

National Aeronautics and  
Space Administration



# EXPLORE SCIENCE

## **NASA Astrophysics Update**

SSB Committee on Astronomy and Astrophysics  
Telecon Meeting  
November 26, 2019

### **Paul Hertz**

Director, Astrophysics Division  
Science Mission Directorate  
@PHertzNASA 



# NASA'S CHANDRA X-RAY OBSERVATORY

## SCIENCE BY THE NUMBERS SO FAR

### 0.002 seconds

for a neutron star (47 Tuc W) observed with Chandra to spin around once

### 2.3 days

before Chandra started observing a neutron star merger and gravitational wave source after it was discovered

**3** number of remnants observed with Chandra of thermonuclear supernova explosions seen with the unaided eye

### 300 million

Sun masses are swallowed by a black hole to create enormous cavities in hot gas in a galaxy cluster

### 100

factor of energy that particles obtain over the Large Hadron Collider after being accelerated in a supernova remnant

### 32 million miles

expansion speed per hour of blast wave in supernova remnant G1.9+0.3

### 20,000 light years

distance between the black hole in the "Death Star" galaxy and the target galaxy it is striking

### 10 years

for a supermassive black hole took to dine on the remains of a star it tore apart

### 3 quintillion

quantity of Sun masses in the El Gordo galaxy cluster

### 1 quadrillion

how many times stronger the magnetic field of a magnetar is than the magnetic field of Earth

### 4 inches

height of atmosphere of the neutron star in Cassiopeia A

**0.01** number of electrons per cubic centimeter in hot gas in a galaxy cluster

### 100 million quadrillion

hydrogen bombs are needed to produce the energy a quasar releases every second

**99.9** fraction of the speed of light that particles reach in a jet formed by a neutron star

### 110 years

age of the youngest supernova remnant, timed from Earth, in the Milky Way galaxy

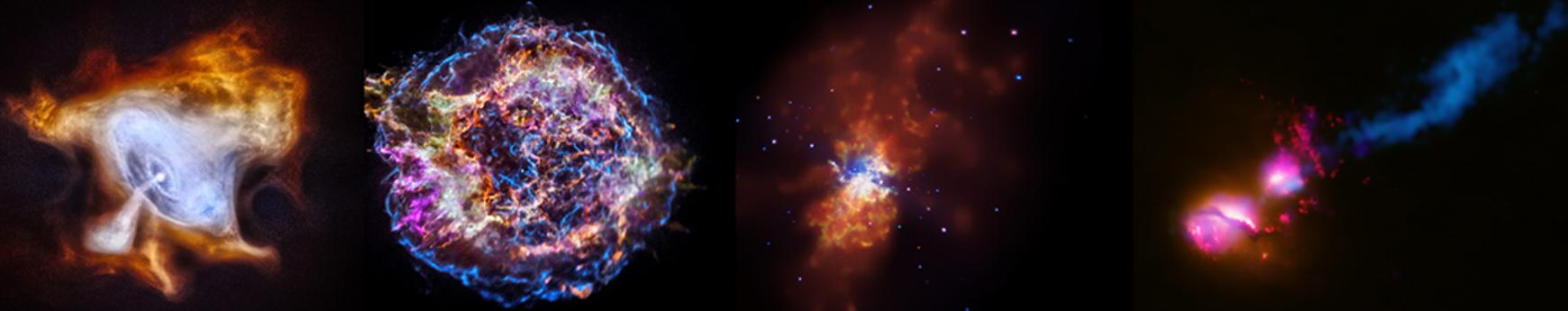
### 1 billion tons

weight of a sugar cube-sized piece of neutron star

### 1 million

number of Earth masses worth of oxygen ejected into space in the Cassiopeia A supernova remnant

**57** number of octaves below middle C of a note produced by a supermassive black hole observed by Chandra.



# Neil Gehrels Swift Observatory Celebrated its 15<sup>th</sup> Launch Anniversary on Nov 20



Launched on a Delta II rocket from Cape Canaveral the Swift Mission has been revolutionary in allowing scientists to determine that gamma ray bursts arise from the birth-cries of stellar-mass black holes. Swift continues using its unique capabilities to increase our understanding of the entire transient universe.

## Key Achievements and Discoveries:

- 1330 Gamma Ray Bursts and counting
- Over 4,489 refereed publications since launch, spanning scales from the Solar System to the high-redshift Universe.
  - May 2005 – detected gamma ray burst 050509B, marking the first time that the accurate location of a short-duration gamma ray burst had been identified and the first detection of its X-ray afterglow.
  - January 2008 – identified the beginning of supernova in NGC 2770, the earliest stage yet seen in a supernova.
  - March 2011 – detected X-ray flares thought to be caused by a black hole devouring a star.
  - June 2013 – made observations of short-duration gamma ray burst 130603B which, when combined with Hubble measurements, confirmed the presence of a new kind of stellar blast called a kilonova, thought to arise from a neutron star merger.
  - August 2017 – made the first UV measurements of the electromagnetic counterpart to a gravitational wave source.

*This mosaic of the Neil Gehrels Swift Observatory is created from images of astronomical objects captured by the satellite's Ultraviolet/Optical Telescope which captured its millionth image on May 13, 2018. Each tile is 52 x 39 pixels, and at maximum resolution, the entire mosaic is 5,252 x 3,744 pixels.*

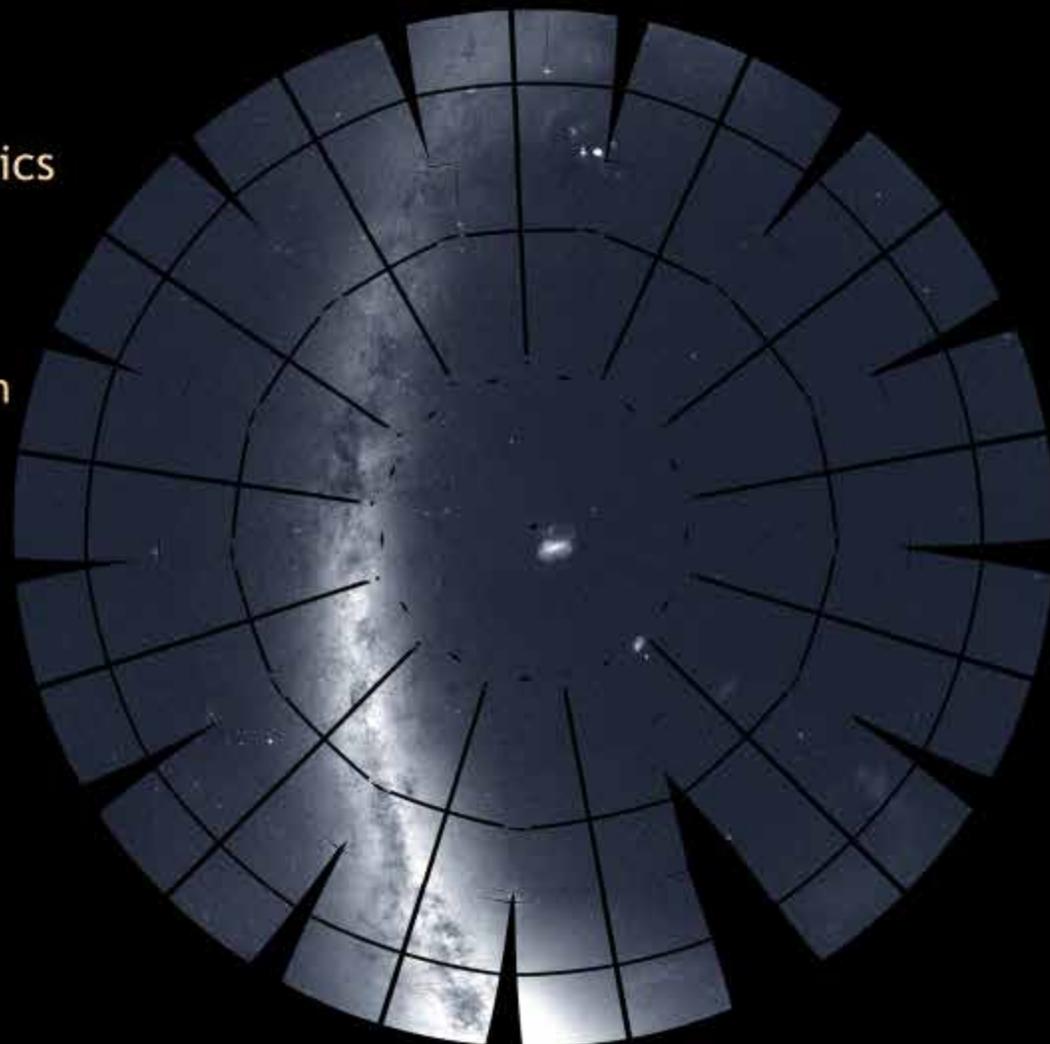
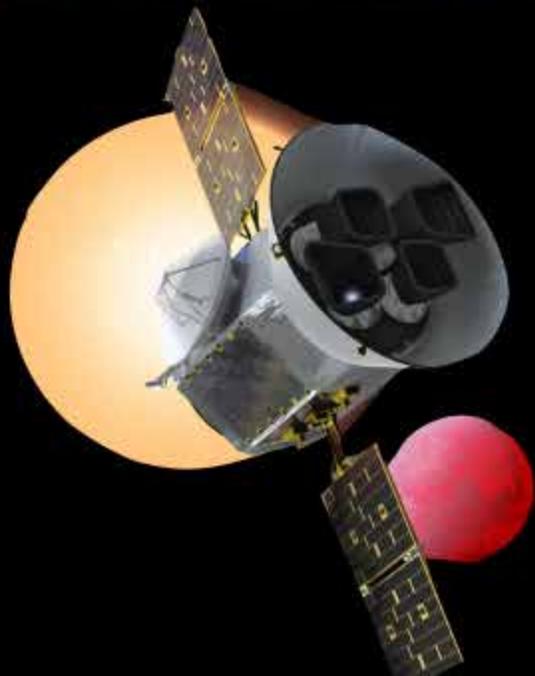
*Credit: NASA/Swift and AndreaMosaic*

# TESS Completes First Year of Prime Mission, Begins Year 2

1414 planet candidates  
34 confirmed planets  
+ many discoveries in astrophysics  
136 peer-reviewed publications  
+51 more submitted

