National Aeronautics and
Space Administration

MARS EXPLORATION PROGRAM

August 28, 2017

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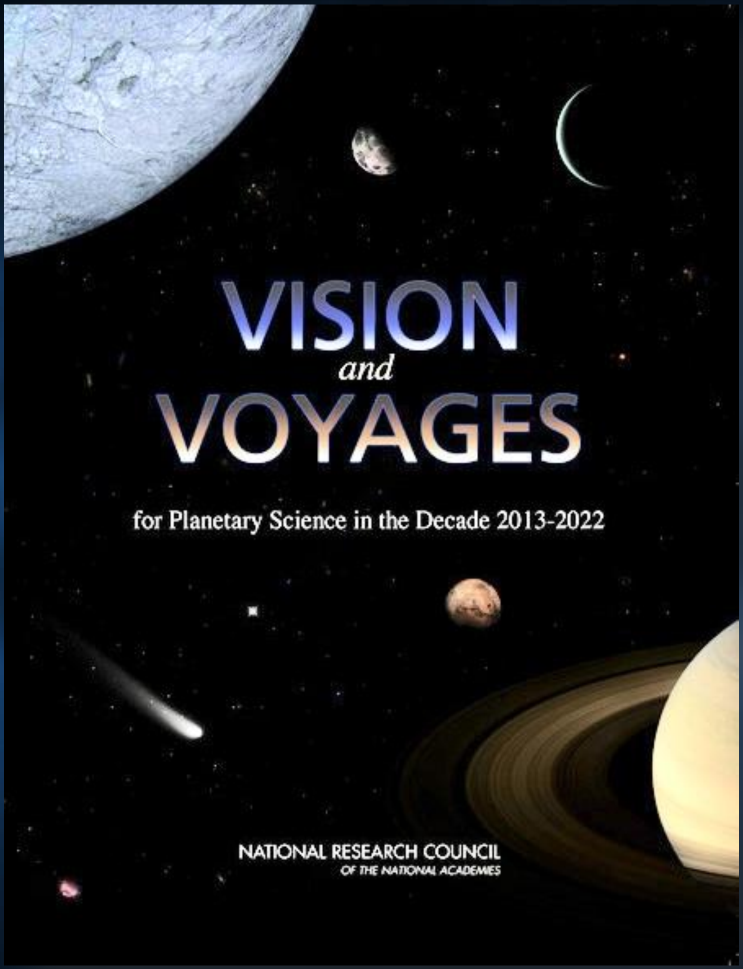
NASA SMD Associate Administrator

