# Planetary Science Division

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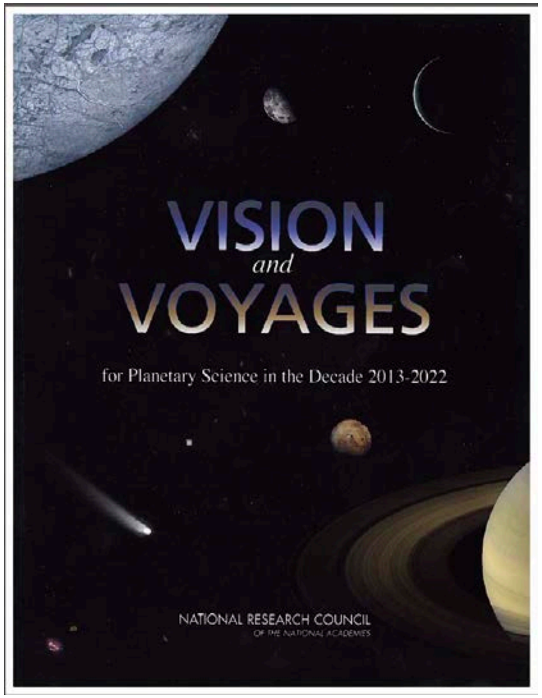
NAS Planetary Decadal Mid-Term

# Timeline of NAS Studies

- 1st Planetary decadal: 2002-2012
- 2nd Planetary decadal: 2013-2022
- Cubesat Review: Completed June 2016
- Extended Missions Review: Completed Sept 2016
- R&A Restructuring Review:  Completed April 2017
- Large Strategic NASA Science Missions:
  - Tasked December 23, 2015
  - Report due to NASA August 2017
- Midterm evaluation:
  - Tasked August 26, 2016 - 1st meeting May 4-5, 2017
  - Cubesat, Ext. Missions, R&A Restructuring, Large Strategic Missions - will be input
- Sample Analysis Future Investment Strategy (Tasked Sept 23, 2016)
- Next Committee on Astrobiology & Planetary Science – CAPS (Sept 13-14, 2017)
  - Tasked to provide input on what are the next mission studies we should perform
- 3rd Planetary Decadal: 2023-2032
  - To be tasked *before* October 2019
  - Expect report to NASA due 1st quarter 2022

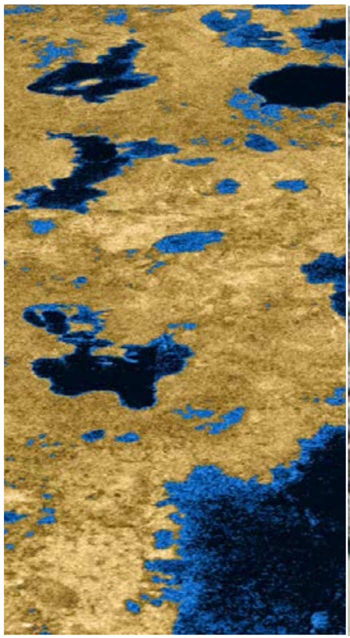


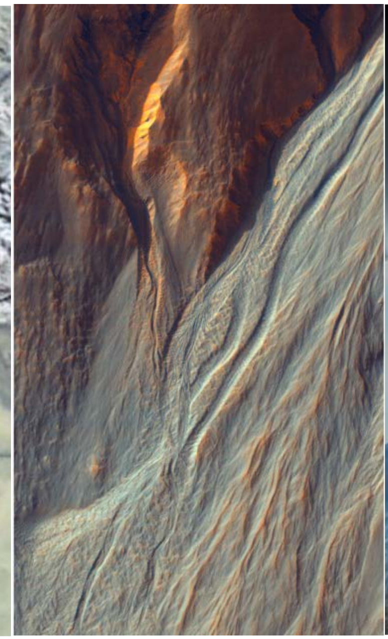
# Decadal Survey Crosscutting Themes

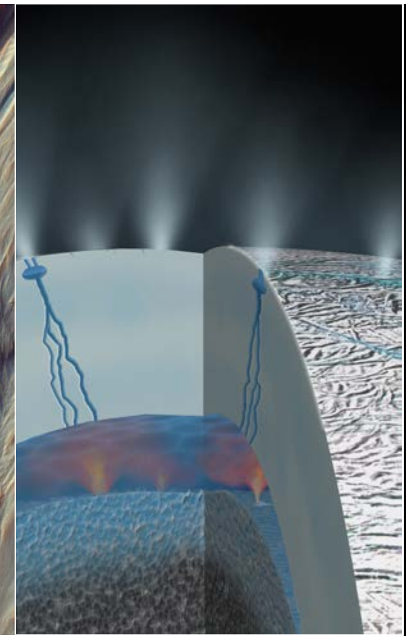
- **Emerging Worlds** → How did the Sun's family of planets, satellites, and minor bodies form and evolve?
- **Solar System Workings** → How do the chemical and physical processes active in our solar system operate, interact and evolve?
- **Habitable Worlds** → What are the characteristics of the solar system that lead to habitable environments?
- **Exobiology** → How did life originate and evolve here on Earth and can that guide our search for life elsewhere?
- **Solar System Observations** → What are characteristics of planetary objects and environments that pose threats to, or offer potential resources for, humans as we expand our presence into the solar system?

# Planetary Science Objectives

## Goal 1.5 - Ascertain the content, origin, and evolution of the Solar System and the potential for life elsewhere.







Objective 1.5.1
Explore & observe the objects in the Solar System to understand how they formed and evolve

Objective 1.5.2
Advance the understanding of how the chemical & physical processes in the Solar System operate, interact and evolve

Objective 1.5.3
Explore & find locations where life could have existed or could exist today

Objective 1.5.4
Improve our understanding of the origin & evolution of life on Earth to guide the search for life elsewhere

Objective 1.5.5
Identify & characterize objects in the Solar System that pose threats to Earth or offer resources for human exploration

*Government Performance and Results Act Modernization Act (GPRAMA) requires Planetary Science Division to have a progress review of each objective each year*

# Government Performance and Results Act Modernization Act (GPRAMA)

GPRAMA of 2010, P.L. 111-352, provides a framework for NASA's performance planning and reporting activities covering the 2014-2018 timeframe.


| | |
|---|---|
| GREEN | Expectations for the research program fully met or exceeded in context of resources invested. |
| YELLOW | Some notable or significant shortfalls in context of resources invested, but some worthy scientific advancements achieved. |
| RED | Major disappointments or shortfalls in scientific outcomes in context of resources invested, uncompensated by other unusually positive results. |

# Government Performance and Results Act Modernization Act (GPRAMA)

On an annual basis:

1. PSD coordinates assessment of progress on each of the Planetary Science Goals
   - Draft assessment developed by PSD and reviewed and rated by the Planetary Science Subcommittee (PSS)
2. For each goal a color-coded ranking assigned (Green, Yellow, Red)
3. NASA's complete Annual Performance Report is submitted to Congress after the end of each Fiscal Year and posted on nasa.gov for public access.

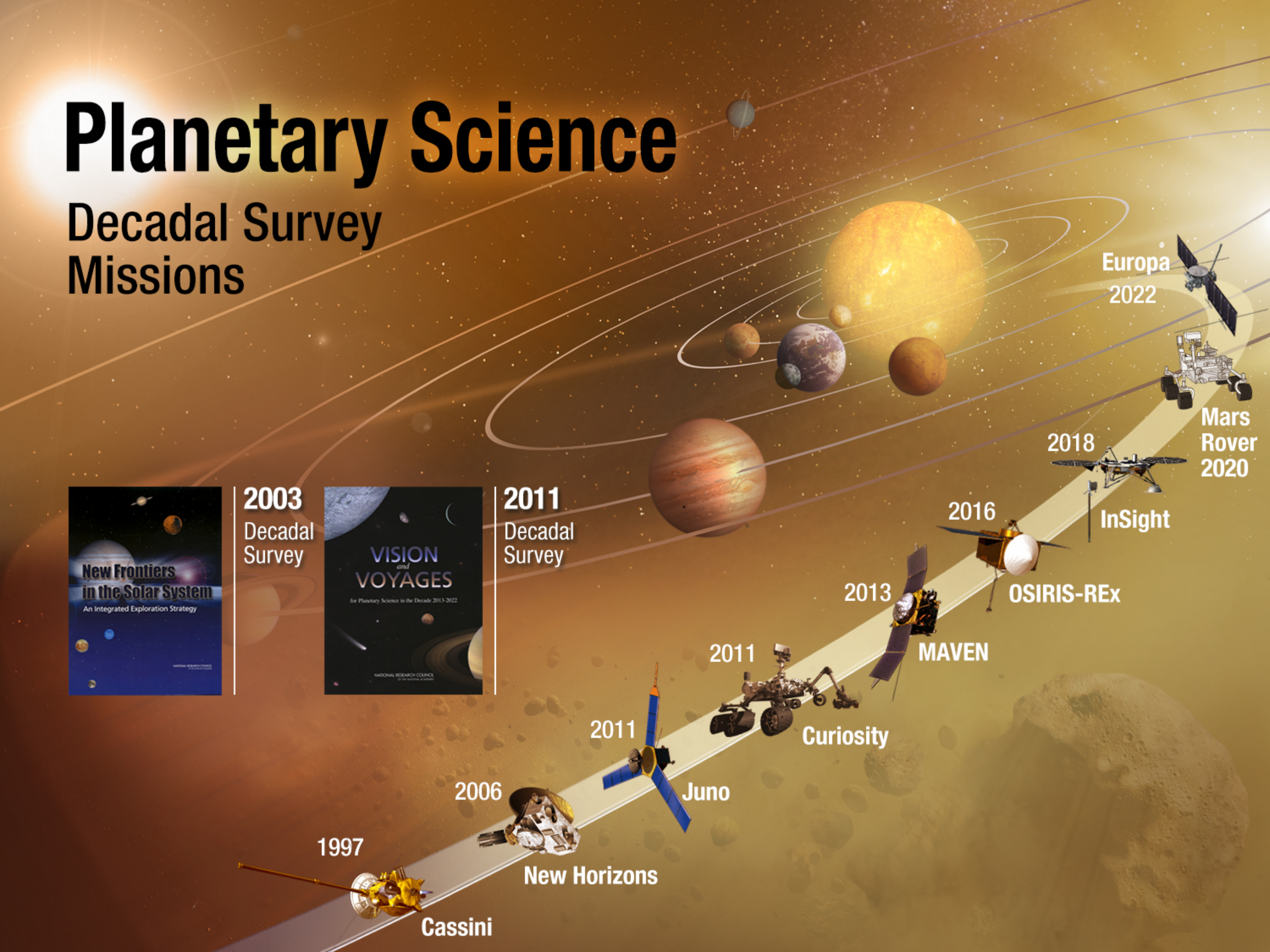
The compilation of planetary science accomplishments into the annual GPRAMA report received all **GREEN for all Objectives since FY11**

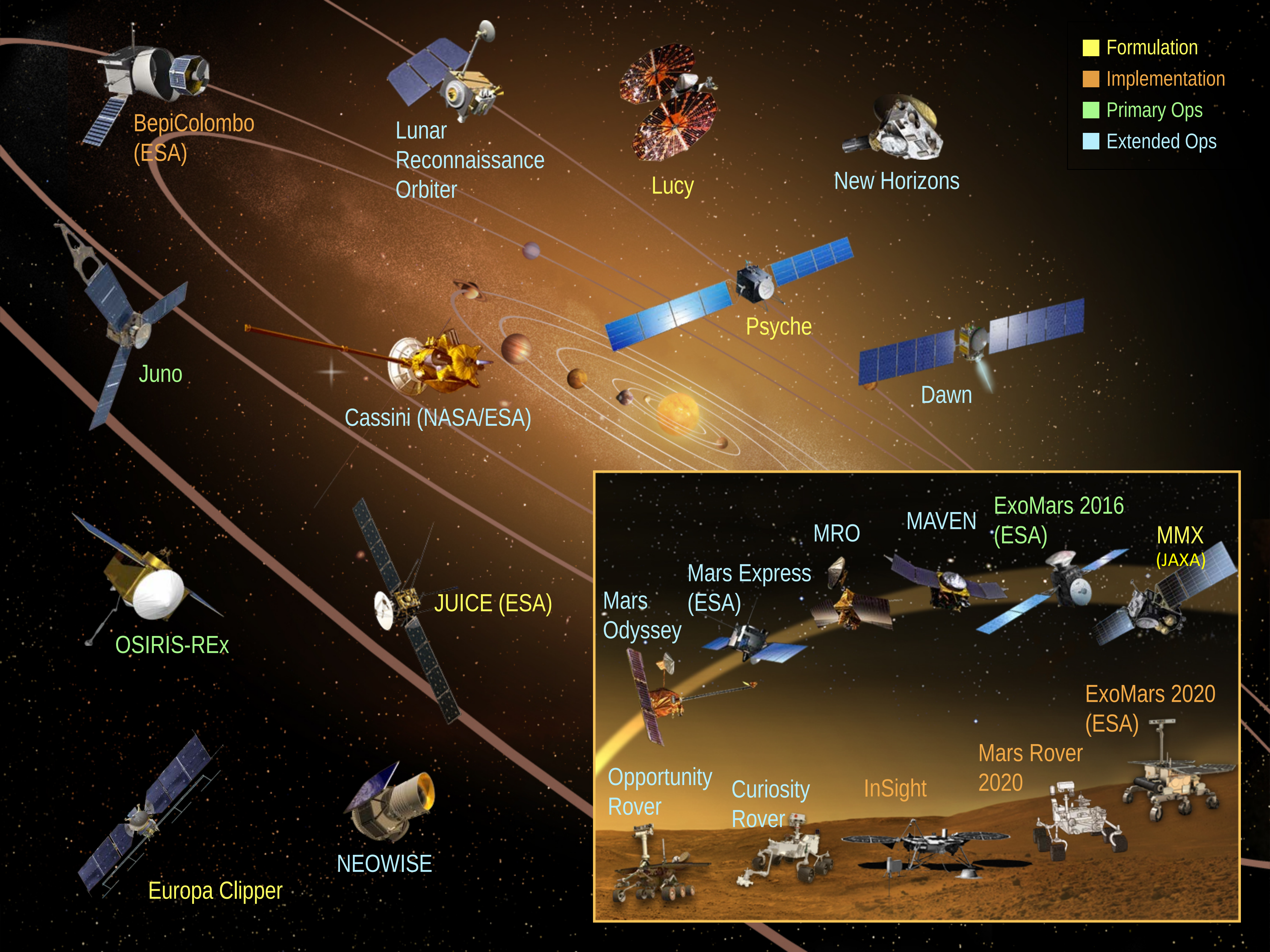
# Strategic Objective Annual Review (SOAR)

- SOAR is an annual assessment of 15 NASA Strategic Objectives:
  - Required by Congress and implemented by OMB for all major Federal agencies
  - Review includes: long-term impact, implementation, strategic risks & challenges, and opportunities. With only 1 to 3 objectives to be evaluated noteworthy.
  - Procedure: PSD performs a self-assessment, concurrent with an independent Agency review. The Agency's proposed ratings are submitted to OMB, with OMB's final ratings and report subsequently provided to Congress.
- OMB uses this information to understand Agency plans, evaluate an Agency's budget, and take action where appropriate
- Categories: **Noteworthy Progress** | **Satisfactory Performance** | **Focus Area for Improvement**

## Results for the Planetary Science Division:

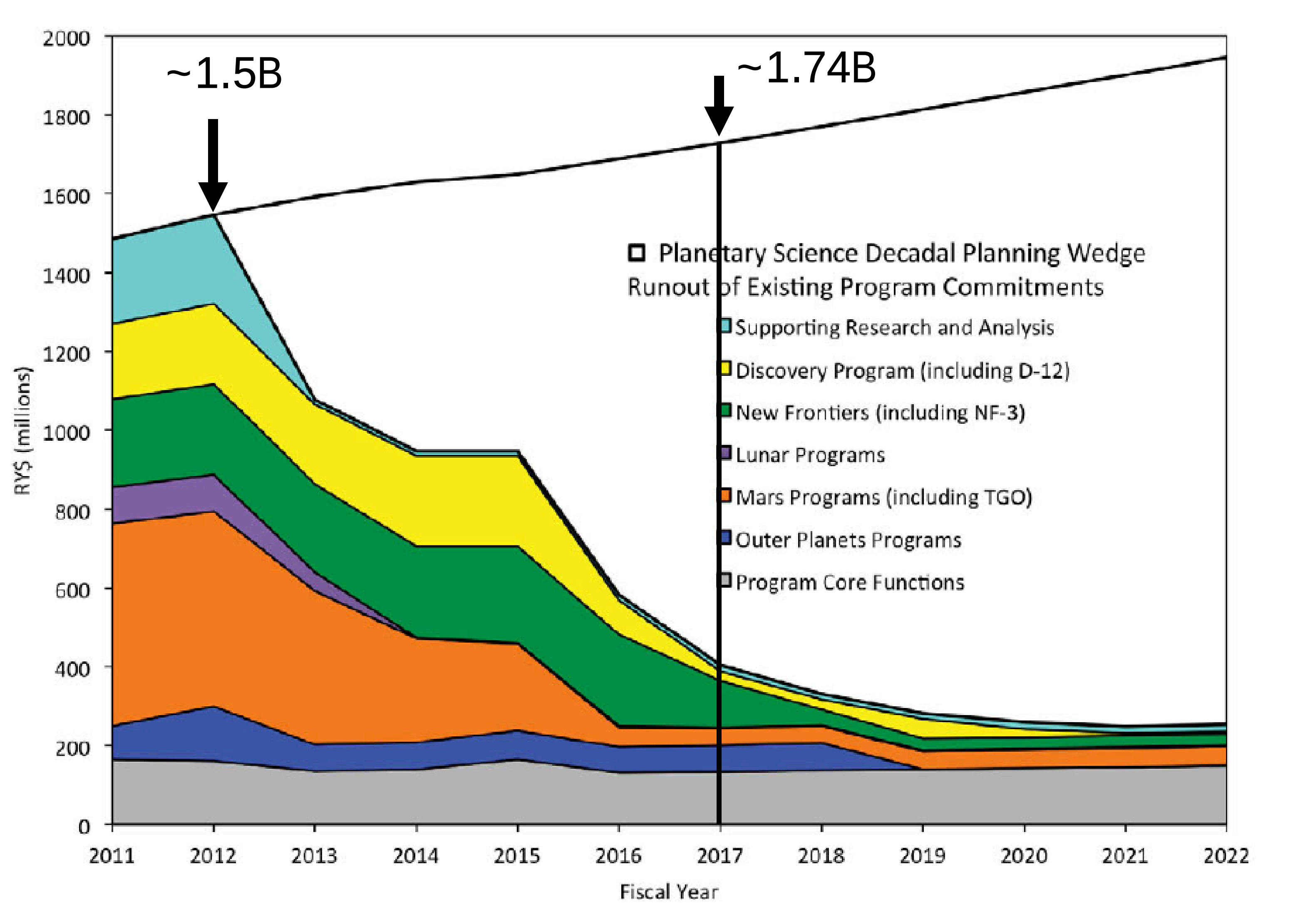
| | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|
| GPRAMA | GREEN | GREEN | GREEN | GREEN | GREEN |
| SOAR | | | Noteworthy Progress | Noteworthy Progress | Noteworthy Progress |


Planetary Science
Decadal Survey
Missions
New Frontiers
in the Solar System
An Integrated Exploration Strategy
2003
Decadal
Survey
VISION
and
VOYAGES
for Planetary Science in the Decade 2013-2022
2011
Decadal
Survey
1997
Cassini
2006
New Horizons
2011
Juno
2011
Curiosity
2013
MAVEN
2016
OSIRIS-REx
2018
InSight
Mars
Rover
2020
Europa
2022



Formulation
Implementation
Primary Ops
Extended Ops
BepiColombo (ESA)
Lunar Reconnaissance Orbiter
Lucy
New Horizons
Juno
Psyche
Dawn
Cassini (NASA/ESA)
OSIRIS-REx
JUICE (ESA)
Europa Clipper
NEOWISE
MRO
MAVEN
ExoMars 2016 (ESA)
MMX
(JAXA)
Mars Express (ESA)
Mars Odyssey
ExoMars 2020 (ESA)
Mars Rover 2020
Opportunity Rover
Curiosity Rover
InSight

# Budget Assumed for the Recommended Program*



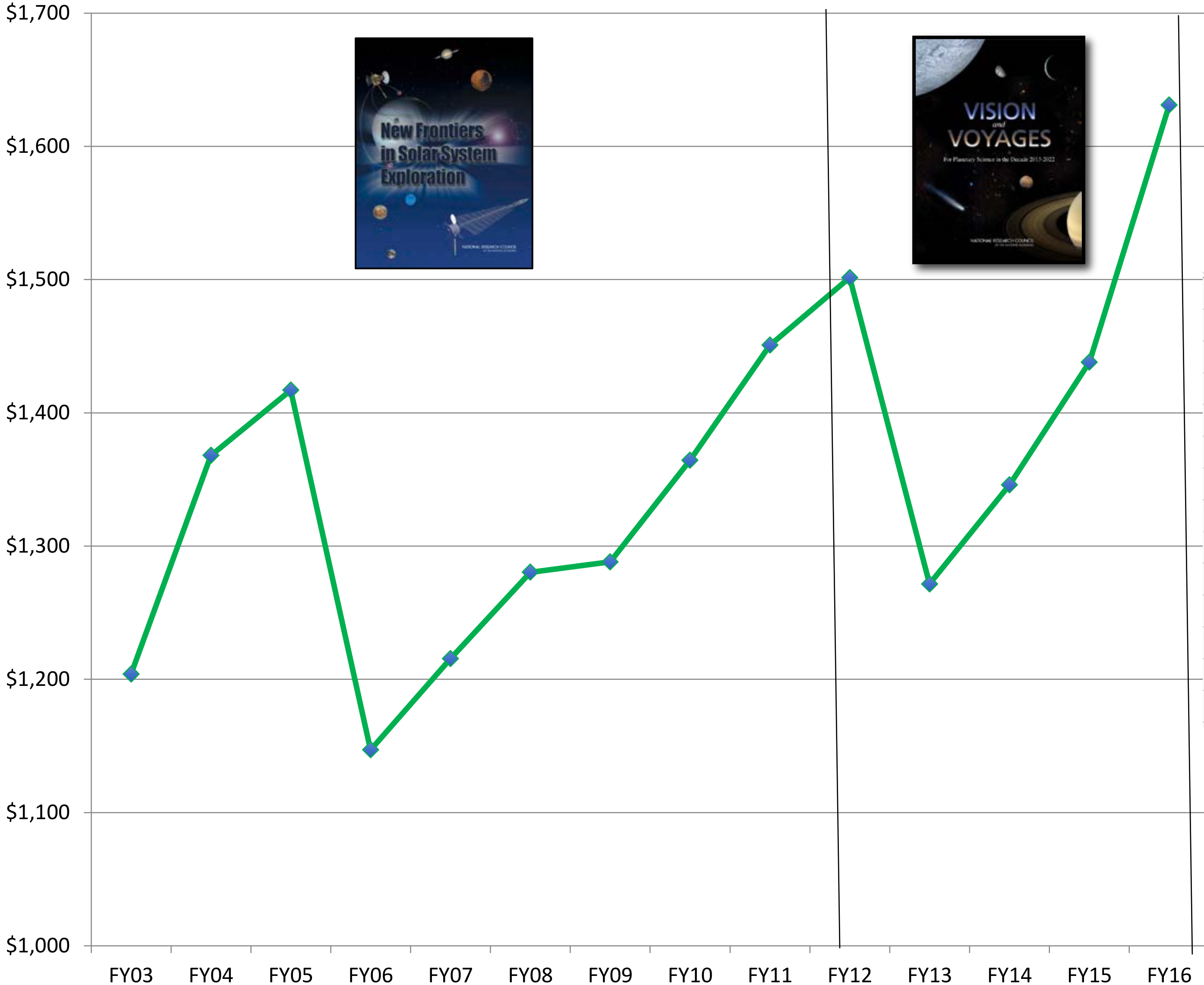

* from PSD Decadal V&V

# The Recommended Program

## (not in priority order)

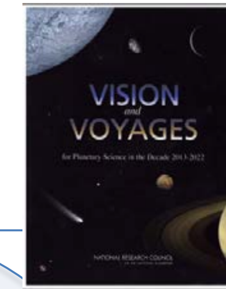
- *Ongoing and approved missions*
- *R&A program*
- *Technology program*
- *Discovery program at the current level adjusted for inflation*
- *Mars Trace Gas Orbiter conducted jointly with ESA*
- *New Frontiers Mission 4*
- *New Frontiers Mission 5*
- *Descoped MAX-C mission*
- *Descoped JEO mission*
- *Uranus Orbiter and Probe*

# NASA Planetary Science Budget History




| | |
|---|---|
| FY03 | $1,204.00 |
| FY04 | $1,368.00 |
| FY05 | $1,417.00 |
| FY06 | $1,147.00 |
| FY07 | $1,215.60 |
| FY08 | $1,280.30 |
| FY09 | $1,288.10 |
| FY10 | $1,364.40 |
| FY11 | $1,450.80 |
| FY12 | $1,501.40 |
| FY13 | $1,271.50 |
| FY14 | $1,346.00 |
| FY15 | $1,438.00 |
| FY16 | $1,631.00 |

# Planetary Program Architecture
# Recommended by the Planetary Decadal Survey




## Large Missions ("Flagship"-scale)

*"Recommended Program"*
*(budget increase for JEO new start)*

1) **Mars Astrobiology Explorer-Cacher – descoped**
2) **Jupiter Europa Orbiter (JEO) – descoped**
3) **Uranus Orbiter & Probe (UOP)**

4/5) **Enceladus Orbiter & Venus Climate Mission**

*"Cost Constrained Program"*
*(based on FY11 Request)*

1) **Mars Astrobiology Explorer-Cacher – descoped**
2) **Uranus Orbiter & Probe (UOP)**

*"Less favorable" budget picture than assumed*
*(e.g., outyears in FY12 request)*

**Descope or delay Flagship mission**

## Discovery

**$500M (FY15) cap per mission (exclusive of launch vehicle) and 24 month cadence for selection**

## New Frontiers

**$1B (FY15) cap per mission (exclusive of launch vehicle) with two selections during 2013-22**

## Research & Analysis (5% above final FY11 amount then ~1.5%/yr)

## Technology Development (6-8%)

## Current Commitments (ie: Operating Missions)

# If Less Funding Is Available…

- Descope or delay Flagship missions.
- Slip New Frontiers and/or Discovery missions only if adjustments to Flagship missions cannot solve the problem.
- Place high priority on preserving R&A and technology development funding.

# Implications

- Protect Discovery and New Frontiers.
- Fly a 2018 NASA/ESA Mars mission only if:
  - The cost to NASA is no more than $2.5 billion.
  - It sets both agencies realistically on a path to sample return.
- If Mars '18 does not meet these criteria, second priority is JEO. (There is no recommended "Plan B" for Mars.)
- If JEO is not affordable, third priority is UOP ($2.7 billion).
- If UOP is not affordable, fourth priority is Venus Climate Mission ($2.4 billion) or Enceladus Orbiter ($1.9 billion).

# Decadal Decision Rules Implemented

- "NASA's suite of planetary missions … should consist of a *balanced mix of Discovery, New Frontiers, and Flagship* missions, enabling both a steady stream of new discoveries and challenges …"

- "It is also possible that the budget picture could turn out to be less favorable … If cuts to the program are necessary, the committee recommends that the first approach should be *descoping or delaying Flagship missions*. *Changes to the New Frontiers or Discovery programs should be considered only if adjustments to Flagship missions cannot solve the problem*."

- Actions based on Decadal Guidance:
  - Maintain R&A and technology
  - Maintain a balanced program – small, medium, large missions
  - Maintain a partnership with ESA
  - Descope flagship missions as a first resort due to tight budgets
  - If flagship descopes are *not sufficient* then stretch out New Frontiers and Discovery AOs

# Key Recommendations

- *Increase the NASA planetary R&A budget by 5% above the total finally approved FY'11 expenditures in the first year, and then by 1.5% above inflation each successive year.*
- *Continue missions in development, and missions in flight subject to senior review.*
- *Continue the Discovery program at its current funding level, adjusted for inflation, with a cost cap per mission also adjusted for inflation (i.e., to $500 million FY'15).*
- *Assure a regular, predictable, and rapid (≤ 24-month) cadence of Discovery AOs and selections.*
- *Carry out Mars TGO as long as the current division of responsibilities with ESA is preserved.*
- *Establish a planetary exploration technology development program, funded at 6-8% of the total NASA PSD budget.*



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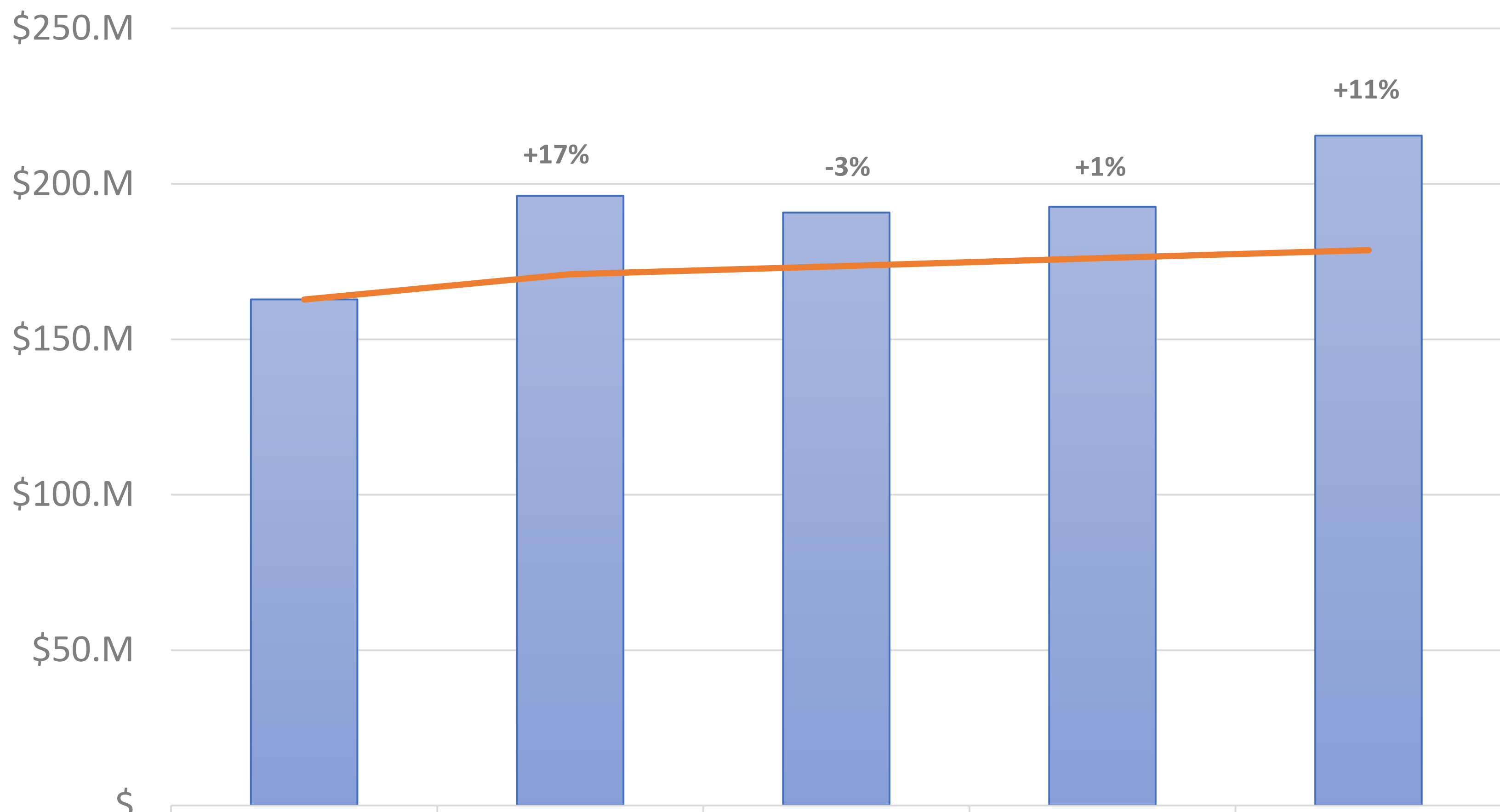
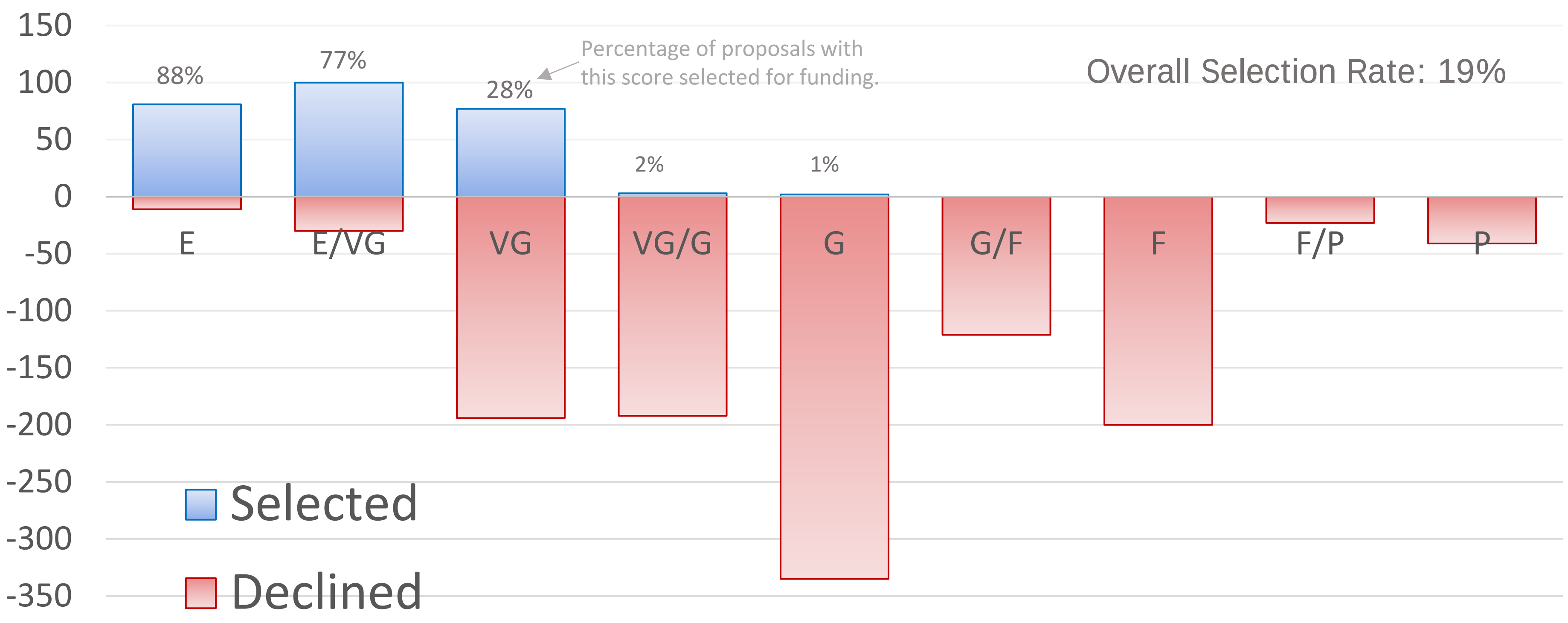
# R&A Program Expenditures




| | FY2011 | FY2012 | FY2013 | FY2014 | FY2015 |
|---|---|---|---|---|---|
| Actual Spending | $162.8M | $196.2M | $190.7M | $192.6M | $215.5M |
| Decadal Suggested | $162.8M | $170.9M | $173.5M | $176.1M | $178.7M |

# PSD R&A SELECTIONS - ROSES 2015



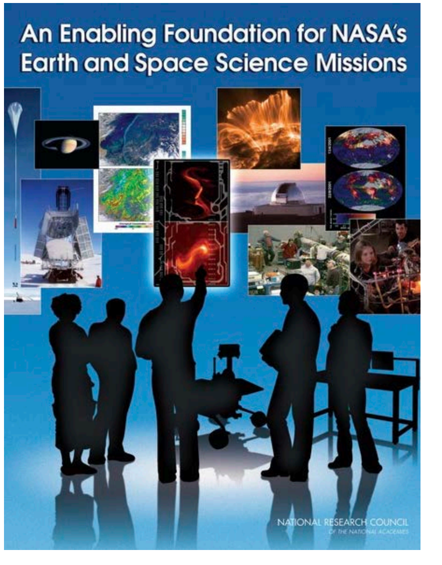

Metrics for proposals submitted to ROSES 2015, including all core programs (EW, SSW, HW, SSO, EXO) and all DAPs (MDAP, DDAP, LDAP, CDAPS).

