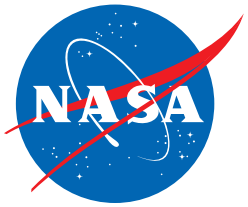


KEPLER SCIENCE CONFERENCE II
NASA AMES RESEARCH CENTER

The Future of NASA's Exoplanet Exploration Program

Gary Blackwood, Exoplanet Exploration Program Manager
Jet Propulsion Laboratory, California Institute of Technology

Douglas Hudgins, Exoplanet Exploration Program Scientist
NASA Headquarters, Astrophysics Division

November 7, 2013

The Exoplanet Exploration Program: Exploring New Worlds

Exploring *How the Universe Works*
Discovering *and Characterizing Exoplanets*
Searching *for Signs of Life in the Galaxy*

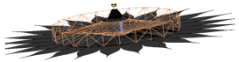
Space Missions and Mission Studies

Kepler

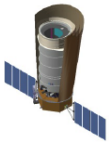
AFTA

Probe-Scale:

External Occulter (Starshade)



Coronagraph

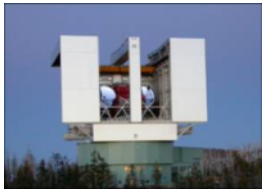


Public Engagement

Supporting Research & Technology

Key Sustaining Research

Keck Single Aperture Imaging and RV



Large Binocular Telescope Interferometer

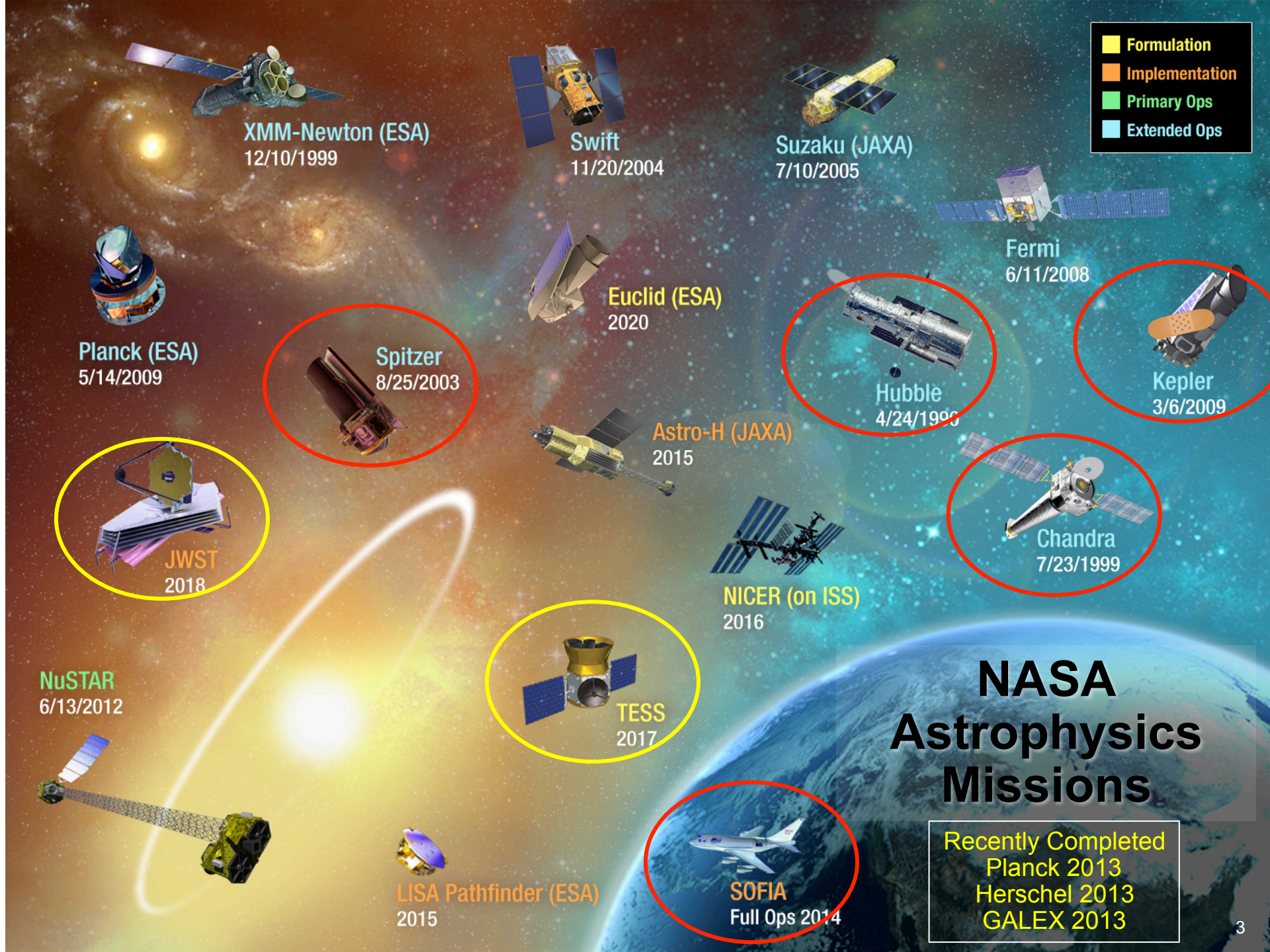
Technology Development

High Contrast Imaging

Deployable Star Shades

Archives, Tools & Professional Education

NASA Exoplanet Science Institute

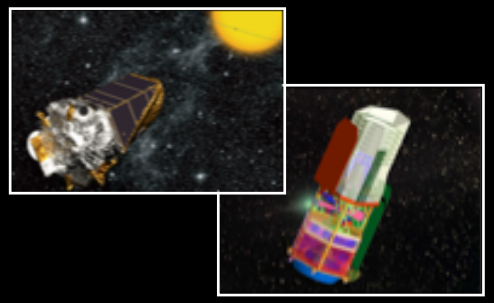

Formulation
Implementation
Primary Ops
Extended Ops
XMM-Newton (ESA)
12/10/1999
Swift
11/20/2004
Suzaku (JAXA)
7/10/2005
Fermi
6/11/2008
Planck (ESA)
5/14/2009
Euclid (ESA)
2020
Spitzer
8/25/2003
Hubble
4/24/1990
Kepler
3/6/2009
Astro-H (JAXA)
2015
JWST
2018
Chandra
7/23/1999
NICER (on ISS)
2016
NuSTAR
6/13/2012
TESS
2017
LISA Pathfinder (ESA)
2015
SOFIA
Full Ops 2014
NASA Astrophysics Missions
Recently Completed
Planck 2013
Herschel 2013
GALEX 2013

The Search for Life in the Universe Requires η_{Earth}

Complete the census

Kepler (warm)

WFIRST μ-lensing (cool)



Find nearby transiting planets

TESS

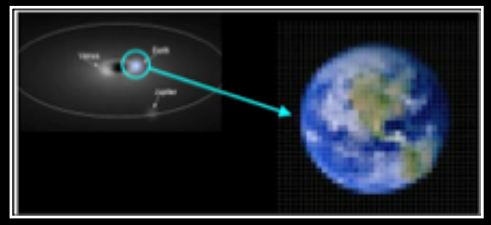
Characterize super-earth/mini-Neptunes

JWST

Imaging and Spectroscopy of planets

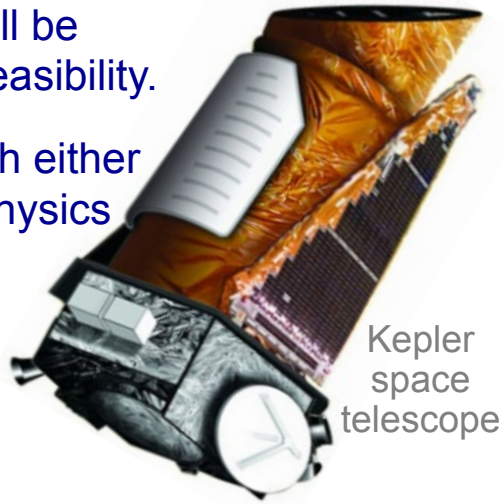
WFIRST-AFTA coronagraph (Jupiters, Neptunes, Super-Earths)

New Worlds Mission (Earth 2.0)



Program Update – Kepler

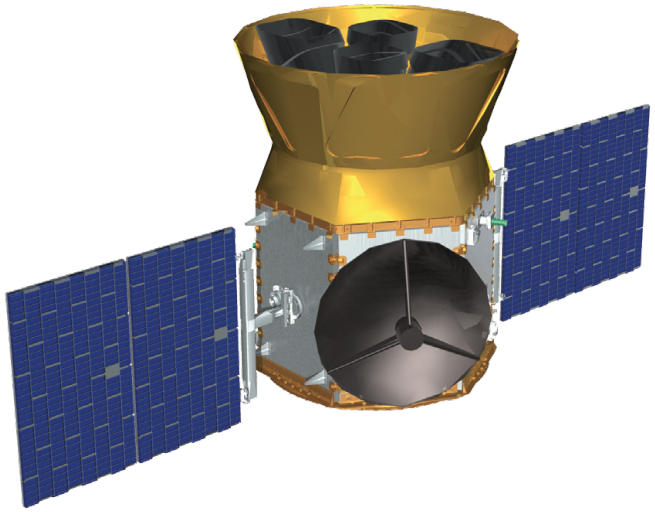
- The flight system is behaving nominally in Point-Rest-State.
- The Call for White Papers resulted in 42 submitted papers covering exoplanets, asteroseismology, open cluster studies, NEOs, and more.
- An interim report on the potential science and operations of a 2-wheel Kepler mission ("K2") was delivered to HQ in late Sept. Final report is due Nov. 20.
- A series of engineering demonstrations of 2-wheel performance on the spacecraft is under way.
- Path Forward
  - November 20 - Due date for final report from Kepler project on the science, operational strategy, and cost of a 2-wheel Kepler Mission. The report will be independently reviewed for both science and cost/technical feasibility.
  - NLT December 6 – HQ/ApD will respond to Kepler project with either approval to continue working on a K2 proposal for the Astrophysics Senior Review proposal or a decision to terminate Kepler Spacecraft operations if K2 concept is determined to be scientifically noncompetitive, technically infeasible, and/or cost prohibitive.



