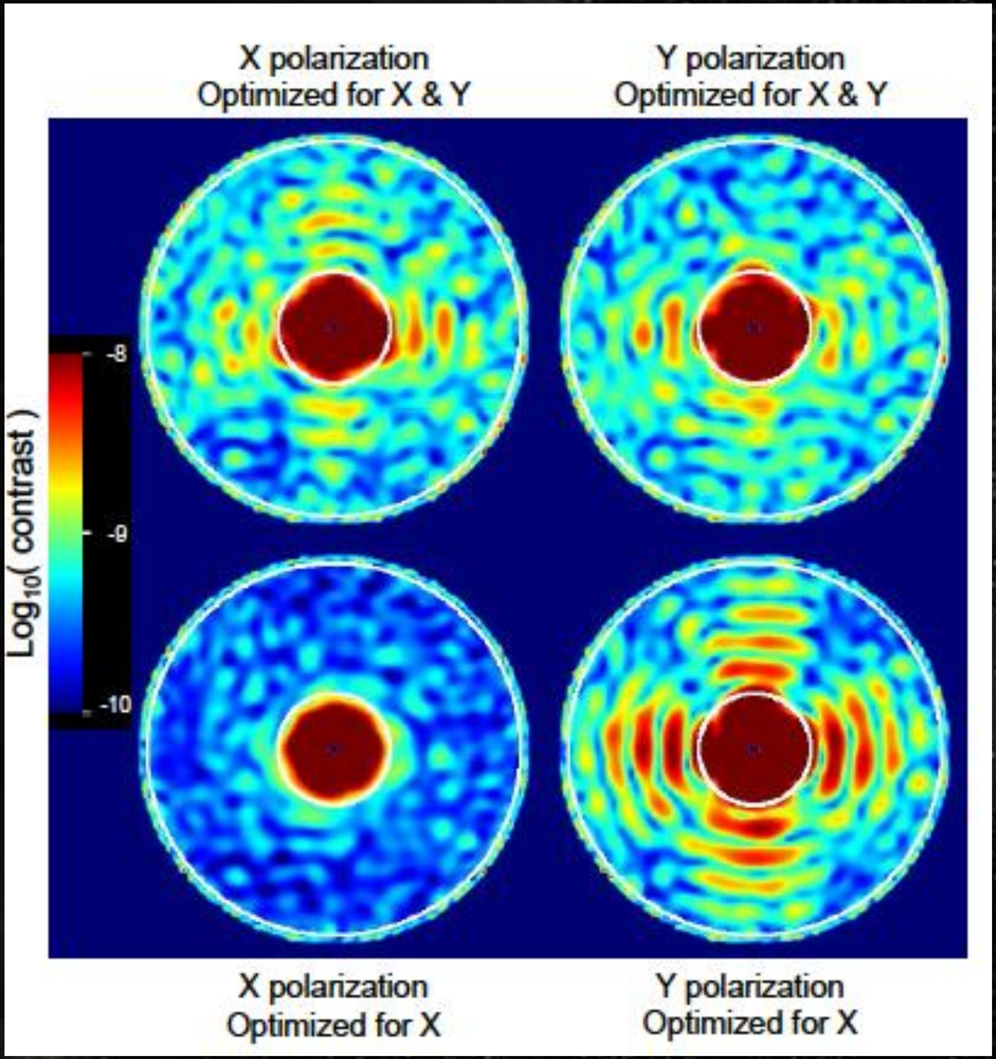


1

Key Requirements and Challenges for exo-Earths imaging and characterization

- Required no matter what architecture:
  - Very high contrast observations: >10^{10} dynamic range (after post-processing)
  - At very high spatial resolution (~50 mas) : that is 2*λ/D at 0.5μm for a 4m telescope
  - Over a broad wavelength range: At least from 400nm (250nm) to 1000nm (1700nm)
  - With very low noise/ high QE detectors over that range
- Large aperture: 3.5 to 8m, diffraction limited at ~300nm
- Light weight, high throughput telescope with fast primary
- If internal coronagraph: exquisite wavefront stability
  - Slow LOW drifts (<1Hz) need to be kept <10 pm rms (after correction)
  - Pointing jitter (>1Hz) need to be <0.1 mas rms per axis after correction
  - Polarization independent aberrations or at least low cross-talk
  - Or pay the price: split polar and double WFC trains (1 for each polar)