Successful Guest Investigator Program  
Cycles 1 and 2 for Prime Mission

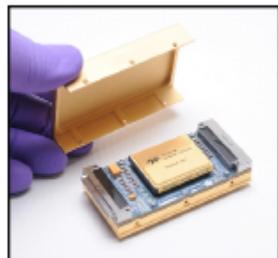
Extended mission approved!  
Cycle 3 proposal deadline 1/16/2020



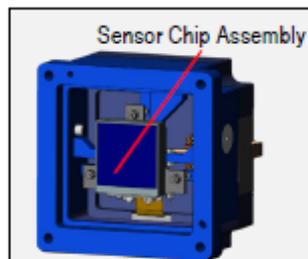
TESS observed southern hemisphere in Yr 1  
Currently observing northern hemisphere for Yr 2  
Current Sector: 18 of 26 in Prime Mission  
Data from Sectors 1-16 all publicly available at MAST

# Partner Mission of Opportunity: CASE

## Contribution to ARIEL Spectroscopy of Exoplanets: PI Mark Swain (JPL)

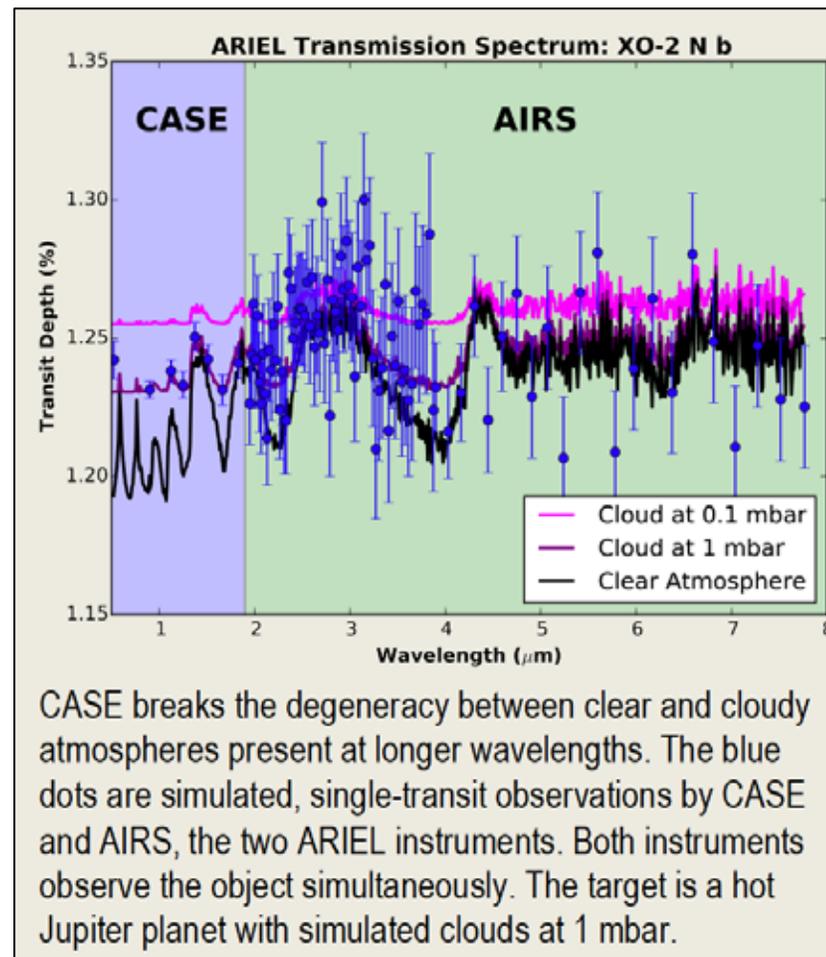


Cold Front End Electronics



Focal Plane Module

CASE detectors and electronics would provide fine guidance for ARIEL; blueward data ( $0.5\mu\text{m}$ - $2\mu\text{m}$ ) enables studies of aerosols (clouds and hazes) which are important for the energy budget of the atmosphere.



## ARIEL: ESA M4 mission for Infrared Spectroscopy of Exoplanet Atmospheres PI Giovanna Tinetti (UK)

Launch in 2028 to L2 for 4-yr mission; primary mirror 1.1m x 0.7m; CASE photometry complements AIRS spectroscopy  $2\mu\text{m}$ - $8\mu\text{m}$ .

ARIEL is next step beyond Kepler and TESS; will obtain spectra of hundreds of warm transiting exoplanets to study atmospheric chemistry and energy budget



# Astrophysics Division Hiring

Deputy Division Director – Jeffrey Volosin

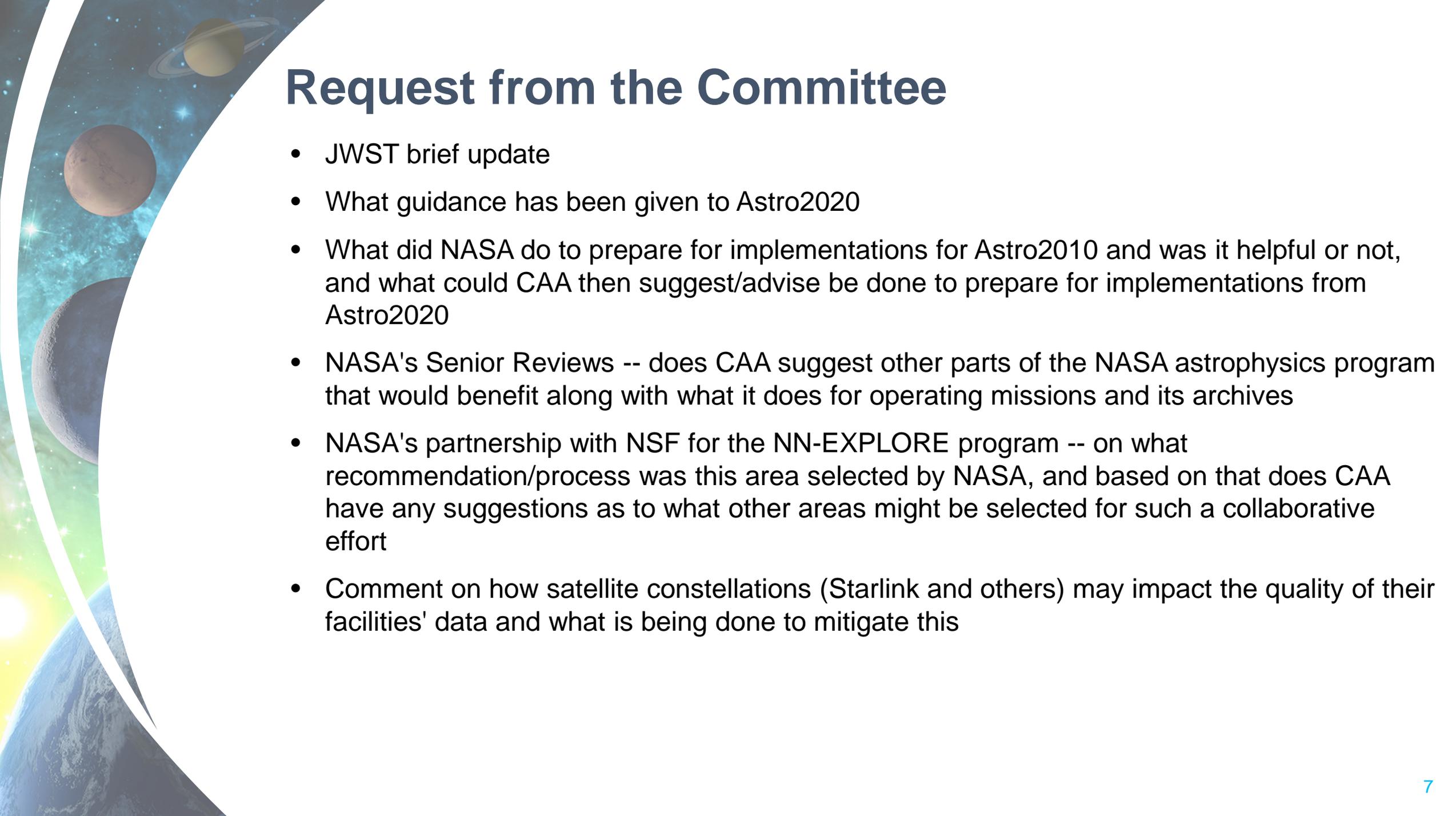
Associate Division Director for Flight Projects – Announcement pending OPM approval

Program Scientist(s) – Stefan Immler, possibly more

Program Executive(s) – David Jarrett, possibly more

All advertisements have closed for 2019

NASA will be calling for applications in the Fall for new IPAs and other visiting scientists