Kepler space telescope

TESS

Transiting Exoplanet Survey Satellite

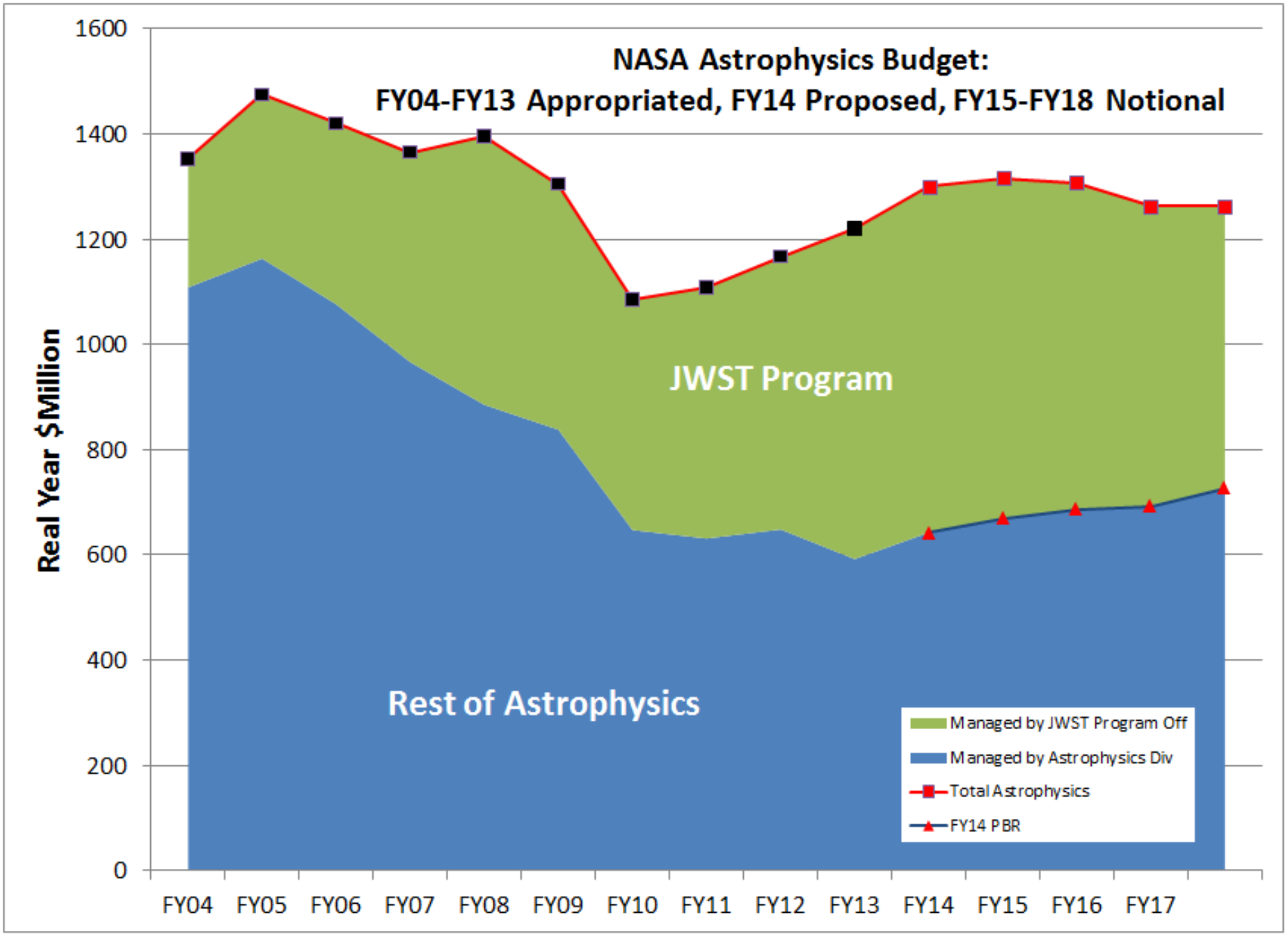


Mission: All-Sky, two-year photometric exoplanet mapping mission.

Instruments: Four WFOV CCD cameras with overlapping FOV of 23x90deg mounted in a common lens hood. Passively-cooled 600-1000nm 4096x4096 pixel FPA

Science goal: Will search for transiting planets around the brightest stars in the sky over a nominal 2-year mission.

- Selection occurred April 5, 2013.
- Mission PI: George Ricker.
- Category 2, Class C mission managed within the GSFC Explorer Program.
- Tentative launch readiness date August 2017.
- High-Earth elliptical orbit (17 x 58.7 Earth radii).
- Development progressing on plan.
  - SRR tentatively planned for February/March 2014.
- No major milestones affected by the shutdown.


NASA Astrophysics Budget:
FY04-FY13 Appropriated, FY14 Proposed, FY15-FY18 Notional
Real Year $Million
1600
1400
1200
1000
800
600
400
200
0
JWST Program
Rest of Astrophysics
Managed by JWST Program Off
Managed by Astrophysics Div
Total Astrophysics
FY14 PBR
FY04
FY05
FY06
FY07
FY08
FY09
FY10
FY11
FY12
FY13
FY14
FY15
FY16
FY17

Astrophysics Budget Strategy

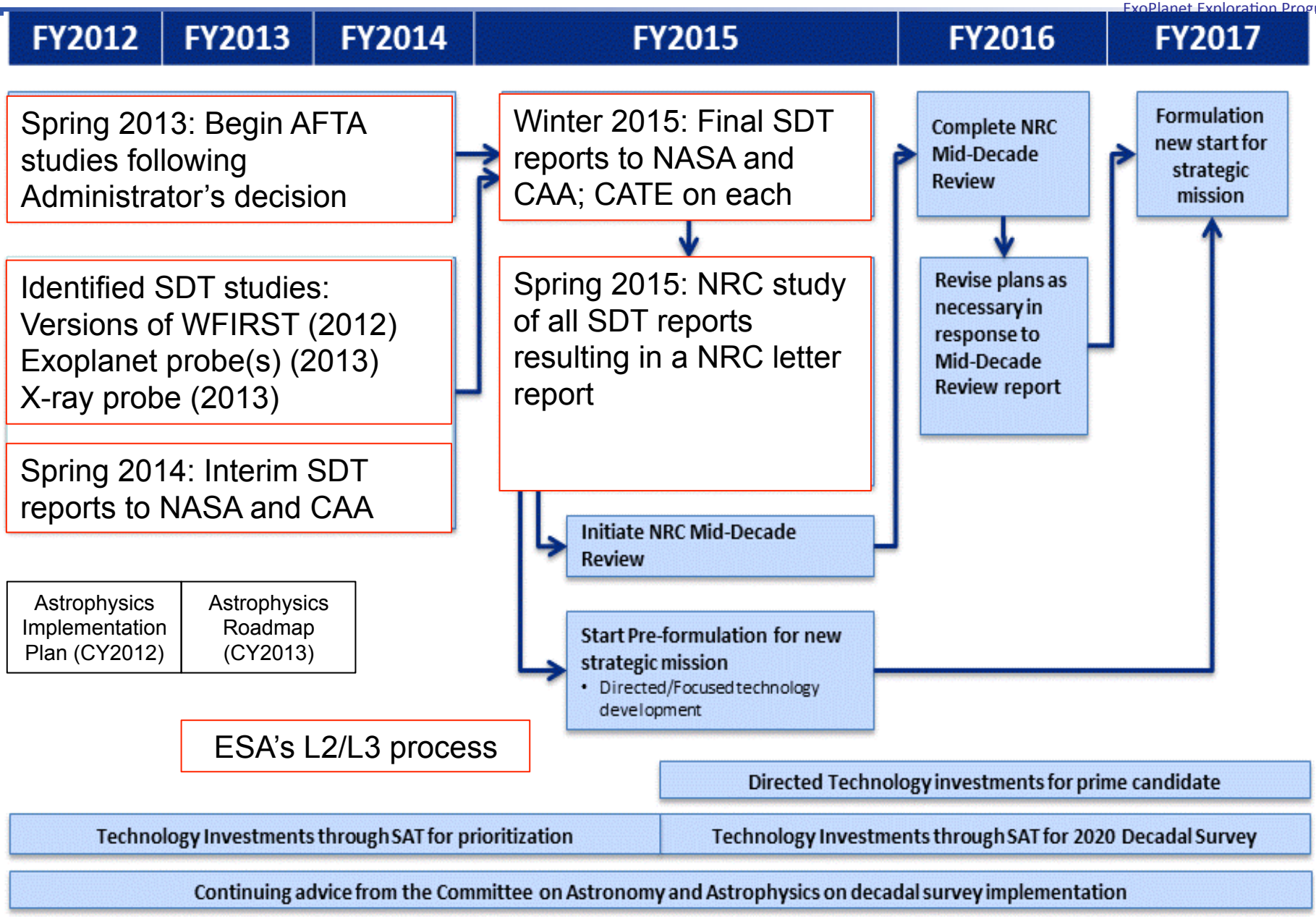
- Use the scientific priorities of the 2010 Decadal Survey to guide strategy and inform choices.
- There is inadequate available budget to implement the 2010 Decadal Survey recommendations as written.
- In the absence of new missions, progress against decadal priorities is maintained through the core program: research and analysis (R&A), supporting and enabling technology development, operation of existing missions and their GO programs, the suborbital programs, and Explorer opportunities.
- A goal is to be prepared to start a new strategic Astrophysics mission to follow JWST as soon as funding becomes available, while continuing to advance Decadal Survey science during the interim.