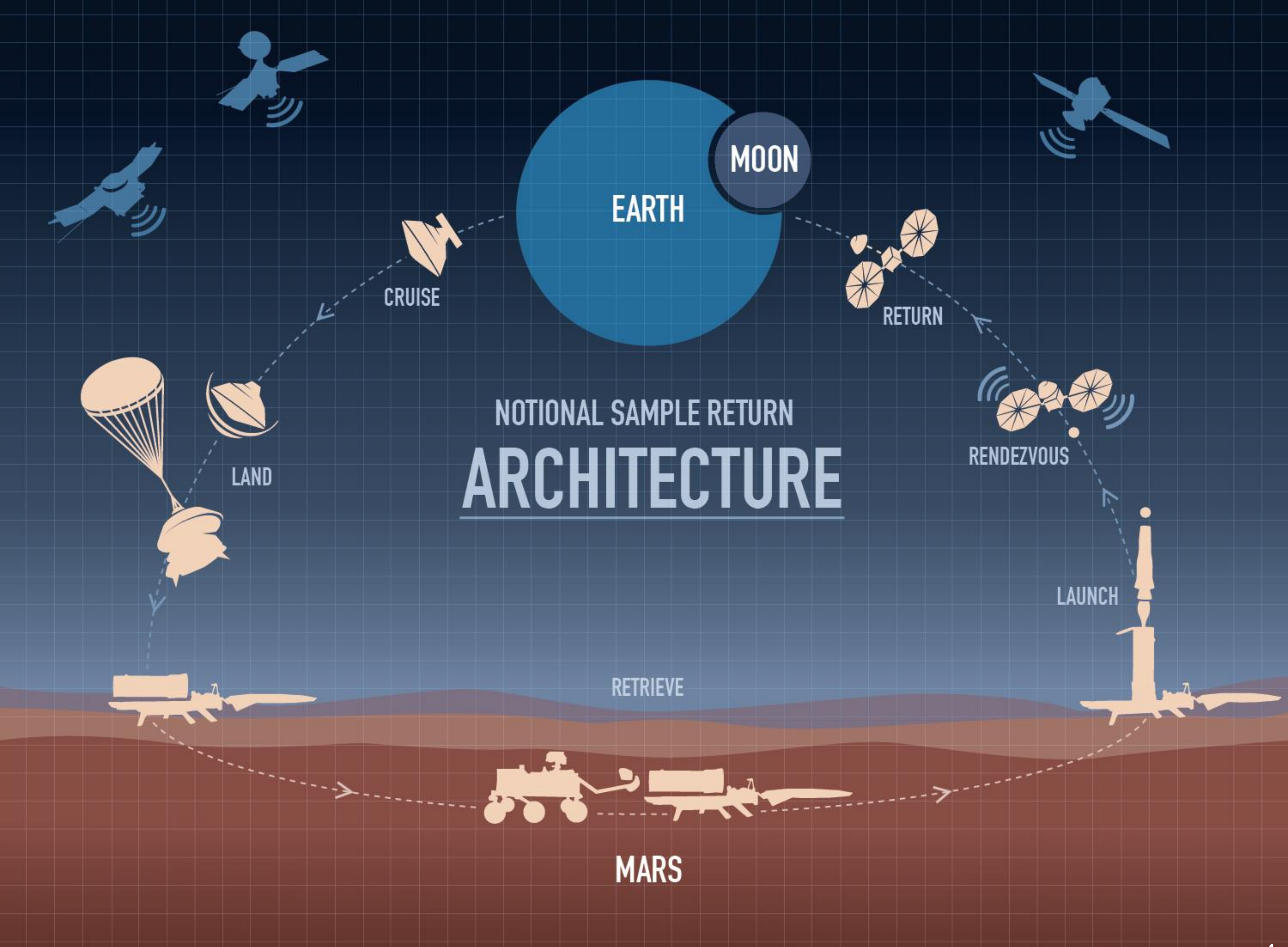
MARS EXPLORATION PROGRAM – SUMMARY

- Decadal Survey science goals
  - Determine if life ever arose on Mars
  - Understand the processes and history of climate
  - Determine the evolution of the surface and interior
- Progress report
  - Making breakthroughs in Mars science
  - Gaining knowledge in preparation of future Mars exploration
  - Current missions are healthy and performing well
  - Technology investments are addressing pivotal issues for future Mars exploration architectures
- Our future architectures should adapt to evolving in Mars exploration
  - Existing program capabilities
  - Multiple international interests
  - Multiple commercial interests
- Investigating new, leaner Mars architectures to respond to global changes in Mars exploration

MARS EXPLORATION PROGRAM – DECADAL PRIORITY

- The committee established three high-priority science goals for the exploration of Mars:
  - Determine if life ever arose on Mars
  - Understand the process and history of climate
  - Determine the evolution of the surface and interior
- *“A critical next step …. will be provided through the analysis of carefully selected samples from geologically diverse and well-characterized sites that are returned to Earth for detailed study using a wide diversity of laboratory techniques”*
- *“The highest priority Flagship mission for the decade of 2013-2022 is MAX-C … However, the cost of MAX-C must be constrained in order to maintain programmatic balance.”*