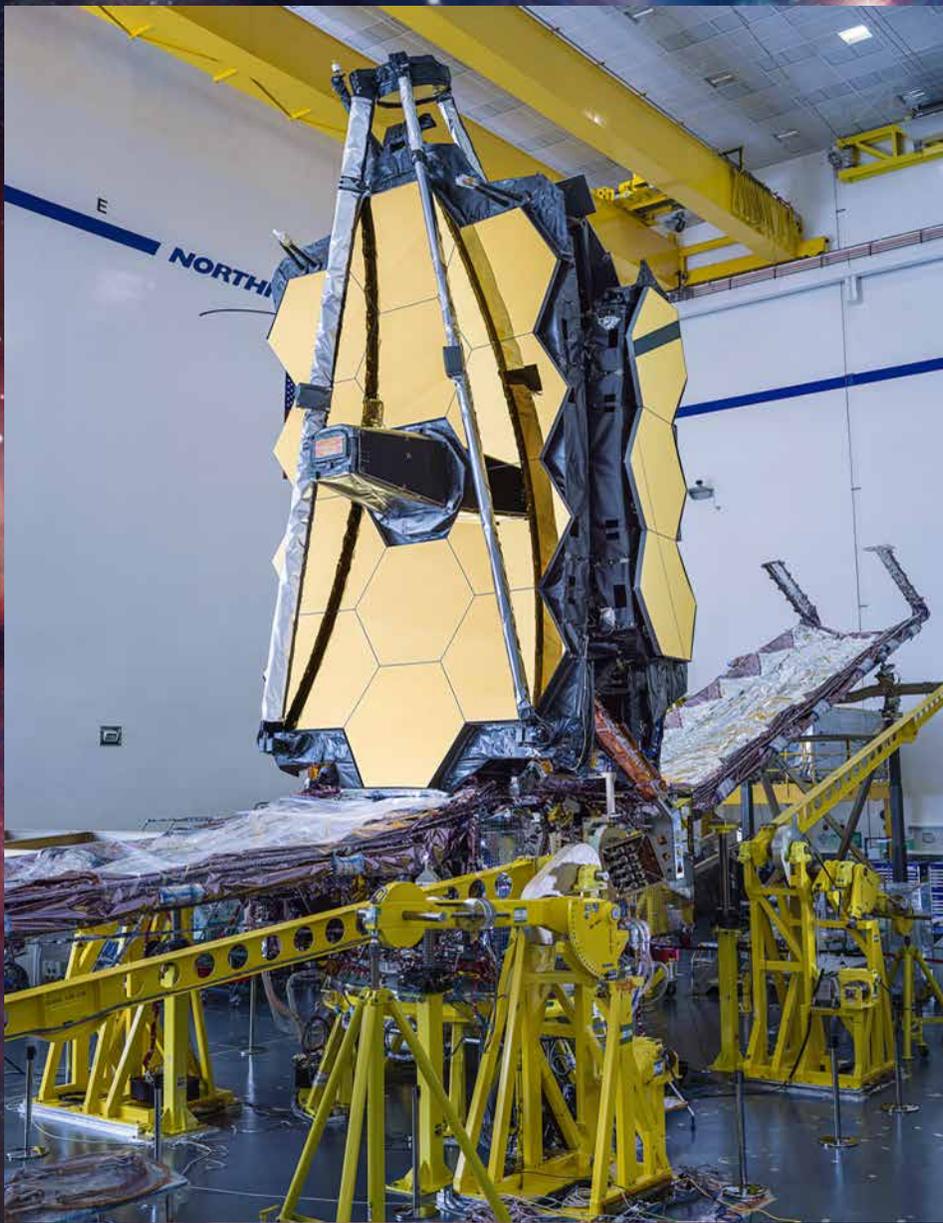
A decorative graphic on the left side of the slide features a curved white border. Inside this border, there is a vibrant space scene with a bright yellow sun at the bottom left, a blue and white Earth at the bottom, a grey crescent moon, a reddish-brown Mars, a brown Saturn with its rings, and a blue and green nebula in the background.

# Request from the Committee

- JWST brief update
- What guidance has been given to Astro2020
- What did NASA do to prepare for implementations for Astro2010 and was it helpful or not, and what could CAA then suggest/advise be done to prepare for implementations from Astro2020
- NASA's Senior Reviews -- does CAA suggest other parts of the NASA astrophysics program that would benefit along with what it does for operating missions and its archives
- NASA's partnership with NSF for the NN-EXPLORE program -- on what recommendation/process was this area selected by NASA, and based on that does CAA have any suggestions as to what other areas might be selected for such a collaborative effort
- Comment on how satellite constellations (Starlink and others) may impact the quality of their facilities' data and what is being done to mitigate this



# James Webb Space Telescope Update



*The Webb observatory in the clean room in Redondo Beach, CA before observatory environmental testing and observatory deployment tests*

# Webb

## The James Webb Space Telescope

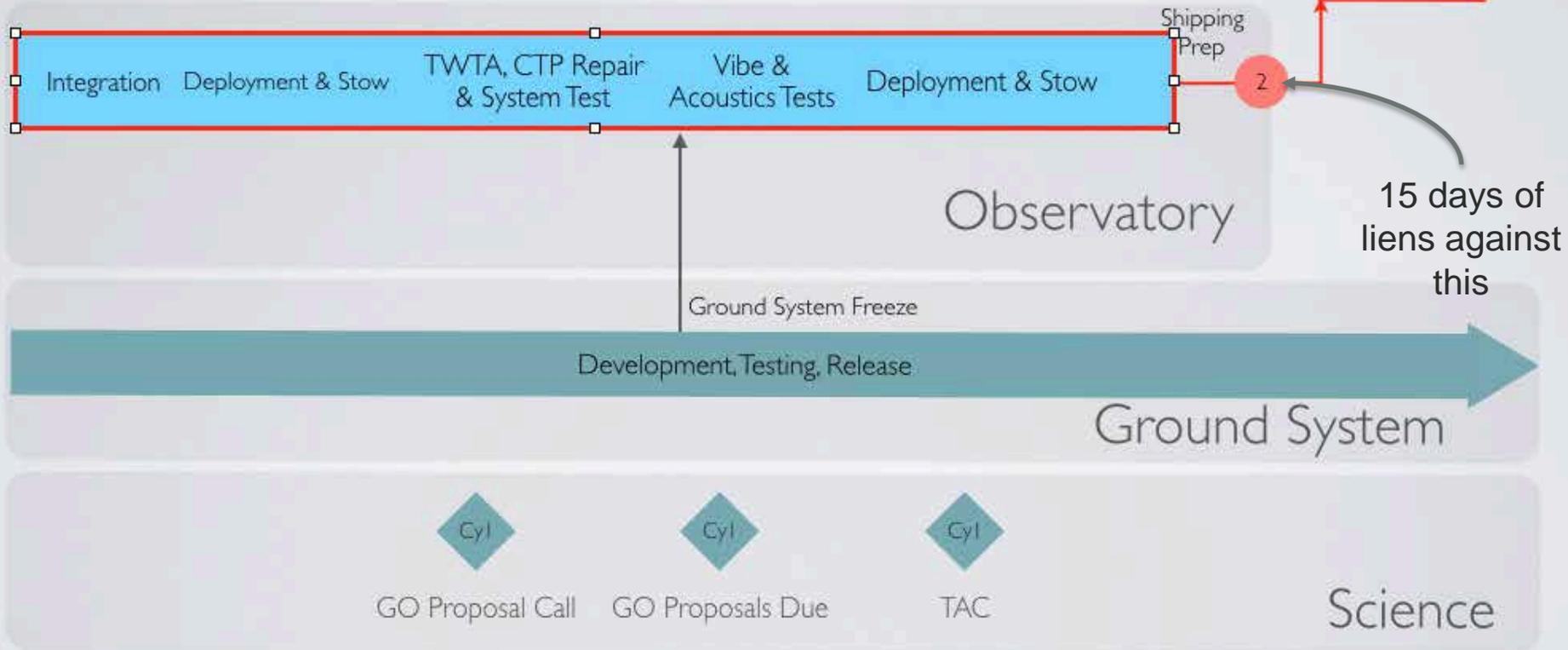


- Science payload completed three months cryogenic testing at end of 2017
- Spacecraft and sunshield integration completed January 2018
- Spacecraft element including sunshield completed environmental testing May 2019
- Science payload and spacecraft integration completed August 2019, to be followed by test deployment of sunshield
- Testing of full observatory begins in 2019 and continues in 2020
- Webb overrun covered using offsets from Astrophysics Probes

# SIMPLIFIED SCHEDULE

2019					2020										2021				
A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M

**k** months of project funded critical path (mission pacing) schedule reserve



# Remaining I&T Activities\*



Post SCE-Environmental Sunshield Deployments & Repairs

Observatory Pre-environmental Deployments

System (electrical) test

Vibration and acoustics tests

Observatory Post-environmental deployments

Final system test

Observatory fold and stow for launch

\*Top-level tasks to go. Many activities are associated with each of these steps



# Recent Accomplishments

- Programmatic

- Conducted the Systems Integration Review (SIR), the prelude to KDP-D by the agency
- Conducted KDP-D, the formal transition from construction into integration and test. KDP-D is where agency plans for remaining costs and schedule are formalized
- Annual GAO audit exit conference held in November, no recommendations expected

- Observatory

- Successfully completed Spacecraft Element (SCE: sunshield + spacecraft bus) thermal vacuum testing
- OTIS (telescope + science instruments) and SCE have been mechanically and electrically integrated forming the Observatory.
- Telescope deployment driven by spacecraft electronics
- Sunshield deployment and tensioning driven by spacecraft electronics

- Science and Operations

- Ground segment testing and operations rehearsals continuing (e.g., science operations, contingencies, early commissioning, wavefront sensing and control)
- All Software elements at better than 98% requirements delivered to-date

# Current Technical Issues

Maintaining schedule performance

Depressurization at fairing jettison

- To be retired after successful test on upcoming Ariane 5 launch

Spacecraft Element (Post thermal vac. work)