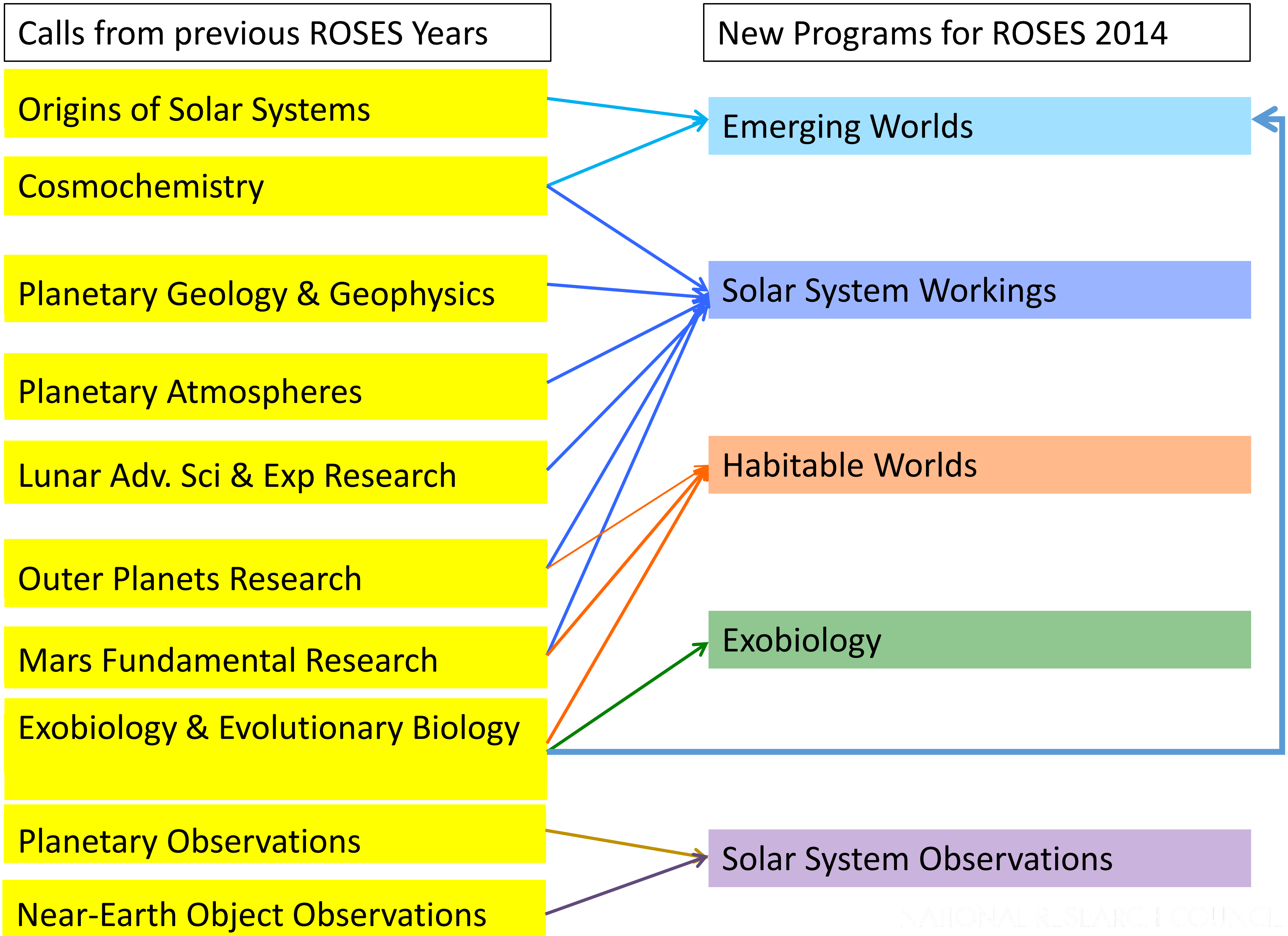
# Findings from the NRC report: An Enabling Foundation for NASA's Earth and Space Science Missions (2010)

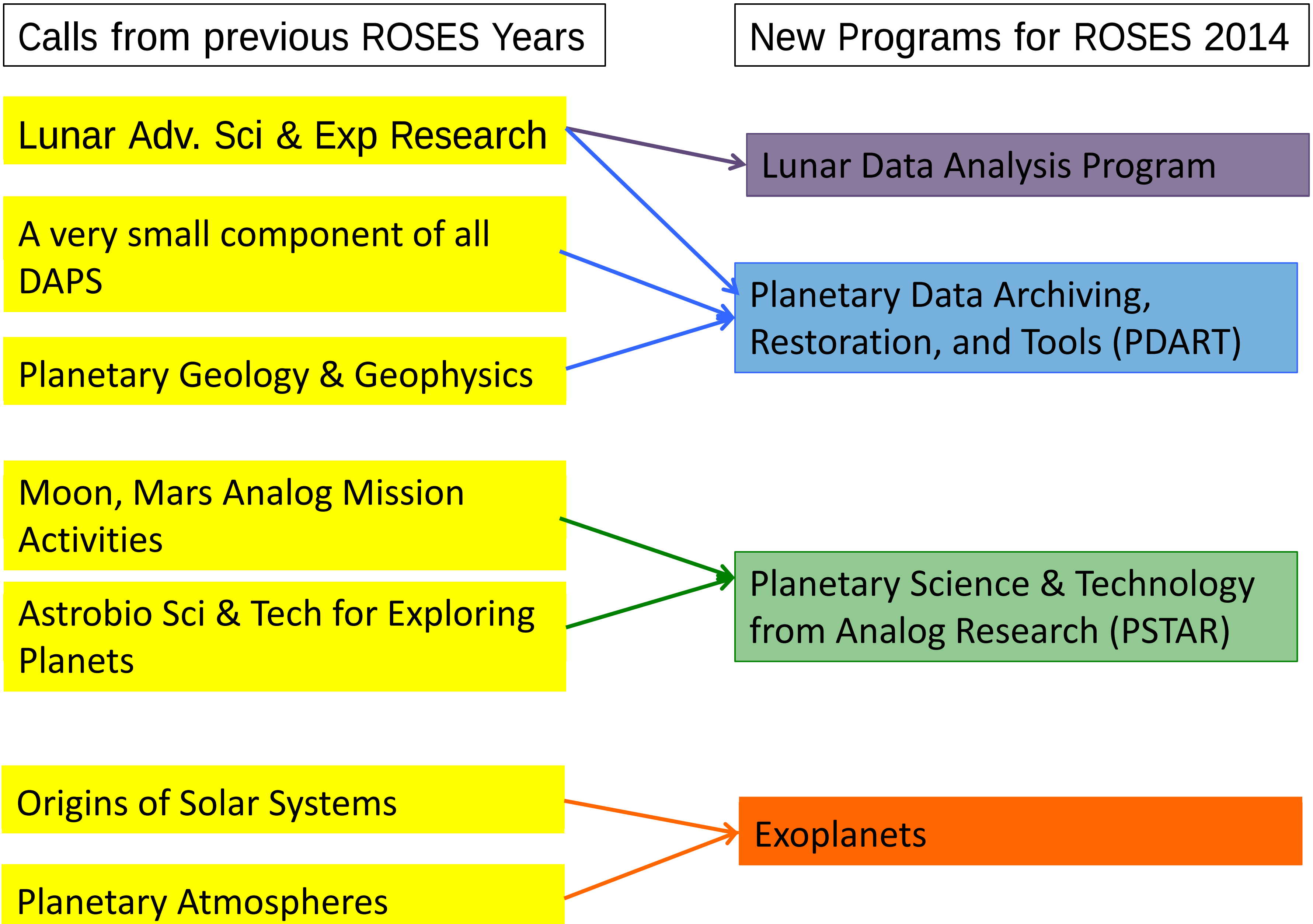
1. NASA should ensure that SMD mission-enabling activities are linked to the strategic goals of the agency and of SMD.
2. NASA's SMD should develop and implement an approach to actively managing its portfolio of mission-enabling activities.
3. NASA should increase the number of scientifically and technically capable program officers so that they can devote an appropriate level of attention to the tasks of actively managing the portfolio of research…

**NASA response** was in agreement with these recommendations: "By *explicitly* tying the ROSES solicitations…to the SMD Science Plan research objectives, SMD ensures that sponsored research contributes directly and substantially to Agency goals."

PSD reorganized its R&A program and the NAS complete a review of its implementation

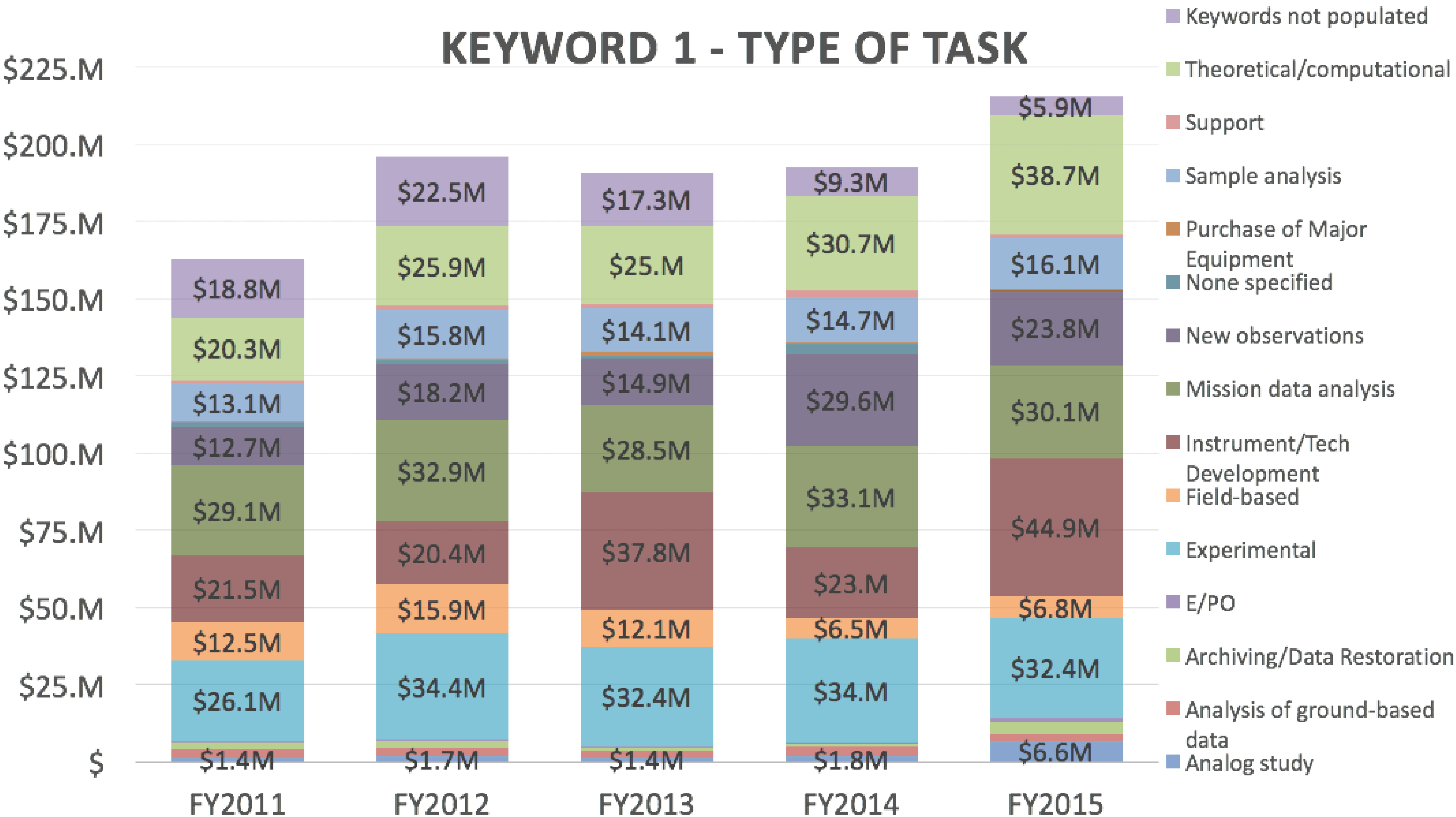



Calls from previous ROSES Years
New Programs for ROSES 2014
Origins of Solar Systems
Cosmochemistry
Planetary Geology & Geophysics
Planetary Atmospheres
Lunar Adv. Sci & Exp Research
Outer Planets Research
Mars Fundamental Research
Exobiology & Evolutionary Biology
Planetary Observations
Near-Earth Object Observations
Emerging Worlds
Solar System Workings
Habitable Worlds
Exobiology
Solar System Observations


Calls from previous ROSES Years
New Programs for ROSES 2014
Lunar Adv. Sci & Exp Research
Lunar Data Analysis Program
A very small component of all DAPS
Planetary Data Archiving, Restoration, and Tools (PDART)
Planetary Geology & Geophysics
Moon, Mars Analog Mission Activities
Astrobio Sci & Tech for Exploring Planets
Planetary Science & Technology from Analog Research (PSTAR)
Origins of Solar Systems
Exoplanets
Planetary Atmospheres

# Keyword Analysis

- Analysis of keyword distribution, 2011-2015 for categories:
  - Type of Task (keyword category 1)
  - Object(s) of Study (keyword category 2)
  - Science Discipline (keyword category 3)
- Analysis includes:
  - R&A awards, including NAI CAN awards
  - Data Analysis Programs
  - Participating Scientist and Guest Investigator Programs
- Analysis excludes:
  - Support activities
  - Facilities (e.g. RPIFs, AVGR, GEER, PAL, RELAB, …)
- Caveats
  - If more than one keyword was used within any category, approved amount was equally divided between keywords
  - Return rate varied from year to year, portfolio to portfolio, and keyword category to keyword category
  - Keywords might have been used inconsistently between program officers



KEYWORD 1 - TYPE OF TASK
$225.M
$200.M
$175.M
$150.M
$125.M
$100.M
$75.M
$50.M
$25.M
$
FY2011
FY2012
FY2013
FY2014
FY2015
$18.8M
$20.3M
$13.1M
$12.7M
$29.1M
$21.5M
$12.5M
$26.1M
$1.4M
$22.5M
$25.9M
$15.8M
$18.2M
$32.9M
$20.4M
$15.9M
$34.4M
$1.7M
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$25.M
$14.1M
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$5.9M
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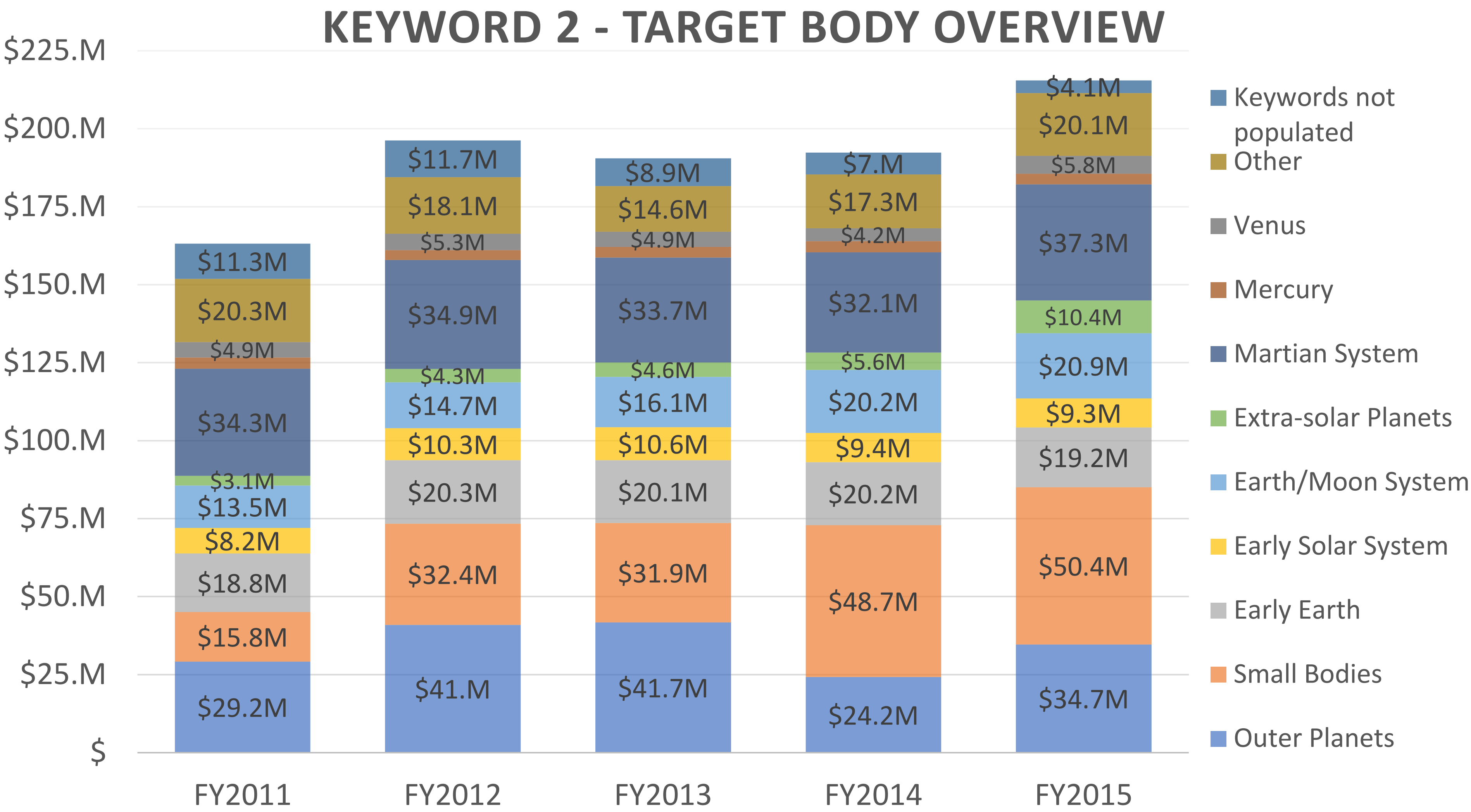
$23.8M
$30.1M
$44.9M
$6.8M
$32.4M
$6.6M
Keywords not populated
Theoretical/computational
Support
Sample analysis
Purchase of Major Equipment
None specified
New observations
Mission data analysis
Instrument/Tech Development
Field-based
Experimental
E/PO
Archiving/Data Restoration
Analysis of ground-based data
Analog study


KEYWORD 2 - TARGET BODY OVERVIEW
$225.M
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$150.M
$125.M
$100.M
$75.M
$50.M
$25.M
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FY2011
FY2012
FY2013
FY2014
FY2015
$11.3M
$20.3M
$4.9M
$34.3M
$3.1M
$13.5M
$8.2M
$18.8M
$15.8M
$29.2M
$11.7M
$18.1M
$5.3M
$34.9M
$4.3M
$14.7M
$10.3M
$20.3M
$32.4M
$41.M
$8.9M
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$4.6M
$16.1M
$10.6M
$20.1M
$31.9M
$41.7M
$7.M
$17.3M
$4.2M
$32.1M
$5.6M
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$48.7M
$24.2M
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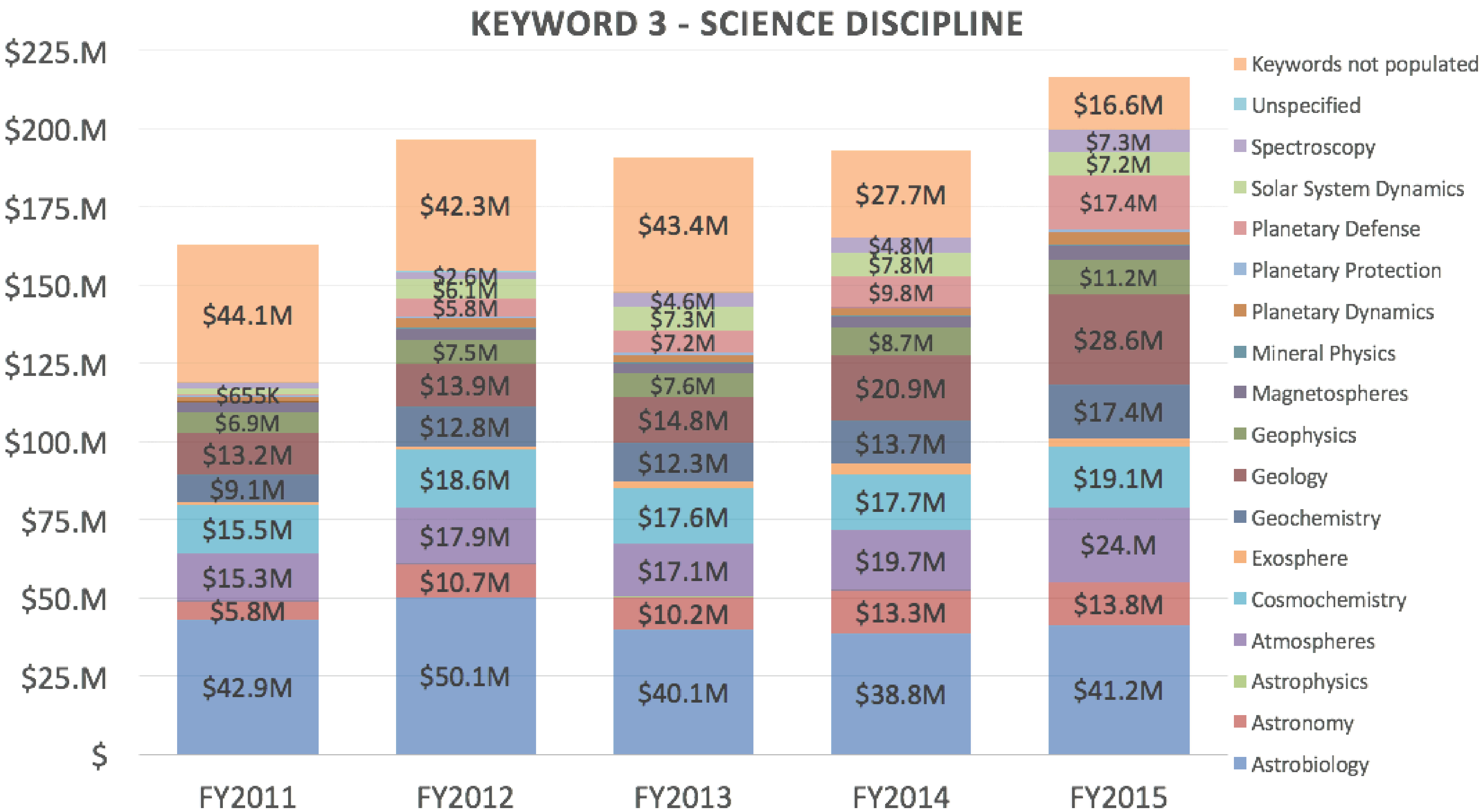
$5.8M
$37.3M
$10.4M
$20.9M
$9.3M
$19.2M
$50.4M
$34.7M
Keywords not populated
Other
Venus
Mercury
Martian System
Extra-solar Planets
Earth/Moon System
Early Solar System
Early Earth
Small Bodies
Outer Planets



KEYWORD 3 - SCIENCE DISCIPLINE
$225.M
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$125.M
$100.M
$75.M
$50.M
$25.M
$
$44.1M
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$15.5M
$15.3M
$5.8M
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$7.2M
$17.4M
$11.2M
$28.6M
$17.4M
$19.1M
$24.M
$13.8M
$41.2M
FY2011
FY2012
FY2013
FY2014
FY2015
Keywords not populated
Unspecified
Spectroscopy
Solar System Dynamics
Planetary Defense
Planetary Protection
Planetary Dynamics
Mineral Physics
Magnetospheres
Geophysics
Geology
Geochemistry
Exosphere
Cosmochemistry
Atmospheres
Astrophysics
Astronomy
Astrobiology

# Planetary Funded Facilities

Objective:

Ensure that NASA-funded, science-enabling research facilities support the needs of planetary science community. These facilities are open to the community.

Current Funded Facilities:

- NASA Ames Planetary Aeolian Laboratory (PAL)
- NASA Ames Vertical Gun Range (AVGR)
- Reflectance Experiment Laboratory (RELab)
- NASA Glenn Extreme Environments Rig (GEER)

Soliciting New Facilities:

- Release a Cooperative Agreement Notice (CAN) to fund facilities that would answer the needs of the community
- CAN delayed until NASA receives the National Academies report regarding laboratory analytical capabilities and the current sample laboratory support infrastructure.

# NAS Review of the Restructured Research& Analysis Programs of NASA's Planetary Science Division

1. Are the PSD R&A program elements appropriately linked to, and do they encompass the range and scope of activities needed to support the NASA strategic objective for planetary science and the Planetary Science Division's science goals, as articulated in NASA's *2014 Science Plan*?

NAS Response: The committee finds that the current R&A structure is properly aligned with scientific priorities of the decadal survey and the Planetary Science Division 2014 science goals.

2. Are the PSD R&A program elements appropriately structured to develop the broad base of knowledge and broad range of activities needed both to enable new spaceflight missions and to interpret and maximize the scientific return from existing missions?

NAS Response: The committee finds that the structure of the program elements will allow NASA PSD to prepare for future spaceflight missions and to maximize science value from existing missions.