Polarization effects on Contrast



Krist et al. 2016

Key Requirements and Challenges for exo-Earths imaging and characterization

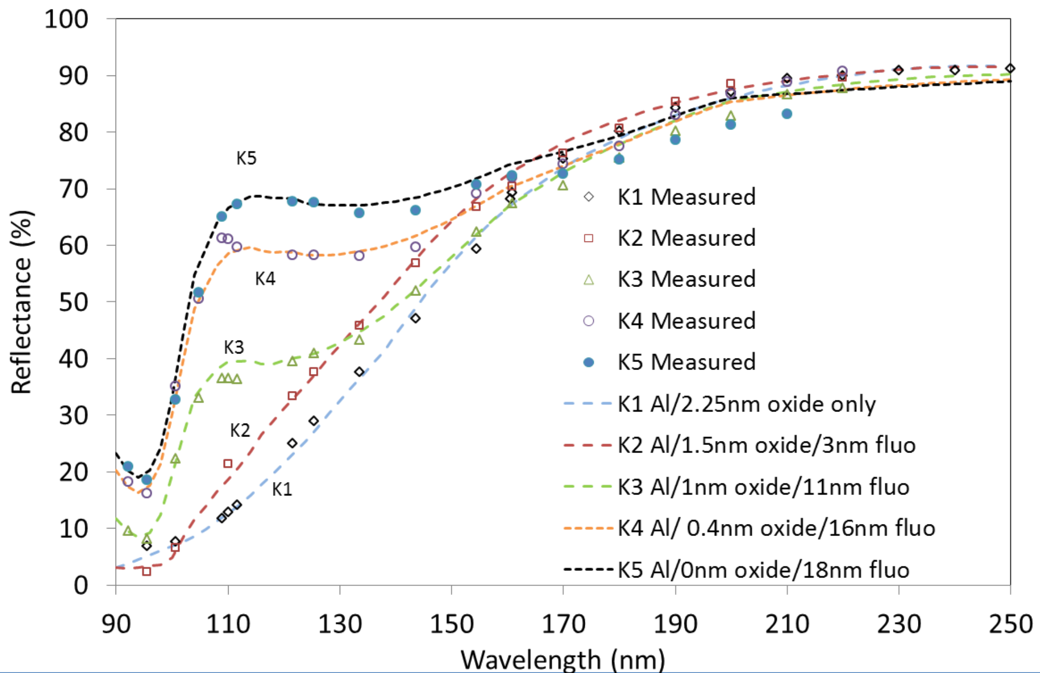
- Required no matter what architecture:
  - Very high contrast observations: $>10^{10}$ dynamic range (after post-processing)
  - At very high spatial resolution (~50 mas) : that is 2*λ/D at 0.5μm for a 4m telescope
  - Over a broad wavelength range: At least from 400nm (250nm) to 1000nm (1700nm)
  - With very low noise/ high QE detectors over that range
- Large aperture: 3.5 to 8m, diffraction limited at ~300nm
- Light weight, high throughput telescope with fast primary
- If internal coronagraph: exquisite wavefront stability
  - Slow LOW drifts (<1Hz) need to be kept <10 pm rms (after correction at a few mHz)
  - Pointing jitter (>1Hz) need to be <0.1 mas rms per axis after correction at a few 100Hz
  - Polarization independent aberrations or at least low cross-talk (differential
  - Or pay the price: split polar and double WFC trains (1 for each polar)
- High Strehl ratio after WF correction (planet light encircled energy)
  - If segmented: small struts and segment gaps
  - If on-axis design: small central obscuration (15% or less)
  - High contrast imaging on segmented apertures workshop: encircled energy currently low for high contrast at small IWA (e.g. 3λ/D) in presence of moderately obscured pupils (Ruane et al. 2016)