- #2 Command Telemetry Processor
- #1 Traveling Wave Tube Amplifier

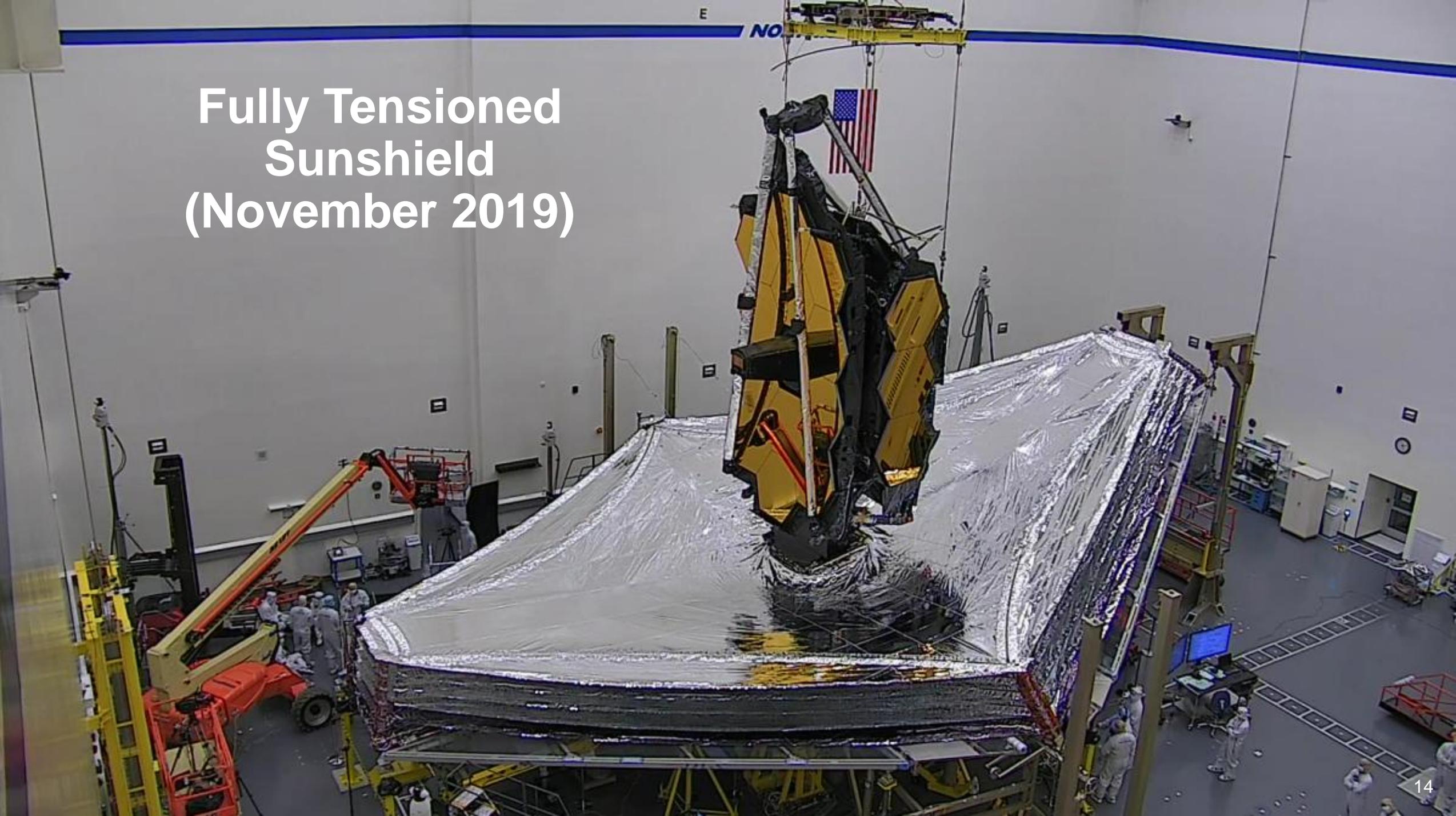


TWTA



CTP

# Fully Tensioned Sunshield (November 2019)



# Wide Field Infrared Survey Telescope



Work continues with FY19 funding

2016 – Completed Mission Concept review and began Phase A

2018 – Completed Mission Design review / System requirements Review and began Phase B

2019 – Completed Preliminary Design Reviews

2020 – Complete Confirmation Review and begin Phase C

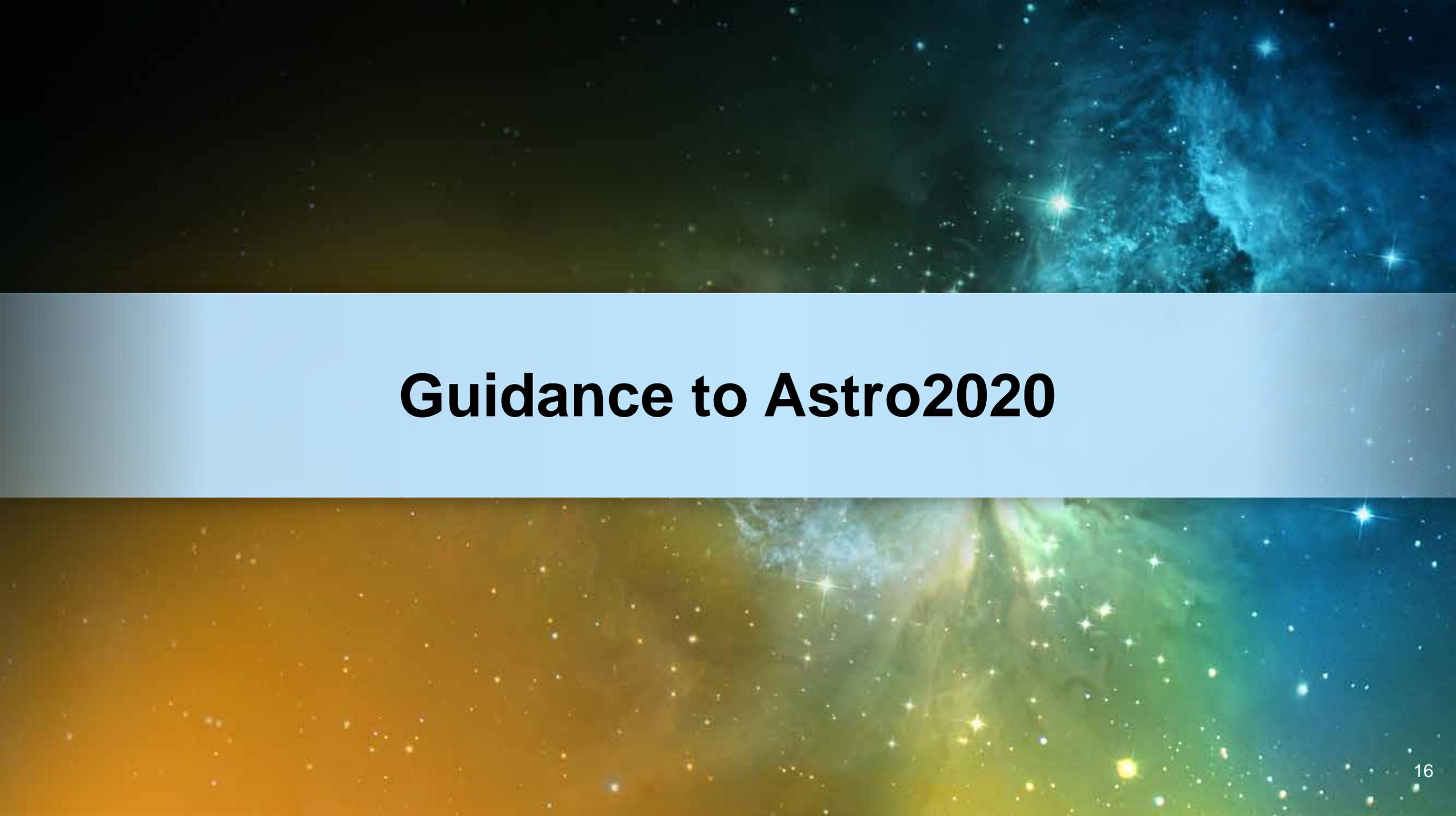
2021 – Call for Core Surveys

Mid-2020s – Launch

WFIRST is 100 to 1500 times faster than Hubble for large surveys at equivalent area and depth

Science Program includes

- Dark energy and the fate of the universe through surveys measuring the expansion history of the universe and the growth of structure
- The full distribution of planets around stars through a microlensing survey
- Wide-field infrared surveys of the universe through General Observer and Archival Research programs
- Technology development for the characterization of exoplanets through a Coronagraph Technology Demonstration Instrument

The background of the slide is a composite of two cosmic images. The top half features a dark blue and black space filled with numerous small stars and a prominent, bright blue nebula on the right side. The bottom half shows a similar starry field but with a large, glowing orange and yellow nebula on the left side, transitioning into a greenish-blue nebula on the right. A horizontal white band with a light blue gradient runs across the middle, containing the title text.

# Guidance to Astro2020



# Statement of Task

The binding guidance is the Statement of Task

1. Provide an overview of the current state of astronomy and astrophysics science ... ;
2. Identify the most compelling science challenges and frontiers in astronomy and astrophysics ... ;
3. Develop a comprehensive research strategy to advance the frontiers of astronomy and astrophysics for the period 2022-2032 ... The strategy should be balanced ... ;
4. Utilize and recommend decision rules ... that can accommodate ... deviations in the projected budget or changes ... precipitated by new discoveries or unanticipated competitive activities;
5. Assess the state of the profession ... Where possible, provide specific, actionable and practical recommendations to the agencies and community to address these areas. This report shall be made available following the completion of the study.

[https://sites.nationalacademies.org/DEPS/Astro2020/DEPS\\_192912](https://sites.nationalacademies.org/DEPS/Astro2020/DEPS_192912)



# Statement of Task

The Agencies consider the “Additional counseling for the Committee and staff as they carry out their work” to be part of the Statement of Task

## Scope

In: Ground/Space A&A, Observational/Theoretical/Computational/Laboratory/Archival A&A, Solar Astronomy (ground only), Gravitational Wave Observations, Multi Messenger Astrophysics, Exoplanets

Out: Fundamental Physics, Dark Matter Direct Detection, Microgravity Research, Projects under construction (JWST, DKIST, LSST, DESI)

Advise but do not rank: WFIRST, Athena, LISA

## Considerations

Future budget scenarios, Activities of all sizes, Programs of Record, Balanced Program, Other NASA capabilities, Technology needs, Cyber-infrastructure, Existing and proposed U.S. facilities, Non-Federal entities

## Approach

Recipients of advice, Composition of Committee, Use of Panels, Assembling Committee and Panels, Town Halls, Independent cost analysis, Unrealized activities from prior surveys, Binning recommended activities