# Key Recommendations

- *Increase the NASA planetary R&A budget by 5% above the total finally approved FY'11 expenditures in the first year, and then by 1.5% above inflation each successive year.*
- *Continue missions in development, and missions in flight subject to senior review.*
- *Continue the Discovery program at its current funding level, adjusted for inflation, with a cost cap per mission also adjusted for inflation (i.e., to $500 million FY'15).*
- *Assure a regular, predictable, and rapid (≤ 24-month) cadence of Discovery AOs and selections.*
- *Carry out Mars TGO as long as the current division of responsibilities with ESA is preserved.*
- *Establish a planetary exploration technology development program, funded at 6-8% of the total NASA PSD budget.*



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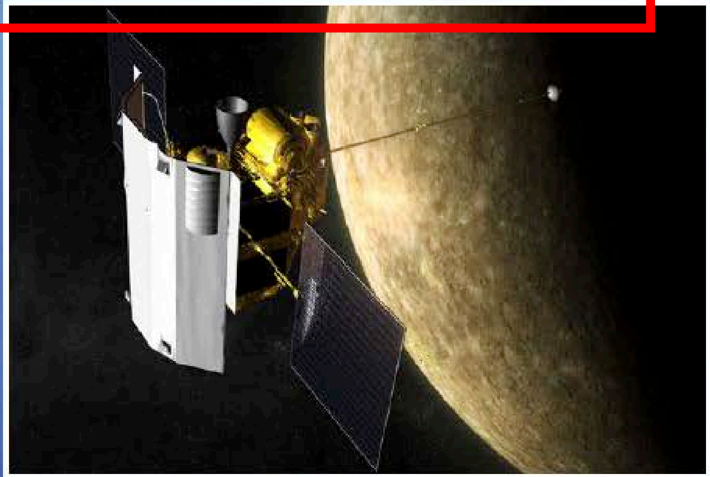
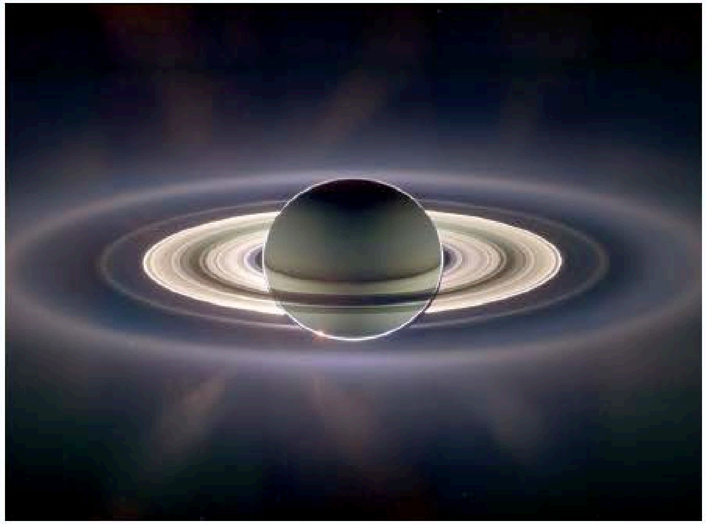
# Ongoing and Approved Missions

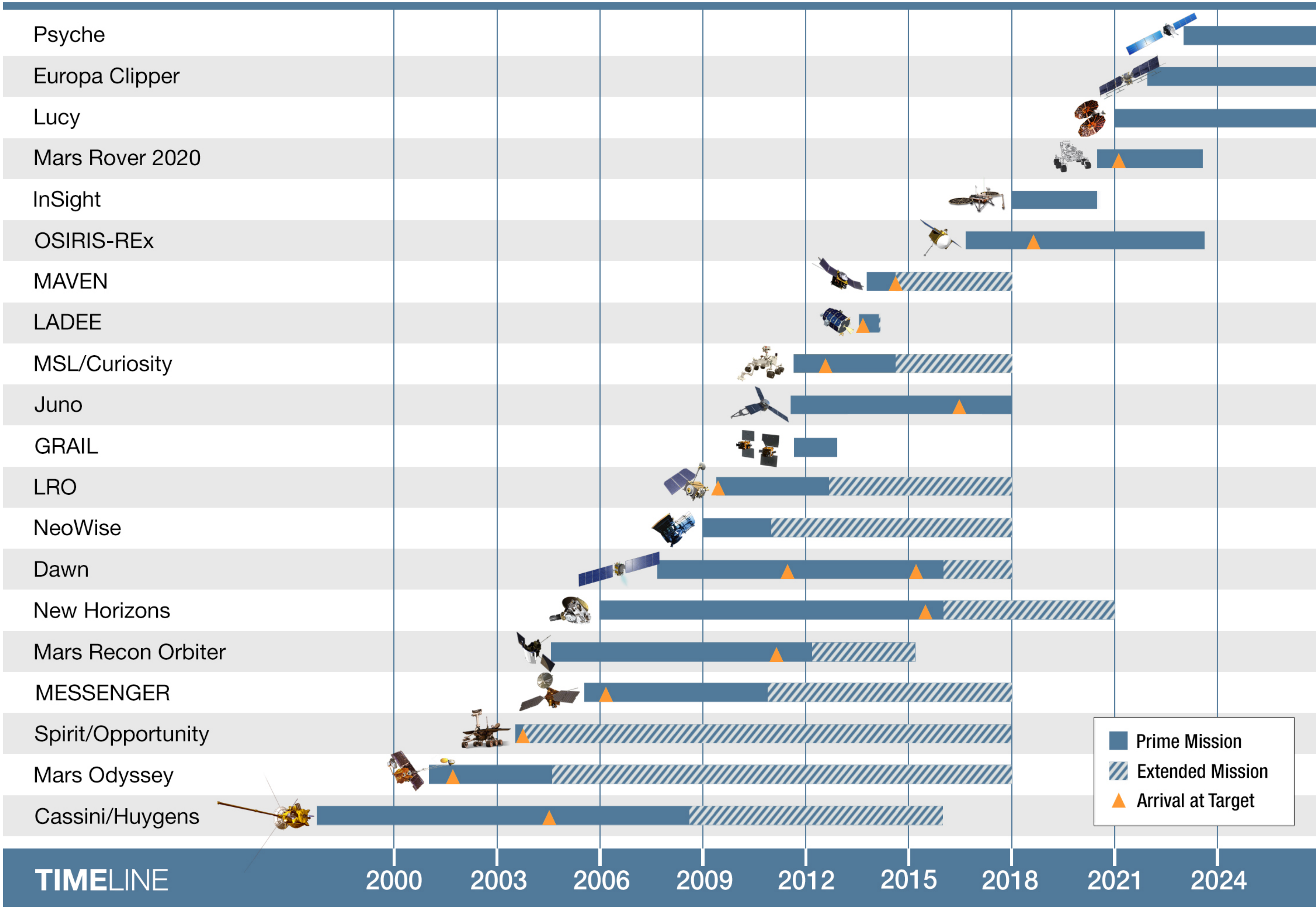
- *Continue missions in development, and missions in flight subject to senior review.*

- Discovery:
  - MESSENGER (in flight)
  - Dawn (in flight)
  - Kepler (in flight)
  - GRAIL (in development)
- New Frontiers:
  - NF-1: New Horizons (in flight)
  - NF-2: Juno (in development)
  - NF-3: TBD (to be selected soon)
- Others:
  - Cassini (in flight)
  - ODY/MRO/MER (in flight)
  - MSL/MAVEN (in development)
  - LADEE (in development)



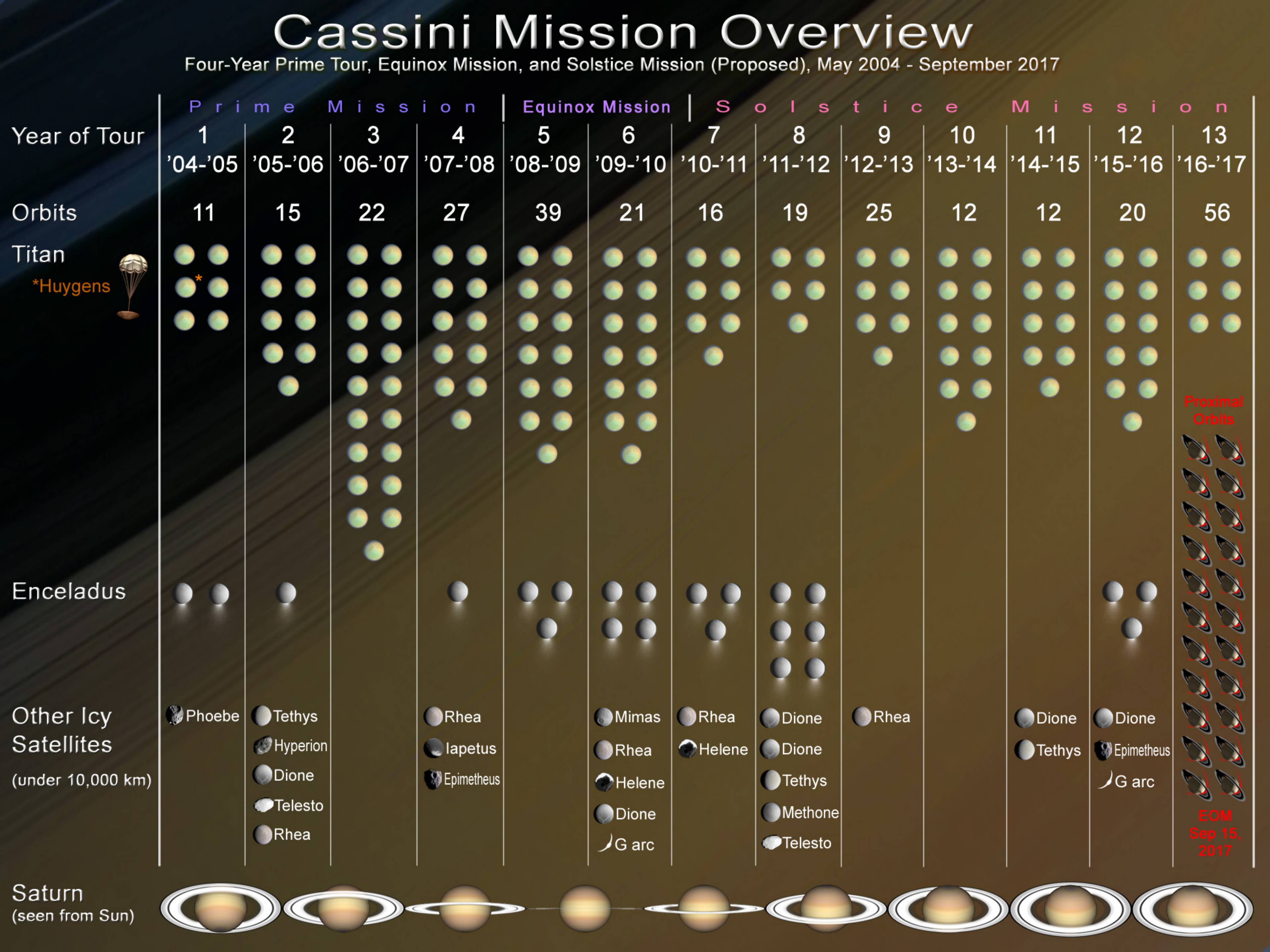


# Planetary Science: NASA Missions

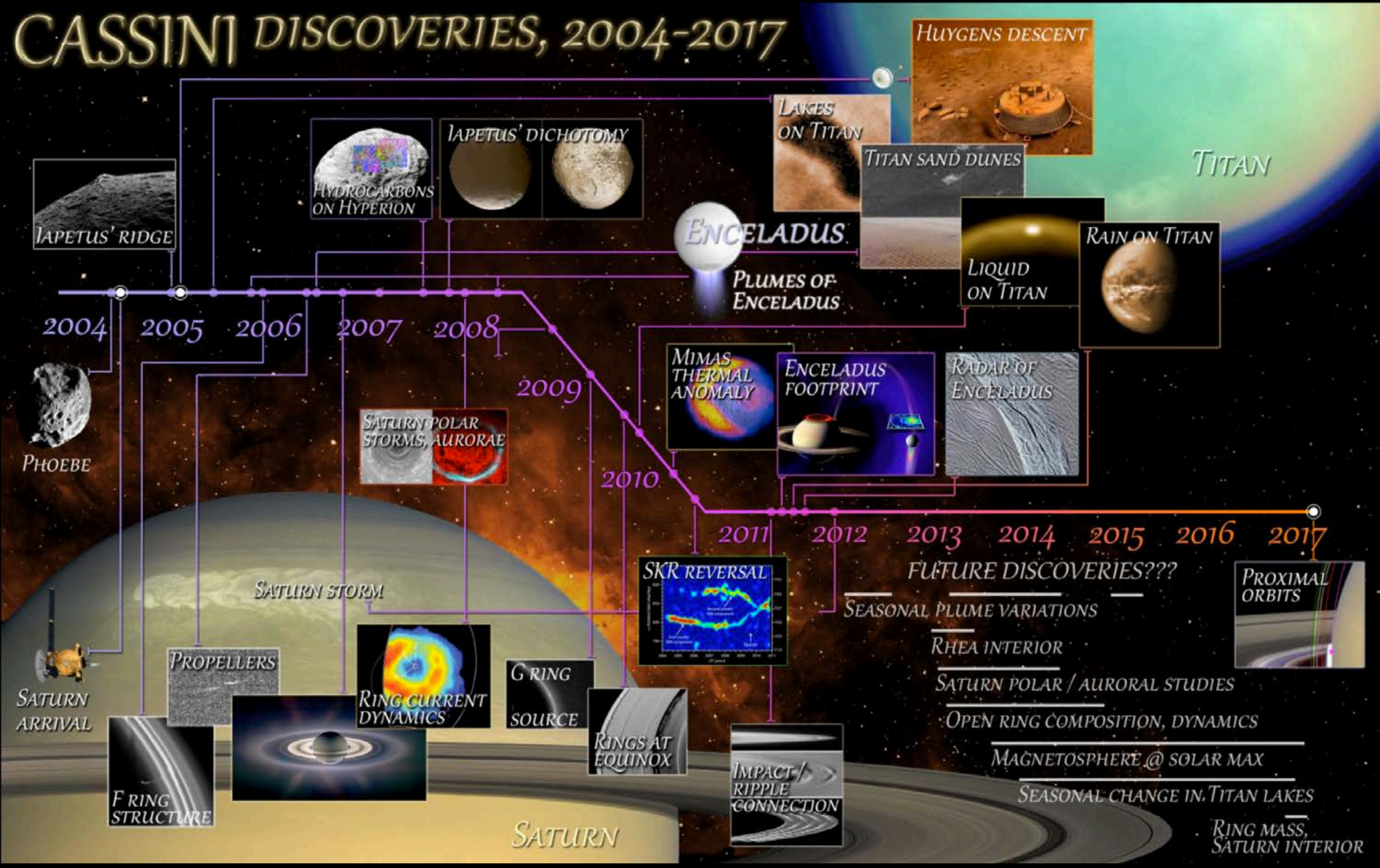


# Cassini

- The Cassini spacecraft has returned an unprecedented volume of data from the Saturn system. It completed its main mission in 2008, returning nearly 2 terabytes of data on the planet, magnetosphere, rings, and satellites.
- The mission has also completed its first extended mission, ending in mid-2010. During this time, many advances were made in our understanding of Saturn, including a new value for the most basic of quantities—its deep internalrotation rate.
- In the so-called Solstice mission, Cassini will continue its operations until a planned atmospheric entry in 2017.
- ***The value of this data set cannot be overestimated.***
- ***The extended time base of observations is critical for understanding several aspects of Saturn's atmosphere, including the much longer and larger seasonal variations (as compared with those of Jupiter), as well as its long-period equatorial oscillation.***
- The Solstice mission results will provide many insights into the dynamics and circulation on this planet, as well as understanding of polar vortex formation, ring shadowing effects, and other atmospheric phenomena.
- It will also greatly extend the time baseline for the study of variable features in the rings, such as spokes, propellers, and noncircular ring edges, while permitting radio occultation probes of ring structure at many different incidence angles.
- In addition, the planned end-of-life scenario to place the craft into a Juno-like orbit (to constrain the internal mass distribution and higher-order magnetic-field components) adds an economic mini-mission that will allow comparison of the internal structures of Jupiter and Saturn.

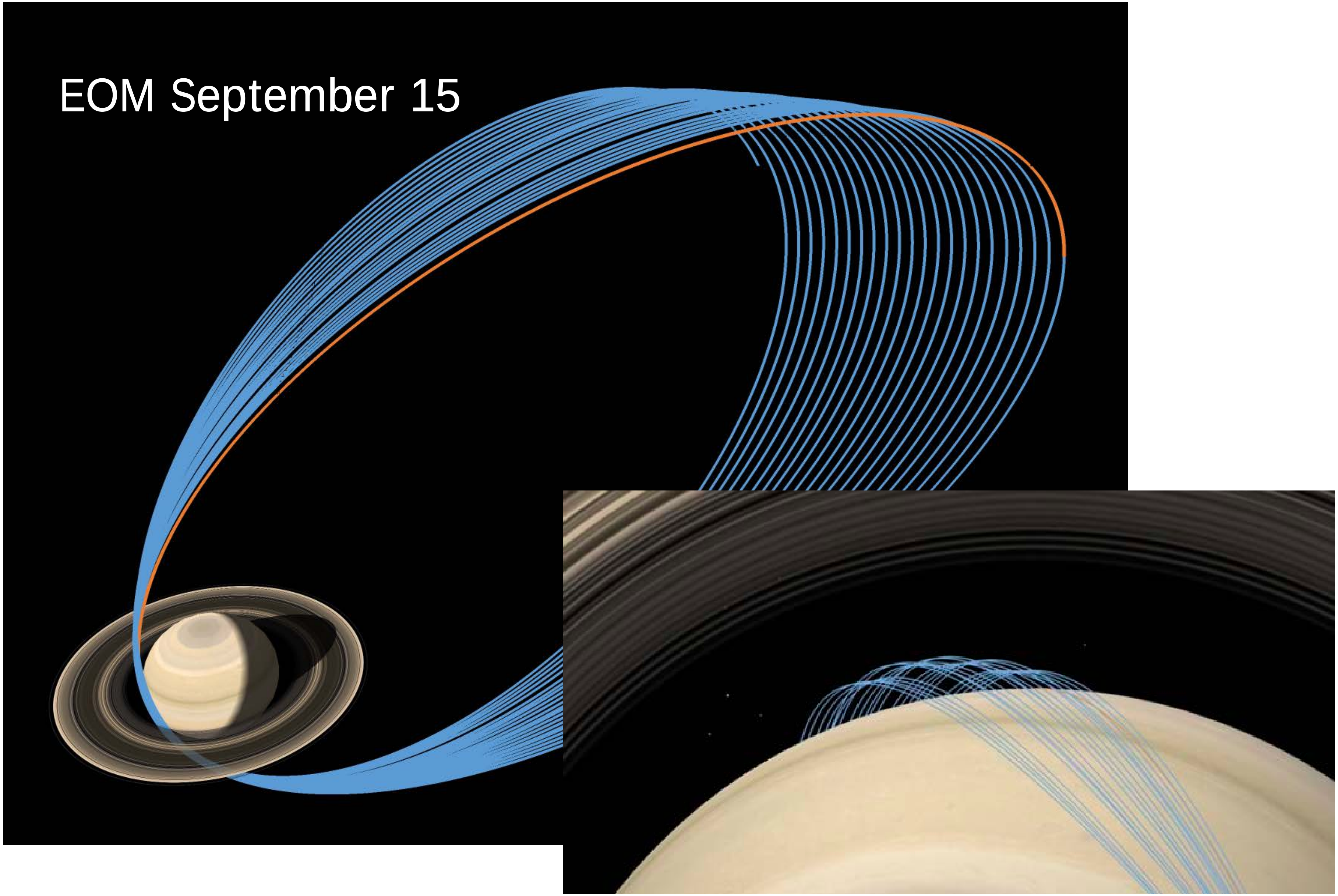


Cassini Mission Overview
Four-Year Prime Tour, Equinox Mission, and Solstice Mission (Proposed), May 2004 - September 2017
Prime Mission
Equinox Mission
Solstice Mission
Year of Tour
1 '04-'05
2 '05-'06
3 '06-'07
4 '07-'08
5 '08-'09
6 '09-'10
7 '10-'11
8 '11-'12
9 '12-'13
10 '13-'14
11 '14-'15
12 '15-'16
13 '16-'17
Orbits
11
15
22
27
39
21
16
19
25
12
12
20
56
Titan
*Huygens
Proximal Orbits
Enceladus
Other Icy Satellites
(under 10,000 km)
Phoebe
Tethys
Hyperion
Dione
Telesto
Rhea
Rhea
Iapetus
Epimetheus
Mimas
Rhea
Helene
Dione
G arc
Rhea
Helene
Dione
Dione
Tethys
Methone
Telesto
Rhea
Dione
Tethys
Dione
Epimetheus
G arc
EOM Sep 15, 2017
Saturn
(seen from Sun)



CASSINI DISCOVERIES, 2004-2017
Huygens descent
Lakes on Titan
Titan sand dunes
Titan
Iapetus' dichotomy
Hydrocarbons on Hyperion
Iapetus' ridge
Enceladus
Plumes of Enceladus
Liquid on Titan
Rain on Titan
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Phoebe
Mimas thermal anomaly
Enceladus footprint
Radar of Enceladus
Saturn polar storms, aurorae
SKR reversal
Future discoveries???
Seasonal plume variations
Rhea interior
Saturn polar / auroral studies
Open ring composition, dynamics
Magnetosphere @ solar max
Seasonal change in Titan lakes
Ring mass, Saturn interior
Proximal orbits
Saturn storm
Saturn arrival
Propellers
Ring current dynamics
G ring source
Rings at equinox
Impact / ripple connection
F ring structure
Saturn

# Grand Finale Orbits Have Started



# Senior Reviews & Selected Recommendations

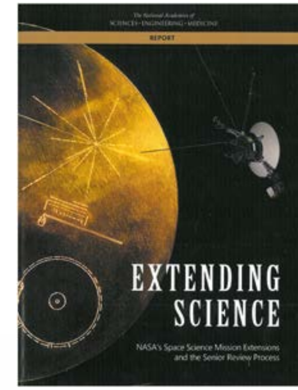



**TABLE 3.4** Planetary Science Division Senior Reviews by Year and Missions Reviewed

| | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2016 |
|---|---|---|---|---|---|---|---|---|---|---|
| Cassini | | ● | | ● | | | ● | | ● | |
| Curiosity | | | | | | | | | ● | ● |
| Dawn | | | | | | | | | | ● |
| Deep Impact | | | | | | | ● | | | |
| GRAIL | | | | | | | ● | | | |
| LRO | | | | | | | ● | | ● | |
| MAVEN | | | | | | | | | | ● |
| MER | ● | | ● | | ● | | ● | | ● | ● |
| Mars Global Surveyor | ● | | | | | | | | | |
| Mars Express | ● | | ● | | ● | | ● | | ● | ● |
| MRO | | | ● | | ● | | ● | | ● | ● |
| MESSENGER | | | | | | ● | | ● | | |
| Odyssey | ● | | ● | | ● | | ● | | ● | ● |
| Phoenix | | | ● | | | | | | | |
| New Horizons | | | | | | | | | | ● |
| Stardust-NExT | | | ● | | | | | | | |

- Recommendation: NASA should strongly support a robust portfolio of extended-phase science missions.
- Recommendation: NASA should conduct full Senior Review ... on a 3 year cadence.

# Key Recommendations

- *Increase the NASA planetary R&A budget by 5% above the total finally approved FY'11 expenditures in the first year, and then by 1.5% above inflation each successive year.*

- *Continue missions in development, and missions in flight subject to senior review.*

- *Continue the Discovery program at its current funding level, adjusted for inflation, with a cost cap per mission also adjusted for inflation (i.e., to $500 million FY'15).*

- *Assure a regular, predictable, and rapid (≤ 24-month) cadence of Discovery AOs and selections.*

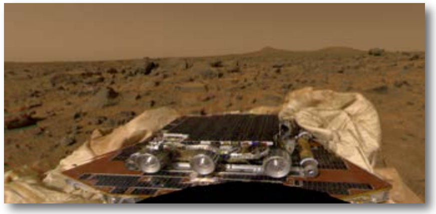
- *Carry out Mars TGO as long as the current division of responsibilities with ESA is preserved.*

- *Establish a planetary exploration technology development program, funded at 6-8% of the total NASA PSD budget.*

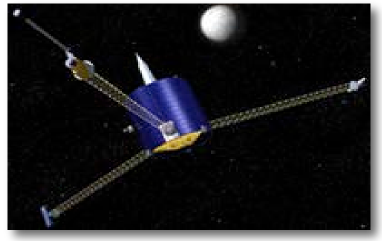
# Discovery Program

**Completed**

**Mars evolution:
Mars Pathfinder (1996-1997)**



**Lunar formation:
Lunar Prospector (1998-1999)**

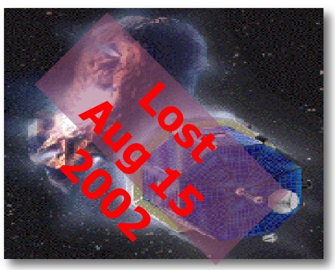


**NEO characteristics:
NEAR (1996-1999)**

**Solar wind sampling:
Genesis (2001-2004)**

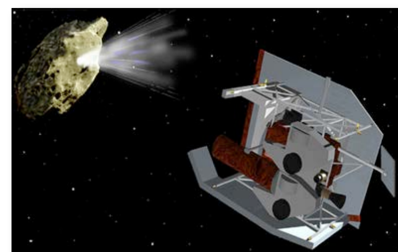
**Completed**

**Comet diversity:
CONTOUR (2002)**

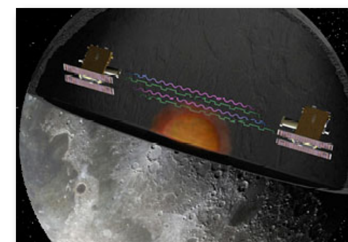



**Nature of dust/coma:
Stardust (1999-2011)**

**Comet internal structure:
Deep Impact (2005-2012)**

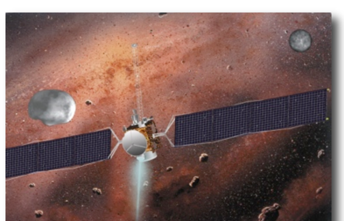


**Lunar Internal Structure
GRAIL (2011-2012)**



**Mercury environment:
MESSENGER (2004-*2015*)**

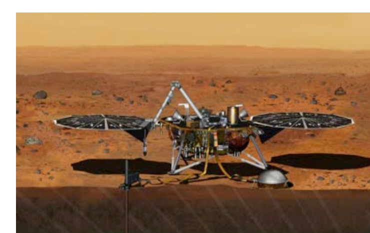
**Main-belt asteroids:
Dawn (2007-*TBD*)**



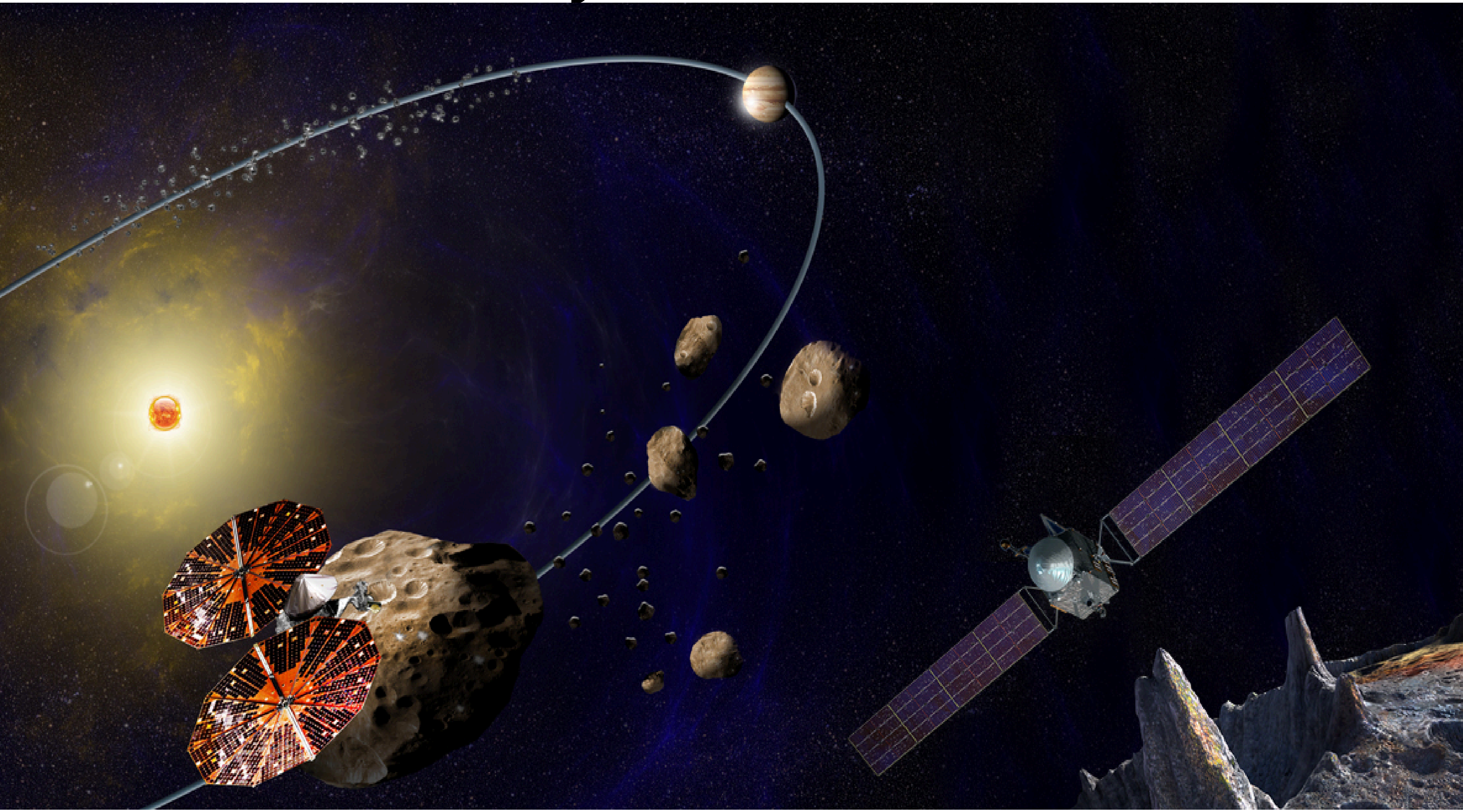
**Lunar surface:
LRO (2009-*TBD*)**

**ESA/Mercury Surface:
Strofio (*2017-TBD*)**

**Mars Interior:
InSight (*2018*)**



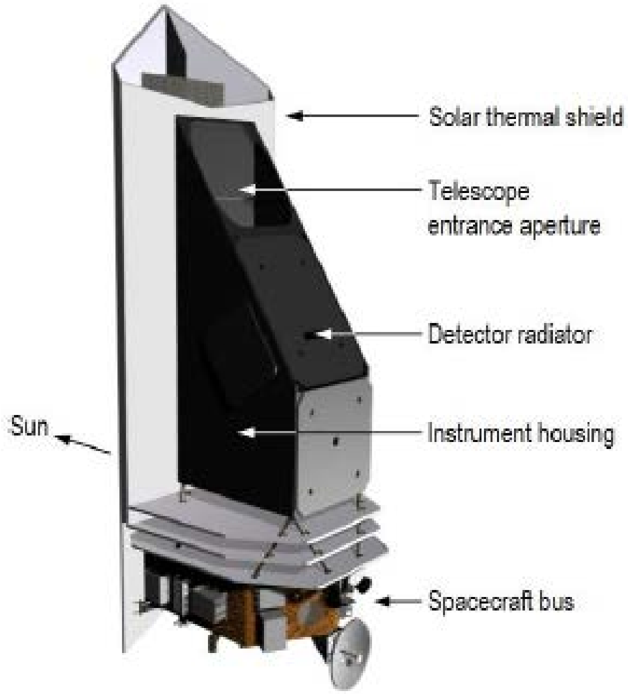
# Discovery Selections 2017



Lucy: Surveying the Diversity of Trojan Asteroids
PI: Harold Levison, SwRI

Psyche: Journey to a Metal World
PI: Linda Elkins-Tanton, ASU
**Deep-Space Optical Comm (DSOC)**

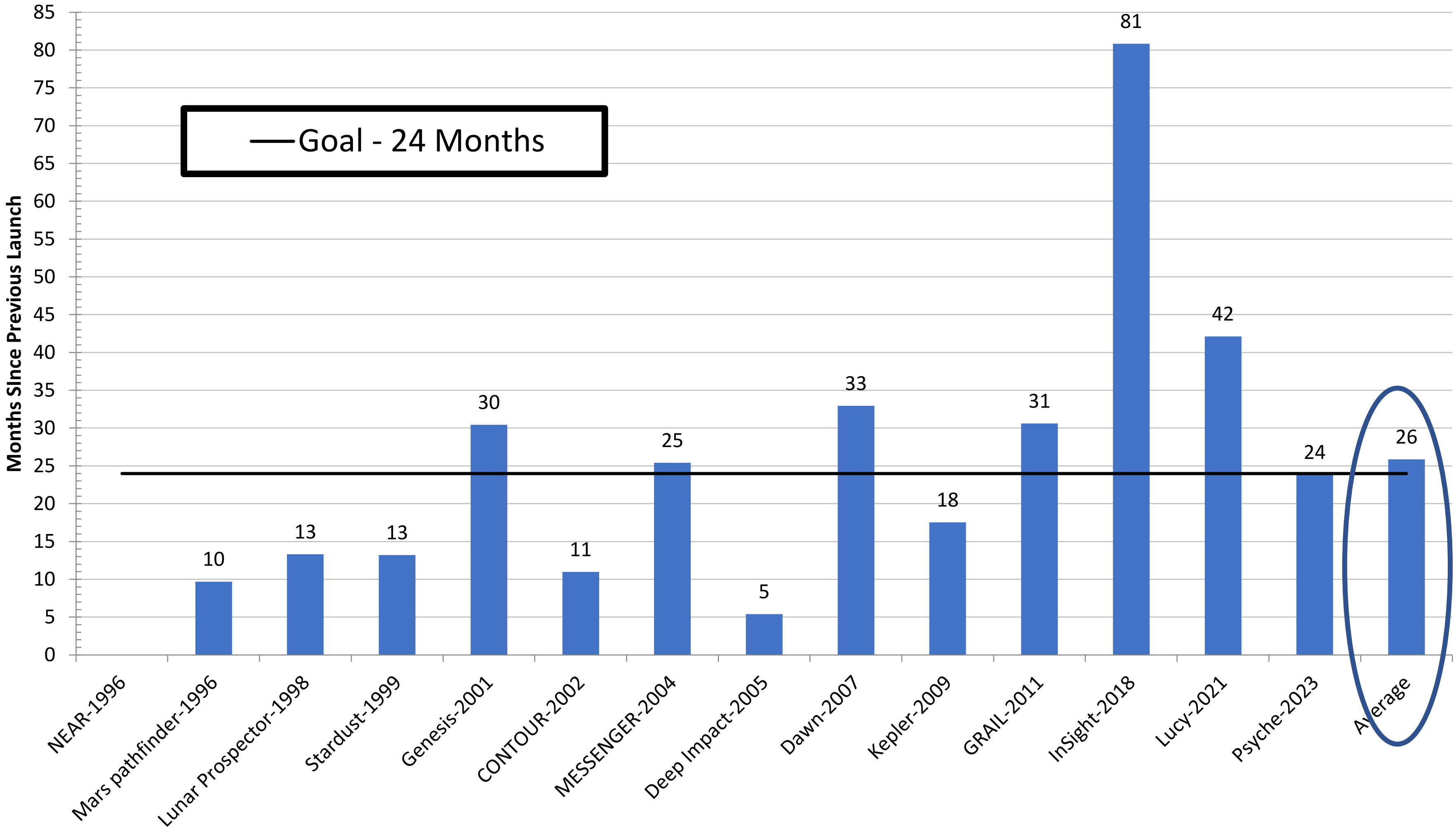
# Discovery Selections 2017




NEOCam:
Near-Earth Object Camera
PI: Amy Mainzer, JPL

The Discovery Program selection of NEOCam for an extended Phase A effort is an acknowledgement that, even though it was not selected for full mission implementation, it is an important capability for the Agency that will continue formulation efforts to address issues identified in the Discovery evaluation process.