Key Requirements and Challenges for exo-Earths imaging and characterization

- Required no matter what architecture:
  - Very high contrast observations: $>10^{10}$ dynamic range (after post-processing)
  - At very high spatial resolution (~50 mas) : that is $2*\lambda/D$ at $0.5\mu m$ for a 4m telescope
  - Over a broad wavelength range: At least from 400nm (250nm) to 1000nm (1700nm)
  - With very low noise/ high QE detectors over that range
- Large aperture: 3.5 to 8m, diffraction limited at ~300nm
- Light weight, high throughput telescope with fast primary
- If internal coronagraph: exquisite wavefront stability
  - Slow LOW drifts (<1Hz) need to be kept <10 pm rms (after correction)
  - Pointing jitter (>1Hz) need to be <0.1 mas rms per axis after correction at HF
  - Polarization independent aberrations or at least low cross-talk (differential
  - Or pay the price: split polar and double WFC trains (1 for each polar)
- High Strehl ratio after WF correction (planet light encircled energy)
  - If segmented: small struts and segment gaps
  - If on-axis design: small central obscuration (15% or less)
  - High contrast on segmented apertures workshop: encircled energy currently low for high contrast at small IWA (e.g. $3\lambda/D$) in presence of moderately obscured pupils

Key Requirements and Challenges for exo-Earths imaging and characterization

- Compatibility of high contrast exoplanet observations with UV coatings used for General Astrophysics applications
  - In terms of throughput, i.e reflectivity per mirror (progress since 2009 THEIA proposal?)
  - Polarization effects
  - Possible low T operation, contamination issues
  - Any technical or cost threshold effect below some λ_{UV}^{min} , from 380nm to 91nm?



FUV reflectance of unprotected vs AlF3 protected Al mirror samples.

Mirror coating developments at JPL.

Summary of Key Study Trades and Challenges

- HCI Technology: Coronagraph and/or Starshade?
- Telescope size and technology (passive, active, metrology, on vs off axis, monolith vs segmented)
- Wavelength ranges for GA and exoplanet science
- Approach to Xpl Spectroscopy: low R IFS vs high R low SN spectral template correlation (Snellen et al. 2014 , Wang & Mawet 2016)
- *Should HabEx include an RV or Astrometry precursor detection program as an integral part of the mission?*
- *Should planet masses be determined in advance, concurrently or after HabEx for science enhancement?*
- What launch vehicle and corresponding mass limit to consider ?(assumption to be defined by HQ)

HabEx STDT

APPOINTED STDT MEMBERS	EXPERTISE
Cahoy, Kerri (MIT)	Space Systems technology and Xpl spectra
Domagal-Goldman, Shawn (GSFC)	Bio-signatures and Xpl spectra
Feinberg, Lee (GSFC)	Picometer wavefront control
Gaudi, Scott (Ohio State)	Xpl Demographics / WFIRST
Guyon, Olivier (Arizona)	Coronagraph design / Wavefront control
Kasdin, Jeremy (Princeton)	Starshade and Coronagraph designs
Mawet, Dimitri (Caltech)	Coronagraph design / Disks/ Post processing
Mennesson, Bertrand (JPL)	Debris disks / High Contrast Imaging
Robinson, Tyler (UC Santa Cruz)	Atmospheric spectral retrieval
Rogers, Leslie (Chicago)	Low mass Xpl Interior structure & evolution
Scowen, Paul (Arizona State)	General astro/ UV/ ISM COPAG Chair
Seager, Sara (MIT)	Starshade / Bio-signatures
Somerville, Rachel (Rutgers)	Star and galaxy formation / theory vs observations
Stapelfeldt, Karl (NASA JPL)	Disks/ ExEP CS
Stern, Daniel (JPL)	General astrophysics/ AGNs/ NIR
Turnbull, Margaret (SETI)	Mission design / target selection

Community Chair: Gaudi, Scott (Ohio State)