# Strategic Missions and Competed Missions

NASA science missions are generally initiated in two different ways

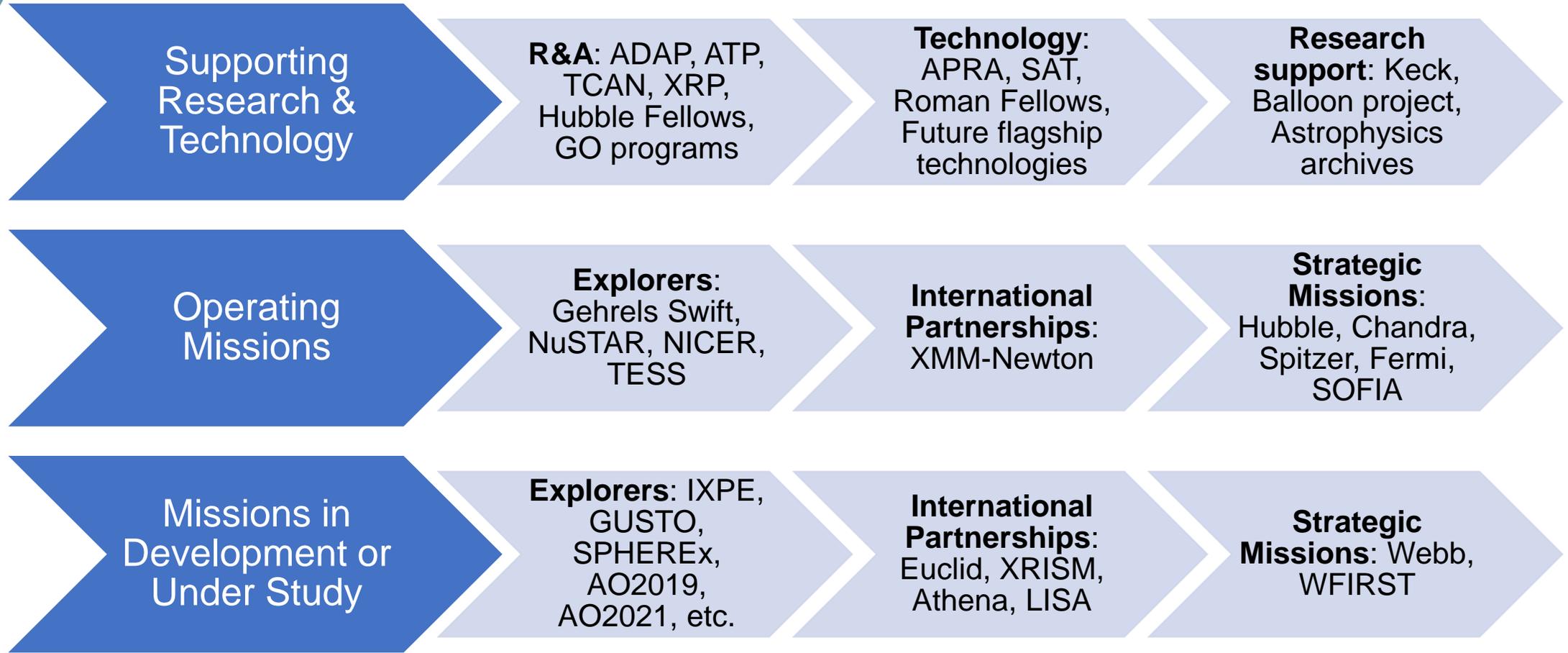
Strategic missions are initiated to respond to specific science objectives

- Mission architecture and acquisition strategy is tailored to the science objectives
- Project management is generally directed to a NASA Center
- Aspects of the mission may be competed through an AO (instruments), ROSES (science team, key science projects), or an RFP (spacecraft, integration and test)
- Can be any mission size: Flagship, Medium/Probe, International Contribution, or Small
- Astro2020 should recommend strategic missions

Competed missions are initiated through an AO

- AO solicits both the science objectives and the implementation plan (architecture, team)
- NASA selection of PI-led proposal is generally “take it or leave it”
- Can be any size except flagship, though only small (MIDEX, SMEX, MOs) are in the current astrophysics program
- Astro2020 should recommend competed programs, but not specific competed missions

# Program of Record



# Medium Mission Concepts (Probes)

Probes are strategic missions that have had a strong impact on astrophysics, either through a focused investigation or as a broadly-capable observatory

COBE <sup>11/89</sup> NASA Strategic Explorer	EUVE <sup>06/92</sup> NASA Strategic Explorer	Rossi XTE <sup>12/95</sup> NASA Strategic Explorer	GP-B <sup>04/04</sup> NASA Strategic Mission	Fermi <sup>6/08</sup> NASA Strategic Mission	Kepler <sup>3/09</sup> NASA Discovery Mission
					
Cosmic Background Explorer	Extreme Ultraviolet Explorer	Rossi X-ray Timing Explorer	Gravity Probe B The Relativity Mission	Fermi Gamma-ray Space Telescope	Kepler Space Telescope

NASA funded probe studies are available at <https://science.nasa.gov/astrophysics/2020-decadal-survey-planning>

## Options for 2020 Decadal Survey

- Do not recommend a medium mission in Astro2020
- Recommend specific probe(s) as medium-size strategic missions
- Recommend several specific science concepts for an AO (New Frontiers)
- Recommend an unconstrained AO (Super-Explorer)

# Why Flagships

Flagships drive science

Flagships drive US capabilities and contribute to US leadership

Flagships drive NASA budget and create stakeholder support

Hubble 04/90  
NASA Great Observatory



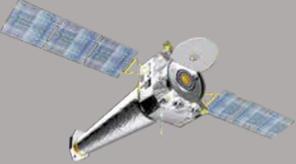
Hubble Space Telescope

Compton 05/91  
NASA Great Observatory



Compton Gamma Ray Observatory

Chandra 09/99  
NASA Great Observatory



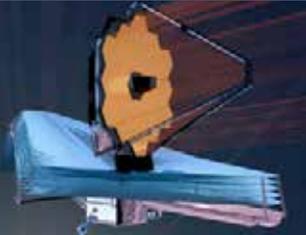
Chandra X-ray Observatory

Spitzer 8/03  
NASA Great Observatory



Spitzer Space Telescope

Webb 2021  
NASA Mission



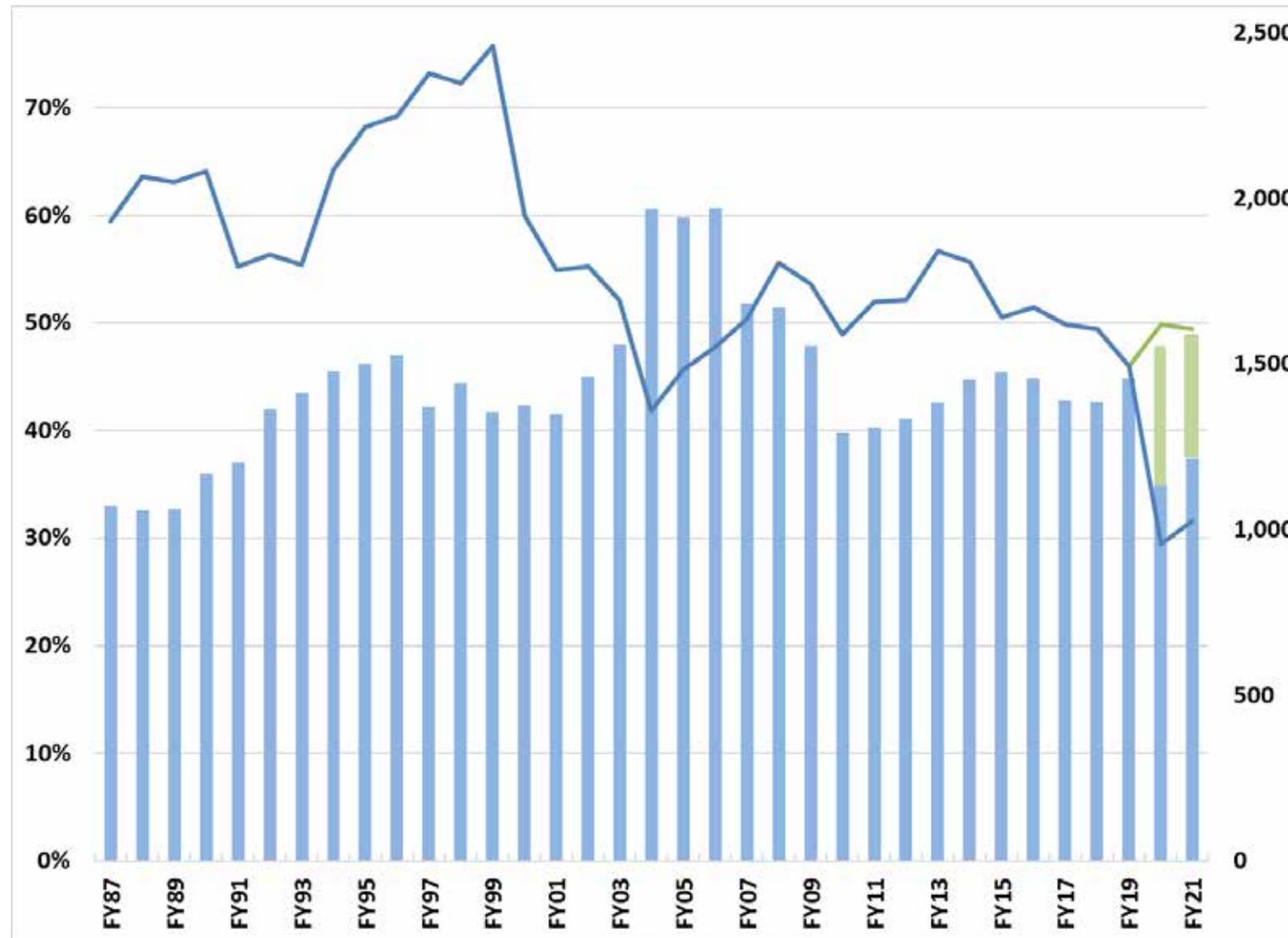
James Webb Space Telescope

WFIRST Mid 2020s  
NASA Mission



Wide Field Infrared Survey Telescope

# Flagship Fraction of Astrophysics Budget



All dollars inflated to FY18\$.  
Development only, no ops.

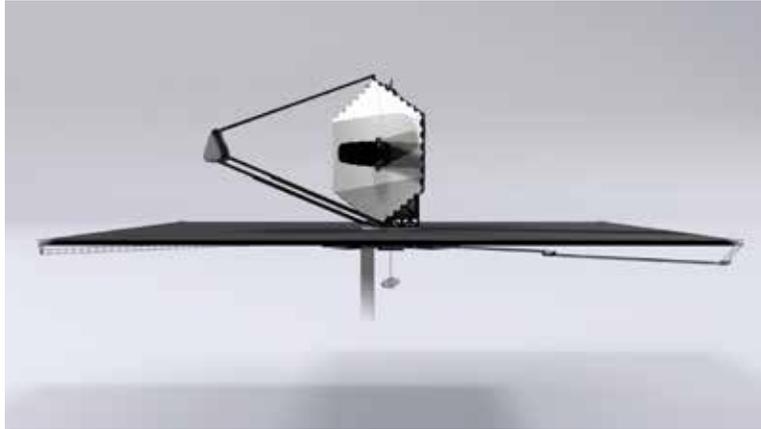
- Large mission fraction (left scale)
- ■ Inflation adjusted Astrophysics budget (right scale)
- Current planning budget (without WFIRST beyond FY19)
- What if WFIRST is funded as needed on top of FY20 President's Budget Request?