MOON
EARTH
CRUISE
RETURN
NOTIONAL SAMPLE RETURN
ARCHITECTURE
LAND
RENDEZVOUS
LAUNCH
RETRIEVE
MARS

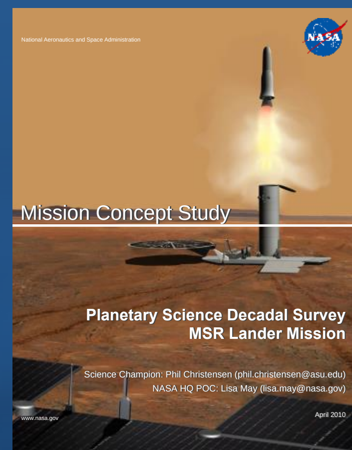
DECADAL SURVEY MSR CONCEPTS

Sample Caching Rover

- MSL-heritage Skycrane EDL
- MAX-C Rover (solar powered)
  - Sample Caching System
  - Instrument suite for sample selection/context
  - 2 integrated caches, each w/ 19 sample tubes

Key Technologies
- Sample Caching System
- Terrain Relative Navigation

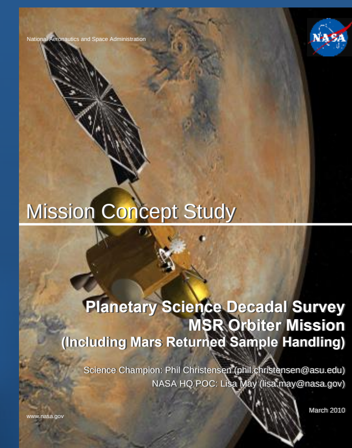
Sample Return Lander



- MSL-heritage Skycrane EDL
- Pallet Lander
  - Fetch Rover (157 kg)
  - Mars Ascent Vehicle (2-stage Solid-Solid)
  - 17-cm OS

Key Technologies
- Mars Ascent Vehicle
- Fast Fetch Rover

Sample Return Orbiter



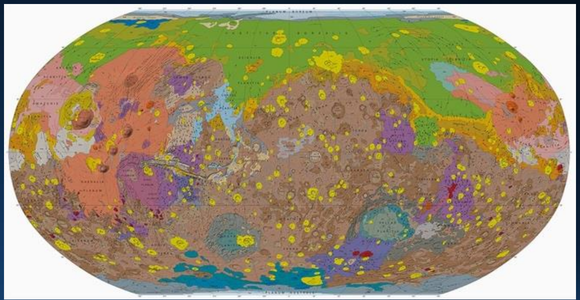
- Round-trip Orbiter (ChemicalPropulsion)
  - MOI, Aerobrake
  - OS Rendezvous & Capture
  - Earth Return
  - Earth Entry Vehicle
- Mars Returned Sample Handling

Key Technologies
- OS Rendezvous and Capture
- Back Planetary Protection

MARS SCIENCE HIGHLIGHTS

- Orbiters and rovers confirmed ancient habitable environment
- Rovers measured the environment for human explorers
- MRO revealed complex and evolving planet