Astrophysics Budget Strategy

- In order to be prepared for a new mission, a near term program of science definition teams, mission concept studies and technology development is being undertaken with the goal of informing a mid-decade decision on whether to begin formulation.
- Moderate missions ("probes") are being studied, in addition to a large mission (WFIRST), to be prepared for a mid-decade decision.
- Mission concepts studied derive from the science objectives of the prioritized missions and recommendations in the 2010 Decadal Survey.
  - AFTA (WFIRST using existing 2.4 m telescopes)
  - WFIRST (2 design reference missions already studied, including WFIRST-probe)
  - X-ray Astrophysics Probe (moderate mission addressing IXO science)
  - Exoplanet Probes (moderate missions using internal or external occulters)

Preparing the next strategic mission

ExoPlanet Exploration Program



Exoplanet Missions

JWST

AFTA

TESS

Kepler

New Worlds Telescope

Spitzer

Hubble

Ground-based Observatories

2001 Decadal Survey

2010 Decadal Survey

Exoplanet Missions

JWST

AFTA

TESS

Kepler

New Worlds Telescope

Spitzer

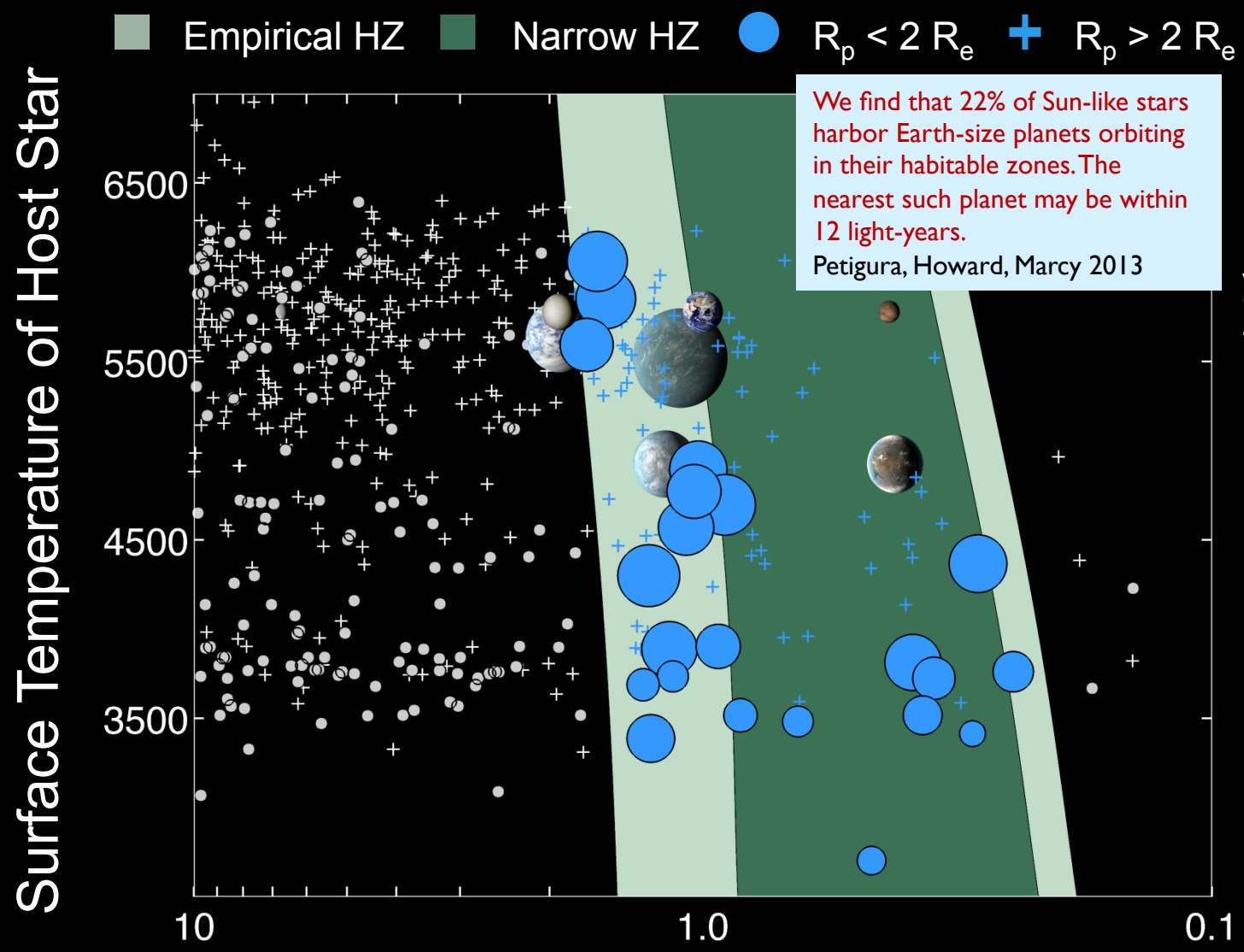
Hubble

Ground-based Observatories

2001 Decadal Survey

2010 Decadal Survey

Habitable Zone Candidates



Based on 3 years of data

104 habitable zone candidates

24 smaller than 2 Re.

Courtesy: N Batalha

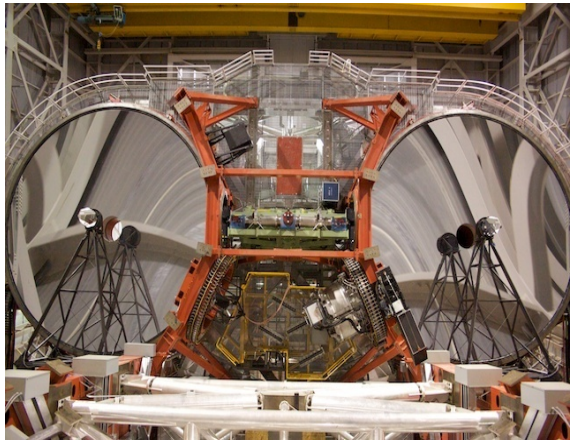
Large Binocular Telescope Interferometer (LBTI)
University of Arizona

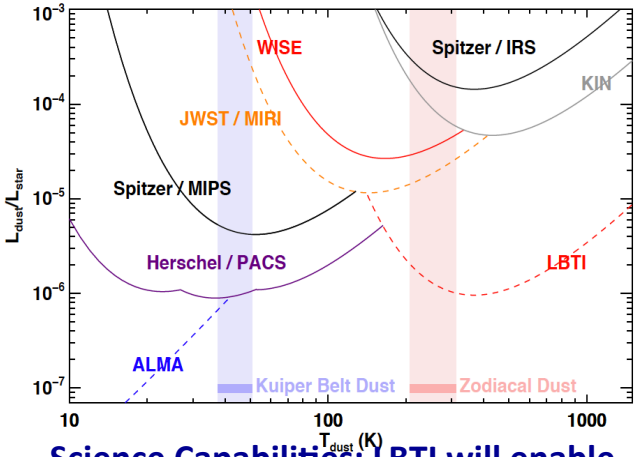
- **Instrument Status:**
  - All subsystems finalized and demonstrated on-sky.
  - Achieved open loop nulls on the sky.

- **Commissioning Status & Plans:**
  - Spring 2013 observing runs postponed due to failure of LBT adaptive secondary. Spare now ready.
  - Finalize commissioning during Fall 2013 (3 runs, 6 nights):
    - On-sky nulling with closed phase loop.
    - Optimized & automated data sequences.
    - First science demonstration data.
    - ORR planned for Jan 2014.