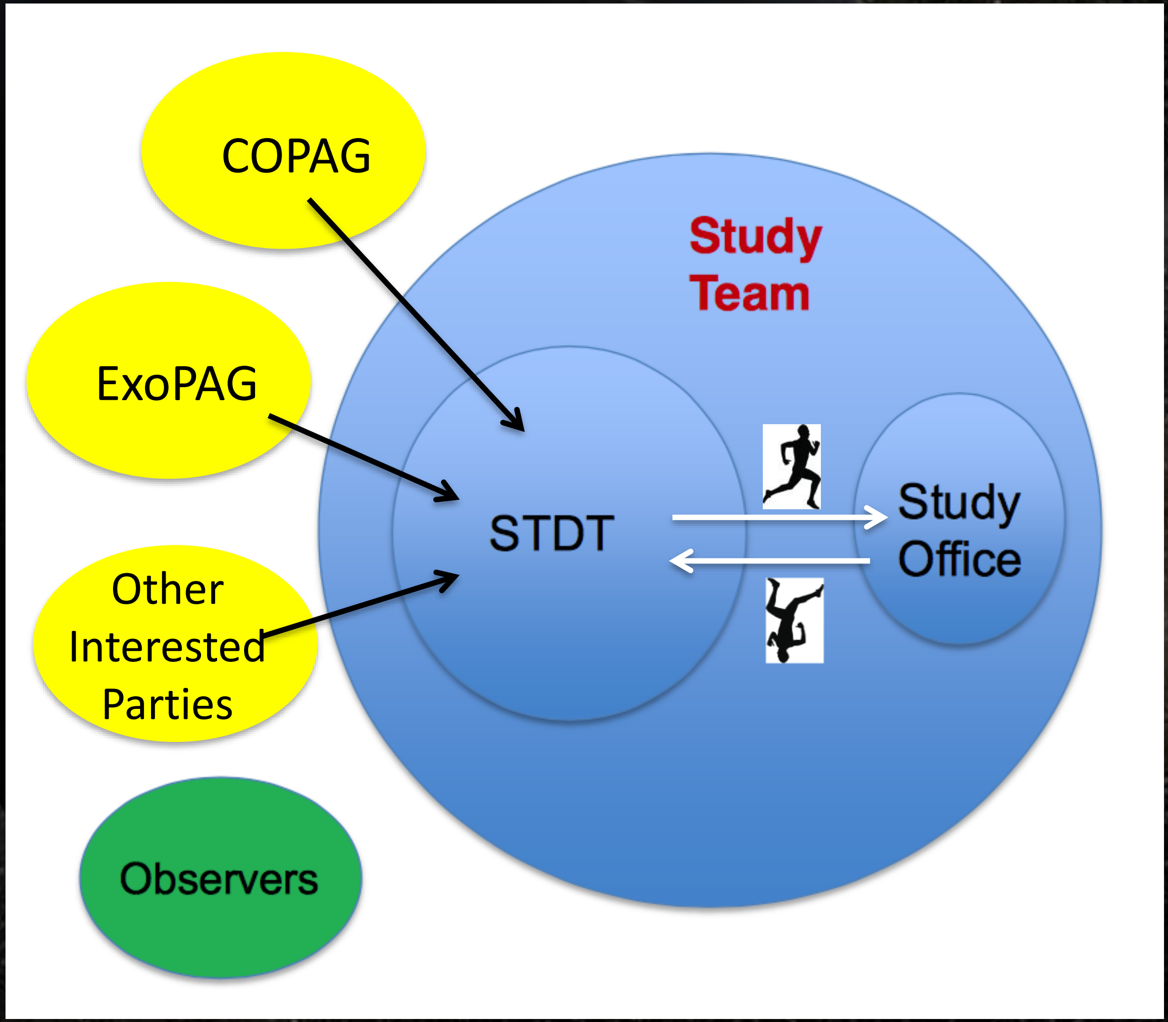
Community Chair: Seager, Sara (MIT)

EX-OFFICIO STUDY TEAM MEMBERS	
Hudgins, Doug (NASA HQ)	HabEx Deputy Program Scientist
Still, Martin (NASA HQ)	HabEx Program Scientist
Warfield, Keith (NASA JPL)	HabEx Study Manager
Marois, Christian (NRC Canada)	CSA Observer
Mouillet, David (IPAG Grenoble)	CNES Observer
Prusti, Timo (ESA)	ESA Observer
Quirrenbach, Andreas (Heidelberg Univ)	DLR Observer
Tamura, Motohide (Univ. of Tokyo)	JAXA Observer