# Discovery Program Launch Rate



# Summary: Discovery Program

- Decadal: Cost cap of $500M-FY15 (Phase A-E w/o LV)
  - Cost cap raised $450M-FY15$ (Phase A-D w/o LV)
  - Phase E costs developed in Phase A and is part of Step 2
  - Better approach than $500M for Phase A-E
    - Does not penalize missions with long cruise periods
    - Obtain more accurate cost estimates for Phase-E

- Decadal: 24 month cadence
  - InSight -> Launched delayed to 2018 (due to 26 mo window)
  - Not possible due to previous budget constraints
  - Next Discovery Call is planned for 2018
  - Goal is to bring the cadence back to 24 months – budget dependent

- Discovery 14 -> Selected 5 -Phase A missions studies with 2 selected for flight (Lucy and Psyche)

# Key Recommendations

- *Increase the NASA planetary R&A budget by 5% above the total finally approved FY'11 expenditures in the first year, and then by 1.5% above inflation each successive year.*
- *Continue missions in development, and missions in flight subject to senior review.*
- *Continue the Discovery program at its current funding level, adjusted for inflation, with a cost cap per mission also adjusted for inflation (i.e., to $500 million FY'15).*
- *Assure a regular, predictable, and rapid (≤ 24-month) cadence of Discovery AOs and selections.*
- *Carry out Mars TGO as long as the current division of responsibilities with ESA is preserved.*
- *Establish a planetary exploration technology development program, funded at 6-8% of the total NASA PSD budget.*

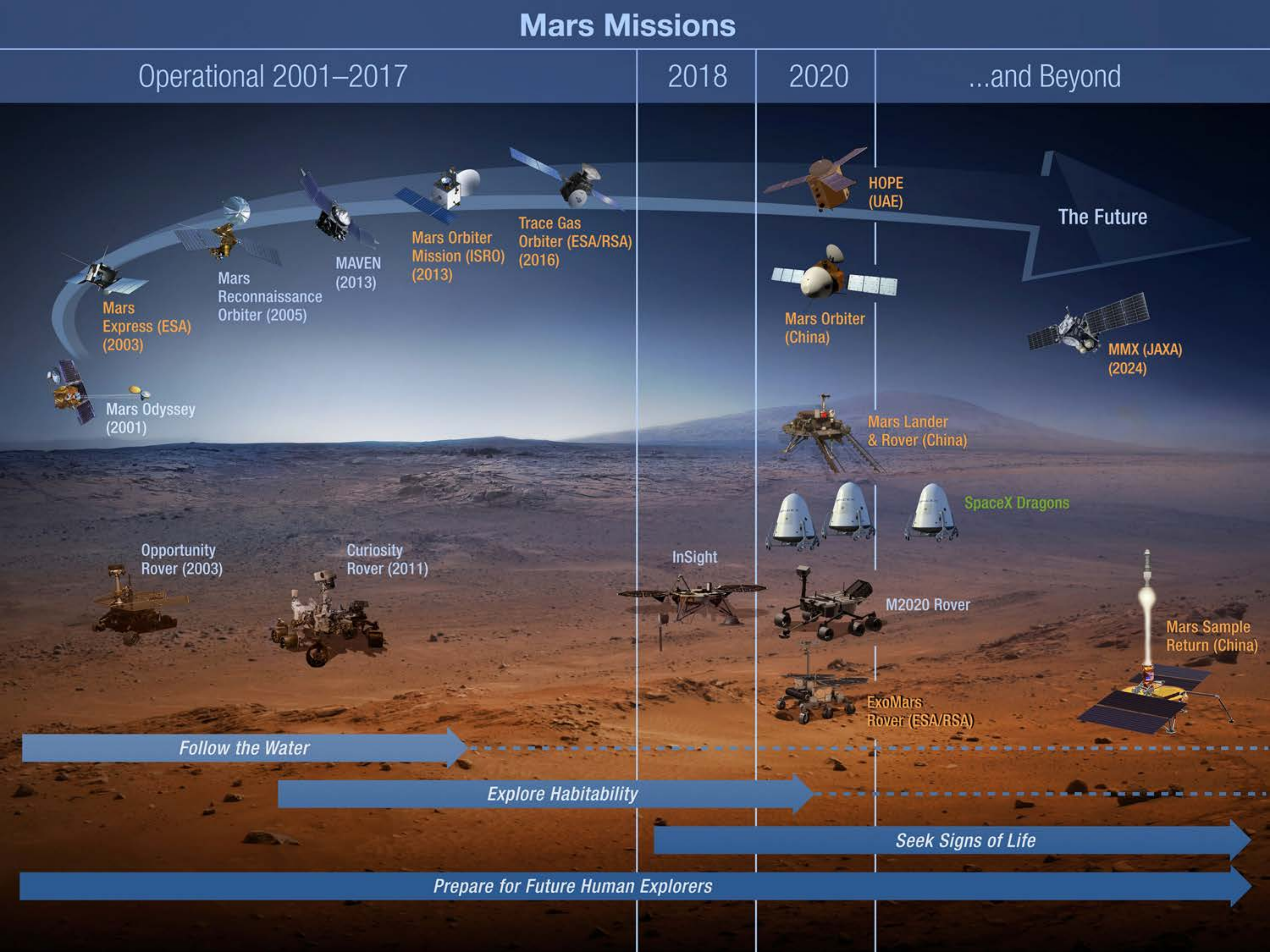
# Summary: ESA's ExoMars Program

## ESA Trace Gas Orbiter

- TGO had a significant change in NASA's responsibility:
  - Electra system installed and will be used as a communications relay with surface assets: Opportunity, Curiosity, and future missions (InSight, ExoMars Rover, and Mars 2020 Rover)

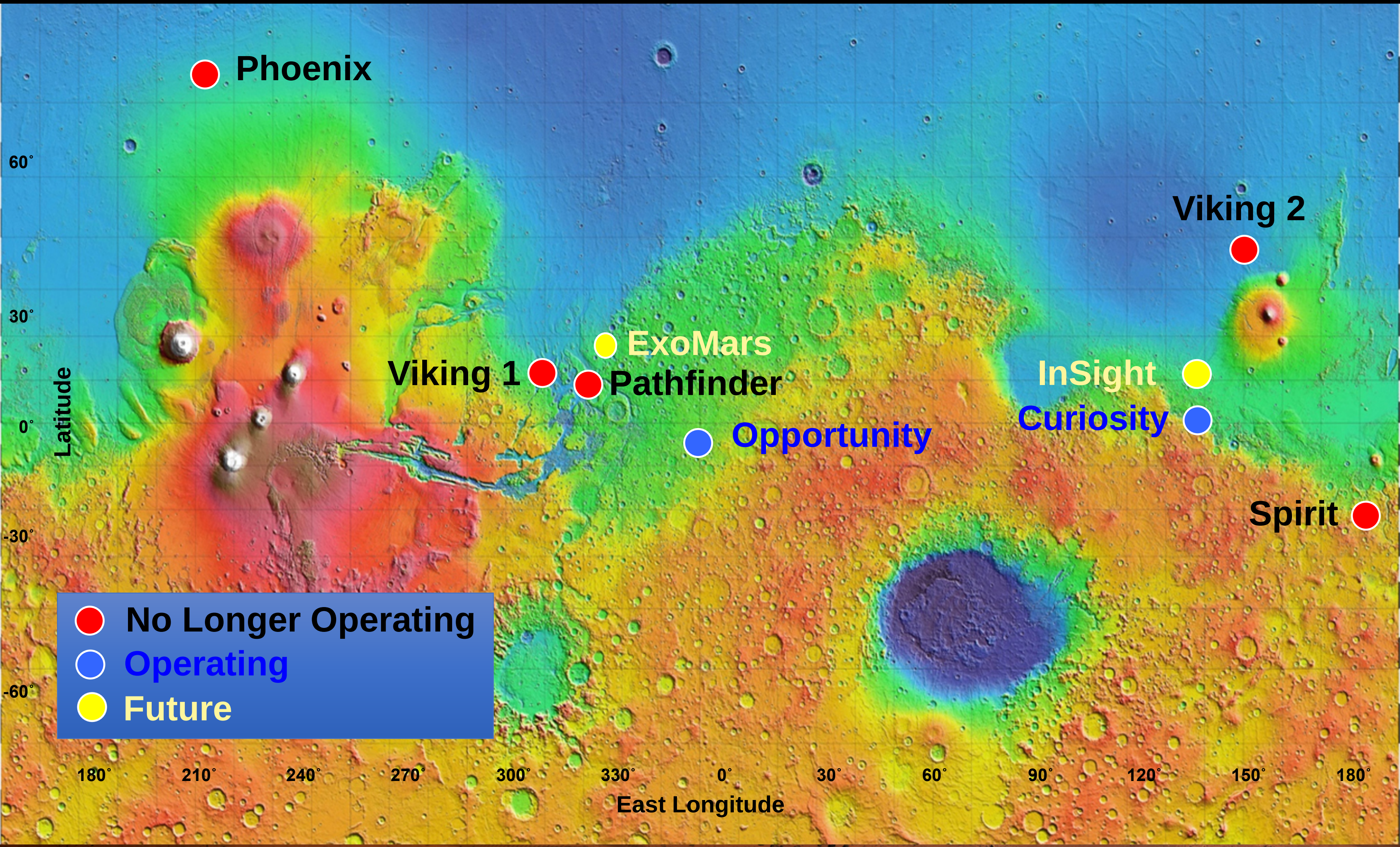
## ESA ExoMars Rover

- NASA's responsibility limited to the following:
  - Participation in providing instrument elements for the Mars Organic Molecule Analyzer (MOMA)
  - MRO data used in the landing site selection process
  - Consultation on Entry Decent & Landing (EDL)



Mars Missions
Operational 2001–2017
2018
2020
...and Beyond
Mars Odyssey (2001)
Mars Express (ESA) (2003)
Mars Reconnaissance Orbiter (2005)
MAVEN (2013)
Mars Orbiter Mission (ISRO) (2013)
Trace Gas Orbiter (ESA/RSA) (2016)
HOPE (UAE)
Mars Orbiter (China)
The Future
MMX (JAXA) (2024)
Mars Lander & Rover (China)
SpaceX Dragons
Opportunity Rover (2003)
Curiosity Rover (2011)
InSight
M2020 Rover
Mars Sample Return (China)
ExoMars Rover (ESA/RSA)
Follow the Water
Explore Habitability
Seek Signs of Life
Prepare for Future Human Explorers

# Location of the Landers & Rovers




Landing site for NASA's Mars 2020 Rover has not been determined

# The New Frontiers Program

- The New Frontiers program of PI-led strategic missions has been a success, and should continue.

- *Change the New Frontiers cost cap to $1.0 billion FY'15, excluding launch vehicle costs.*

- *Select New Frontiers missions NF-4 and NF-5 in the decade 2013-2022.*

# New Frontiers 4 Selection

- Select NF-4 from among:
  - *Comet Surface Sample Return*
  - *Lunar South Pole-Aitken Basin Sample Return*
  - *Saturn Probe*
  - *Trojan Tour and Rendezvous*
  - *Venus In Situ Explorer*

- No relative priorities among these are assigned.

- If the selected NF-3 mission addresses the goals of one of these, remove that one from the list.

# New Frontiers Program

1st NF mission
<u>New Horizons:</u>

Pluto-Kuiper Belt

Launched January 2006
Flyby July 14, 2015
PI: Alan Stern (SwRI-CO)

2nd NF mission
<u>Juno:</u>

Jupiter Polar Orbiter

Launched August 2011
Arrived July 4, 2016
PI: Scott Bolton (SwRI-TX)

3rd NF mission
<u>OSIRIS-REx:</u>

Asteroid Sample Return

<u>Selected: May 25, 2011</u>
Launched September 2016
PI: Dante Lauretta (UA)

# New Frontiers 4 AO

Investigations (listed without priority):

- Comet Surface Sample Return
- Lunar South Pole-Aitken Basin Sample Return
- Ocean Worlds (Enceladus and/or Titan)
- Saturn Probe
- Trojan Tour and Rendezvous
- Venus In Situ Explore

Release of final AO........................................ December 9, 2016
Preproposal Conference ................................ January 20, 2016
Electronic Proposal Submittal Deadline............ April 28, 2017
Step-1 Selections Announced (target)............. November 2017
Phase A Concept Study Reports due................ December 2018
Downselection for Flight (target)...................... July 2019 (target)
Launch Readiness Date.................................. NLT Dec. 31, 2025

# Planetary Science Status:

CAPS Chart, April 27, 2016
Presentation to the SSB

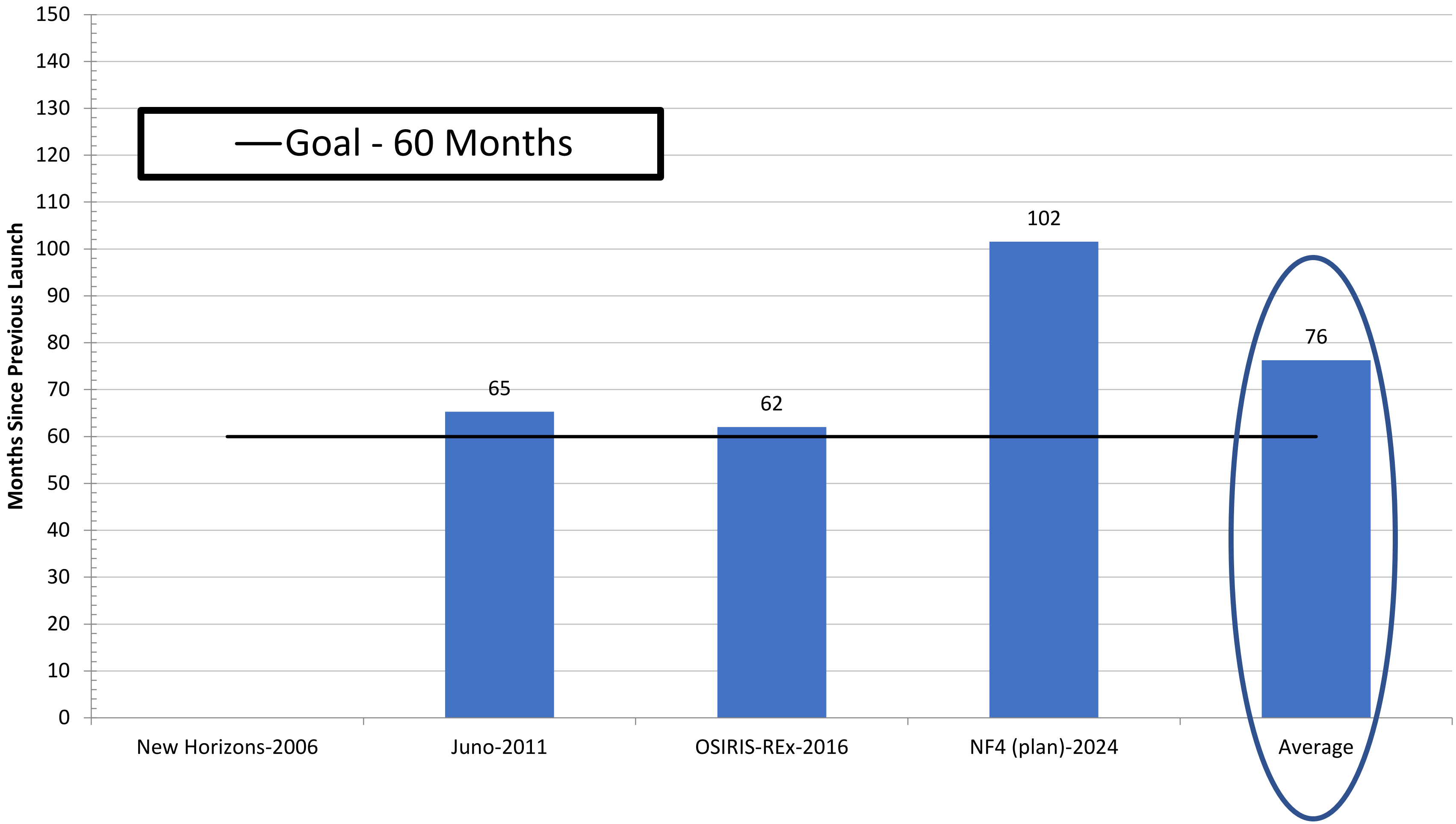
3. Discussed plans for next New Frontier mission AO with Jim Green
    - The draft solicitation for the New Frontiers 4 mission includes a strategic theme - Ocean Worlds - that was not included in the current planetary decadal survey
    - Proposed change does not alter the scientific priorities that are laid out in the current planetary decadal survey
        - Enceladus and Titan are significant elements of the decadal survey, and their inclusion consistent with the overall scientific priorities discussed in the survey report
    - A sound management approach should allow the program manager the flexibility to add elements as the situation changes throughout the decade
    - The peer review process is the appropriate means to rank all of the missions that are proposed for NF-4
    - It is essential that whatever mission is selected for NF-4 must be capable of accomplishing New-Frontier-class science

# New Frontiers 5 Selection

- For NF-5:
  - *The remaining candidates from NF-4*
  - *Io Observer*
  - *Lunar Geophysical Network*

- Again, no relative priorities are assigned.

# New Frontiers Program Launch Rate



# Summary: New Frontiers

- OSIRIS-REx selected on May 25, 2011 & launched in Sept. 2016
  - Has Earth flyby for gravity assist in September 2017
  - Arrives at Bennu in August 2018
- Decadal: Cost cap of $1B-FY15 (Phase A-E w/o LV)
  - NF-4 has been solicited and proposals under evaluation
  - Cost Cap raised to $850M FY15$ (Phase A-D without LV)
  - Options for technology demonstration include: NEXT, RPS, and HEEET
- On track to solicit NF-5 before 2023
  - Additional targets to include: Io Observer & Lunar Geophysical Network
- PSD is targeting 2 New Frontier missions per decade – budget dependent

# Key Recommendations

- *Increase the NASA planetary R&A budget by 5% above the total finally approved FY'11 expenditures in the first year, and then by 1.5% above inflation each successive year.*
- *Continue missions in development, and missions in flight subject to senior review.*
- *Continue the Discovery program at its current funding level, adjusted for inflation, with a cost cap per mission also adjusted for inflation (i.e., to $500 million FY'15).*
- *Assure a regular, predictable, and rapid (≤ 24-month) cadence of Discovery AOs and selections.*
- *Carry out Mars TGO as long as the current division of responsibilities with ESA is preserved.*
- *Establish a planetary exploration technology development program, funded at 6-8% of the total NASA PSD budget.*



NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

# FY16 Planetary Science Technology Funding

## $125.7M total
## 7.7% of $1.631B PSD Budget

| $ 10.80 | | $ 75.51 | | $ 36.18 | | $ 3.19 | | $ 114.18 | |
|---|---|---|---|---|---|---|---|---|---|
| **Mission Technology** | | **Planetary Technology** | | **Science Instruments** | | **Planning/Studies** | | **Infrastructure** | |
| MEP | 3.5 | RPS | 15.3 | PICASSO | 8.7 | RPS | 0.5 | RPS | 77.8 |
| Europa | 7.3 | Balloon | 4.9 | MATISSE | 3.3 | Adv Tech | 0.5 | AMMOS | 35.6 |
| | | NEXT | 2.9 | PSTAR | 6.5 | Mars | 0.2 | Mars | 0.3 |
| | | ColdTech | 15.8 | ColdTech Instr | 9.2 | Europa | 0.1 | Adv Tech | 0.5 |
| | | HotTech | 5.2 | NEO Search | 7.0 | Discovery | 1.0 | | |
| | | Helicopter | 6.5 | Others | 1.5 | PSPS | 0.9 | | |
| | | Energy Conversion | 7.0 | | | | | | |
| | | Sample Handling | 2.1 | | | | | | |
| | | AMMOS | 1.0 | | | | | | |
| | | Others | 8.1 | | | | | | |
| | | STMD Co-Fund | 6.8 | | | | | | |

| | | |
|---|---|---|
| $36.2M | Science Instruments | (29%) |
| $31.9M | In Situ Exploration | (26%) |
| $54.9M | Space Access and Core Technologies | (45%) |

Of these, $25.3M is for Extreme Environment Technologies (21%)

STMD investing and additional $78.6M in PSD-relevant space access and core technologies

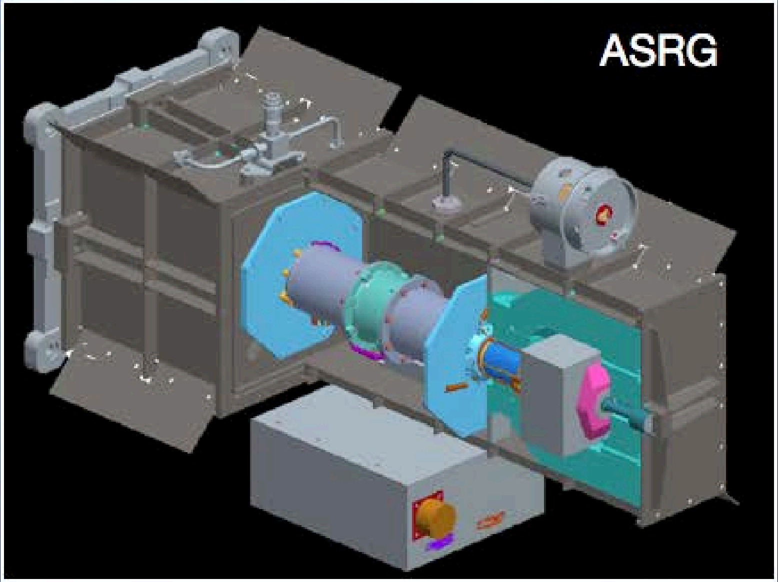
# Availability of Plutonium-238

- The amount of plutonium-238 available for spacecraft power systems is shrinking alarmingly.

- *Without a restart of plutonium-238 production, it will be impossible for NASA to carry out important planetary missions, particularly in the outer solar system.*

- JEO should switch to Advanced Stirling Radioisotope Generators (which require substantially less plutonium) for power production.

- ASRG development should receive attention comparable to a flight project.



# NASA-Department of Energy Status

- NASA is now funding DoE operations and analysis infrastructure
  - Maintaining worker certifications and performing operational maintenance activities to support future RPS fueling and assembly capabilities at multiple DOE laboratories
  - Augmented funding to accelerate design and installation of a new Hot Press and furnace capability to reduce fuel clad production risk at Los Alamos National Laboratory (LANL)
  - Updated the hot press with new units
  - Have enough Pu-238 for Mars2020
- NASA-funded Pu-238 supply project with DoE has started
  - Goal of 1.5 kg/year of Plutonium Oxide production capacity by ~2021
  - Technology demonstration efforts continue on schedule
    - Target development, irradiation tests, and Pu-238 chemical recovery continue to be individually developed
    - Completed several integrated end-to-end demonstrations
    - Assessment of Pu-238 product quality shows a high yield
  - The remainder of the project involves scaling up to the 1.5 kg/yr production rate
  - Expect to have enough Pu-238 for use in New Frontiers-4 if necessary
- The restart of Pu-238 production leaves PSD in a good position to support radioisotope missions well into the future

# Technology Development

- *Place highest priority on completion and validation of the Advanced Stirling Radioisotope Generator.*
- *Make significant investments in Ultraflex solar array technology and aerocapture.*
- *Continue to provide technology incentives in AOs. Include advanced solar power and optical communications.*
- *Establish a broad, sustained program of science instrument technology development, including development through TRL 6 for instruments with the highest potential for making new discoveries.*

# Science Instrument Technology Program Evolution

| | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mars Instrument Development Project** | | | | | | | | | | |
| **Planetary Instrument Definition and Development** | | | | | | | | | | |
| **Astrobiology Science and Technology Instrument Development, including Concept Studies for Small Payloads and Satellites** | | | | | | | | | | |
| | | | | | | | | | | |
| **Maturation of Instruments for Solar System Exploration** | | | | | | | | | | |
| **Planetary Inst Concepts for Advancement of Solar System Observations** | | | | | | | | | | |
| **Instrument Concepts for Europa Exploration** | | | | | | | | | | |
| **Small, Innovative Missions for Planetary Exploration** | | | | | | | | | | |
| **New Frontiers Homesteader** | | | | | | | | | | |
| **Concepts for Ocean worlds Life Detection Technology (COLDTech)** | | | | | | | | | | |
| **Hot Operating Temperature Technology (HOTTech)** | | | | | | | | | | |

- PICASSO – Low TRL instrument development
- MatISSE – Mid-TRL instrument development

| | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Astrobiology Science and Technology for Exploring Planets** | | | | | | | | | | |
| **Moon and Mars Analogue Mission Activities (with HEO)** | | | | | | | | | | |
| | | | | | | | | | | |
| **Planetary Science and Technology Through Analog Research** | | | | | | | | | | |

- Instrument field testing also supported

# Summary: Technology

- Completed securing PU-238 production and forging a new relationship with DoE
  - Delayed the further development of the ASRG
  - Investigated new thermal electric materials to enable an enhanced MMRTG
- Redesigned instrument development program filling "valley of death"
  - PICASSO – Low TRL instrument development
  - MatISSE – Mid-TRL instrument development
- Developed targeted instrument enhancement calls:
  - Instrument Concepts for Europa Exploration (ICEE supporting Clipper) in FY13
  - Homesteader (supporting New Frontier) in FY14
  - Concepts for Ocean worlds Life Detection Technology (COLDTech) in FY16
  - Hot Operating Temperature Technology (HOTTech) in FY16
- Developed partnerships with STMD
  - Leading to Optical Communication System to be tested on Pysche and other technologies to be available for New Frontiers missions
- Percentage of the technology budget within Decadal recommendations

# Flagship Missions

(in priority order)

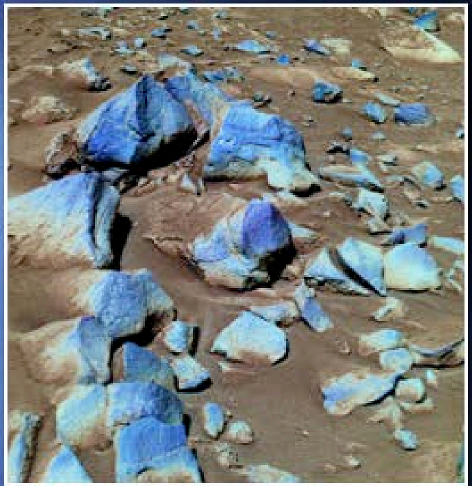
1. Begin NASA/ESA Mars Sample Return campaign: *Descoped Mars Astrobiology Explorer-Cacher (MAX-C)*

2. Detailed investigation of a probable ocean in the outer solar system: *Descoped Jupiter Europa Orbiter (JEO)*

3. First in-depth exploration of an Ice Giant planet: *Uranus Orbiter and Probe*

4. Either *Enceladus Orbiter* or *Venus Climate Mission* (no relative priorities assigned)

# Flagship Priority 1: MAX-C



- The view of the Mars community is that Mars science has reached a point where the most fundamental advances will come from study of returned samples.
- MAX-C will perform *in situ* science and collect and cache samples, beginning a three-mission campaign to return samples from Mars.
- Mars Sample Return is enabled by ESA participation throughout the campaign.
- Of the three missions in the campaign, only MAX-C is recommended for 2013-2022.
- The campaign is multi-decadal, and its priority is based on its anticipated total science return and total cost.

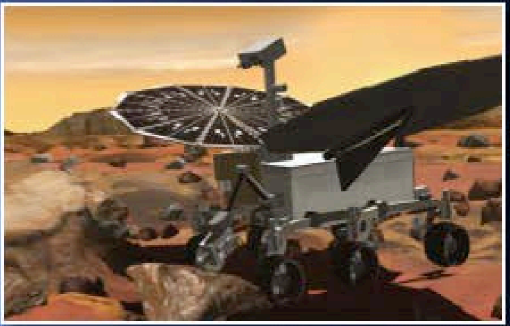
# The Need For A Descope

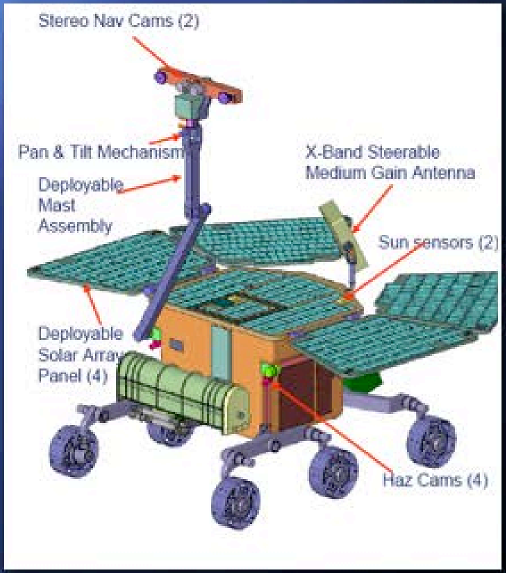
- The CATE estimate for the cost to NASA of MAX-C/ ExoMars is $3.5 billion. This is too large a fraction of the planetary budget.

- *Fly MAX-C only if it can be conducted at a cost to NASA of ≤ $2.5 billion FY'15.*

- Descopes must be equitable between NASA and ESA. *It is critical that the partnership with ESA be preserved.*

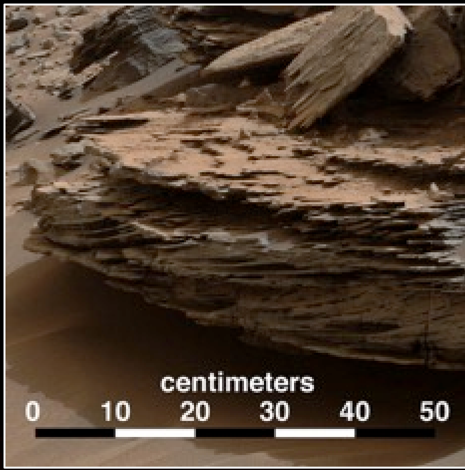
- If the goal of $2.5 billion cannot be achieved, MAX-C should be deferred to a subsequent decade or cancelled.

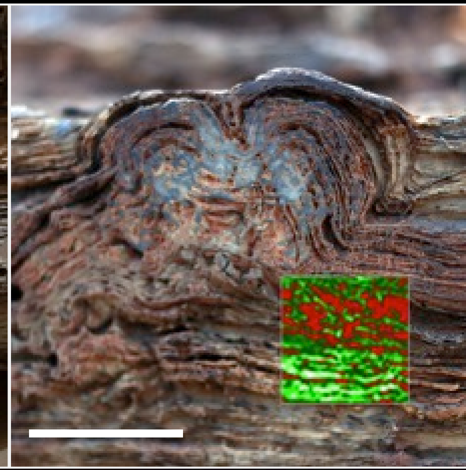


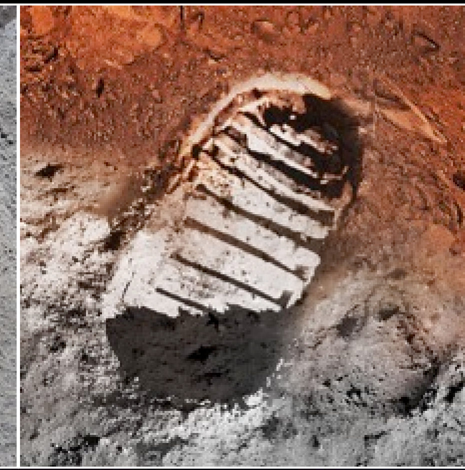



- No alternate plan for Mars exploration is recommended. If MAX-C cannot be carried out for a cost to NASA of $2.5 ≤ billion then other Flagship missions take precedence.