- **NExScI Archive:**
  - **Level 0 data archive v 1.0: operational since Jul 2012.**
  - **Development plan:**
    - **L1 v 1.0: Dec 2013.**
    - **L2 v 1.0: Apr 2014.**
    - **L0 v 2.0: Jun 2014.**

- **Science Team: very active with data pipeline dev, definition of exozodi survey and target list, dev of observable modelling tools (leak ➔ zodis).**





Science Capabilities: LBTI will enable characterization of exo-solar planetary systems

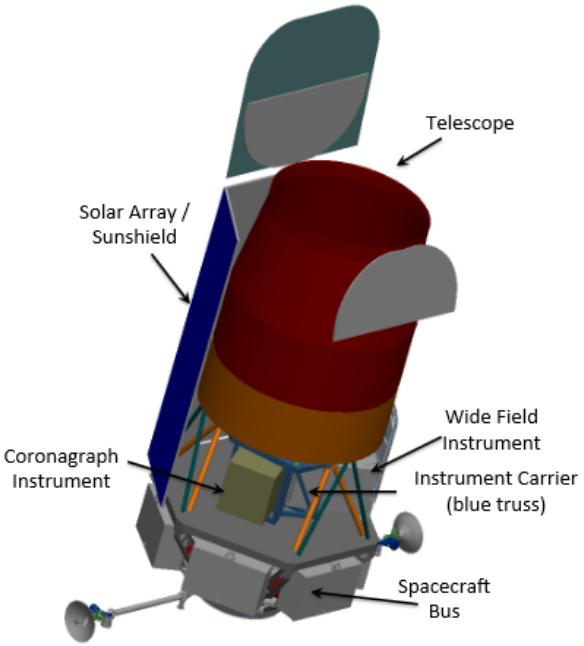
- **Survey 50 nearby stars for exozodiacal dust, at levels of 3-6 times(1σ) the dust in our own planetary system.**

NASA use of 2.4 m Telescope Assets for WFIRST

- Since Fall 2012, NASA has been studying potential uses of the 2.4 m telescope assets: (1) focused Astrophysics study (AFTA) and (2) an assessment of possible applications to other NASA objectives in science, technology, and human space flight.
- The focused astrophysics study showed that use of these telescope assets satisfy all mission requirements for WFIRST. For approximately the same costs, the telescope assets would enable a WFIRST mission with significantly improved science capabilities relative to the design described in the Astrophysics Decadal Survey.
  - AFTA's 2.4 m aperture + Wide Field Imager meets (and exceeds) WFIRST requirements:
    - ✓ Higher spatial resolution enhances science capability.
    - ✓ Larger collecting area enables more science in fixed time.
  - Use of the telescope assets would also enable the addition of an exoplanet imaging instrument to WFIRST that would enable imaging and characterization of planets around nearby stars up to a decade earlier than contemplated in the Decadal Survey; AFTA's 2.4 m aperture enables richer scientific return at much lower cost than a dedicated smaller coronagraphic telescope mission.
- The Administrator directed the Science Mission Directorate to continue pre-formulation activities for a mission using the 2.4 m telescope assets to prepare for a later decision as to whether a WFIRST mission would be undertaken with these optics.
- No decision on a future wide field infrared survey mission is expected until early 2016.
- There was no decision to proceed with design studies for any other concepts at this time.

AFTA-WFIRST

- 2.4m aperture on-axis obscured telescope, 270K
- 28.5 degree inclination geosynchronous orbit, Atlas V 541 launch vehicle
- Two-channel widefield instrument with IFU channel 0.6 to 2.0 um for Dark Energy, NIR Surveys, and Exoplanet Microlensing
- FPA: 6x3 4kx4k HgCdTe detectors, 0.76 to 2.0 um
- Coronagraph instrument for Exoplanet Direct Imaging and Characterization
- Mission life 6 years with coronagraph
- Dedicated 18m Ka and S-band antenna in White Sands, NM. Ka-band downlink of 150 Mbps.



WFIRST final report May 23, 2013
http://wfirst.gsfc.nasa.gov/

AFTA Study: Near-Term Activities

- SDT is reconvened with new charter and additional members.
  - Co-Chairs are David Spergel (Princeton) and Neil Gehrels (GSFC).
- NASA requesting a NRC study in late 2013/early 2014 to assess AFTA design reference mission against Decadal Survey recommendations for WFIRST and New Worlds technology.
- APD down-selects to 2 coronagraph technologies for further development – decision by December 2013.
  - SDT delivered coronagraph science drivers analysis in early October 2013.
  - ExEP Program Office and AFTA Study Office coronagraph technology downselect recommendations due to APD December 2013.
- No decision on a mission will be made before early 2016.
  - Interim report by SDT and project due by April 2014.
  - Final report by SDT and project due by January 31, 2015.
  - CATE due February 27, 2015.
- NASA will request a study by the NRC in early CY 2016 of all SDT reports in context of Decadal Survey recommendations.

AFTA-WFIRST SDT Membership 2013-2015

Co-Chairs

David Spergel, Princeton
Neil Gehrels, GSFC

Members

Charles Baltay, Yale
David Bennett, Notre Dame
James Breckinridge, Caltech
Megan Donahue, Michigan State
Alan Dressler, Carnegie
Chris Hirata, Caltech
Scott Gaudi, Ohio State
Tom Greene, ARC
Olivier Guyon, Steward Observatory
Jason Kalirai, STScI
Jeremy Kasdin, Princeton
Bruce Macintosh, LLNL
Warren Moos, JHU
Saul Perlmutter, UC Berkeley
Marc Postman, STScI
Bernard Rauscher, GSFC
Jason Rhodes, JPL
David Weinberg, Ohio State
Yun Wang, Oklahoma

Ex Officio Members

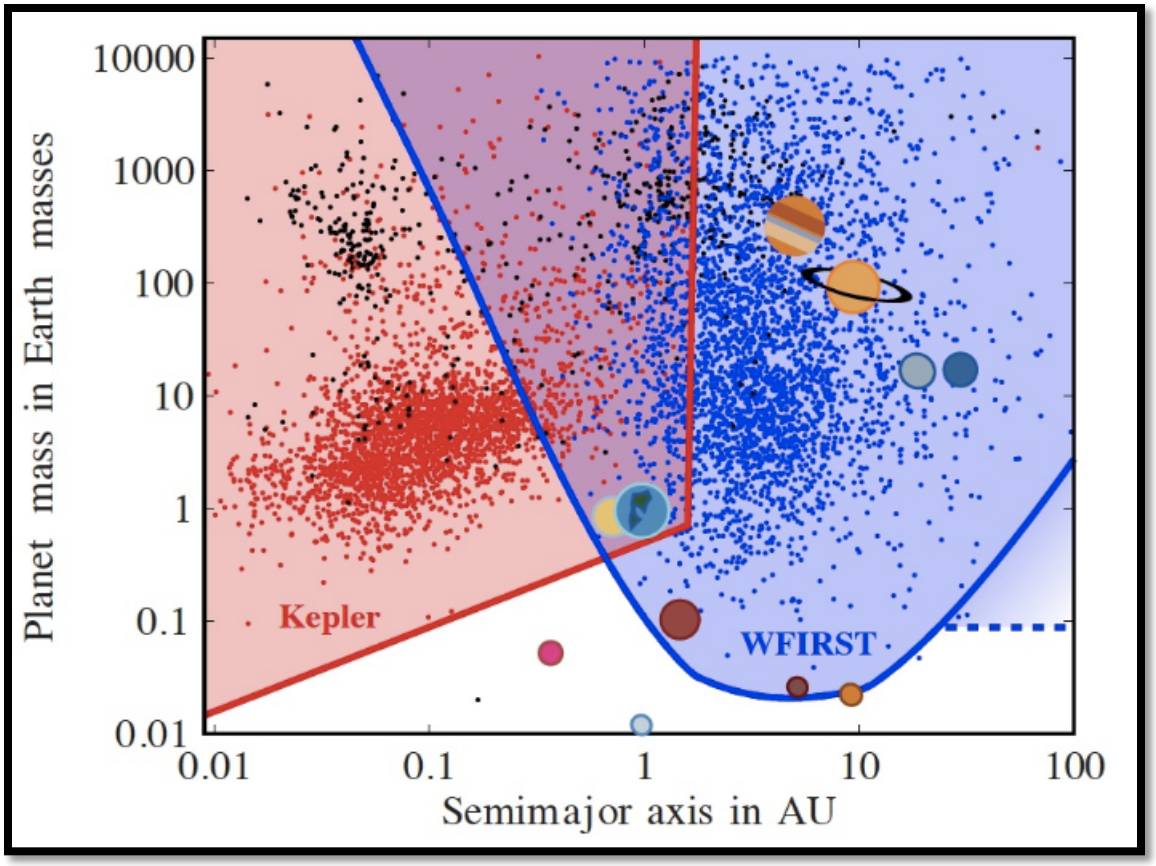
Dominic Benford, NASA HQ (starting Sept 1, 2013)
Joan Centrella, NASA HQ (until Sept 1, 2013)
Yannick Mellier, IAP, France (ESA)
Wes Traub, JPL
Toru Yamada, Tohoku U., Japan (JAXA)