# Large Mission Concepts

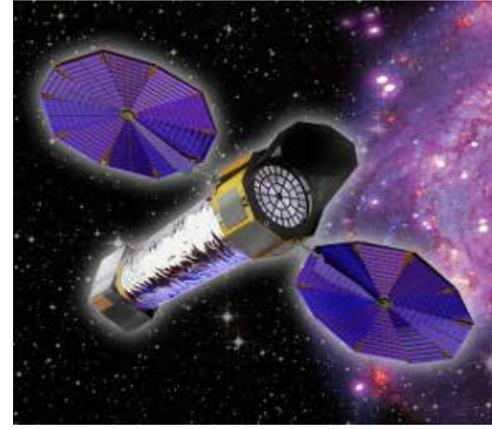
*“NASA should ensure that robust mission studies that allow for trade-offs (including science, risk, cost, performance, and schedule) on potential large strategic missions are conducted prior to the start of a decadal survey. These trade-offs should inform, but not limit, what the decadal surveys can address.” – Powering Science: NASA's Large Strategic Science Missions (NAS, 2017)*



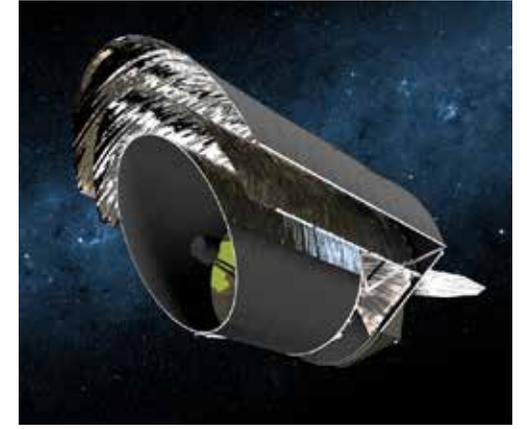
HabEx



LUVOIR

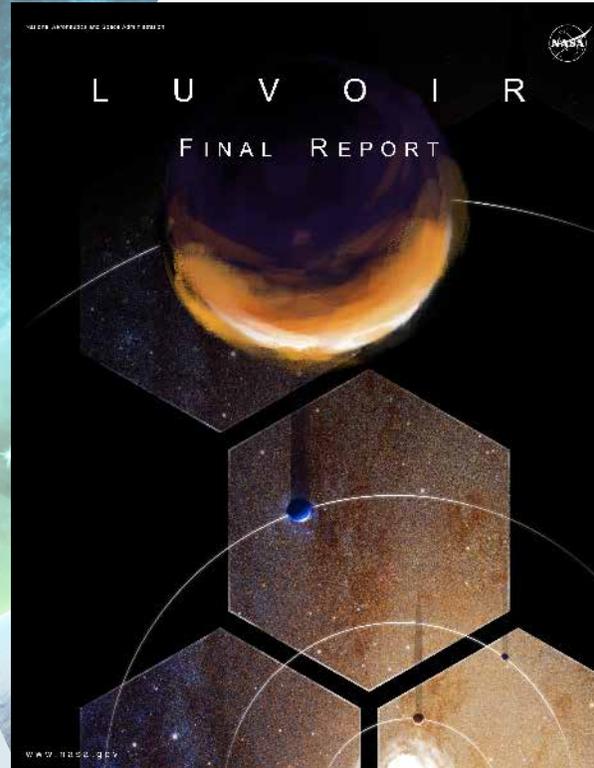
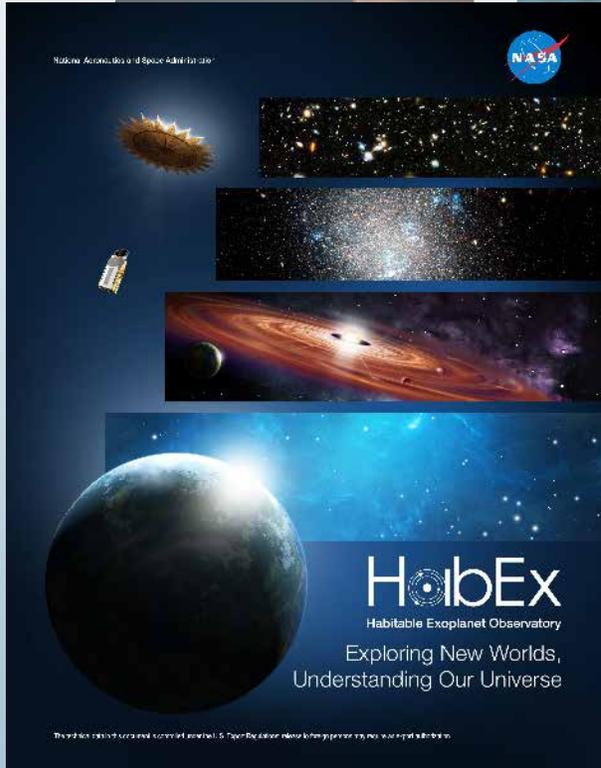


Lynx



Origins

# Large Mission Studies



Links to the concept study reports are posted at  
<https://science.nasa.gov/astrophysics/2020-decadal-survey-planning>  
and at  
<https://www.greatobservatories.org/>



# Guidance on Future Budgets

All guidance is for Astrophysics including Webb Telescope

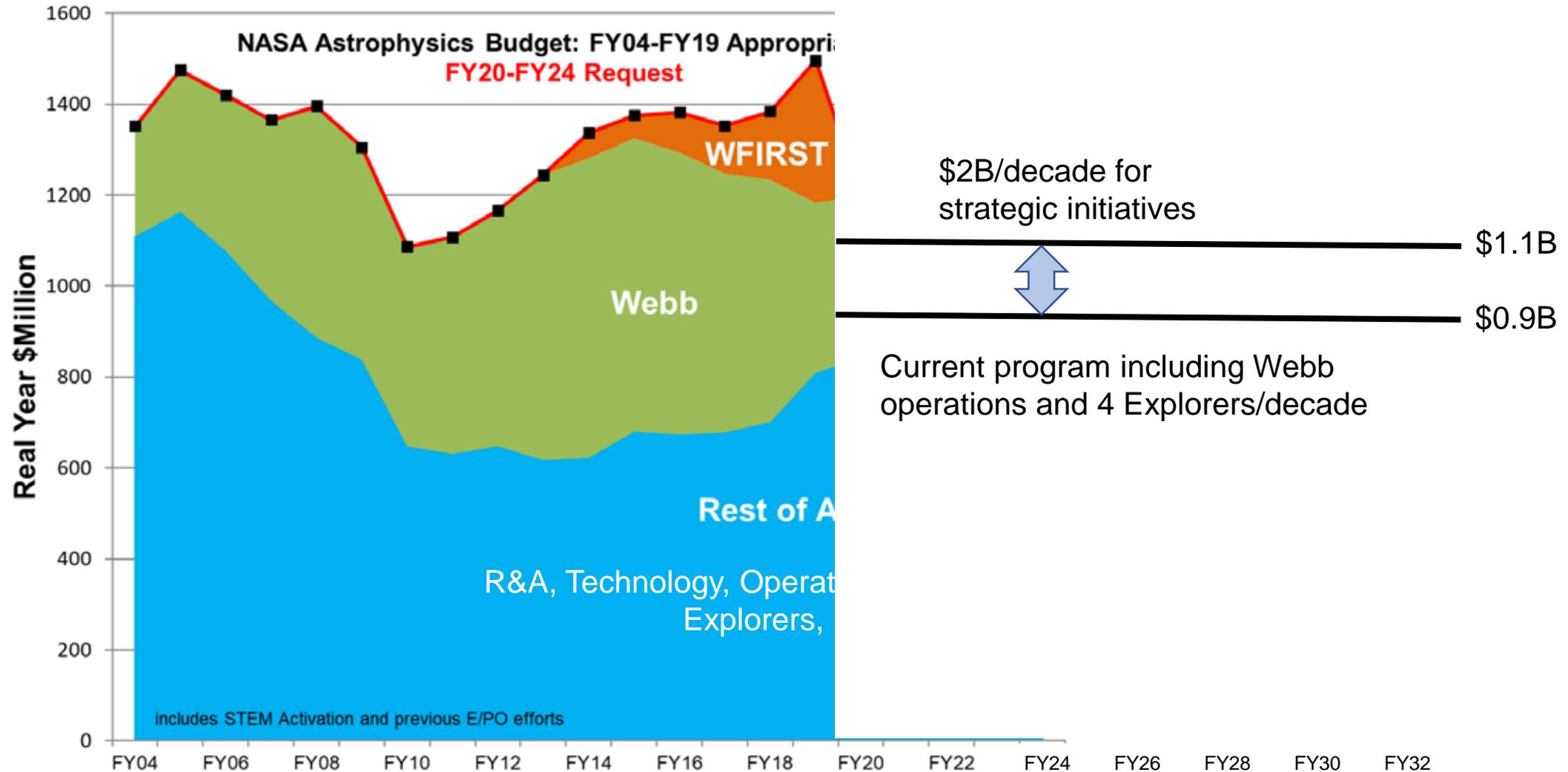
Lower bound budget projection – Extrapolation of out year planning numbers for President's FY20 budget request. Average of FY22-FY24 planning numbers is \$1.1B/yr

Empirical budget projection – Extrapolation of recent NASA Astrophysics appropriations. Average of FY17-FY19 appropriations is \$1.4B/yr