# Mars 2020 Mission Objectives





## GEOLOGIC EXPLORATION

- Explore an ancient environment on Mars
- Understand processes of formation and alteration

## HABITABILITY AND BIOSIGNATURES

- Assess habitability of ancient environment
- Seek evidence of past life
- Select sampling locations with high biosignature preservation potential

## PREPARE A RETURNABLE CACHE

- Capability to collect ~40 samples and blanks, 20 in prime mission
- Include geologic diversity
- Deposit samples on the surface for possible return

## PREPARE FOR HUMAN EXPLORATION

- Measure temperature, humidity, wind, and dust environment
- Demonstrate In Situ Resource Utilization by converting atmospheric $CO_2$ to $O_2$

# Seeking Signs of Life: Mars 2020 Rover

<u>**Conduct rigorous *in situ* science**</u>

**Geologically diverse site of ancient habitability**

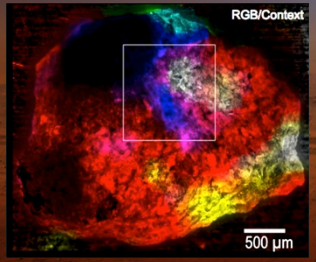
**Coordinated, nested context and fine-scale measurements**

<u>**Enable the future**</u>

**Returnable cache of samples**

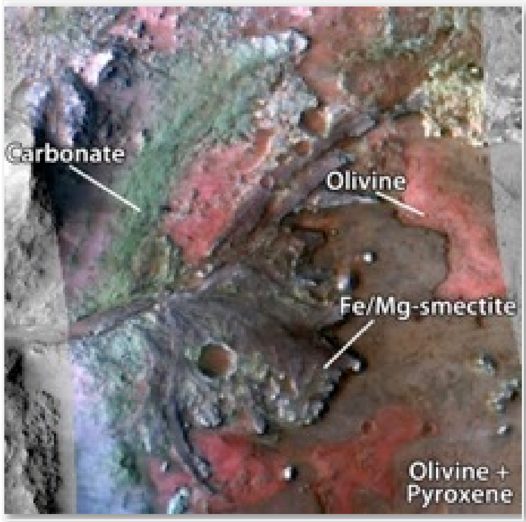
**Critical ISRU and technology demonstration required for future Mars exploration**

LCC: $2.4B RY




# Mars 2020 Landing Site Workshop

# Final Mars 2020 Candidate Landing Sites

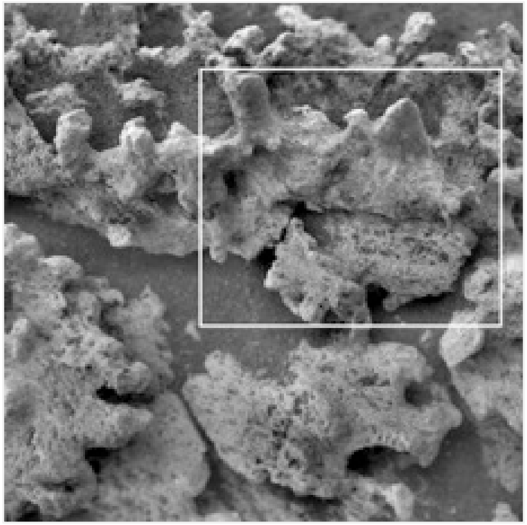



## JEZERO

- Deltaic/lacustrine deposition with Hesperian lava flow and hydrous alteration
- Evidence for hydrous minerals from CRISM, *including carbonates*

## NE SYRTIS

- Extremely ancient igneous, hydrothermal, and sedimentary environments
- High mineralogic diversity with phyllosilicates, sulfates, carbonates, olivine
- Serpentinization and subsurface habitability?



## COLUMBIA HILLS

- Carbonate, sulfate, and silica-rich outcrops of possible hydrothermal origin and Hesperian lava flow
- Potential biosignatures identified
- Previously explored by MER

# Flagship Missions

(in priority order)

1. Begin NASA/ESA Mars Sample Return campaign: *Descoped Mars Astrobiology Explorer-Cacher (MAX-C)*

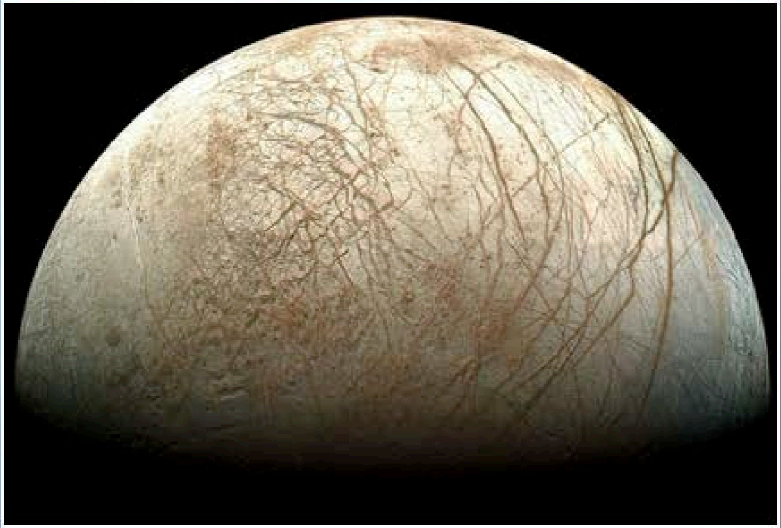
2. Detailed investigation of a probable ocean in the outer solar system: *Descoped Jupiter Europa Orbiter (JEO)*

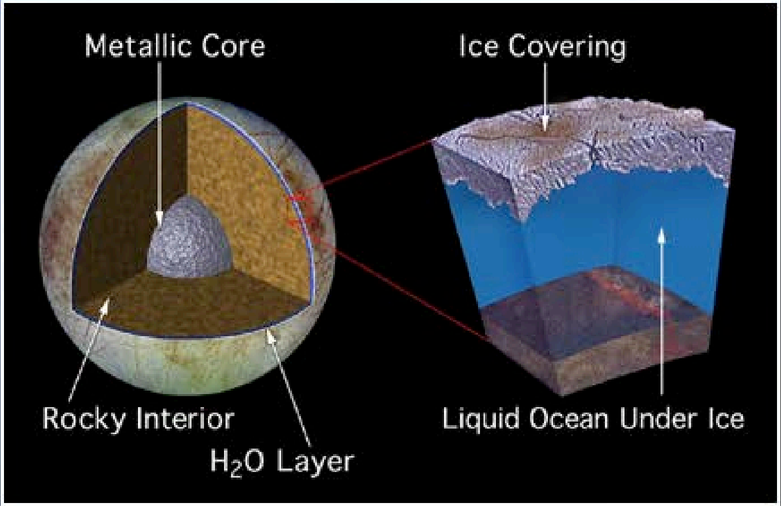
3. First in-depth exploration of an Ice Giant planet: *Uranus Orbiter and Probe*

4. Either *Enceladus Orbiter* or *Venus Climate Mission* (no relative priorities assigned)

# Flagship Priority 2: JEO

- Europa's probable ocean may be the best candidate in the solar system beyond Earth for a presently habitable environment.
- Orbital tour of Jupiter system, followed by 100-200 km Europa orbit
- Instrumentation to characterize Europa's tidal flexure, the thickness of the ice shell, and the character of the surface and subsurface.

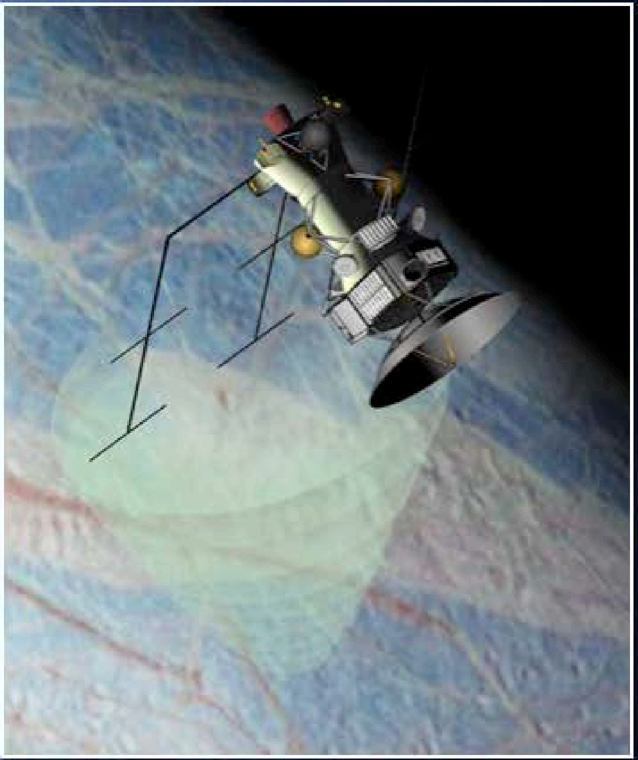




# The Need For A Descope

- The CATE estimate for the cost of JEO is $4.7 billion. This is too large a fraction of the planetary budget.

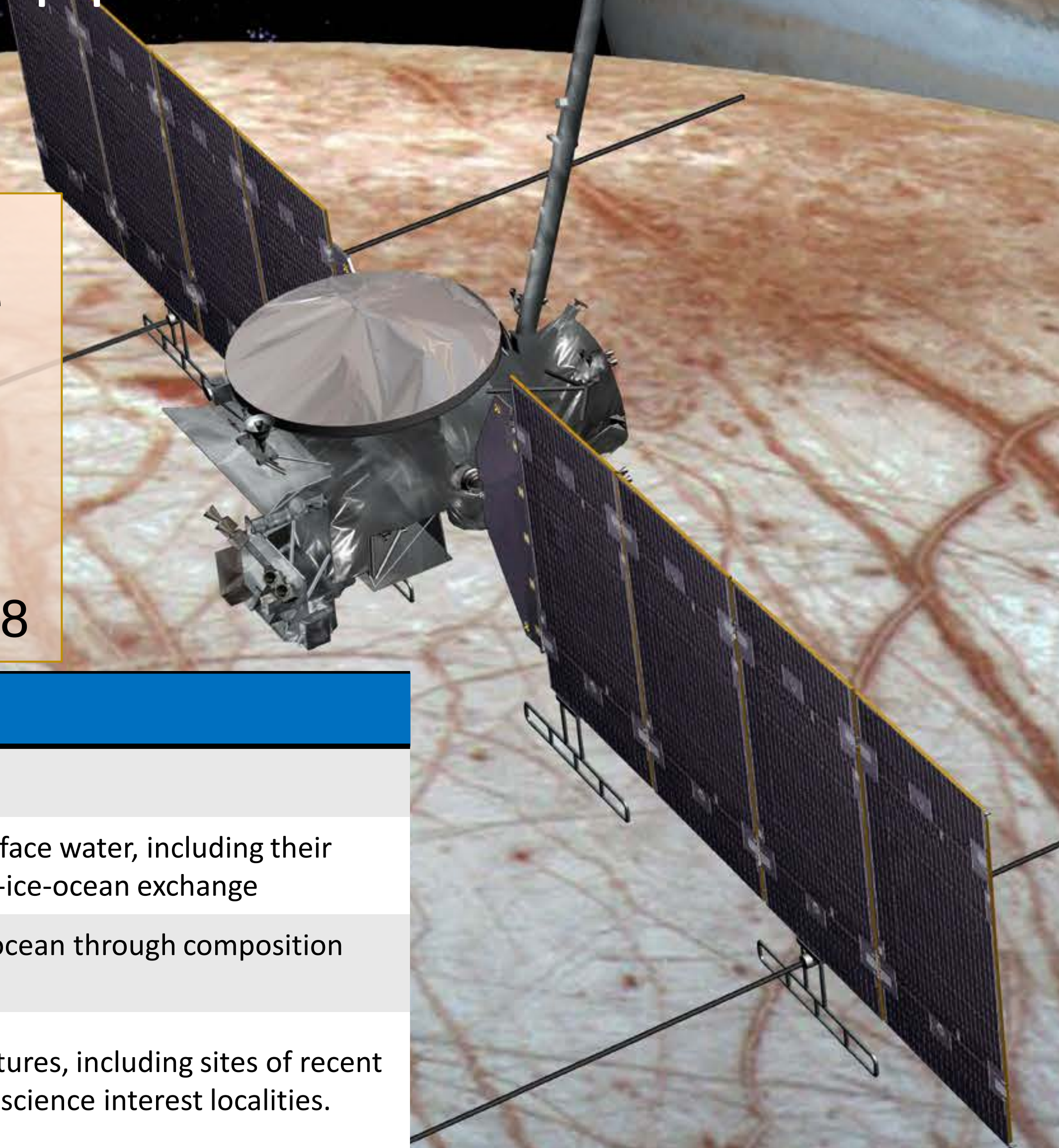
- *Fly JEO only if changes to both the mission and the NASA planetary budget make it affordable without eliminating other recommended missions:*
  - This will require a reduction in the mission's scope and cost
  - JEO will require a new start that increases the overall budget of NASA's Planetary Science Division



- *Immediately begin an effort to find major cost reductions in JEO, with the goal of minimizing the necessary planetary science budget increase.*

- JEO science would be enhanced by conducting the mission jointly with ESA's proposed Ganymede Orbiter mission.

# Europa Clipper Overview



- Conduct 45 low altitude flybys with lowest 25 km (less than the ice crust) and a vast majority below 100 km to obtain global regional coverage

- KDP-C scheduled: October 2018

| Science | |
|---|---|
| **Objective** | **Description** |
| Ice Shell & Ocean | Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange |
| Composition | Understand the habitability of Europa's ocean through composition and chemistry. |
| Geology | Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest localities. |
| Recon | Characterize scientifically compelling sites, and hazards for a potential future landed mission to Europa |

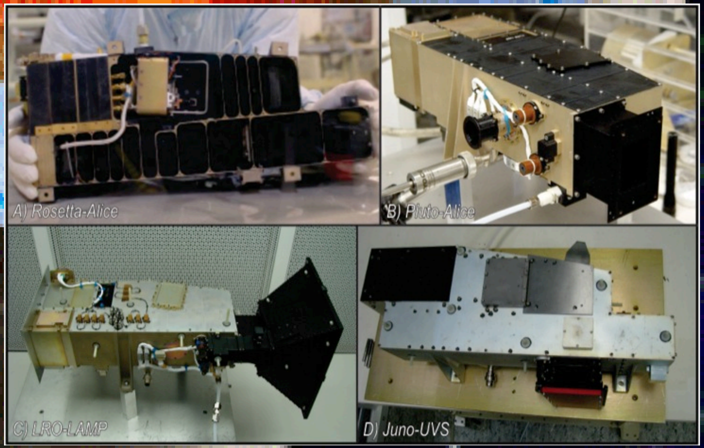
# JUpiter ICy moons Explorer (JUICE)

- ESA's JUICE mission is the first detailed exploration of Ganymede

- JUICE has 11 instruments from 15 countries

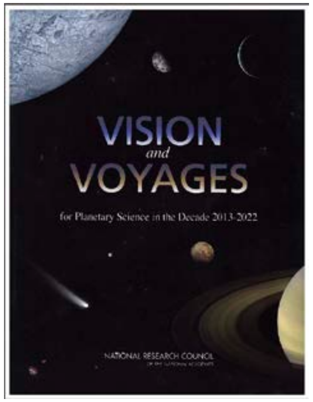
- NASA's Role: one U.S.-led science instrument (UV spectrometer) and hardware for 2 European instruments
  - Particle Env. Package (PEP-Hi)
  - Radar for Icy Moon Exp. (RIME)

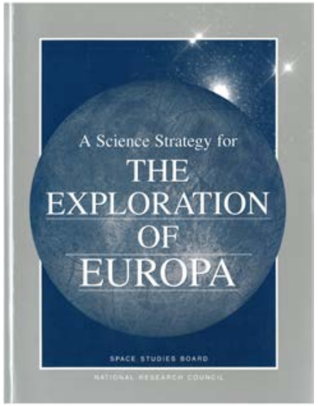
Ultraviolet Spectrometer

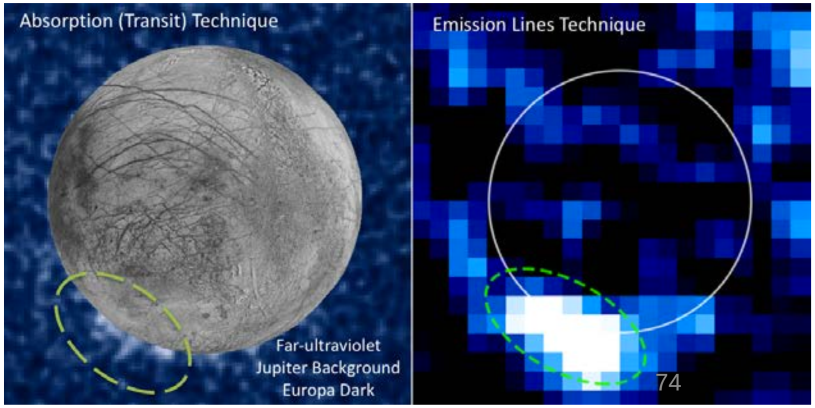


# Exploration of Europa

- Europa on the list of Large-Class Flight missions in Planetary *Vision & Voyages* Decadal
- NAS/COMPLEX Report on Europa (1999):
  - Combination of R&A, technology development, telescope observations, and missions
  - Recommended a staged series of missions be utilized to explore Europa
  - First mission focus on liquid water – *Clipper Orbiter*
  - Follow-on characterize surface material and access and study the liquid water - *Lander*
- Planetary Division's response:
  - As part of the Ocean Worlds Program
  - Issued: ICEE & ColdTech instruments
  - Development of the Clipper mission
  - Europa lander SDT study completed
  - HST observations of Europa plumes
    - STSci Director's Committee on Future Observation Strategies to be released



# Europa Lander SDT


- Science Definition Team (SDT) delivered its report with 3 prioritized goals:
    1. Search for Evidence of Life
    2. Assess habitability
    3. Characterize surface and subsurface
- Applying lessons learned from Viking landers
- Used extreme, limited nutrient Earth environments as analogs
- Approach: Multiple line of evidence are needed to detect life
- Presented a decision framework for life detection to assess how results should be interpreted

# Flagship Missions

(in priority order)

1. Begin NASA/ESA Mars Sample Return campaign: *Descoped Mars Astrobiology Explorer-Cacher (MAX-C)*

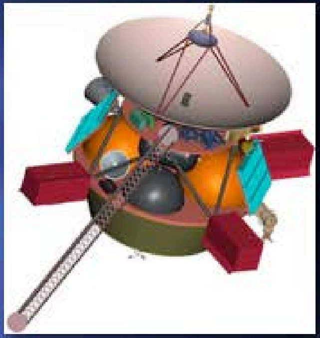
2. Detailed investigation of a probable ocean in the outer solar system: *Descoped Jupiter Europa Orbiter (JEO)*

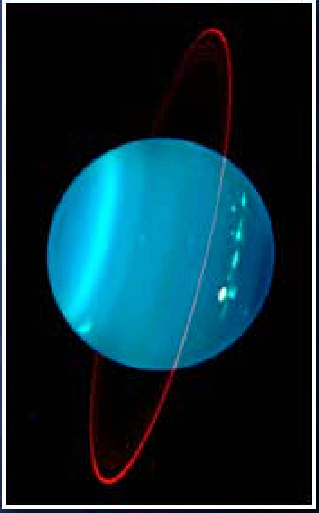
3. First in-depth exploration of an Ice Giant planet: *Uranus Orbiter and Probe*

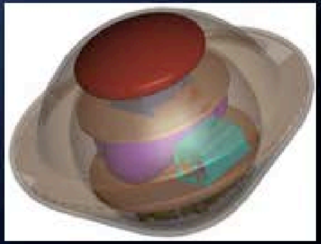
4. Either *Enceladus Orbiter* or *Venus Climate Mission* (no relative priorities assigned)

# Flagship Priority 3: Uranus Orbiter and Probe

- Uranus and Neptune belong to a distinct class of planet: the Ice Giants
  - Small hydrogen envelopes
  - Dominated by heavier elements
  - The only class of planet that has never been explored in detail
- Orbiter to perform remote sensing of planet's atmosphere, magnetic field, rings, and satellites.
- Atmospheric entry probe.
- Potential for new discoveries comparable to Galileo at Jupiter and Cassini at Saturn.
- *Uranus is preferred over Neptune for 2013-2022 for practical reasons involving available trajectories, flight times, and cost.*



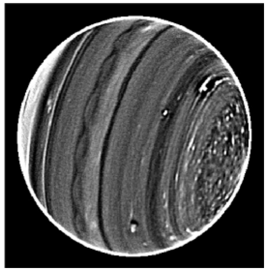




# Why are Uranus & Neptune Important?

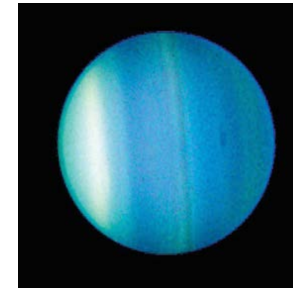
- These relatively unexplored systems are fundamentally different from the gas giants (Jupiter and Saturn) and the terrestrial planets
  - Uranus and Neptune are ~65% water by mass (plus some methane, ammonia and other so-called "ices"). Terrestrial planets are 100% rock; Jupiter and Saturn are ~85% $H_2$ and He
- Ice giants appear to be very common in our galaxy; most planets known today are ice giants
- They challenge our understanding of planetary formation, evolution, and physics
  - Models suggest ice giants have a narrow time window for formation. If that is correct, why are they so common in other planetary systems?
  - Why is Uranus not releasing significant amounts of Internal heat? Does its output vary seasonally?
  - Why are the ice giant magnetic fields so complex? How do the unusual geometries affect interactions with the solar wind?

*Ice Giants are critical to our understanding of how planetary systems form and evolve*

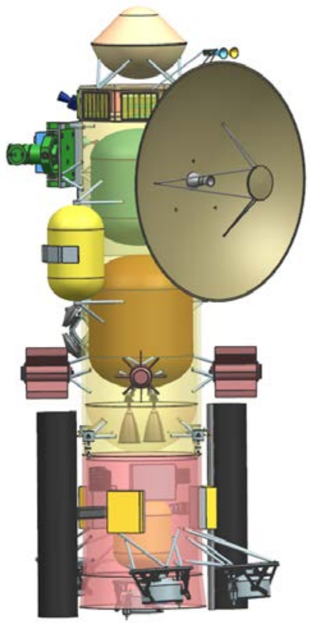


*Uranus in 2012 (top) & 1986 (bottom Voyager)*

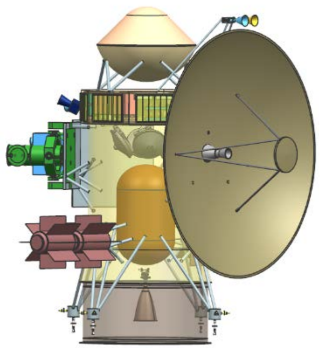
# ICE Giants Study:Uranus & Neptune



Launch mass:7364 kg

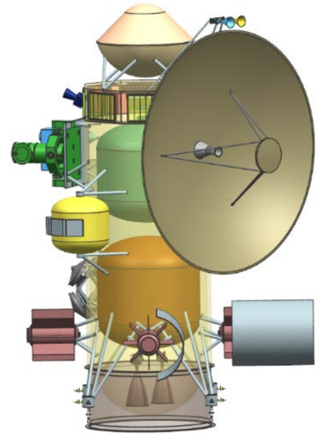


Neptune Orbiter with Probe, SEP, and 50 kg payload



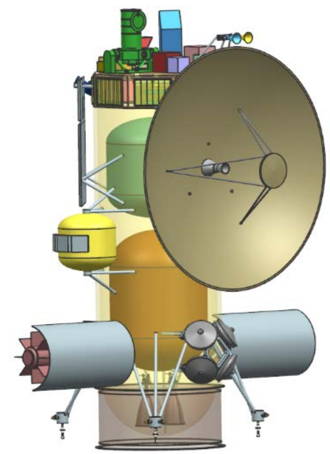
Launch mass: 1525 kg

Uranus Flyby with Probe and 50 kg payload



Launch mass: 4345 kg

Uranus Orbiter with Probe and 50 kg payload



Launch mass: 4718 kg

Uranus Orbiter with 150 kg payload


ICE Giants Study Report Completed April 2017

# Flagship Missions

(in priority order)

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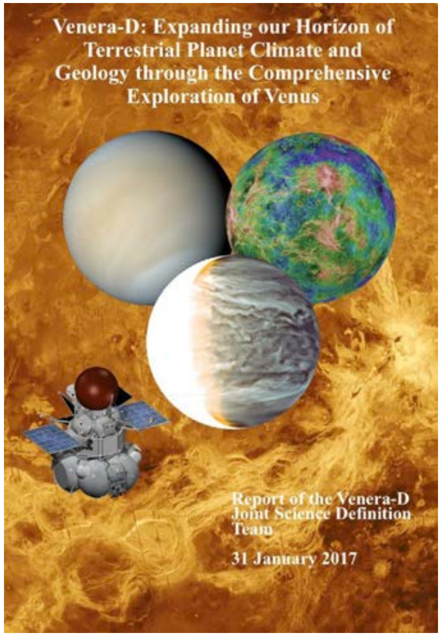
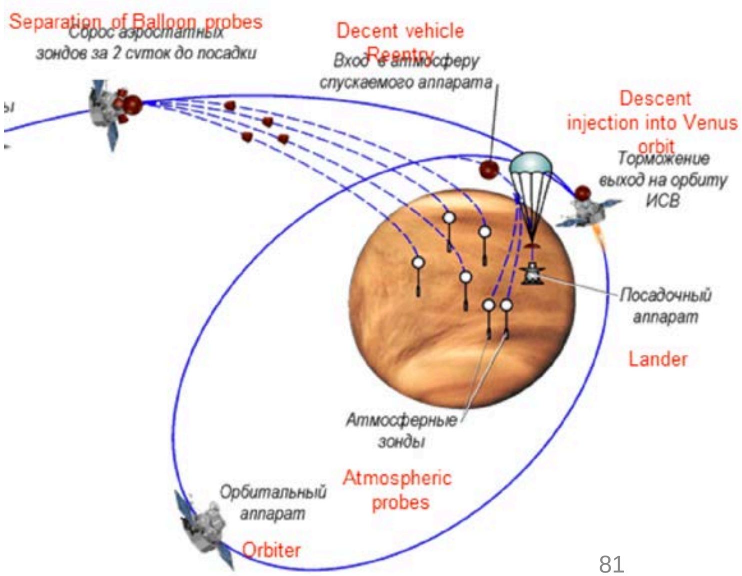
4. Either *Enceladus Orbiter* or *Venus Climate Mission* (no relative priorities assigned)

# Venus Missions Study

- NASA/RSA created a Venera-D Joint Science Definition Team
  - Completed an initial study report Jan 31, 2017
  - Defines all the top decadal science that can be accomplished versus a series of notional platforms
- Baseline missions:
  - Orbiter: Polar 24 hour orbit with a lifetime greater than three years- Can trade orbiter period for communication with other elements of mission for more than 24h
  - Lander: (updated VEGA) 2+ hours on the surface
- Other components discussed as potential augmentations:
  - Free flying aerial platform and balloons
  - Sub-satellite
  - Small long-lived stations




- Next steps:
  - Extend the JSDT for the next two years
  - Focus shifts to realistic mission designs and architectures



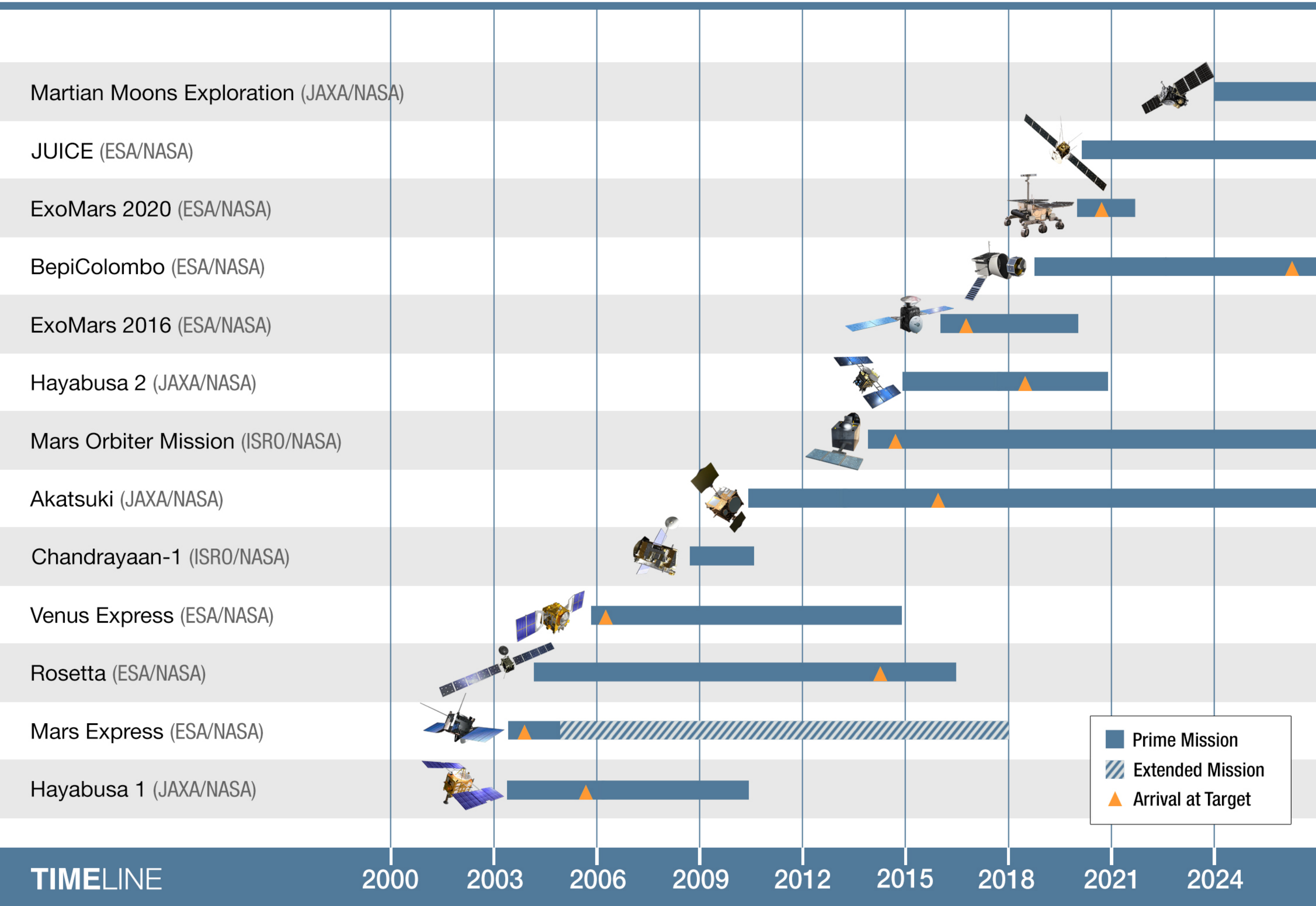
# Flagship Mission Summary

- Decadal: Descope Mars Cacher
  - *MAX-C* descoped into *Mars 2020 rover* with a LCC of $2.4B
  - *Mars 2020* as the first step in a potential future sample return mission
- Decadal: Descoped JEO
  - *Europa Clipper* to be launched in early 2020s
  - Uses advanced solar arrays instead of an RPS
  - *Europa lander* study for consideration in the next decadal
- Uranus – Ice Giant Study (includes Neptune) as a potential mission for consideration in the next decadal
- Enceladus – An opportunity provided within NF-4
- Venus Climate Orbiter – Ongoing study as a joint Science Definition Team with RSA for Venera-D mission

# International Opportunities

- U.S. participation in the Mars Trace Gas Orbiter.
- Strong ESA participation in the Mars Sample Return campaign (beginning with MAX-C) is critical; the campaign cannot proceed without it.
- Jupiter system science on the JEO mission would be enhanced substantially by the ESA Ganymede orbiter.
- Other elements of the plan also offer rich opportunities for international partnerships:
  - International participation in the Uranus Orbiter and Probe mission
  - International participation in New Frontiers and Discovery missions
  - U.S. participation in international missions via the “Stand Alone Mission of Opportunity” (SALMON) mechanism

# Planetary Science: International Missions



# PSD International Activities

- ESA
  - *Continued Past Mission Partnerships: Cassini, Mars Express, Venus Express, Rosetta*
  - Participating scientists program: *ExoMars 2016*
  - Provided the Electra surface communications HW for *ExoMars 2016*
  - Mission Instrument Partnership: *JUICE* (1 full & 2 partial instruments)
- JAXA
  - Participating Scientists Programs: *Akasuki*, *Hayabusa*-2, & *Hisaki*
  - Mission Instrument Partnership: *Martian Moons eXploration* (MMX)
  - Shared samples: *Hayabusa* 1, *O-REx/Hayabusa* -2, *MMX*
- ISRO
  - Navigation support for *Mars Orbiting Mission* (*MOM*)
  - Correlative Mars Data Workshop w/*MOM* & NASA missions
  - Discussing Potential Future Mission Partnerships
- RSA
  - Joint Science Definition Team for a future *Venera-D* mission
  - Participating Scientist Program on *Luna Globe* mission series (TBD)
- CSA - Instrument Partnership on *Phoenix*
- CNES – Instrument Partnerships on *Curiosity*, *InSight* & *Mars 2020*
- Spain – Instrument Partnership on *Curiosity* & *Mars 2020*
- Norway – Instrument Partnership on *Mars 2020*
- Multi-National activity on Mars Sample Return in discussion

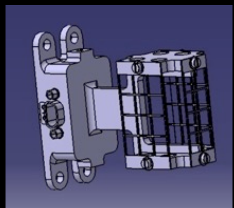
# Interaction With Human Exploration

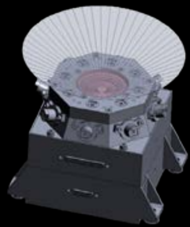
- Some solar system bodies are likely targets of future human exploration:
  - The Moon
  - Asteroids
  - Mars and its moons

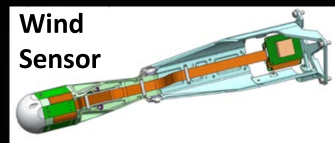

- ***It is vital to maintain the science focus of SMD missions to these bodies, and not incorporate human exploration requirements after the mission has been selected and development has begun.***

- Both the Space Science program and the human exploration program can benefit from carefully crafted intra-agency partnerships (LRO is a good recent example).