Consultants

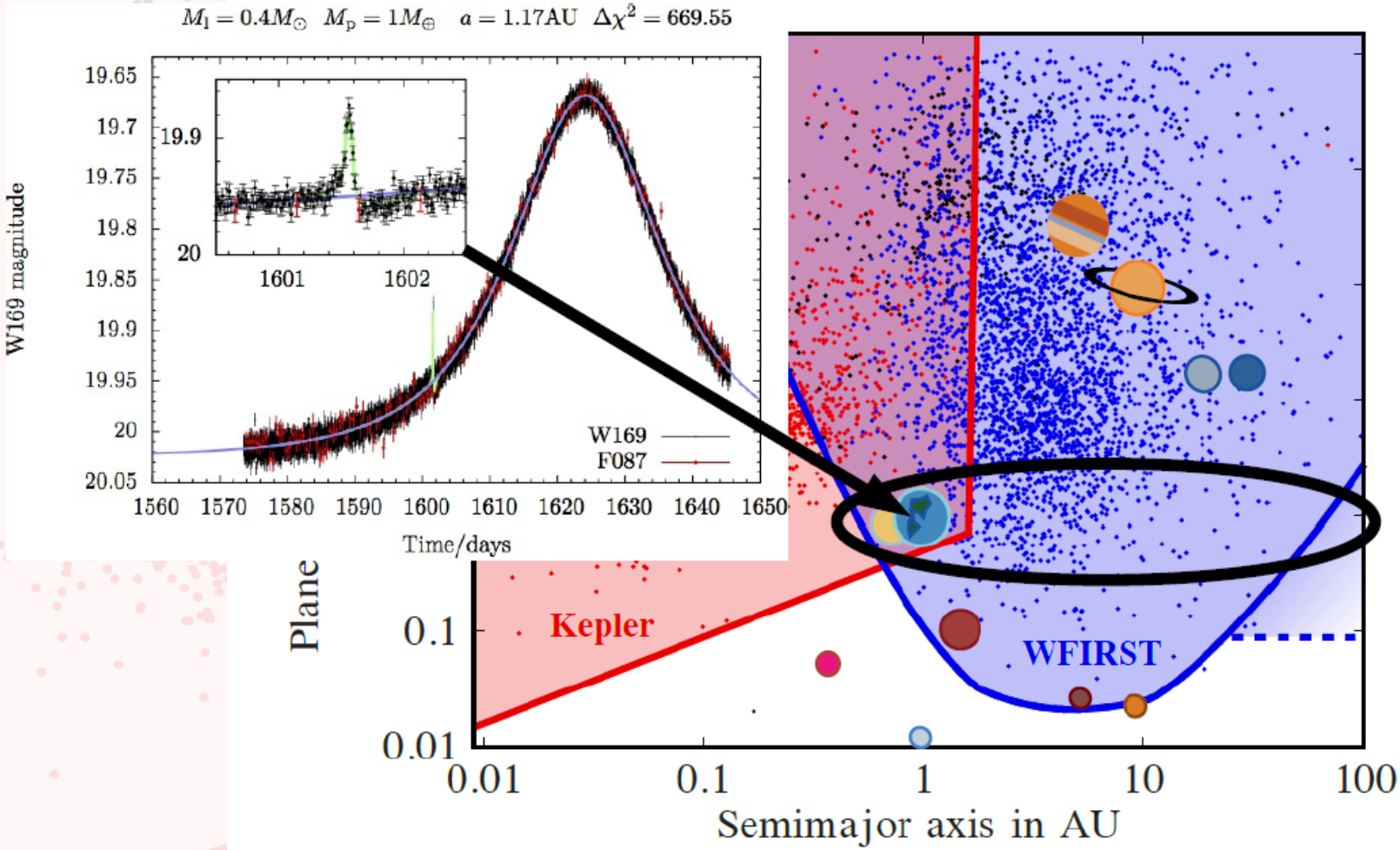
Alina Kiessling, JPL
Matthew Penny, Ohio State U.
Dmitry Savransky, LLNL
Daniel Stern, JPL

Exoplanet detection by AFTA Microlensing

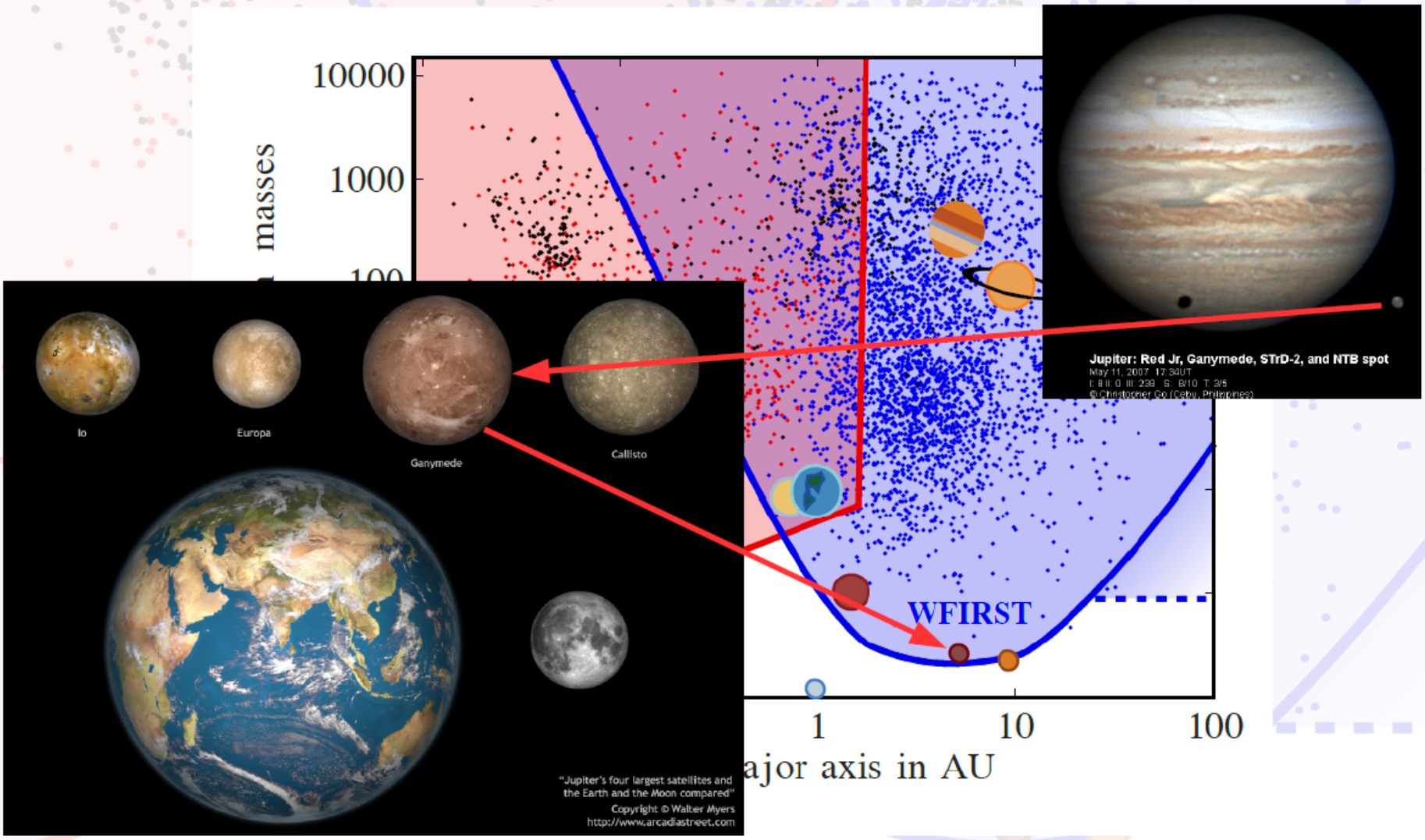
- Search field towards galactic bulge
- Sensitive to ~2800 bound planets
- Sensitive to hundreds of unbound, free-floater, (rogue) planets to ~Mars mass
- Helps complete the census begun by Kepler