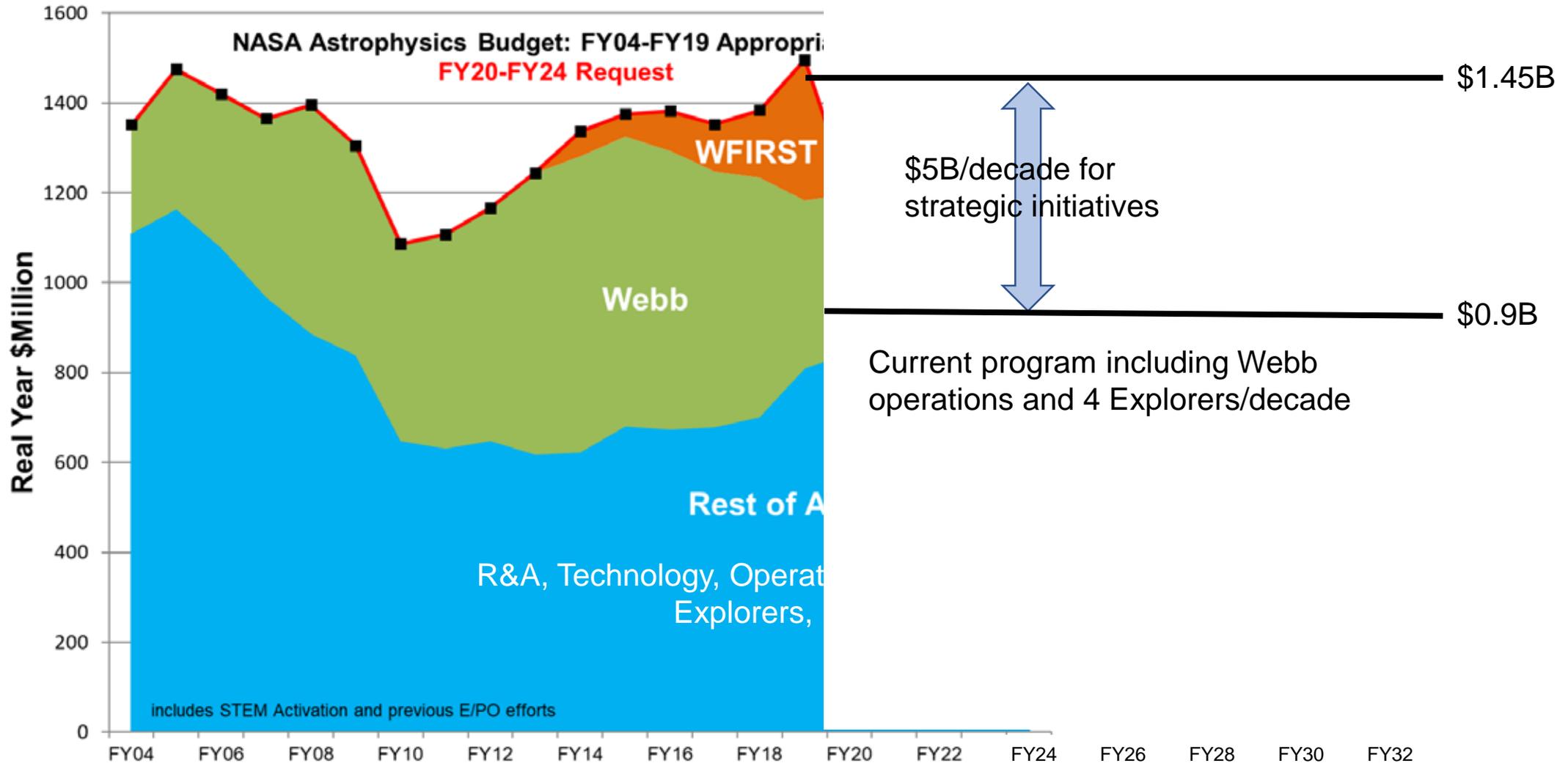
Optimistic budget projection – Empirical budget projection plus 1% inflationary growth in the out years. Budget grows from \$1.5B (FY19) to \$1.6B (FY25) to \$1.7B (FY30)

Upper bound budget projection – Empirical budget projection plus 2% inflationary growth in the out years. Budget grows from \$1.5B (FY19) to \$1.7B (FY25) to \$1.9B (FY30)

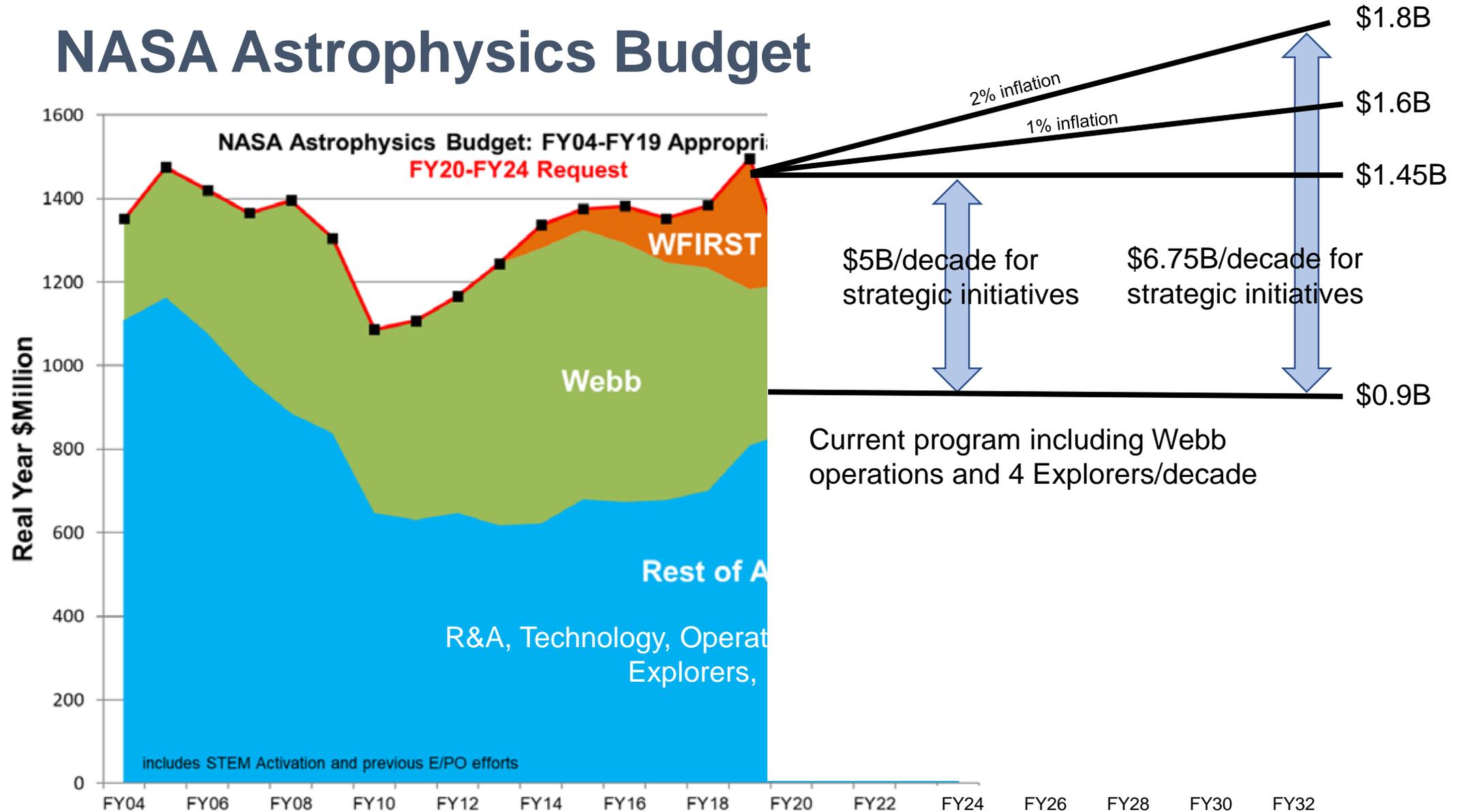
# NASA Astrophysics Budget

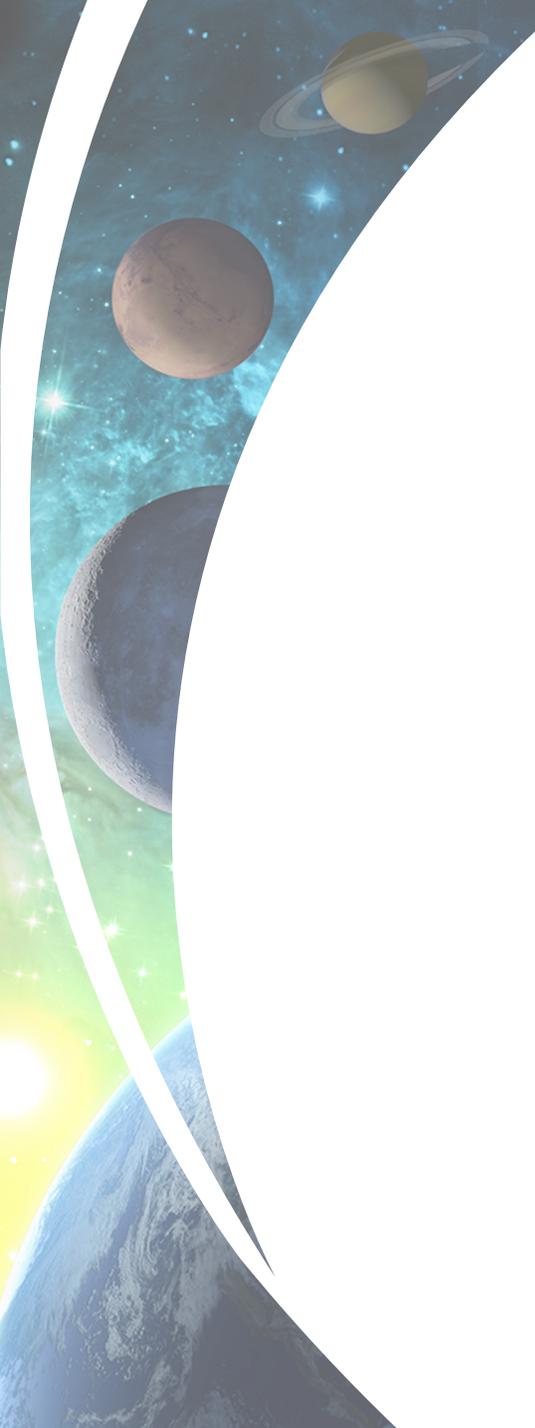


# NASA Astrophysics Budget



# NASA Astrophysics Budget



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# Decadal Survey Goal

- NASA's highest aspiration for the 2020 Decadal Survey is that it be ambitious
  - The important science questions require new and ambitious capabilities
  - Ambitious missions prioritized by previous Decadal Surveys have always led to paradigm shifting discoveries about the universe
- If you plan to a diminishing budget, you get a diminishing program.
  - Great visions inspire great budgets.