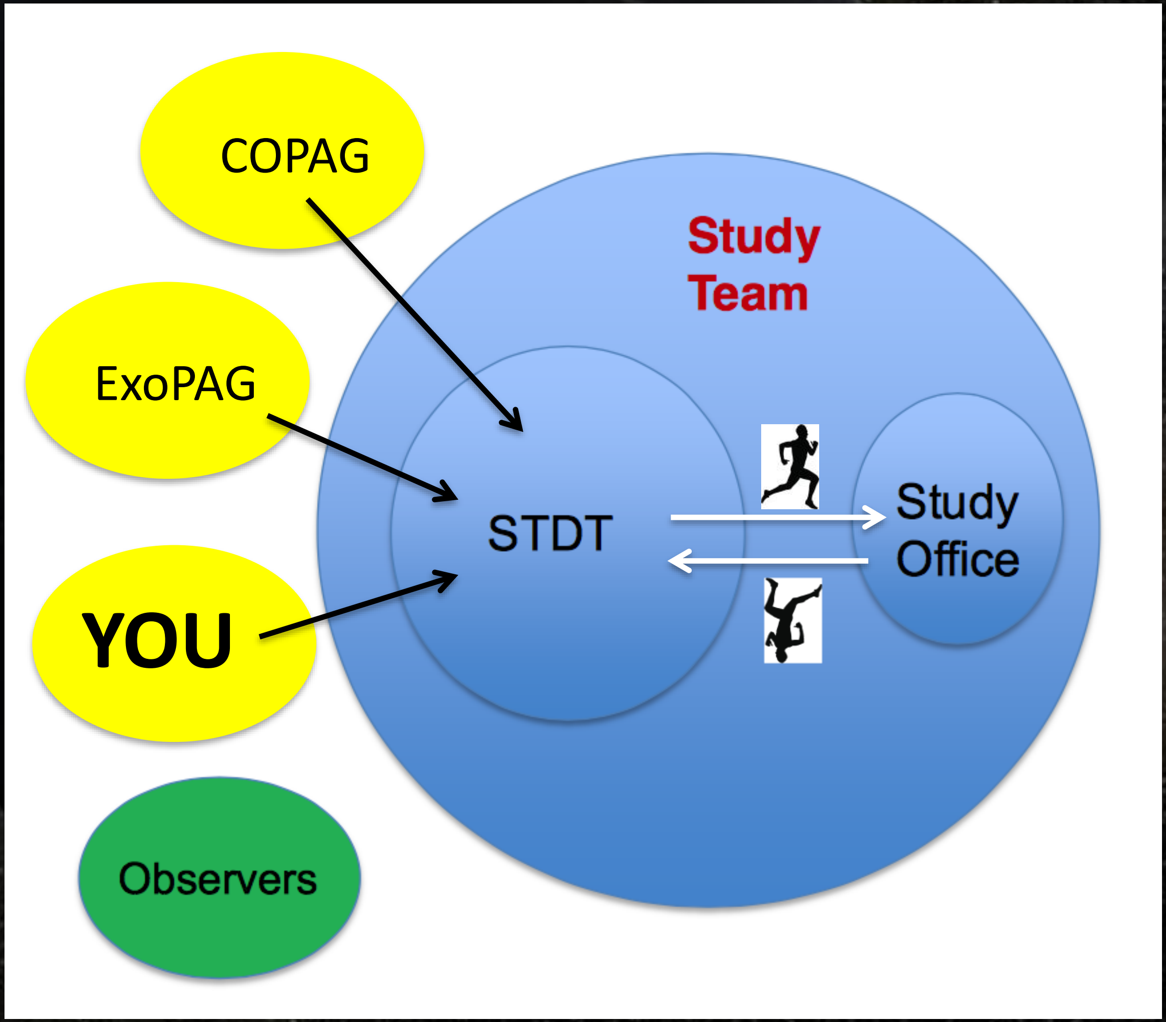
(Current) HabEx Study Team

First in person STDT Meeting: Washington DC, May 11-12 2016