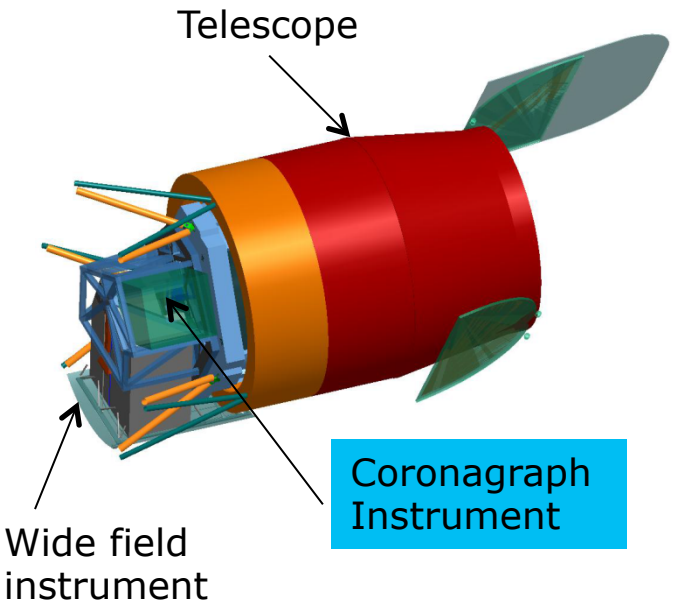
Earth-mass planets from 1AU out



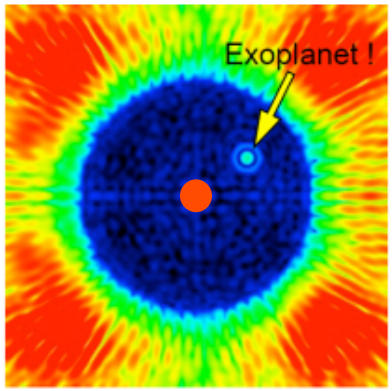
Really low-mass planets



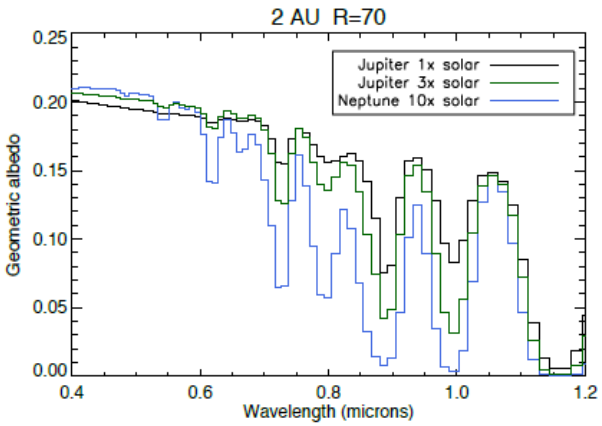
AFTA Coronagraph Instrument



Coronagraph Instrument



Exo-planet Direct imaging



Exo-planet Spectroscopy

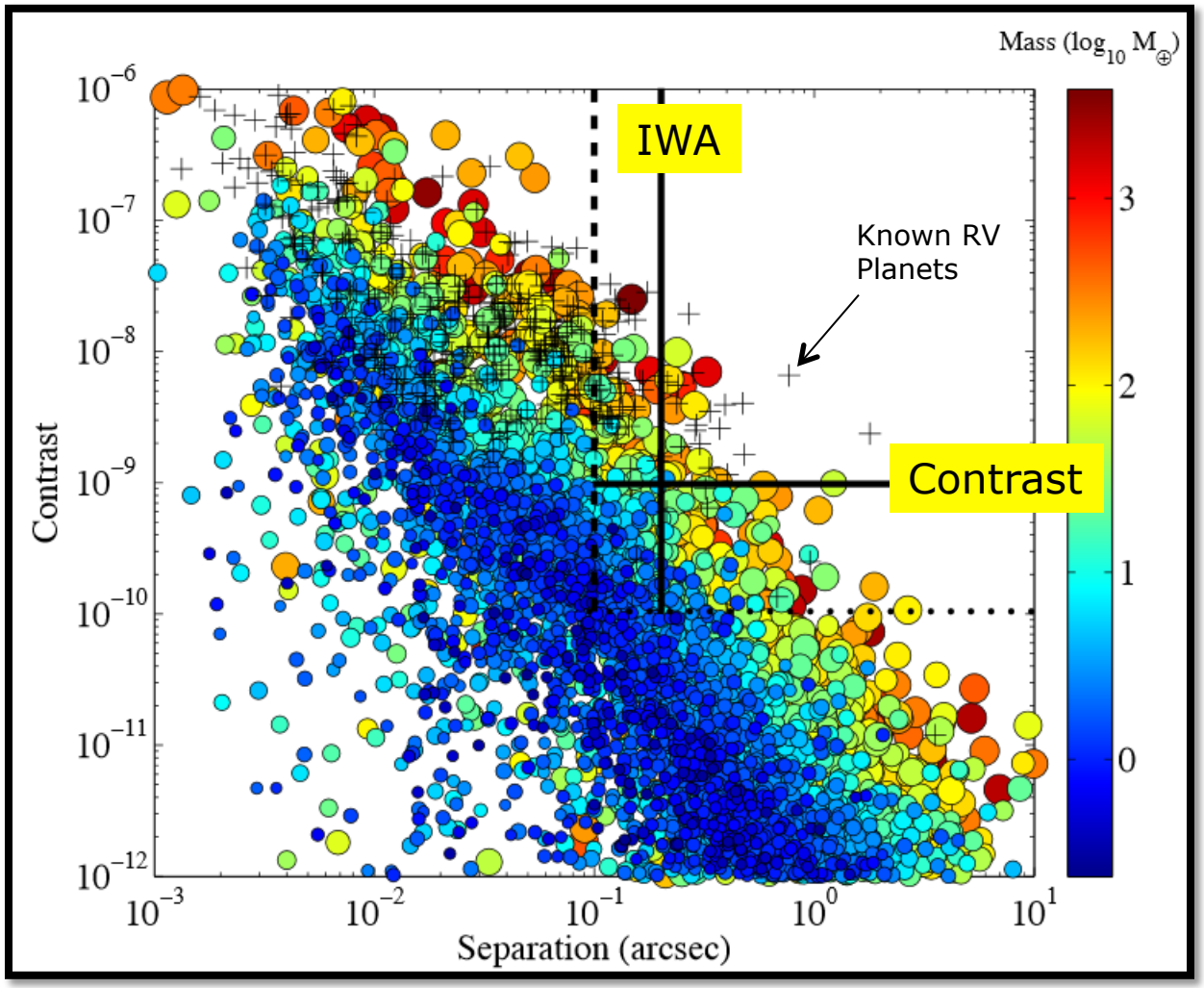
Bandpass	400-1000 nm	Measured sequentially in five 18% bands
Inner Working Angle	100 mas	at 400 nm, 3 λ/D driven by challenging pupil
	250 mas	at 1 um
Outer Working Angle	1 arcsec	at 400 nm, limited by 64x64 DM
	2.5 arcsec	at 1 um
Detection Limit	Contrast $=10^{-9}$	Cold Jupiters, not exo-earths. Deeper contrast looks unlikely due to pupil shape and extrememe stability requirements.
Spectral Resolution	70	With IFS, ~70 across the spectrum.
IFS Spatial Sampling	17 mas	This is Nyquist for λ400 nm.

AFTA Coronagraph Instrument will:

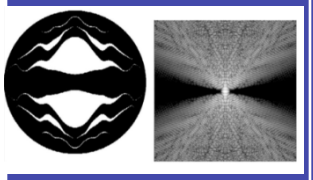
- Characterize the spectra of over a dozen radial velocity planets.
- Discover and characterize up to a dozen more ice and gas giants.
- Provide crucial information on the physics of planetary atmospheres and clues to planet formation.
- Respond to decadal survey to mature coronagraph technologies, leading to first images of a nearby Earth.

Sensitivity of AFTA Coronagraph for Imaging Exoplanets

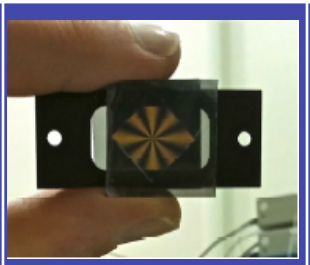
- Survey of ~200 nearest stars within 30 pc
- Model assumes 4 planets per star with size distribution consistent with Kepler results, extrapolated to larger semimajor axis and lower mass
- Crosses: known RV planets



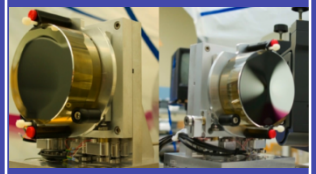
Technical Approach: Mask Technologies for High-Contrast Imaging



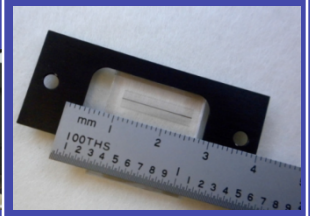
Shaped Pupil Mask Pupil Masking (Vanderbei & Kasdin, Princeton Univ.)