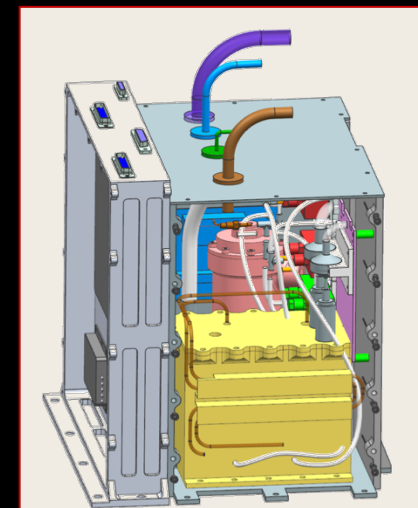
# Mars 2020 Includes Investigations and Technology Demonstrations to Prepare for Human Exploration



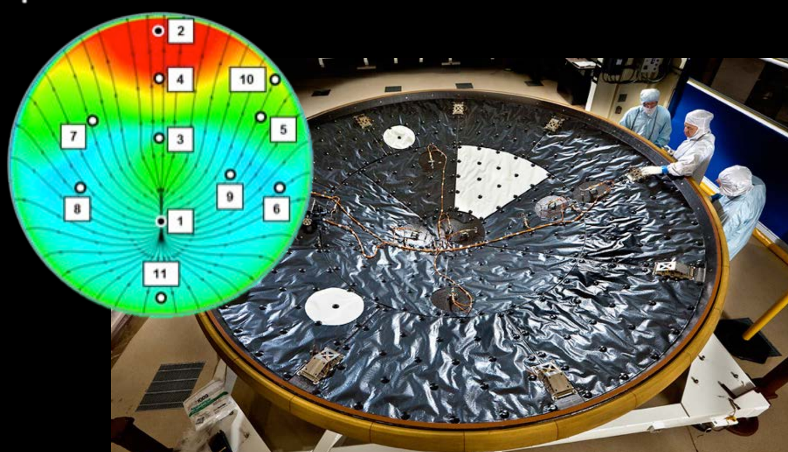




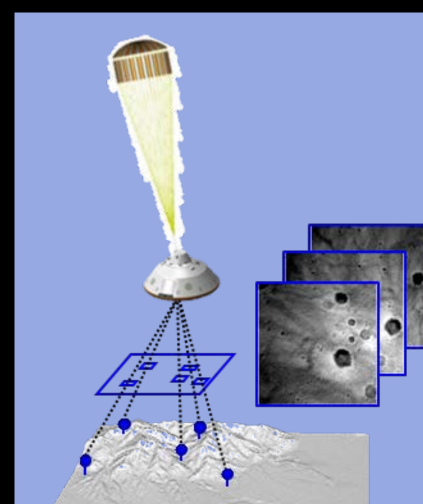

MOXIE: demonstrates the production of oxygen from the Mars atmosphere to enable in-situ propellant production for future human missions.



MEDA: surface weather station contributed by Spain that will measure temperature, pressure, relative humidity, winds, and dust.

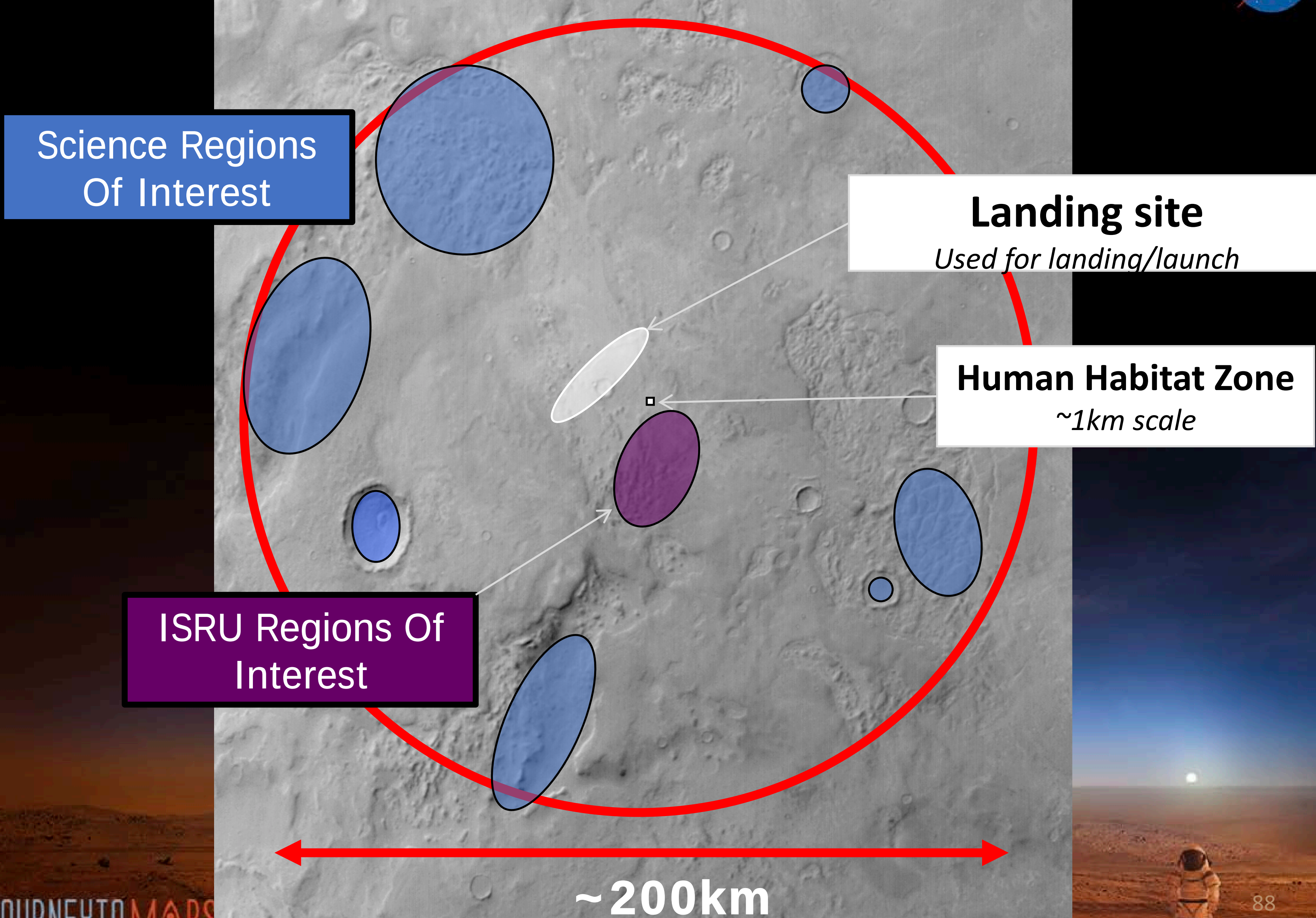


MEDLI-2 sensors on the heat shield and backshell will acquire temperature and pressure data during entry



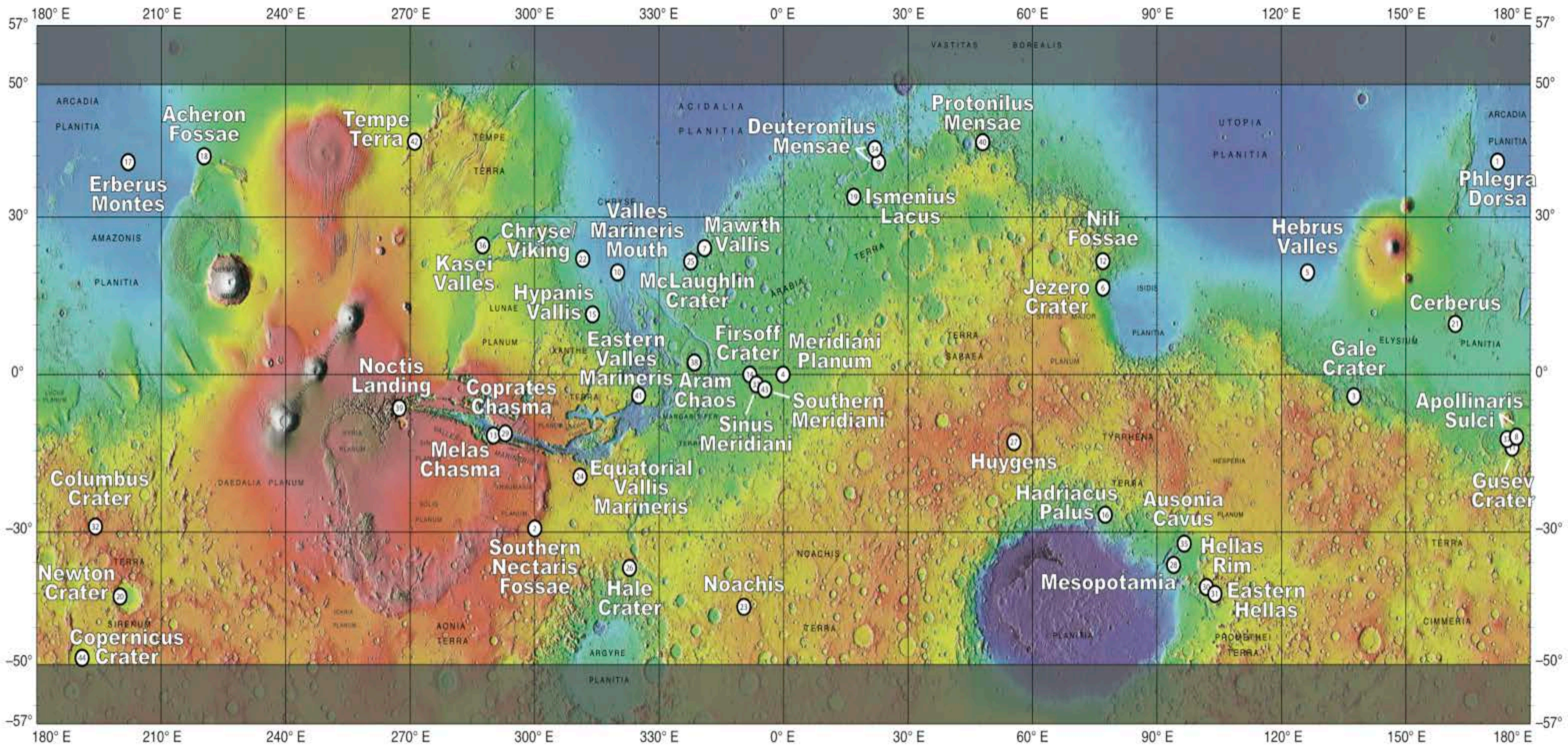
Terrain Relative Navigation provides the capability to avoid large scale landing hazards during EDL and enables safe access to scientifically compelling landing sites

# Human Exploration Zone




#JOURNEYTOMARS

# Potential Exploration Zones




These sites are under study. Data being acquired and analyzed. Future workshop being planned.

# Solar System Exploration Research Virtual Institute

Legend: CAN-1 Teams

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Parker | | | | | | | Orlando |
| | | | | | Parker | | Hendrix | | | | | | | Parker |
| | | | Parker | | Hendrix | | Orlando | | | | | | | Hendrix |
| | | | Hendrix | | Britt | Parker | Heldmann | | | | | | | Burns |
| | | | Heldmann | | Farrell | Heldmann | Britt | | Hendrix | | | | | |
| | | Heldmann | Britt | | Pieters | Britt | Farrell | | Orlando | | | | Parker | |
| | Burns | Pieters | Pieters | Orlando | Rivkin | Pieters | Pieters | Orlando | Heldmann | Parker | Hendrix | | Hendrix | |
| | Pieters | Rivkin | Rivkin | Burns | Bottke | Rivkin | Rivkin | Burns | Farrell | Hendrix | Orlando | | Burns | |
| Burns | Bottke | Bottke | Bottke | Britt | Kring | Kring | Kring | Farrell | Pieters | Burns | Heldmann | | Heldmann | |
| Farrell | Kring | Kring | Kring | Farrell | Horanyi | Horanyi | Horanyi | Horanyi | Rivkin | Heldmann | Rivkin | | Kring | Orlando |
| Horanyi | Horanyi | Glotch | Glotch | Horanyi | Glotch | Glotch | Glotch | Glotch | Glotch | Glotch | Glotch | Britt | Glotch | Glotch |
| Fundamental physical laws, composition and origins of the Universe | Origin and evolution of the inner Solar System | Target body investigations as windows into planetary differentiation processes | Target Body Structure and Composition | Dust and plasma interactions on Target Body(s) | NEA characterization (incl. PHOs and human destinations) | Geotechnical properties | Regolith of Target Bodies | Radiation | Volatiles | Robotic Exploration | ISRU/Prospecting | Propulsion-induced ejecta | Operations/Operability (incl. hazard analysis) | Human health and performance (incl. transit) |

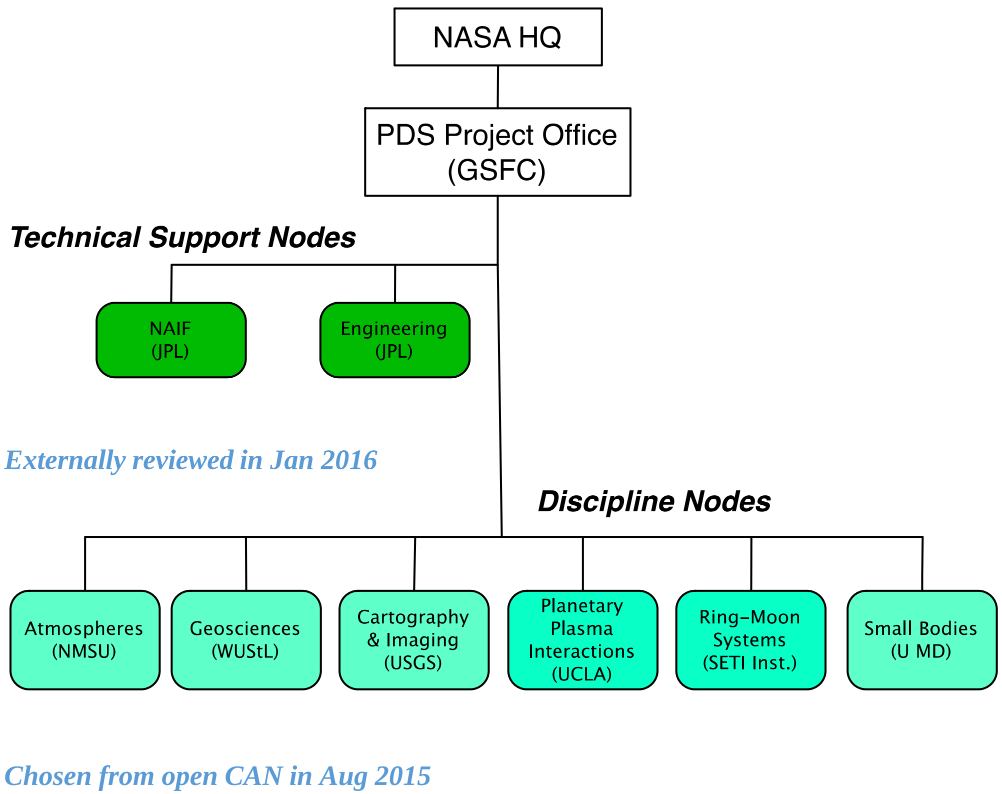
**Science Focus**

**Exploration Focus (SKGs)**

# Supporting NASA Activities

- Data distribution and archiving:
  - *Maintain and upgrade Planetary Data System capabilities.*
  - *Future AOs should mandate that instrument teams propose and be funded to generate derived products before missions have completed Phase E.*
- Education and outreach:
  - *Set aside ~1% of each flight project budget for education and outreach activities.*
- Telescope facilities:
  - *Continue NASA support for IRTF, Keck, Goldstone, Arecibo, and VLBA.*

# Planetary Data System




**Achievements Since Decadal Survey**

- Openly competed all Discipline Nodes; first time in 10 years.
- Externally reviewed performance of the Technical Support Nodes.
- Developed and rolled out new data standard, PDS4.
  - First information model-driven data system in operational use.
- Expanded membership in the International Planetary Data Alliance.
  - IPDA adopted PDS4 as international standard.
- Renewed focus on development of user-focused tools.
- Initiated effort to develop next Roadmap. Completion expected May 2017.
- Began working with grantees to archive data products.

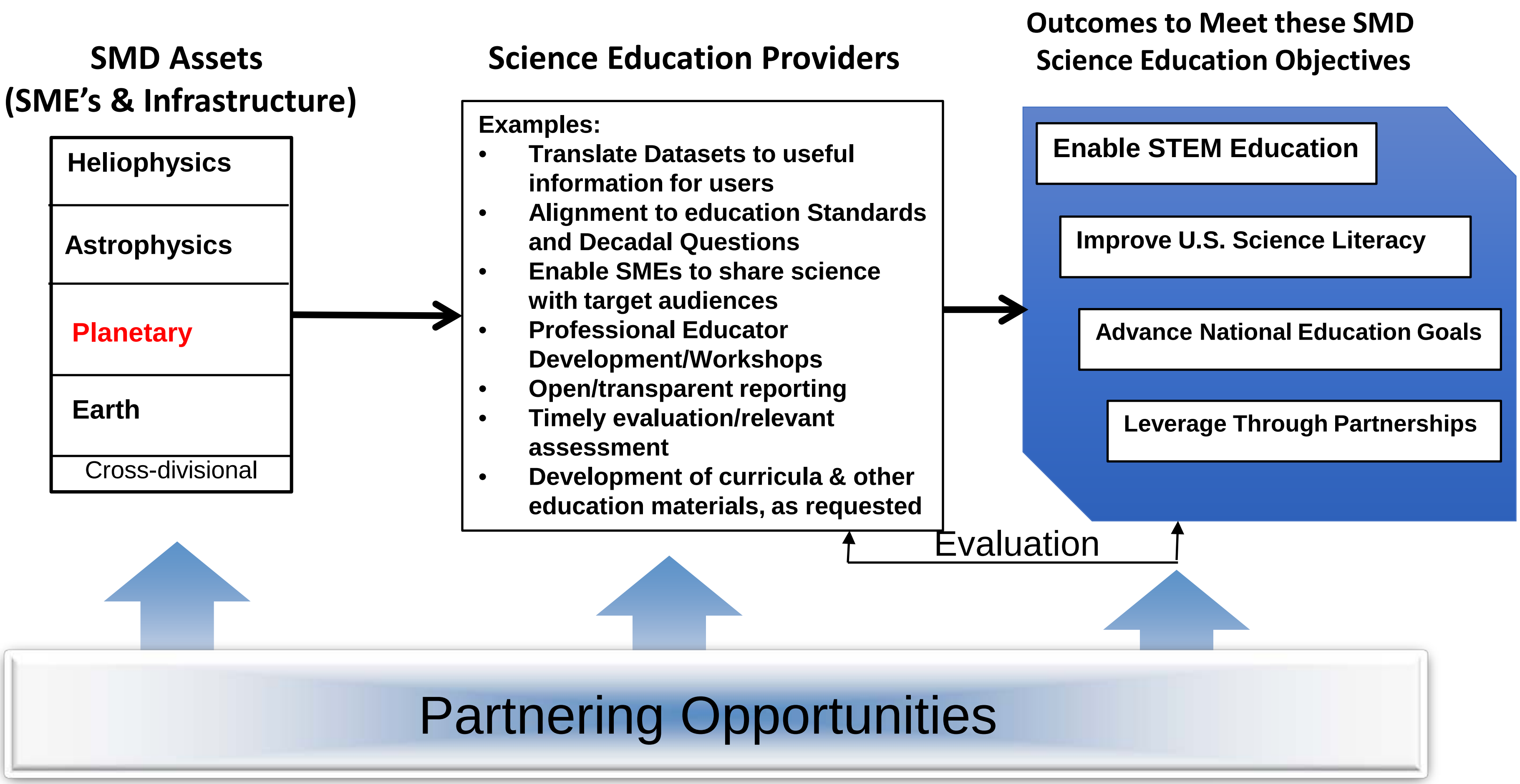
# Supporting NASA Activities

- Data distribution and archiving:
  - *Maintain and upgrade Planetary Data System capabilities.*
  - *Future AOs should mandate that instrument teams propose and be funded to generate derived products before missions have completed Phase E.*

- Education and outreach:
  - *Set aside ~1% of each flight project budget for education and outreach activities.*

- Telescope facilities:
  - *Continue NASA support for IRTF, Keck, Goldstone, Arecibo, and VLBA.*

# SMD Science Education Model



# Planetary Science Cooperative Agreement Awardees

Arizona State University –Tempe, AZ.  Linda Elkins-Tanton, Principal Investigator for "NASA SMD Exploration Connection"

Challenger Center for Space Science Education--Washington, DC  Robert Piercey, Principal Investigator for "CodeRed: My STEM Mission"

Jet Propulsion Laboratory –Pasadena, CA.  Michelle Viotti, Principal Investigator for "NASA Active and Blended Learning Ecosystem (N-ABLE)"

Northern Arizona University—Flagstaff, AZ.  Joelle Clark, Principal Investigator for "PLANETS (Planetary Learning that Advances the Nexus of Engineering, Technology, and Science)"

# Supporting NASA Activities

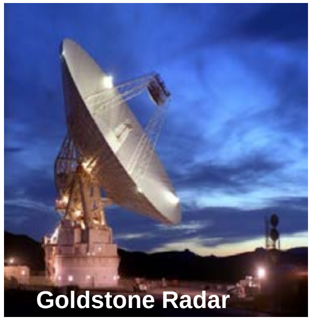
- Data distribution and archiving:
  - *Maintain and upgrade Planetary Data System capabilities.*
  - *Future AOs should mandate that instrument teams propose and be funded to generate derived products before missions have completed Phase E.*

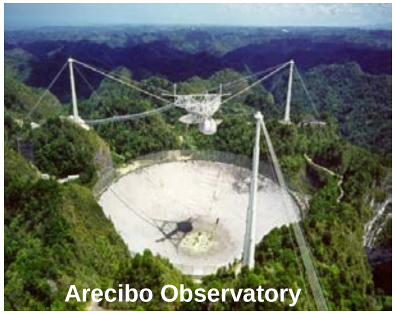
- Education and outreach:
  - *Set aside ~1% of each flight project budget for education and outreach activities.*

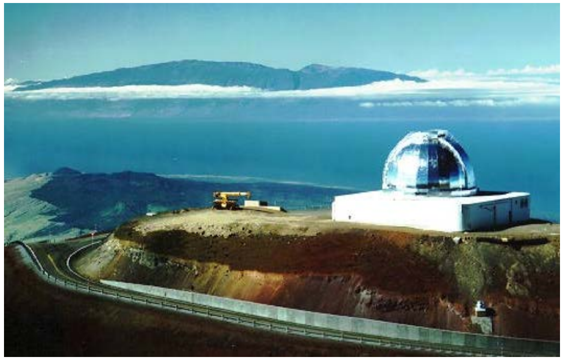
- Telescope facilities:
  - *Continue NASA support for IRTF, Keck, Goldstone, Arecibo, and VLBA.*

# NASA Support for Telescope Facilities

**Goldstone and Arecibo**
- Radar for NEO observations
- Tracking PSD missions



**NASA Infra-Red Telescope Facility (IRTF)**
- Science Observations
- PSD mission support
- Rapid Response
- IRTF MOWG

**Keck Telescopes**
- Science Observations
- PSD mission support
- Keck MOWG

# Supporting NASA Activities

- Suborbital programs:
  - *A funding line to promote use of suborbital platforms for planetary observations would complement and reduce the load on the planetary astronomy program.*

- The Deep Space Network:
  - *Maintain high-power X and Ka band uplink, and S, X, and Ka band downlink at all three complexes.*
  - *Expand capabilities to meet requirements of recommended missions.*

- Sample curation and laboratory facilities:
  - *Establish a single advisory group to provide input on all aspects of sample collection, containment, characterization hazard assessment, and allocation.*
  - *Include the full costs to NASA of receiving and curating samples when planning sample return missions.*
  - *Before samples return, establish a program to develop instruments and facilities for sample analysis.*

# Gondola for High Altitude Planetary Science (GHAPS)

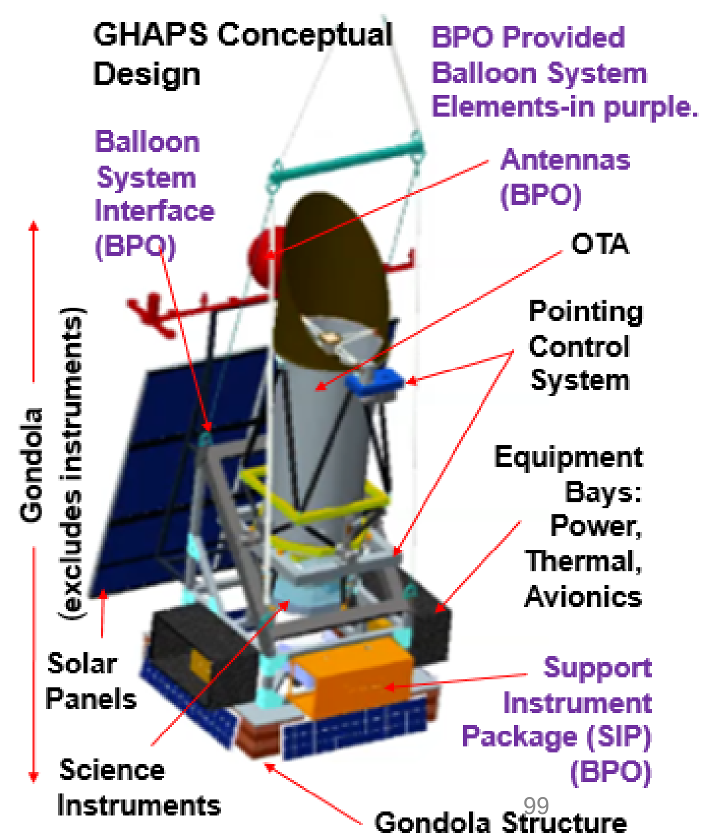
A re-useable balloon platform to meet Planetary Science Decadal Survey and mission support goals – in development

- Designed for a minimum of 5 flights and mission durations up to 100 days
- Low cost refurbishment between flights
- First performance/science demo flight planned for Fort Sumner, NM - Fall 2019
- A competitive process will be used to select guest investigators for the first flight and Principal Investigators for subsequent flights

**GHAPS Status**

GHAPS Preliminary Design Review (PDR)

- Optical Telescope Assembly PDR - Oct 31, 2016
- Science Instrument Definition Team report complete
- Instrument Announcement of Opportunity being developed for release



# Supporting NASA Activities

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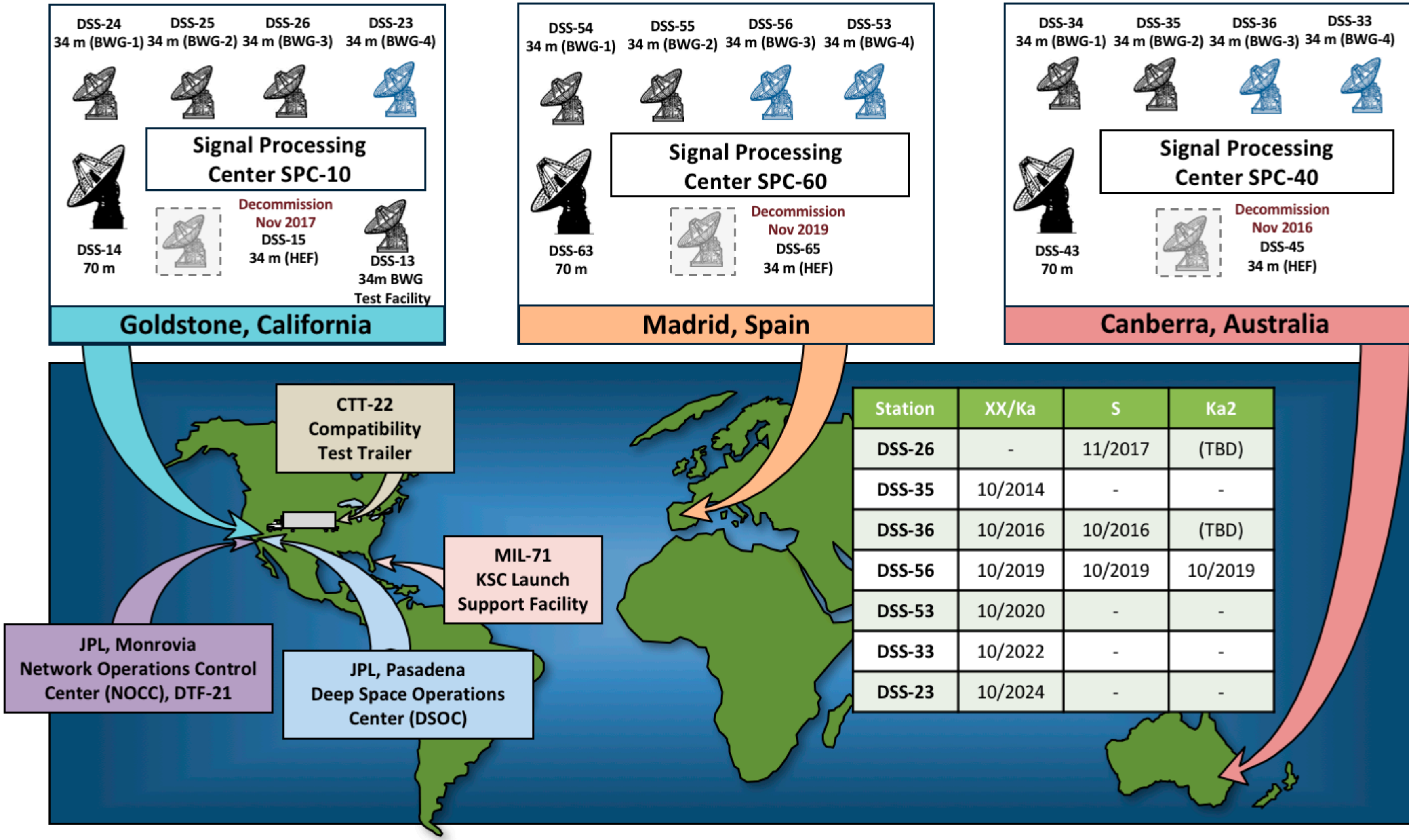
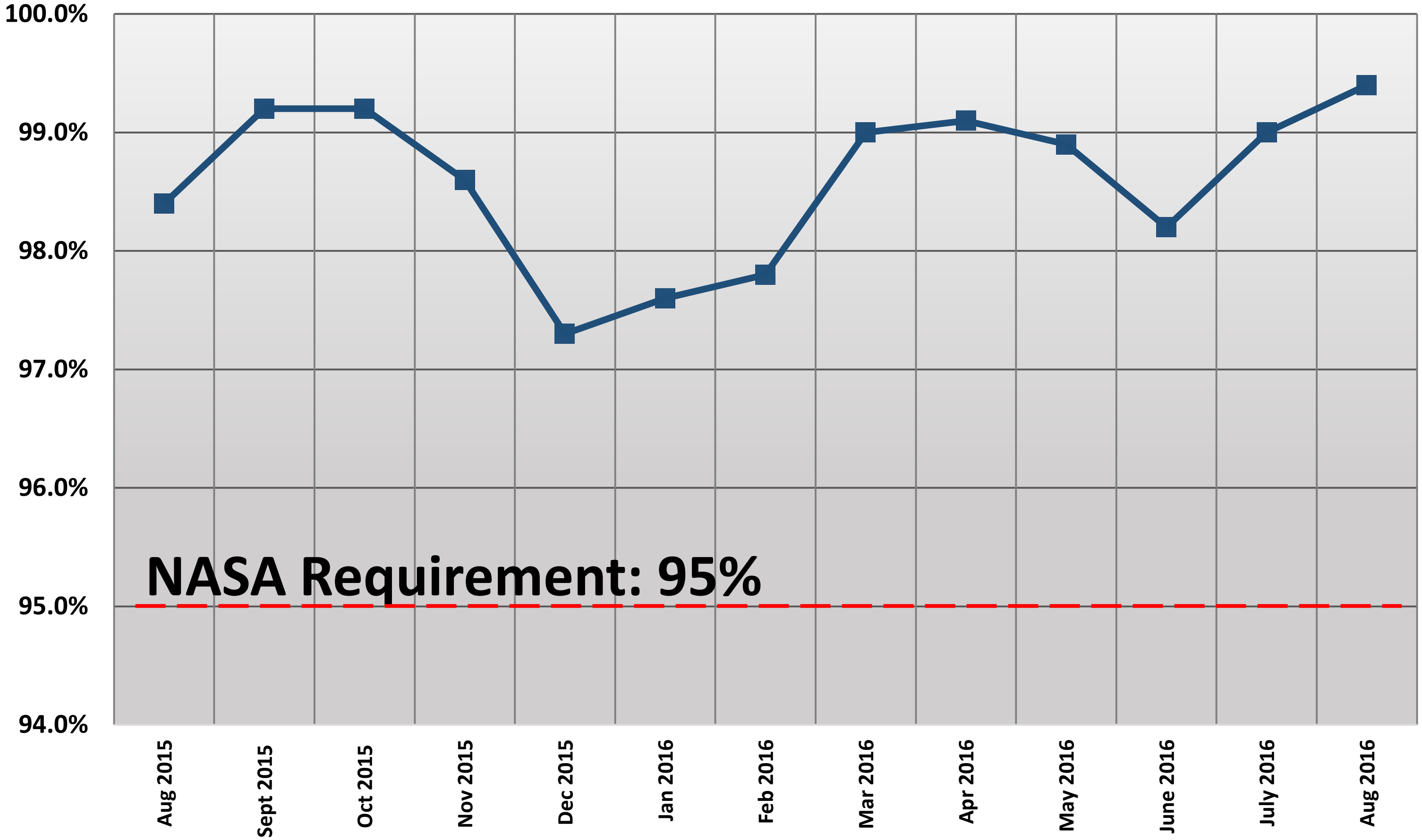
# Deep Space Network Assets




| Station | XX/Ka | S | Ka2 |
|---|---|---|---|
| DSS-26 | - | 11/2017 | (TBD) |
| DSS-35 | 10/2014 | - | - |
| DSS-36 | 10/2016 | 10/2016 | (TBD) |
| DSS-56 | 10/2019 | 10/2019 | 10/2019 |
| DSS-53 | 10/2020 | - | - |
| DSS-33 | 10/2022 | - | - |
| DSS-23 | 10/2024 | - | - |