Science and Technology Community Contributions



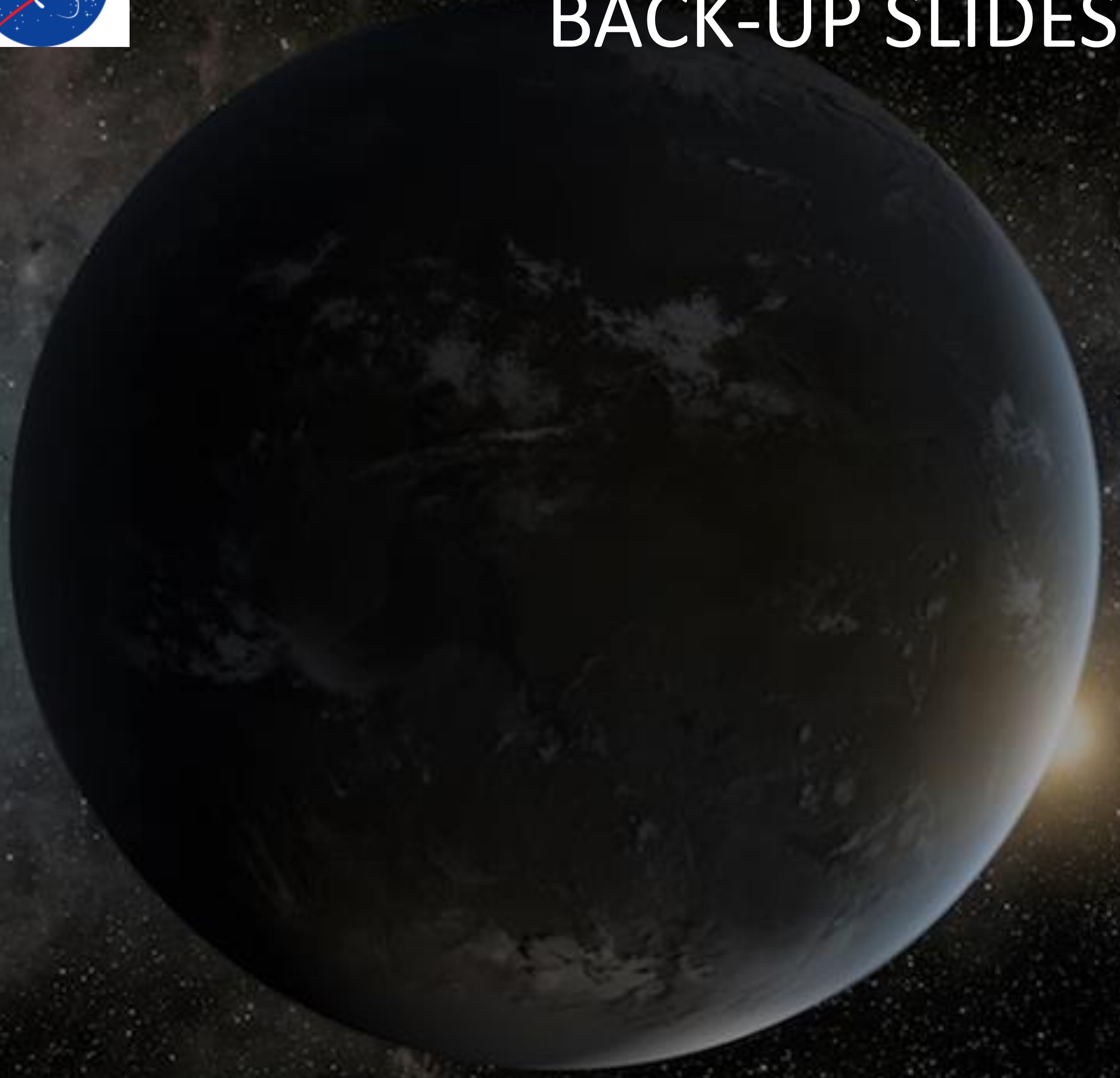
Science and Technology Community Contributions