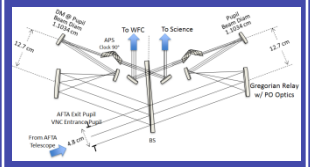
Vector Vortex Mask Image Plane (Serabyn, JPL)



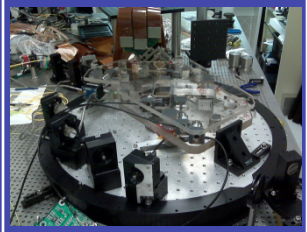
Phase Induced Amplitude Apodization (PIAA) Pupil Re-Mapping (Guyon, Univ. Arizona)



Hybrid / Band-Limited Lyot Mask Image Plane Amplitude & Phase (Trauger, JPL)



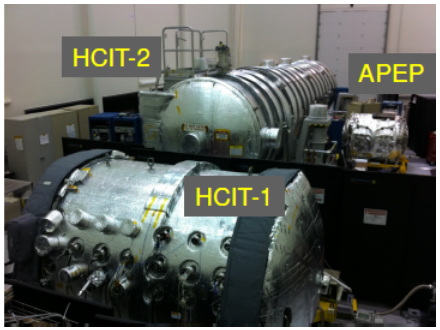
Visible Nuller Coronagraph: Phase-Occulting (Lyon, GSFC)



Visible Nuller Coronagraph: DaVinci (Shao, JPL)

Downselect: 1/6/2014

Primary approach	Back-up approach



TRL-6 @ PDR (10/2018)

TRL-5 @ start of Phase A (10/2016)

AFTA Coronagraph Technology Gaps

- High Relative Gap and Urgency
  - Architecture design (CG-1a)
  - Key component fabrication (CG-1b)
  - Contrast demonstrations (CG-6)
  - Low-order wavefront demonstrations (CG-2)

Importance:	H	Showstopper
	M	Major regret
	L	Not H or M
Urgency	H	Retire by 2015
	M	Retire by start Phase A (fy17)
	L	Retire by start of Phase B (fy19)

- Medium Relative Gap and Urgency
  - Flight readiness of DM and Fast Steering Mirror (CG-7)
  - Two-DM performance demonstration (CG-3)
  - End-to-end dynamic modeling (CG-5)

- Less Urgent Gaps
  - Post-processing of data (CG-4)
  - IFS pixel cross talk (CG-8)
  - Flight readiness of IFS detector (CG-9)

Exoplanet Probe Studies

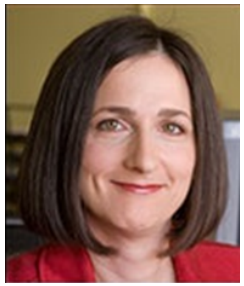
- 2013 Astrophysics Division Implementation Plan calls for two probe-scale exoplanet missions,
  - Consideration by 2020 Decadal Survey
  - Guide technology investment for remainder of decade
  - Candidate for 2017 new start if AFTA cannot be started this decade
- Two Science and Technology Definition Teams (STDTs) selected
  - Exo-C: Probe coronagraph
  - Exo-S: Probe starshade (external occulter)
- Success criteria include: compelling science, viable technology, $1B life cycle cost ($FY15)
- STDT meetings (held jointly)
  - July 1-2, GSFC
  - September 11-12, MIT
  - November 14-15, JPL
- Mission concept reports and CATE due 1/31/15 and 2/28/15, respectively

STDT Membership

Last	First	Organization
* Stapelfeldt	Karl	NASA Goddard Space Flight Center
Belikov	Rus	NASA Ames Research Center
Bryden	Geoff	Jet Propulsion Laboratory
Cahoy	Kerri	Massachusetts Inst. of Technology
Chakrabarti	Supriya	Univ. of Massachusetts, Lowell
Marley	Mark	NASA Ames Research Center
McElwain	Michael	NASA Goddard Space Flight Center
Meadows	Vikki	Univ. of Washington
Serabyn	Gene	Jet Propulsion Laboratory
Trauger	John	Jet Propulsion Laboratory
* Chair		

Karl Stapelfeldt
GSFC
Chairperson

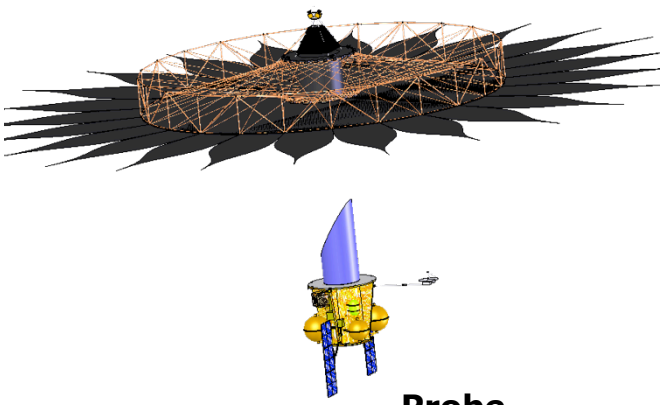
Last	First	Organization
* Seager	Sara	Massachusetts Inst. of Technology
Cash	Webster	Univ. of Colorado
Domagal-Goldman	Shawn	NASA Goddard Space Flight Center
Kasdin	N. Jeremy	Princeton Univ.
Kuchner	Marc	NASA Goddard Space Flight Center
Roberge	Aki	NASA Goddard Space Flight Center
Shaklan	Stuart	Jet Propulsion Laboratory
Sparks	William	Space Telescope Science Institute
Thomson	Mark	Jet Propulsion Laboratory
Turnbull	Margaret	Global Science Institute
* Chair		



Sara Seager
MIT
Chairperson

Exoplanet Probe Study Office

- One Study Office, two coordinated design teams: fully staffed
  - Study Office Manager: Keith Warfield
  - Starshade Design Team Lead: Doug Lisman
  - Coronagraph Design Team Lead: Michael Brenner
  - Each has a full time team Leader and about 10 part time discipline experts
- Completed initial Team X studies of both configurations
  - Initial concepts for both probes designed and costed by JPL's Team X
  - Team X design and cost models (and a Team X engineer) have been delivered to both design teams for quick mission-level trade studies
- Design trades are underway on both Design Teams
  - Error budgets, Mission-level trades
  - An initial telescope optical design established for the coronagraph STDT
  - Mechanical configuration work is underway on both teams
- An initial CATE meeting was held Sept. 3 with Aerospace Corp.
  - Aerospace presented and answered questions on the CATE process
- Preliminary prioritized technology needs delivered by both STDTs



Probe Starshade

Probe Coronagraph

Starshade Technology Gaps

- High Relative Gap and Urgency
  - System engineering, I&T Verification and Validation (SG-1)
  - Control of scattered light from petal edges (SG-5)

- Medium Relative Gap and High Urgency
  - Starshade deployment demonstration (SG-3)

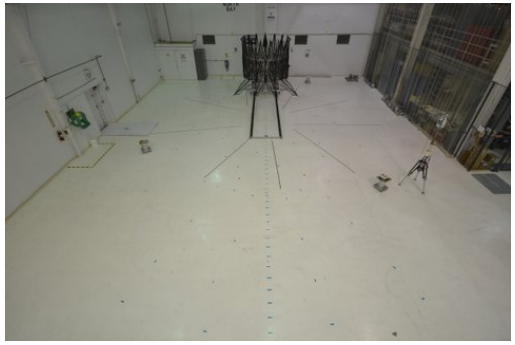
- Medium Relative Gap and Medium Urgency
  - Validation of starshade models (SG-4)
  - Thermal and dynamic stability under flight conditions (SG-9)

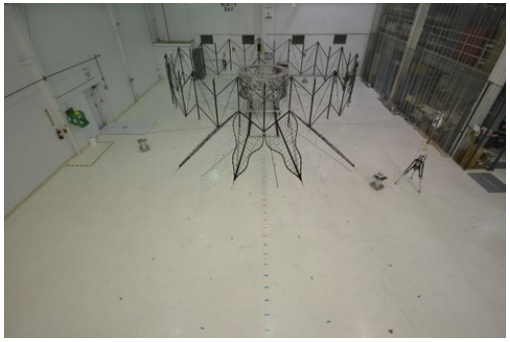
- Technologies with Lower Relative Gap
  - Formation sensing for a dedicated telescope (SG-7)
  - Thruster technology for slew and science observations (SG-10)
  - Guidance, Navigation and Control for retargeting (SG-6)
  - Petal manufacturing (SG-2)

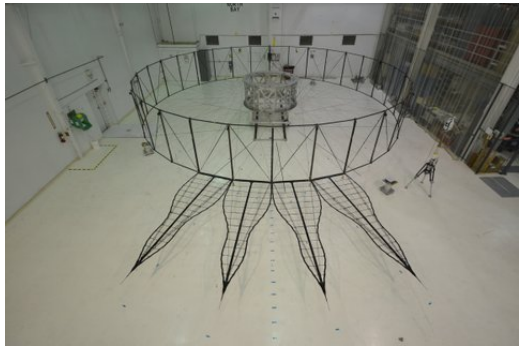
Importance:	H	Showstopper
	M	Major regret
	L	Not H or M
Urgency	H	Retire by 2015
	M	Retire by start Phase A (fy17)
	L	Retire by start of Phase B (fy19)

Starshade Technology

- Starshade technology TDEM led by PI Jeremy Kasdin: a first look test at deployment repeatability from a partially stowed position easily met 500 um deployment requirement
  - Four JPL-built starshade petals were integrated with a NGAS-Astro built inner disk structure and central hub at the Astro facility in Goleta, CA.
  - Integrated system successfully deployed multiple times with metrology of the deployed shape after each deployment.