## Carpe Posterum



# Implementing Astro2020



# NASA Preparations for Astro2020

- Community led, NASA implemented, strategically selected, large mission concept studies (4)
- PI-led and implemented, competitively selected, medium mission concept studies
- Investments in large mission technology tall poles, including initiation of Segmented Mirror Technology Program with industry
- Selected NASA-sponsored studies including Balloon Roadmap, Evolution of Archives, and Joint Simulations/Processing for cosmology experiments (WFIRST, LSST, DESI, Euclid)
- Exoplanet Standards Definitions and Evaluation Team to create common yardstick for exoplanet detection and characterization missions
- PAG organized coordination for science white papers
- PAG studies to inform the Decadal Survey (e.g., Great Observatories SAG, Multimessenger Astrophysics SAG)

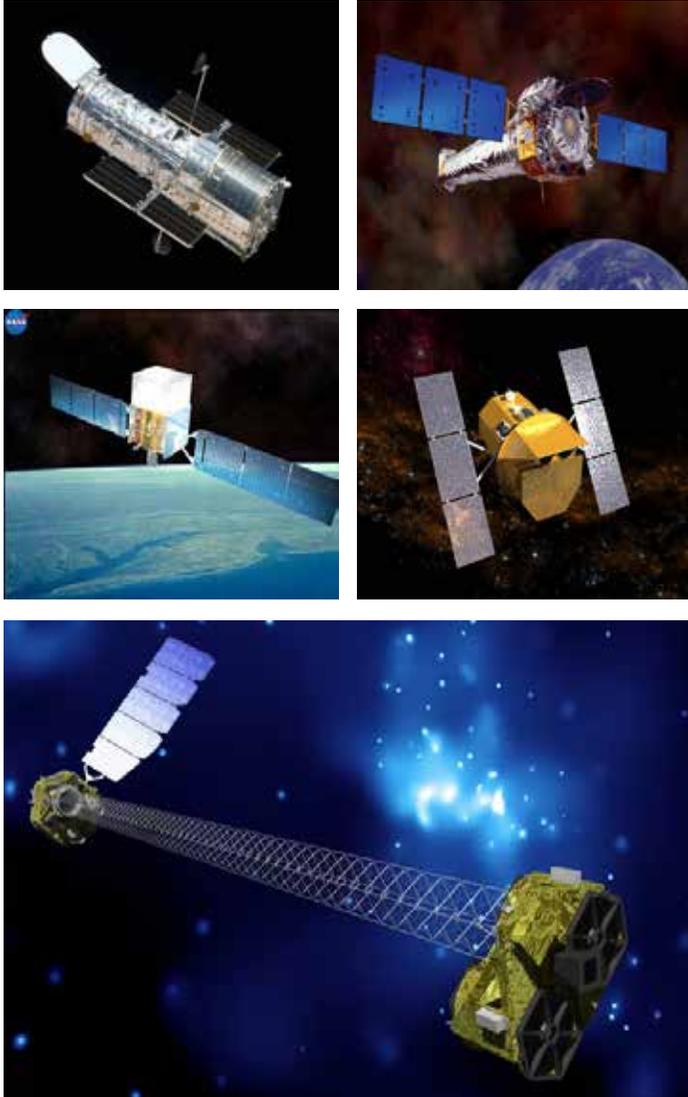


# NASA Preparations for Post Astro2020

- Notional out year planning wedges are available to implement Astro2020 recommendations
- All out year planning wedges are notionally fungible within Administration budget formulation process
- Program of Record includes
  - Continued R&A program & investments in research infrastructure
  - Four Explorer AOs per decade
  - Completion and operation of Explorers, Webb and WFIRST
  - Completion and operation of partner-led missions including Athena and LISA
  - Operation of current mission suite including GO programs
- Early planning wedges include
  - Planning wedge for increased investments in strategic technologies
  - Planning wedge for first Probe mission
- Mid-decade planning wedge includes
  - Beginning next flagship mission

The background of the slide is a cosmic scene. The top half features a dark blue and black space filled with numerous small white stars and a prominent, bright blue nebula on the right side. The bottom half is dominated by a large, glowing orange and yellow nebula on the left, which transitions into a greenish-blue nebula on the right. The text "Senior Reviews" is centered in a white horizontal band across the middle.

# Senior Reviews



# Operating Missions Senior Review 2019

- Hubble No change to budget guideline
- Chandra Selected overguides: Audit fees, labor & GO (inflation)
- TESS Extended mission w/ full funding & continued GO program
- Swift Selected overguides: New tools for Targets of Opportunity (TOO) and Ultraviolet-Optical Telescope (UVOT)
- Fermi Ops w/out Department of Energy (DOE)
- NICER Extended mission w/ reduced ops & new GO program
- NuSTAR Phase out legacy science for GO science
- XMM-Newton No change

Not in Senior Review: Kepler, SOFIA, Spitzer



# Astrophysics Archives Programmatic Review 2020

The Astrophysics Archives Programmatic Review, to be held every four or five years, conducts an independent evaluation of archive activities. The purpose of the review is to assist NASA in maximizing the overall scientific value of the agency's Astrophysics archives and data centers.

## Archives

- Astrophysics Data System (ADS) @ SAO
- High Energy Astrophysics Science Archive Research Center (HEASARC) @ GSFC
- Infrared Science Archive (IRSA) @ IPAC
- Mikulski Archive for Space Telescopes (MAST) @ STScI
- NASA Exoplanet Archive (NEA) @ NExSci/IPAC
- NASA Extragalactic Database (NED) @ IPAC

## Schedule

2019 Oct 29	Call for responses
2020 Feb 3	Responses due
2020 Mar 11-13	Panel review
2020 Apr 30	Programmatic direction issued (target)

The background of the slide is a cosmic scene featuring a blue nebula in the upper right and a green and yellow nebula in the lower right, set against a dark space filled with numerous stars. A light blue horizontal band is centered across the image.

# NN-EXPLORE



- Partnership between NASA Astrophysics and NSF Astronomy
  - Initiated 2015
  - Joint goal: Discovery and characterization of exoplanets
  - NSF provides: Access to ground based telescopes
  - NASA provides: Open access extreme precision RV spectrometer
- Stage 1 (through 2019)
  - Develop the NEID spectrometer for use on WIYN telescope
  - NOAO share of WIYN for open access exoplanet research
- Stage 2 (2019+)
  - Open access use of NEID spectrometer for exoplanet discovery and characterization
  - Archive for all NEID data
  - Open access to RV spectrometers on southern hemisphere telescopes (AAT/Veloce, SMARTS/Chiron)
  - Extreme Precision RV Working Group

<https://exoplanets.nasa.gov/exep/NNExplore/>



Port adapter mounted on the WIYN 3.5-meter telescope.

## **NEID Extreme Precision RV Spectrograph**

PI: Suvrath Mahadevan (PSU)

### **Recent Progress**

Delivered the port adapter to Kitt Peak (10/17/19)

Mounted the port adapter on the WIYN 3.5-meter telescope (10/21/19)

Delivered the NEID spectrograph to WIYN (10/28/19) and installed in the telescope basement cleanroom

Remaining equipment shipped on 11/1/19

2019B semester GO underway for WIYN (NEID), SMARTS/Chiron, and AAT/Veloce

2020A semester GO proposal call completed

### **Near Term Plans**

Continue with the installation and commissioning of NEID, port adapter, pipeline and archive

Support shared-risk NEID observing and non-NEID observing on WIYN

The first night of shared-risk guest observing (GO) on WIYN with NEID is 12/1/19



NEID RV spectrograph prepared for shipping.



# NN-EXPLORE

NWNH : Priority 1 (Medium, Space). New Worlds Technology Development Program for a 2020 Decade Mission to Image Habitable Rocky Planets.

The ultimate goal is to image rocky planets that lie in the habitable zone of nearby stars ... and to characterize their atmospheres. Achieving this ultimate goal requires ... necessary precursor activities. The first is to understand the demographics of other planetary systems, in particular to determine over a wide range of orbital distances what fraction of systems contain Earth-like planets. To this end, the committee recommends ... a vigorous ground-based research program. [NWNH pp 215-216]

This survey strongly supports a vigorous program of exoplanet science that takes advantage of the observational capabilities that can be achieved from the ground and in space. The first task on the ground is to improve the precision radial velocity method by which the majority of the close to 500 known exoplanets have been discovered. [NWNH pp 193]

The background of the slide is a composite of cosmic imagery. The top half features a dark blue and black space filled with numerous small white stars and a prominent, glowing blue nebula on the right side. The bottom half transitions into a warmer color palette, with a golden-yellow and orange glow on the left, transitioning into a green and blue glow on the right, also filled with stars and nebulae. A horizontal light blue band runs across the middle, containing the title text.

# Impact of Satellite Constellations



# Impact of Satellite Constellations

Starlink and other constellations will be operating in the Ka band

- Concern that they will not be careful in filtering out the side lobes, and that those could interfere with our communications
- Affects all missions in LEO using Ka band (e.g. TESS, SPHEREx) and could affect L2 missions later (e.g., Webb, WFIRST)

Starlink is planning 12k satellites in 3 shells by 2025: 1150km, 560km, and 340km

- The plan is to up this to 42k by ~2030 in all sorts of orbits
- Unless one goes to GEO or L2, we have a huge “image/light pollution” problem

There is enormous potential for infrastructure interference with the 5G (25 GHz) net coming online and interfering with ground stations

- The problem will be side lobe interference that acts as noise to ground stations
- The KSAT antenna in Singapore is currently unusable for both NuSTAR and Swift
- NASA brought this up when the licensing was being determined but was outvoted by other agencies
- NASA has no mitigation for this; NEN is commercial now, we don't have a separate government infrastructure to support our missions

- Formulation
- Implementation
- Primary Ops
- Extended Ops

+ SMEX/MO (2025),  
MIDEX/MO (2028), etc.

Spitzer  
8/25/2003

WFIRST  
Mid 2020s

Euclid (ESA)  
2022

SXG (RSA)  
7/13/2019

Webb  
2021

Ariel (ESA)  
2028

Chandra  
7/23/1999

XMM-Newton (ESA)  
12/10/1999

TESS  
4/18/2018

Swift  
11/20/2004

NuSTAR  
6/13/2012

Fermi  
6/11/2008

IXPE  
2021

SPHEREx  
2023

XRISM (JAXA)  
2022

ISS-NICER  
6/3/2017

GUSTO  
2021

Hubble  
4/24/1990

SOFIA  
Full Ops 5/2014

+ Athena (early 2030s),  
LISA (early 2030s)