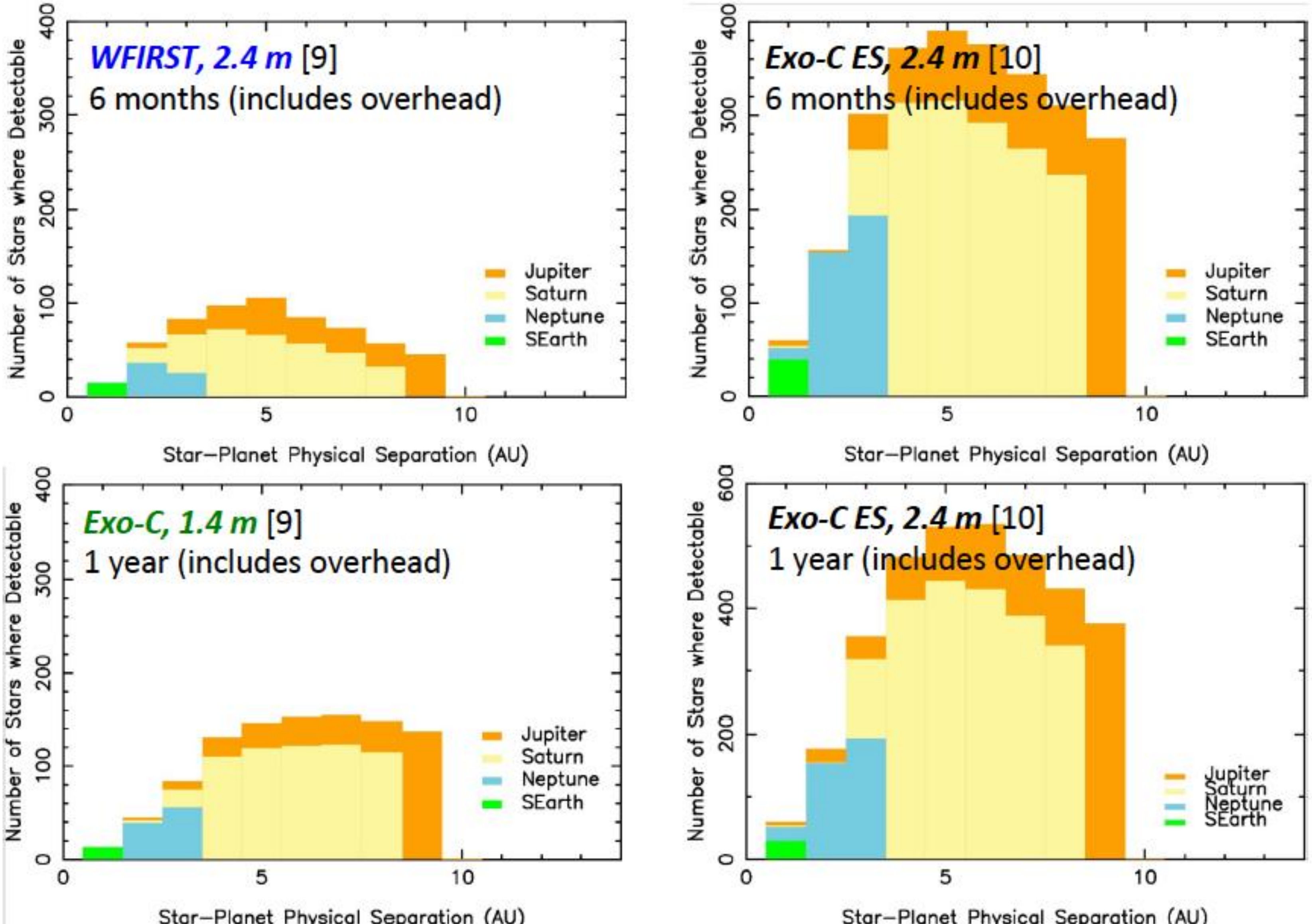
Science and Technology Community Contributions

- Highly interested in organizing/ funneling contributions beyond STDT, and beyond US community
- Collaborations welcomed on all science and technical aspects
- During SPIE meeting:
  - Please contact me (bertrand.mennesson@jpl.nasa.gov)
  - STDT members present: Karl Stapelfeldt, Dimitri Mawet, Olivier Guyon, Jeremy Kasdin (High Contrast Imaging), Paul Scowen (Cosmic Origins, UV science)
  - Program Scientist from NASA HQ: Martin Still (martin.still@nasa.gov)
- Anytime:
  - Please contact chairs Sara Seager (seager@mit.edu) & Scott Gaudi (gaudi.1@osu.edu)
- Next face-to-face STDT meeting: August 2-4 2017 in Pasadena
  - Remote participation at https://ac.arc.nasa.gov/HabEx
- Find News and relevant material at www.jpl.nasa.gov/habex

BACK-UP SLIDES



Exo-C ES increases search yield



K. Stapelfeldt for Exo-C, ES [9,10]