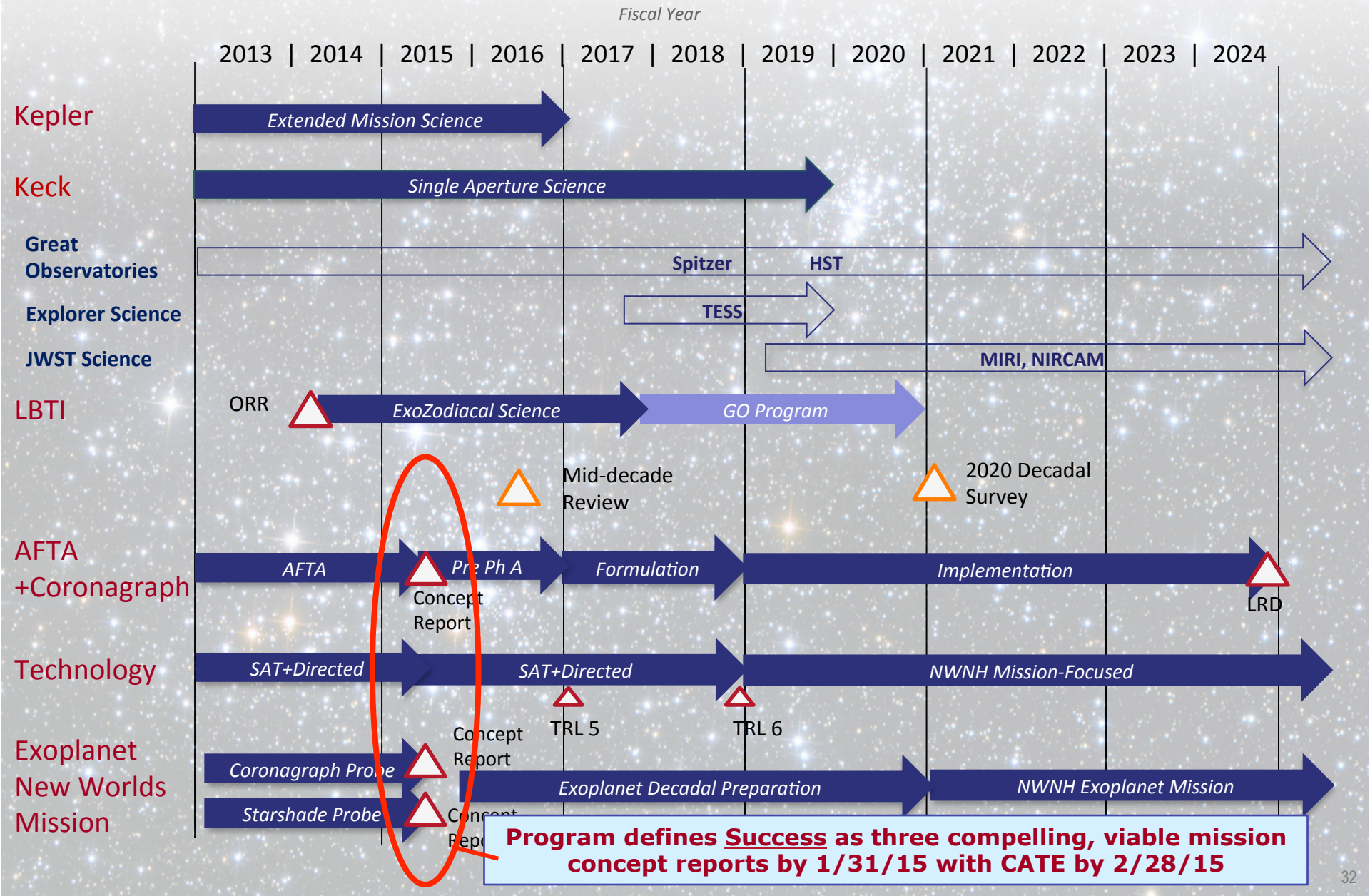


Starshade Deployment

Exoplanet Exploration: A Decade Horizon

NASA-sponsored efforts

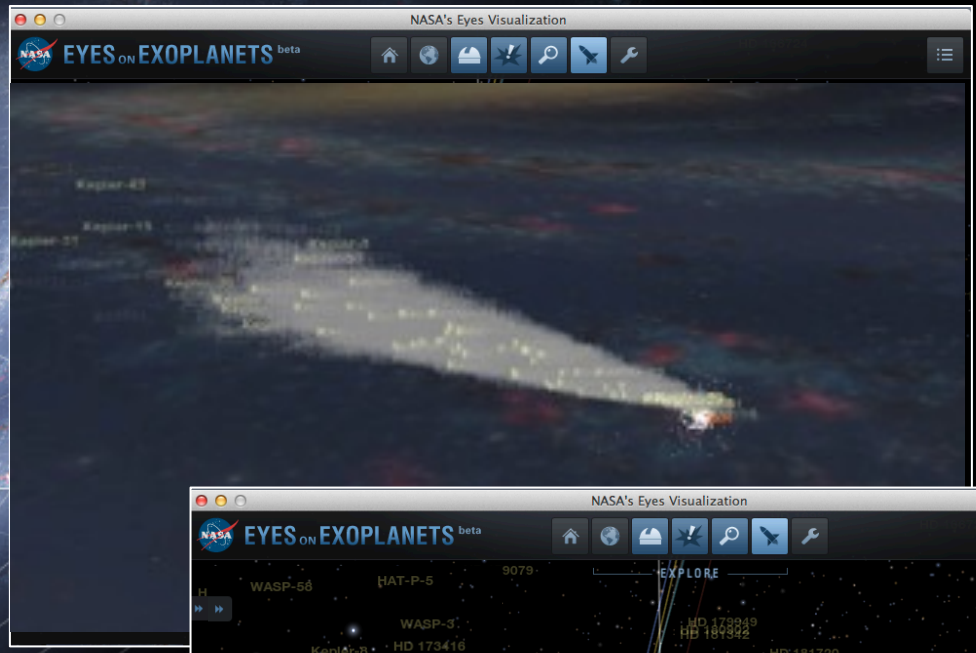
ExoPlanet Exploration Program

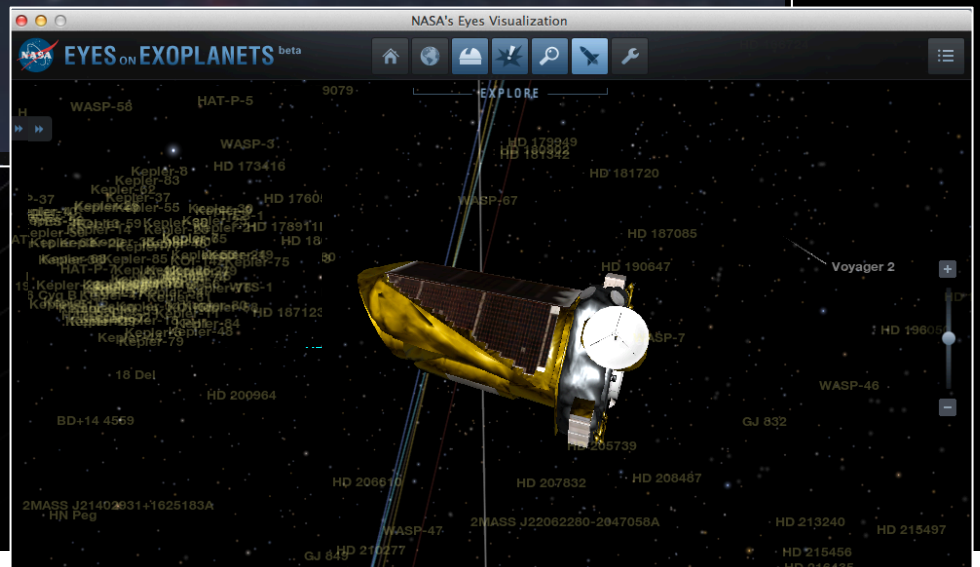


‘Eyes on Exoplanets’
Kepler Candidates–Available November 2013

EYES ON EXOPLANETS

http://exep.jpl.nasa.gov
Go to ‘planetquest’





- All 3,600 candidate systems shown in FOV
- Each confirmed planet can be visited
- Continuously updated as planets are confirmed

Very Near Future of Exoplanet Exploration Program

- Probe Studies: STDT meeting at JPL Nov 13-15, leading to interim report to HQs and CAA in March 2014
- AFTA: Decision on primary and backup architectures for coronagraph
- January AAS: evening sessions on AFTA, ExEP
- Microlensing 14: Santa Barbara, Jan 20-24
- LBTI: ORR January 2014
- ROSES SAT TDEM 2013: Proposals due March 21
- June AAS: Conference on exoplanet science with AFTA

Summary

- LBTI will measure exozodiacal dust levels in 50 nearby solar systems
- AFTA will deliver exoplanet detections (microlensing) that complement the Kepler census, and exoplanet direct imaging of ice and gas giants
- Mask technology down select underway
- Technology priorities established, guide near term investments
- Goal: 3 compelling, viable missions ready for potential FY17 new start
- Look for AFTA and Probe Study presence at upcoming AAS meetings
- We invite science community involvement in AFTA, Probe Studies and in guiding the direction of the Exoplanet Exploration Program

Exoplanet Missions

Acknowledgements

- This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

- Work also carried out by
  - NASA Goddard Space Flight Center
  - NASA Ames Research Center
  - University of Arizona under a contract with the Jet Propulsion Laboratory
  - Princeton University, University of Arizona and Northrop Grumman Aerospace Systems under contracts with the National Aeronautics and Space Administration.

- The authors acknowledge contributions by Wes Traub, Peter Lawson, Nick Siegler, Michael Greene, Keith Warfield

BACKUP

Astrophysics Missions timeline

Last updated: April 15, 2013