# DSN Proficiency
## August 2015 – August 2016




| DSN 12-month Rolling Proficiency | |
|---|---|
| Aug 15 | 98.4% |
| Sep-15 | 99.2% |
| Oct-15 | 99.2% |
| Nov-15 | 98.6% |
| Dec-15 | 97.3% |
| Jan-16 | 97.6% |
| Feb-16 | 97.8% |
| Mar-16 | 99.0% |
| Apr-16 | 99.1% |
| May-16 | 98.9% |
| Jun-16 | 98.2% |
| Jul-16 | 99.0% |
| Aug-16 | 99.4% |

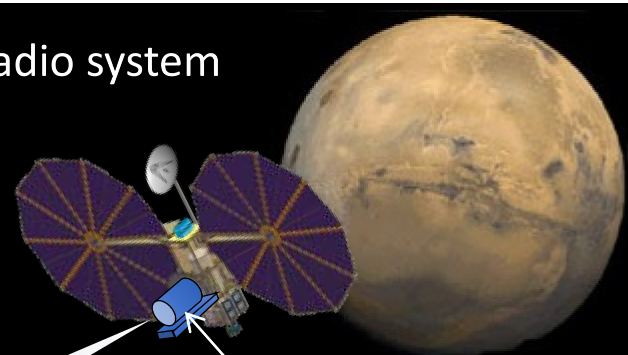
**Serviced 37 missions with 98.6% proficiency**

# Progress in Optical Communications

1st generation technology will perform 10X better than today’s radio system

Narrower beamwidth, increased spectral bandwidth

Technology being pursued today can lead to second 10X factor



Optical Ground Stations:

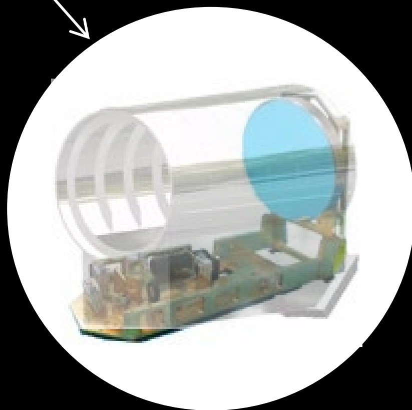
*Can use rented time on large telescopes (e.g. Palomar) for demonstrations*

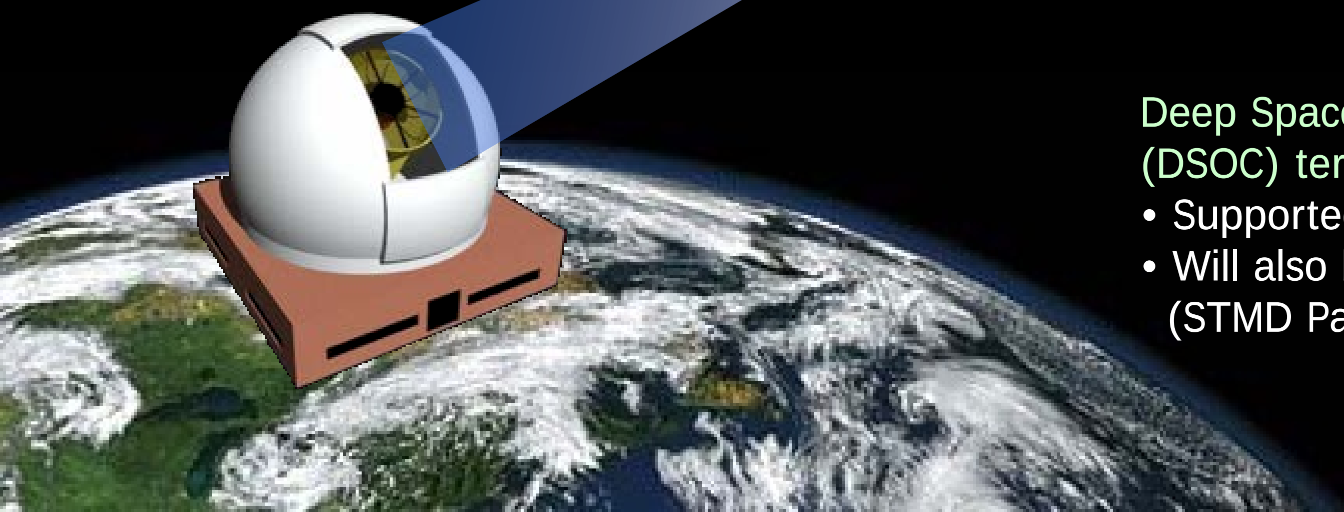
*Trade studies underway for operational stations*

*Investigating hybrid solutions with DSN radio antennas*

*Will require new funding*

*Can partner with other nations*





Deep Space Optical Communications (DSOC) terminal:

- Supported LADEE
- Will also be demonstrated on Psyche (STMD Partnership)

# Supporting NASA Activities

- Suborbital programs:
  - *A funding line to promote use of suborbital platforms for planetary observations would complement and reduce the load on the planetary astronomy program.*
- The Deep Space Network:
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# JSC's Astromaterials Acquisition & Curation Office

The Astromaterials Acquisition and Curation Office comprises a large complex of labs and supporting infrastructure that has been upgraded and maintained over time.

- 8 clean room suites and associated laboratories including 22 clean rooms (ISO class 4-7), sample vaults for pristine and return samples, experimental labs, thin section labs, core and saw rooms, precision tool cleaning facilities, UPW, air handling, filtering, and $N_2$ systems.
- 45+ year archives and public database (mission & sample documents, living records of all aspects of sample handling) Uniquely trained curatorial and technical staff of ~30
- Close and continuing coordination with the mission and research communities, as well as other curation facilities around the world.
- CAPTEM - Curation and Analysis Planning Team for Extraterrestrial Materials - "Dedicated to maximizing planetary sample science while protecting the integrity of  NASA-collected extraterrestrial materials"

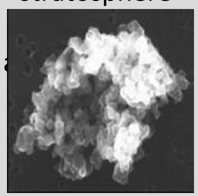
# JSC’s Astromaterials Acquisition & Curation Office

## *Past 50 years – planning for and curating multiple collections*

**Lunar**
(1969)
Apollo program lunar rocks and soils; Luna samples

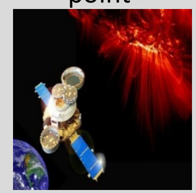
**Meteorite**
(1977)
Antarctic Search for Meteorites (ANSMET) program

**Cosmic Dust**
(1981)
Cosmic dust grains from Earth’s stratosphere

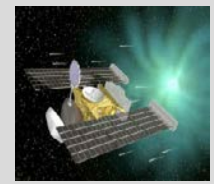


**Microparticle Impact Col.**
(1985)
Space exposed hardware from orbiting spacecraft

**Genesis**
(2004)
Genesis solar wind samples at Earth-Sun L1 point



**Stardust**
(2006)
Cometary and interstellar samples from Comet Wild 2



**Hayabusa**
(2012)
Samples collected from JAXA asteroid mission to Itokawa

## *Our Near Future . . .*

**Hayabusa II**
(2020)
Subset of samples collected from JAXA asteroid mission to (162173) 1999

**OSIRIS-REx**
( 2023)
Asteroid sample return from 101955 Bennu

*Authority from NPD 7100.10F + derivative NPR*

## *Our More Distant Future . . .*

**Moon**
( 2020s)
Volatile-rich farside polar sample return

Next New Frontiers Call Spring 2017

**Comet**
( 2020s)
Cold curated surface sample return from a comet

Next New Frontiers Call Spring 2017

**Phobos**
(2020s)
10% of a JAXA mission to bring back Phobos material

JAXA sample return mission

**Mars**
(~2030+)
Many Mars Sample Return Possibilities

Over 50 years in the planning (est. 1964)

CAPTEM

Curation and Analysis Planning Team for Extraterrestrial Materials

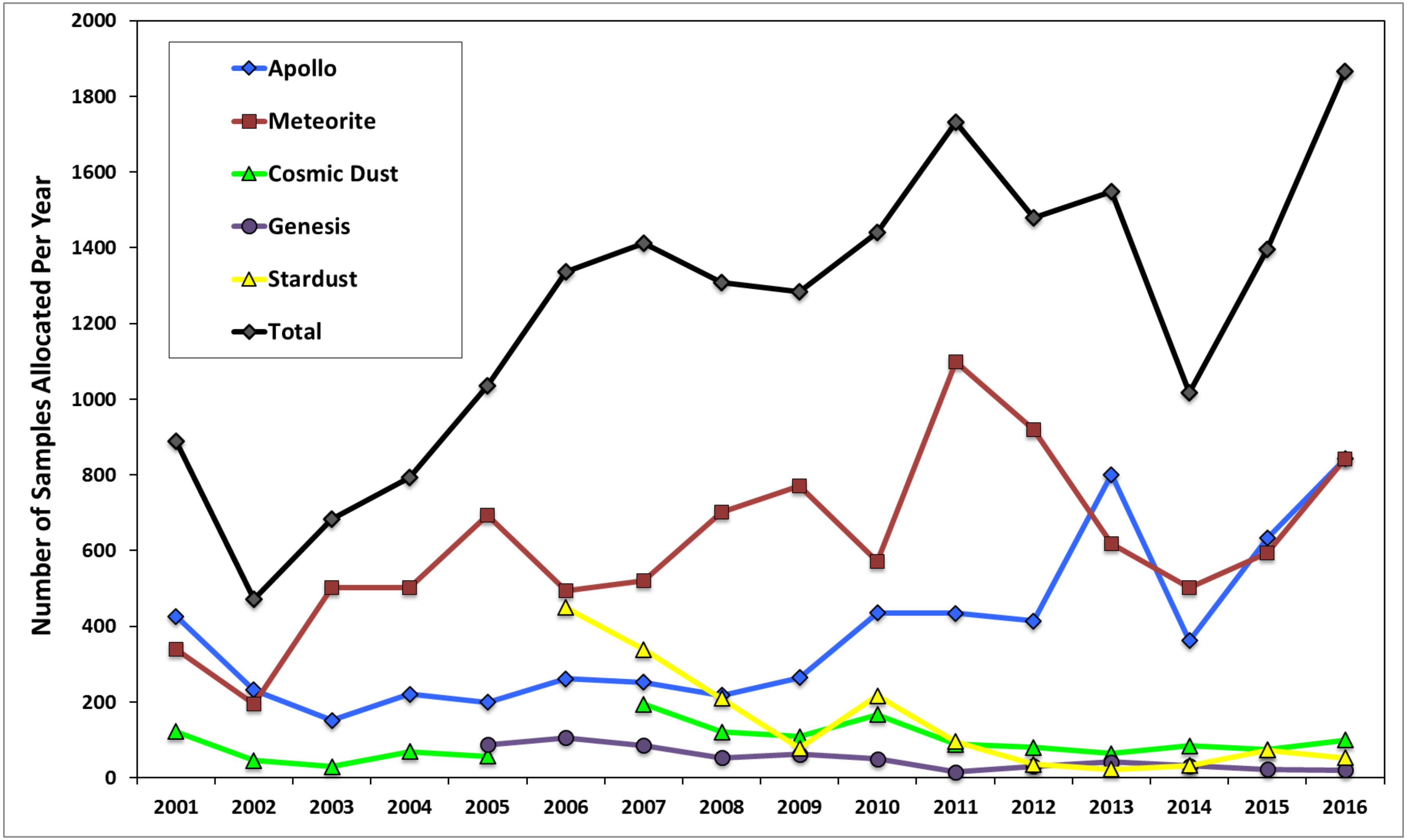
# CAPTEM

*Chair: Hap McSween (University of Tennessee)*

- **Lunar Sample subcommittee** — <u>Chair</u>: *Alan Treiman (LPI)*
- **Stardust subcommittee** — *Andrew Westphal (UC Berkeley)*
  - **Facilities subcommittee** — *Dimitri Papanastassiou (JPL)*
- **Genesis subcommittee** — *Larry Nyquist (JSC)*
  - **Meteorite Working Group** — *Conel Alexander (Carnegie Inst)*
- **Cosmic Dust subcommittee** — *George Flynn (SUNY Plattsburgh)*
  - **Informatics subcommittee** — *Andrew Westphal (UC Berkeley)*
- **Asteroid Sample subcommittee** — *Kevin McKeegan (UCLA)*

*<u>Additional Members</u>: James Day (UCSD), Juliane Gross (U Houston), Kieren Howard (CCNY), Rhianon Mayne (TCU), Jeff Taylor (U Hawaii), Aaron Burton (JSC, Secretary)*

# Total Samples Allocated Per Year



# Societal Needs:
# Near Earth Objects Observations Program

# Commitments & Congressional Actions

## Near Earth Object Observations Program

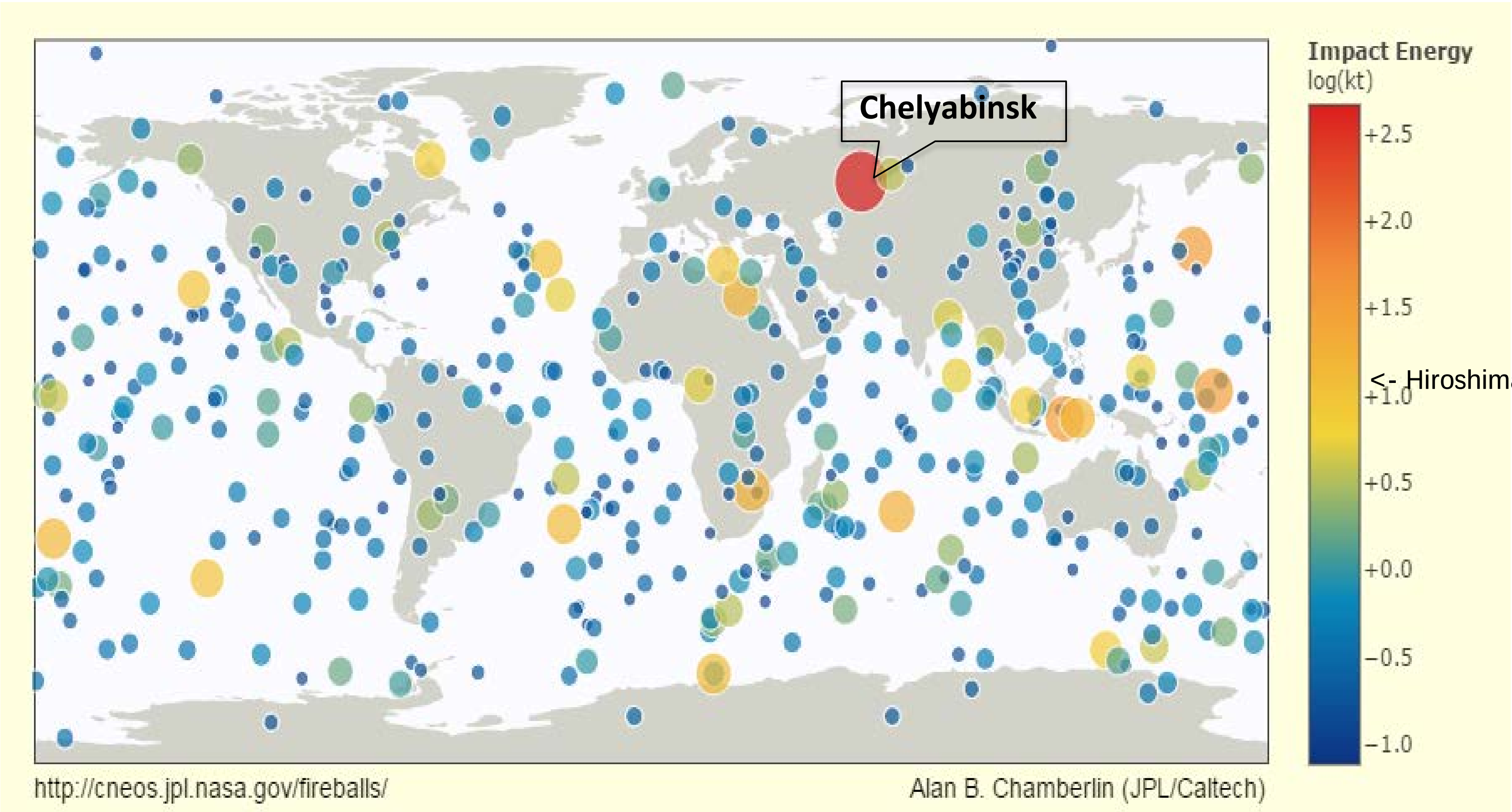
- Began with NASA commitment to House Committee on Science in May 1998 to find at least 90% of 1 km and larger NEOs
- That goal reached by end of 2010

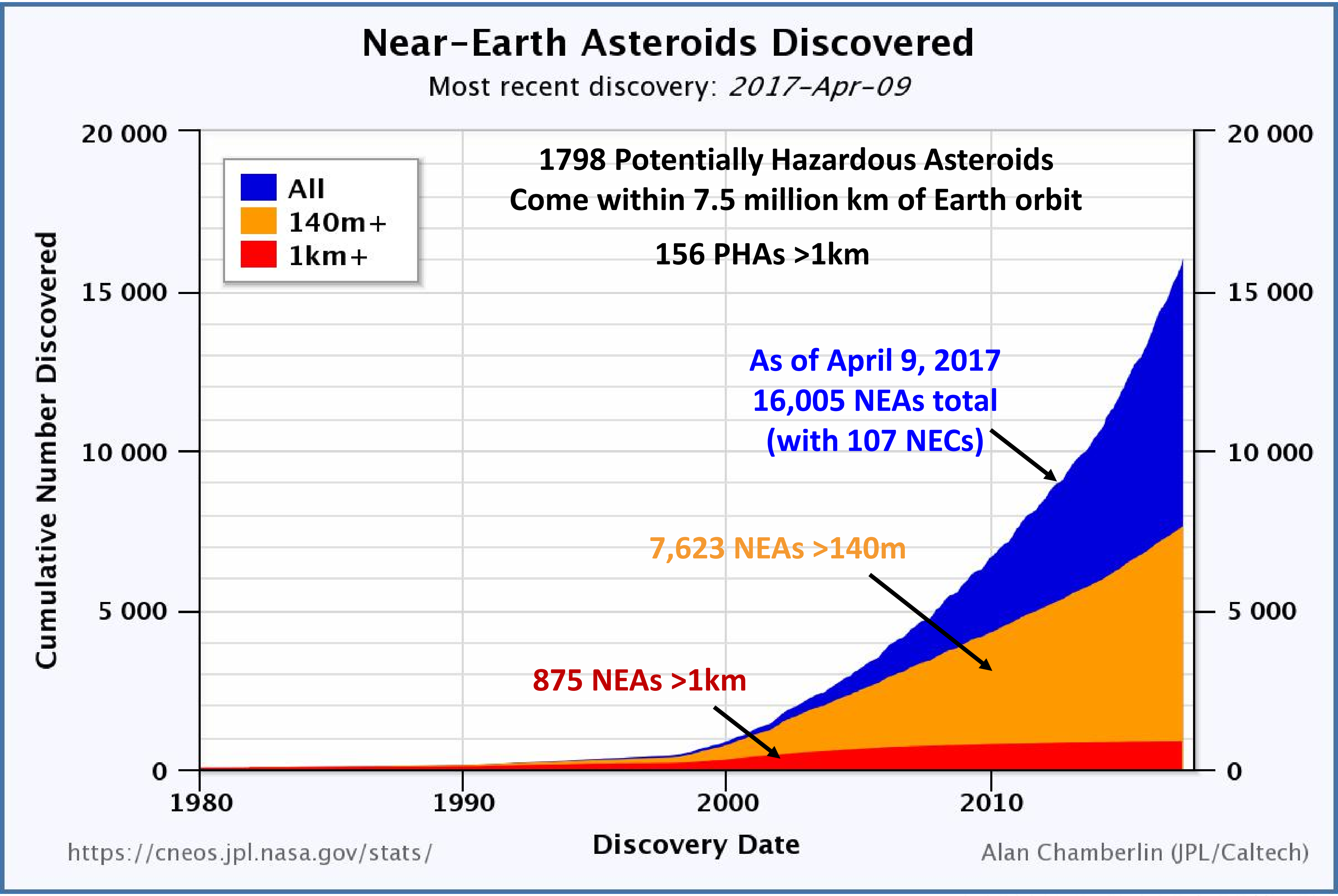
## NASA Authorization Act of 2005

- Amended NASA Act of 1958 to add: ''The Congress declares that the general welfare and security of the United States require that the unique competence of the National Aeronautics and Space Administration be directed to detecting, tracking, cataloguing, and characterizing near-Earth asteroids and comets in order to provide warning and mitigation of the potential hazard of such near-Earth objects to the Earth.''
- Provided additional direction: "…plan, develop, and implement a Near-Earth Object Survey program to detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater than 140 meters in diameter in order to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90% completion of its near-Earth object catalogue within 15 years [by 2020]"

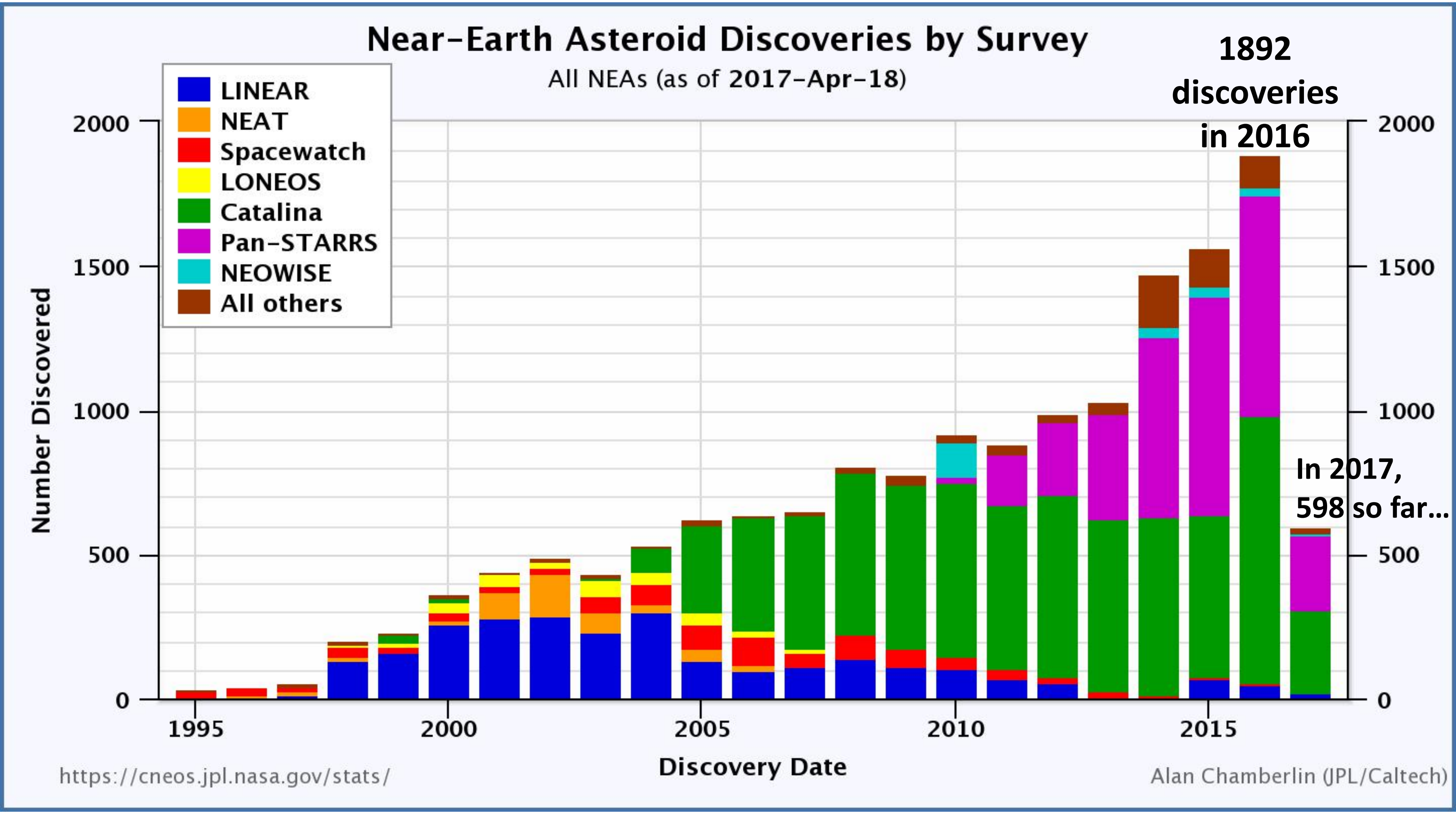
# Bolide Events 1988 – 2016

## Small Asteroids that Disintegrated in Earth's Atmosphere





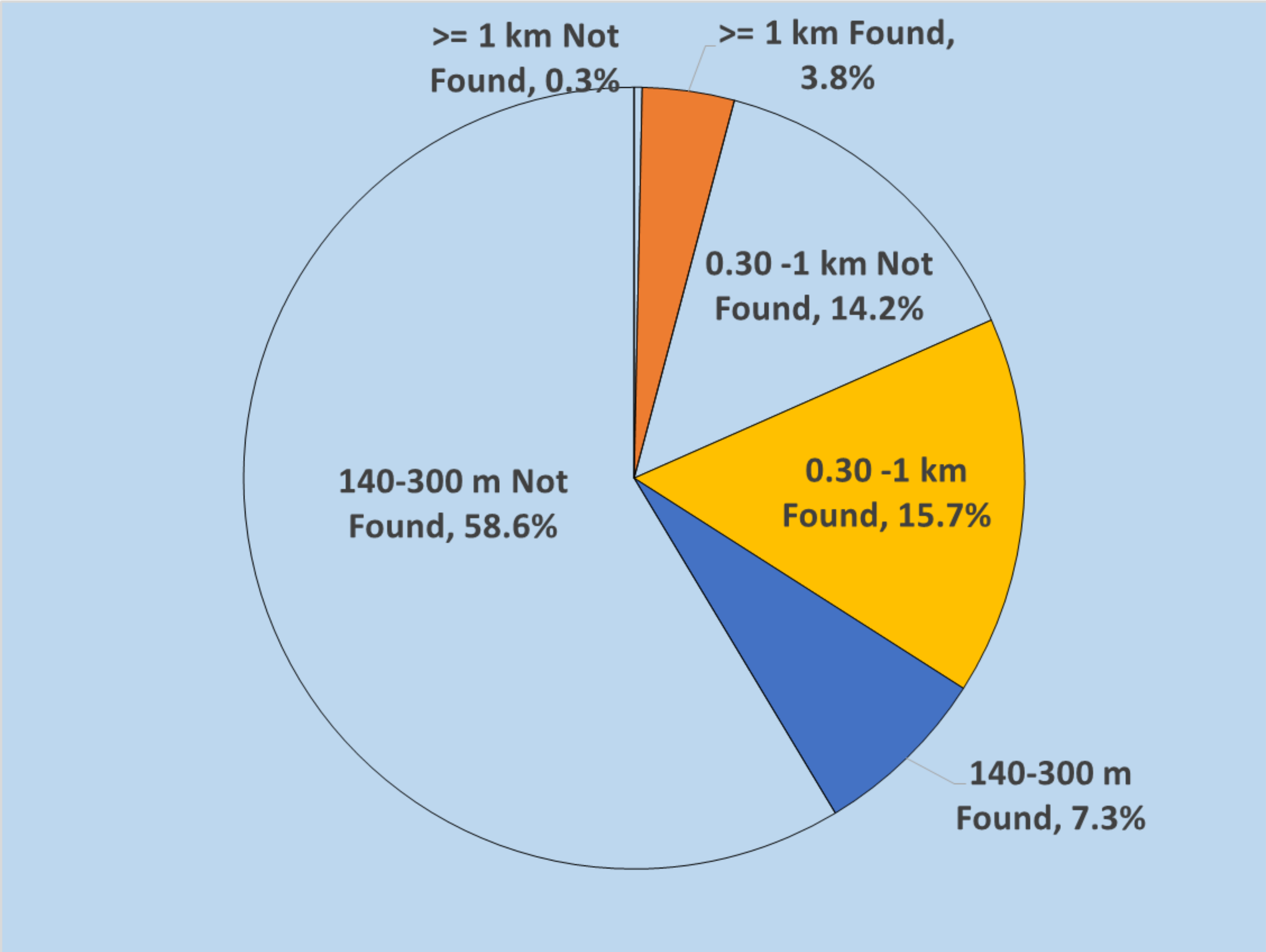
Near-Earth Asteroids Discovered
Most recent discovery: 2017-Apr-09
1798 Potentially Hazardous Asteroids
Come within 7.5 million km of Earth orbit
156 PHAs >1km
All
140m+
1km+
As of April 9, 2017
16,005 NEAs total
(with 107 NECs)
7,623 NEAs >140m
875 NEAs >1km
Cumulative Number Discovered
20 000
15 000
10 000
5 000
0
1980
1990
2000
2010
Discovery Date
https://cneos.jpl.nasa.gov/stats/
Alan Chamberlin (JPL/Caltech)



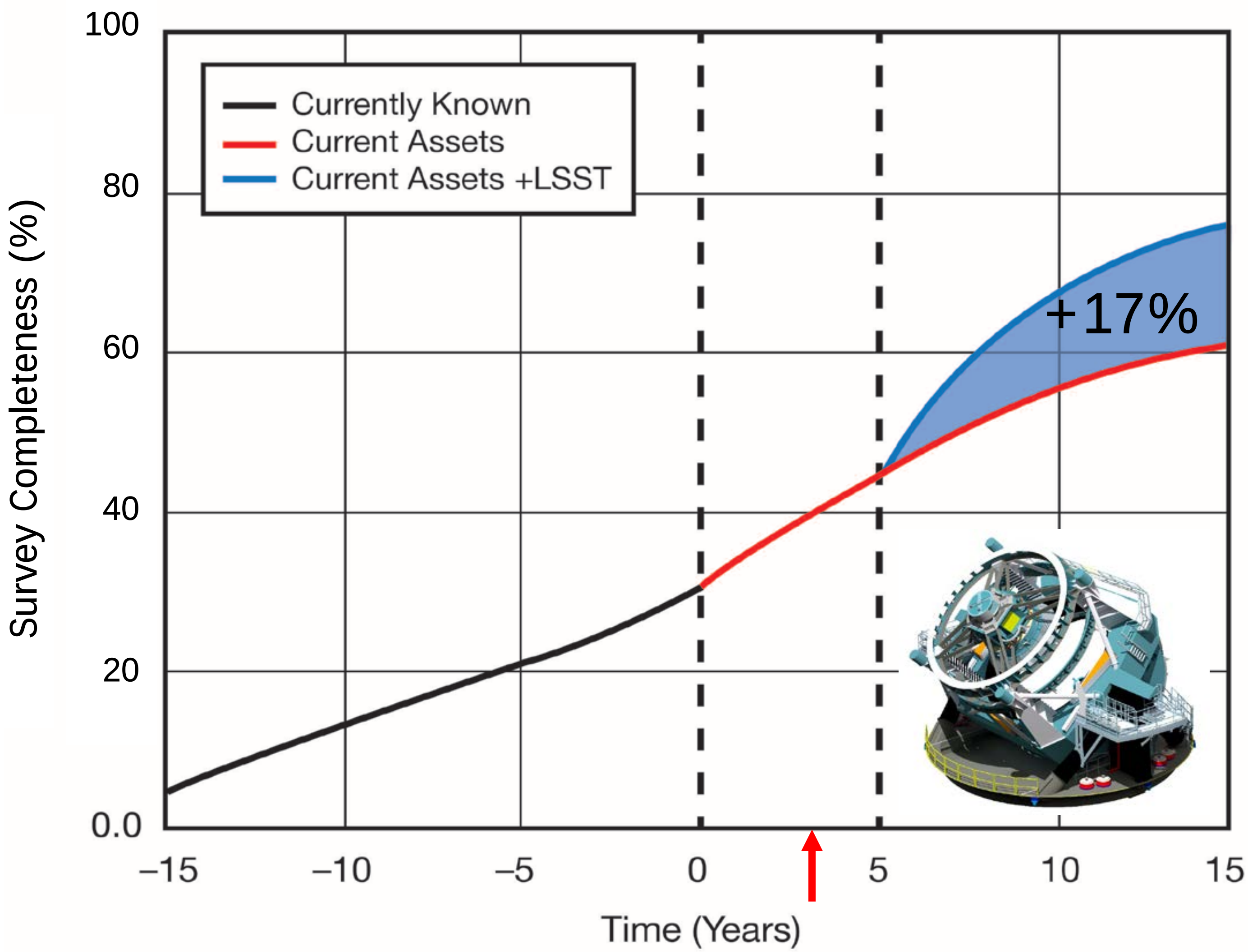
Near-Earth Asteroid Discoveries by Survey
All NEAs (as of 2017-Apr-18)
LINEAR
NEAT
Spacewatch
LONEOS
Catalina
Pan-STARRS
NEOWISE
All others
Number Discovered
0
500
1000
1500
2000
1995
2000
2005
2010
2015
Discovery Date
https://cneos.jpl.nasa.gov/stats/
Alan Chamberlin (JPL/Caltech)
1892 discoveries in 2016
In 2017, 598 so far…

# Near Earth Asteroid Survey Status

If Population 140 meters and greater is ~ 25,500 = 100%



# LSST as a Potential Future Asset




- Will not accomplish Congressional requirement by 2020

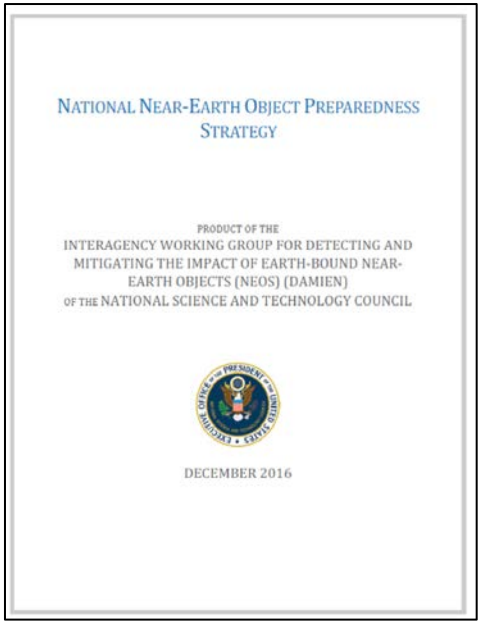
# Planetary Defense Coordination Office

This new office was recently established at NASA HQ to coordinate planetary defense related activities across NASA, and coordinate both US interagency and international efforts and projects to address and plan response to the asteroid impact hazard.

**Lead National and International efforts to:**

- Detect any potential for significant impact of planet Earth by natural objects
- Appraise the range of potential effects by any possible impact
- Develop strategies to mitigate impact effects on human welfare

# Planetary Defense Coordination Office


National Near-Earth Object Preparedness Strategy

Product of the
Interagency Working Group for Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects (NEOs) (DAMIEN)
of the National Science and Technology Council

December 2016

Administrator
Associate Administrator

Associate Administrator,
Science Mission Directorate

Planetary Science Division
Program Director

Lead Program Executive
Planetary Defense Officer

**NEO Observation Program**
Program Manager
Program Scientist

- Minor Planet Center/IAWN
- Center for NEO Studies @ JPL
- Catalina Sky Survey
- Pan-STARRS
- LINEAR/SST
- IRTF
- GSSR
- NEOWISE
- ........

Legacy Program (1998)

Interagency and
Emergency Response
Program Officer(s)

- Interagency coordination
- Emergency Response planning
- Interagency exercise

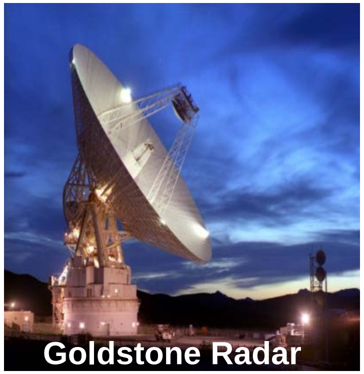
Mitigation Research
Program Officer(s)

- SMPAG
- ARM Gravity Tractor Demo
- AIDA
- Short Warning Mitigation

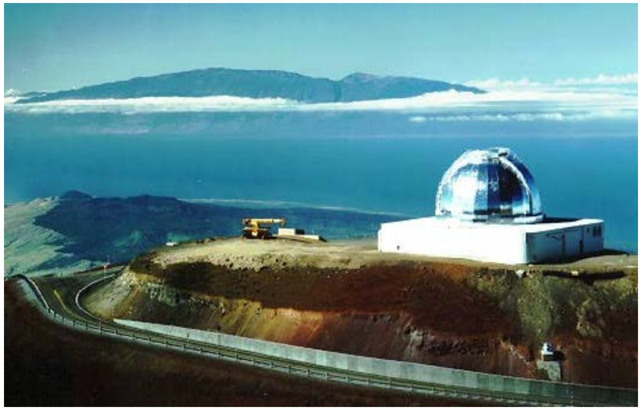
# Primary NEO Characterization Assets

## Radar (Goldstone and Arecibo)

- Increased time for NEO observations
- Streamlining Rapid Response capabilities
- Increased resolution (~4 meters)
- Improve maintainability







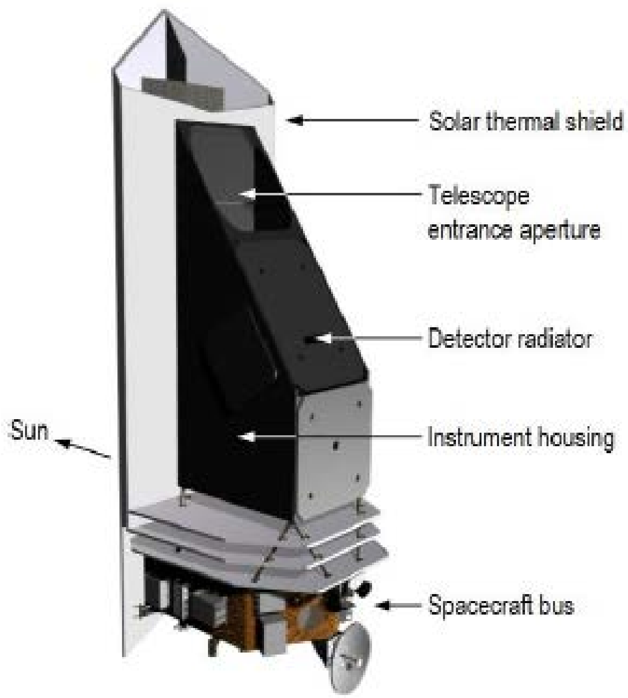
## NASA InfraRed Telescope Facility (IRTF)

- Increased call-up for Rapid Response
- Improving operability/maintainability
- Improve Instrumentation for Spectroscopy and Thermal Signatures

## Spitzer Infrared Space Telescope

- Orbit about Sun, ~176 million km trailing Earth
- In extended Warm-phase mission
- Characterization of Comets and Asteroids
- Thermal Signatures, Albedo/Sizes of NEOs
- Longer time needed for scheduling

# Discovery Selections 2017



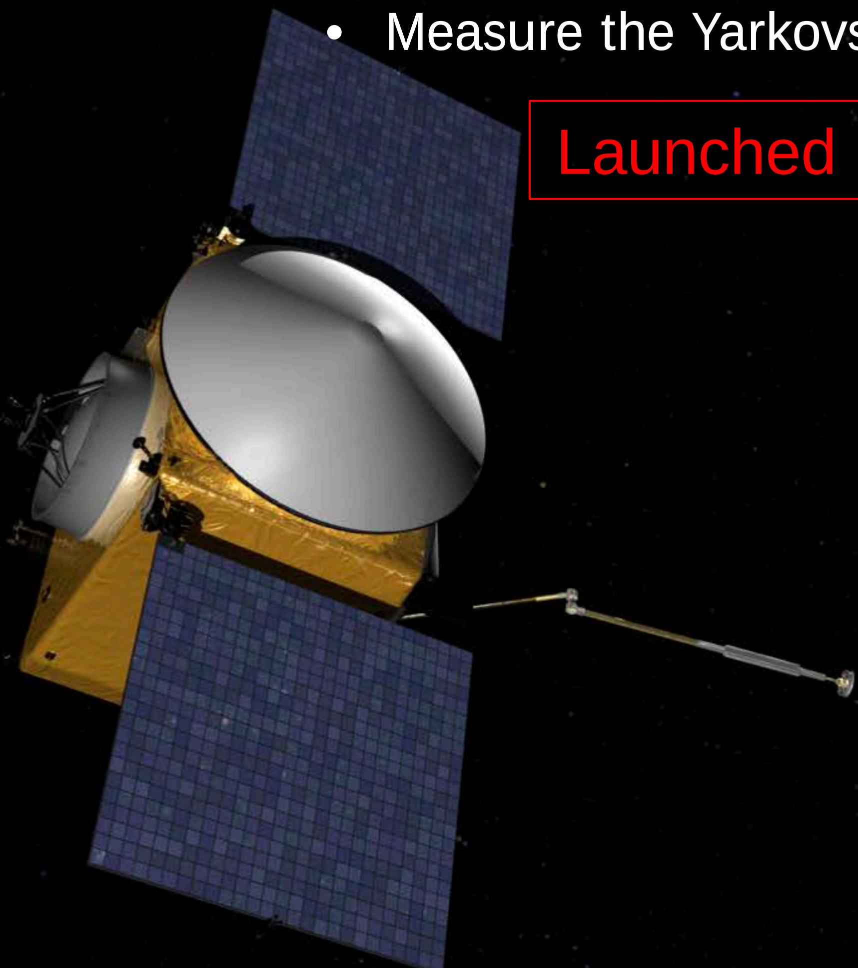

NEOCam:
Near-Earth Object Camera
PI: Amy Mainzer, JPL

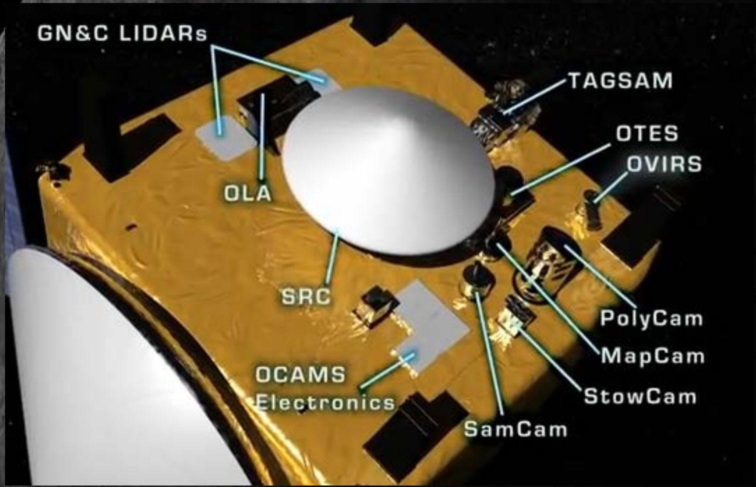
The Discovery Program selection of NEOCam for an extended Phase A effort is an acknowledgement that, even though it was not selected for full mission implementation, it is an important capability for the Agency that will continue formulation efforts to address issues identified in the Discovery evaluation process.

# OSIRIS-REx

- Return and analyze a sample of Bennu's surface
- Map the asteroid & document the sample site
- Measure the Yarkovsky effect

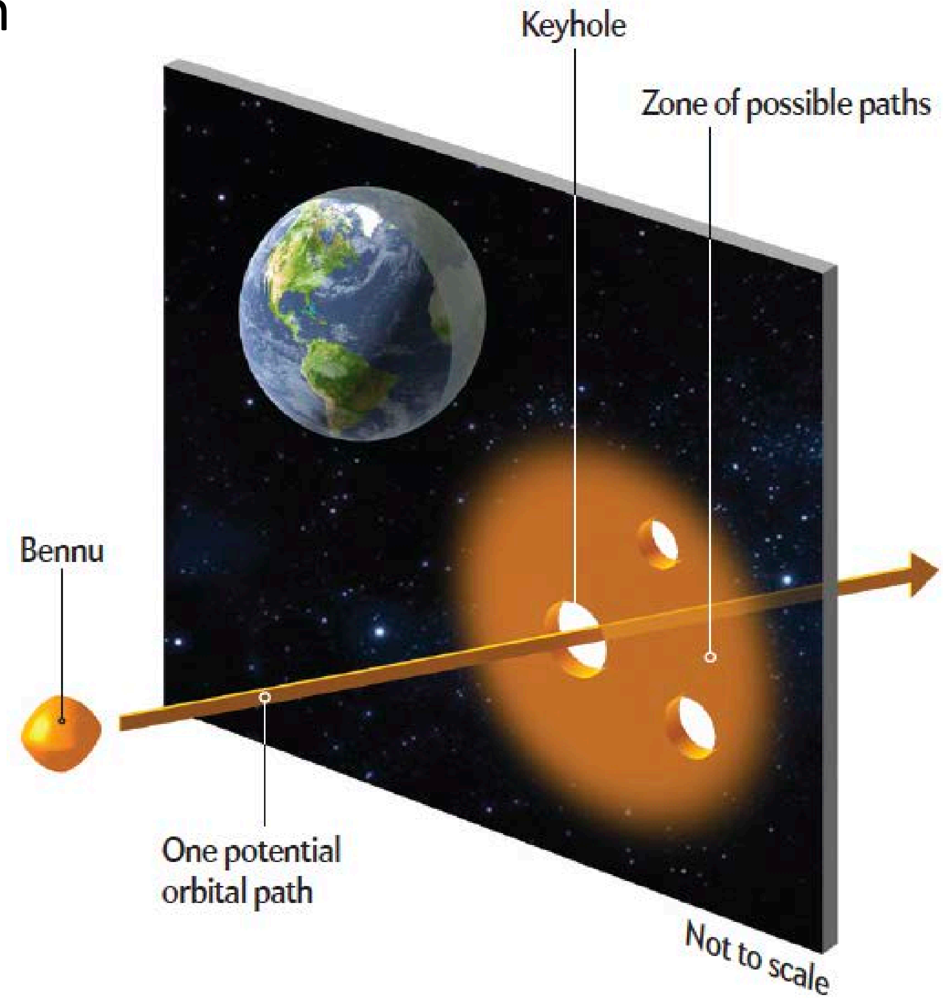
Launched Sept 2016



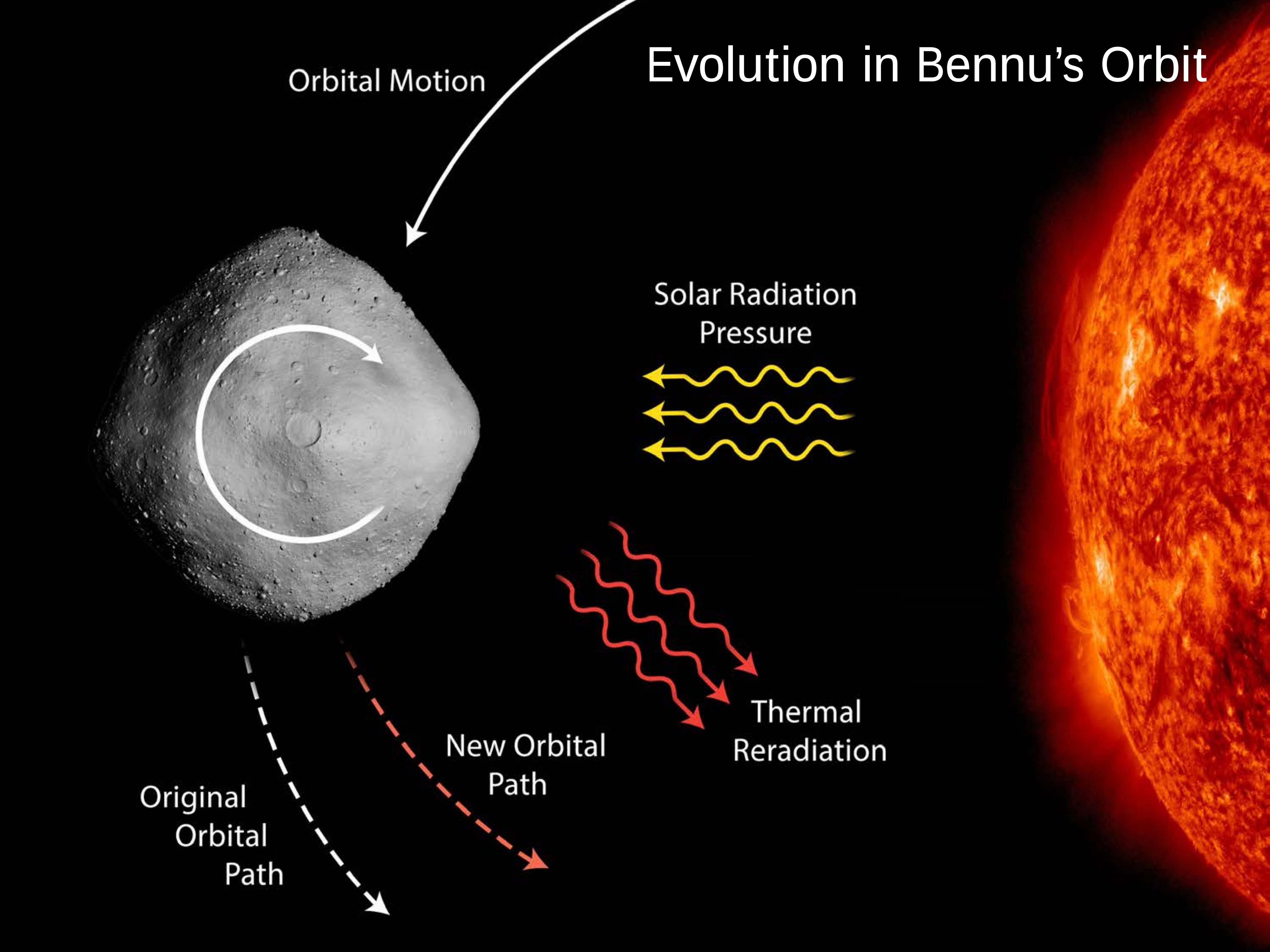



# Bennu as a Potential Hazardous Object

- In 2135 Bennu will pass between the Earth and the Moon
- During that encounter it may go through a "keyhole" in which the Earth's gravity would tweak Bennu's trajectory and put it on a collision course with Earth
- OISIRS-REx will clarify the sources of instabilities in Bennu's orbit

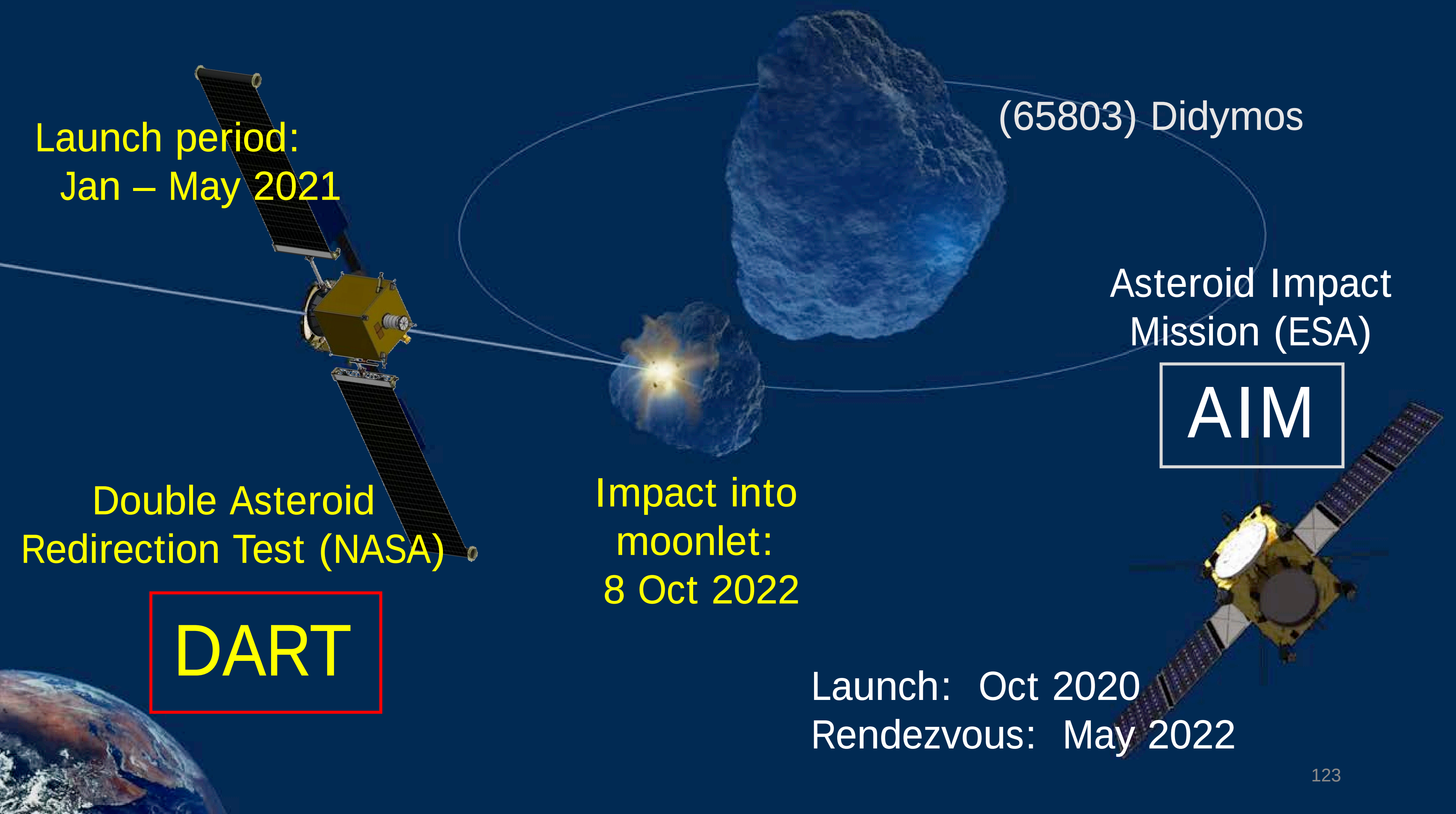


# Evolution in Bennu’s Orbit



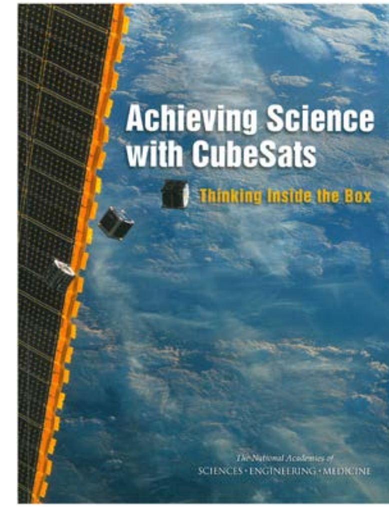
# Asteroid Impact Deflection Assessment (AIDA)

## A Joint Agency Mitigation Concept Under Study



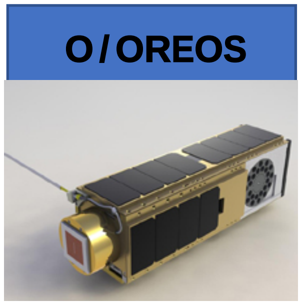
# New Initiatives

# SMD CubeSat/SmallSat Approach

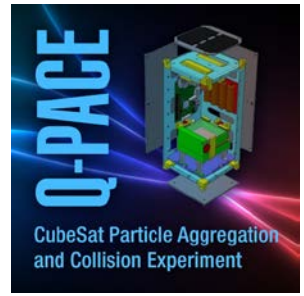



- A National Academies Report (2016) concluded that CubeSats have proven their ability to produce high-value science.
- In particular, CubeSats are useful as targeted investigations to <u>augment</u> the capabilities of larger missions or to make a <u>highly-specific measurement</u>.
- Constellations of 10-100 CubeSat/SmallSat spacecraft have the potential to enable transformational science.
- SMD is developing a directorate-wide approach that has four objectives:
  - Identify high-priority science objectives in each discipline that can be addressed with CubeSats/SmallSats
  - Manage program with appropriate cost and risk
  - Establish a multi-discipline approach and collaboration that helps science teams learn from experiences and grow capability, while avoiding unnecessary duplication
  - Leverage and partner with a growing commercial sector to collaboratively drive instrument and sensor innovation

# Planetary Science CubeSat Missions





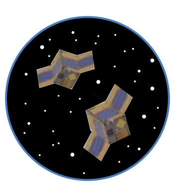
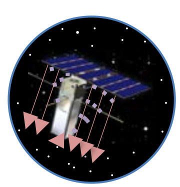
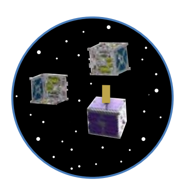
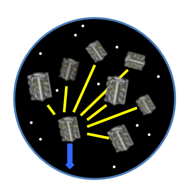


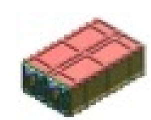



| | O/OREOS | MarCO | Q-PACE | LunaH-Map | INSPIRE |
|---|---|---|---|---|---|
| PI | NASA Ames | JPL | JPL | Arizona St. U. | JPL |
| S/C Size | 3U CubeSat | (2) 6U CubeSats | (2) 6U CubeSats | 6U CubeSat | (2) 3U CubeSats |
| Mission Obj. | Study the effects of the space environment on microorganisms | Provide real-time data relay during InSight entry, descent, and landing | Provide real-time data relay during InSight entry, descent, and landing | Map the water content at lunar South Pole | Demonstrate nav, telecom, C&DH, relay com, deep-space reliability & fault tolerance |
| Launch Date | Nov. 19, 2010 | FY18 w/InSight | FY18 | FY18 (EM-1) | FY18 |

# Planetary Science Deep Space SmallSat Studies

- ROSES Appendix C.23 was released on August 19, 2016
  - NOI/STEP 1 : September 30, 2016 ➔ 107 Submissions
  - STEP 2 : November 18, 2016 ➔ 102 Submissions
- Solicited concept studies for potential CubeSat and SmallSat
  - Concepts sought for 1U to ESPA-class missions
  - Up to $100M mission concept studies considered
  - Not constrained to fly with an existing mission
- PSDS3 Objectives:
  - What Planetary Science investigations can be done with smallsats?
  - What technology development is needed to enable them?
  - What's the anticipated cost range?



# Planetary Science Deep Space SmallSat Studies

Venus

- Christophe Sotin, Cupid's Arrow
- Valeria Cottini, CUVE - Cubesat UV Experiment

Moon

- Suzanne Romaine, CubeSat X-ray Telescope (CubeX)
- Tim Stubbs, Bi-sat Observations of Lunar Atmosphere above Swirls (BOLAS)

**Asteroids**

- Jeffrey Plescia, APEX: Asteroid Probe Experiment
- Benton Clark, CAESAR: CubeSat Asteroid Encounters for Science & Recon

Mars

- David Minton, Chariot to the Moons of Mars
- Tony Colaprete, Aeolus - to study the thermal and wind environment of Mars

Icy Bodies and Outer Planets

- Kunio Sayanagi, SNAP: Small Next-generation Atmospheric Probe
- Robert Ebert, JUpiter MagnetosPheric boundary ExploreR (JUMPER)

# Summary

- This is a time of great promise in the exploration of the solar system, but also a time of serious budget constraints.
- The recommended program is science-driven, and will enable progress across the breadth of solar system research.
- A mixed portfolio of small, medium, and large missions is recommended through the decade.
- Effective international collaboration is required for success of the program.
- A serious effort has been made to evaluate the technical readiness, risk, and cost of all recommended missions.
- The planetary decadal survey has involved broad input from the planetary science community, hard work by the study centers and consultants, and the strong cooperation of NASA, NSF, and professional societies.

# Planetary Science Missions Events

*** Completed**

**2016**

March – Launch of ESA's *ExoMars Trace Gas Orbiter*
July 4 – *Juno* inserted in Jupiter orbit
September 8 – Launch of Asteroid mission *OSIRIS – REx* to asteroid Bennu
September 30 – Landing *Rosetta* on comet CG
October 19 – *ExoMars EDM* landing and *TGO* orbit insertion

**2017**

January 4 – Discovery Mission selection announced
February 9-20 - *OSIRIS-REx* began Earth-Trojan search
April 22 – Cassini begins plane change maneuver for the "Grand Finale"
September 15 – *Cassini* crashes into Saturn – end of mission
September 22 – *OSIRIS-REx* Earth flyby

**2018**

May 5 - Launch *InSight* mission to Mars
August – *OSIRIS-REx* arrival at Bennu
October – Launch of ESA's *BepiColombo*
October – Launch of *JWST*
November 26 – *InSight* landing on Mars

# Planetary Science Missions Events

**2019**
January 1 – *New Horizons* flyby of Kuiper Belt object 2014MU69

**2020**
May – Launch of Mars2020 mission to Mars
July – *OSIRIS-REx* retrieves a sample from Bennu
December – Landing of *Mars2020* rover on Mars

**2021**
March– *OSIRIS-REx* Leaves Bennu
October – Launch of *Lucy*

**2023**
Summer – Launch of *Psyche*
September 23 – Return of Bennu samples from *OSIRIS-REx*

# Questions?