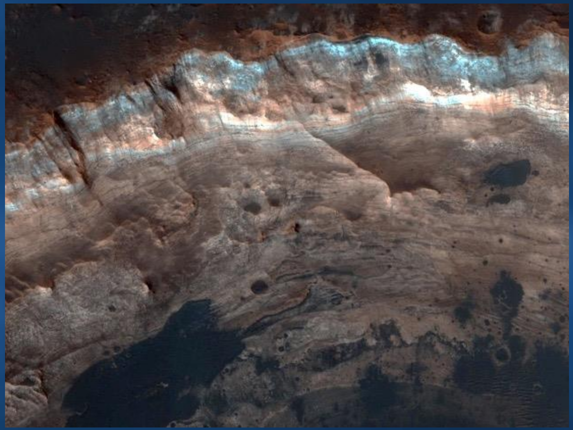
MARS SCIENCE HIGHLIGHTS

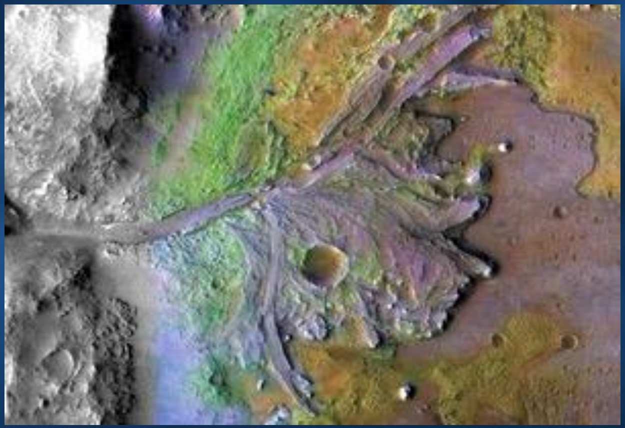


New USGS geologic map of Mars summarizes findings since Viking[5]

Revealed Complex and Evolving Planet

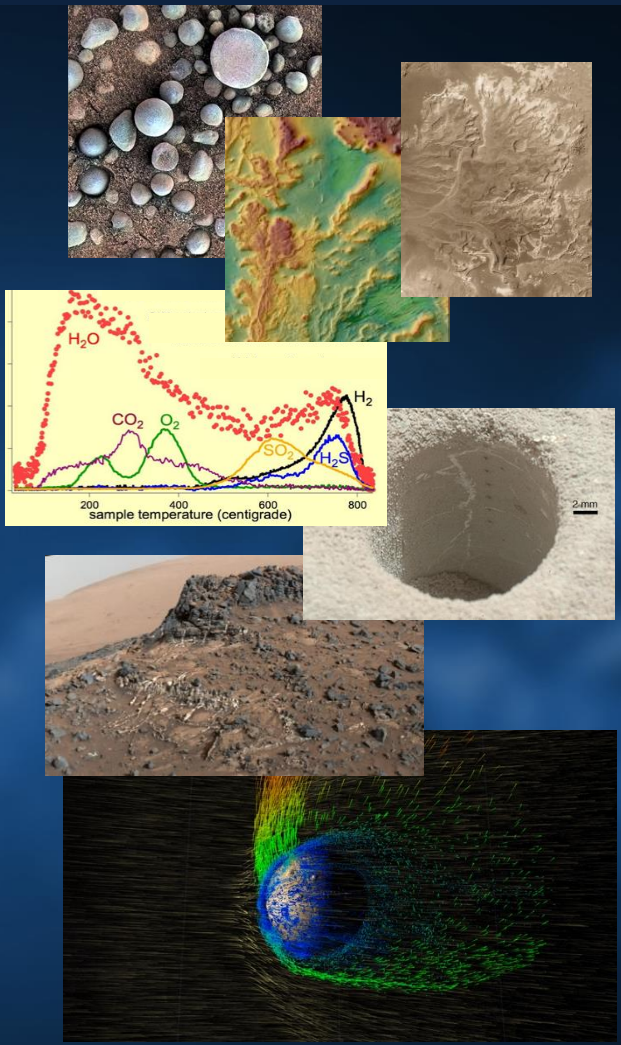
- Imaging and spectroscopy revealed a rich history of geological processes[1,2] , including aqueous activity recorded in the stratigraphy[3] and mineralogy[4] across the Martian surface
- Orbiters and rovers show Mars today is still a dynamic planet





1. Carr and Head, *Earth and Planet. Sci. Lett.*, **294**, 185–203 (2010)
2. Ehlmann, et al., *J. Geophys. Res.*, **121,** 10 (2016)
3. Grotzinger and Milliken, *SEPM Special Pub #102* (2012)
4. Ehlmann and Edwards, Annu. Rev. Earth Planet. Sci., 42, 291–315 (2014)
5. Tanaka et al., Planet. and Space Sci., 95, 11-24 (2014)

MARS SCIENCE HIGHLIGHTS

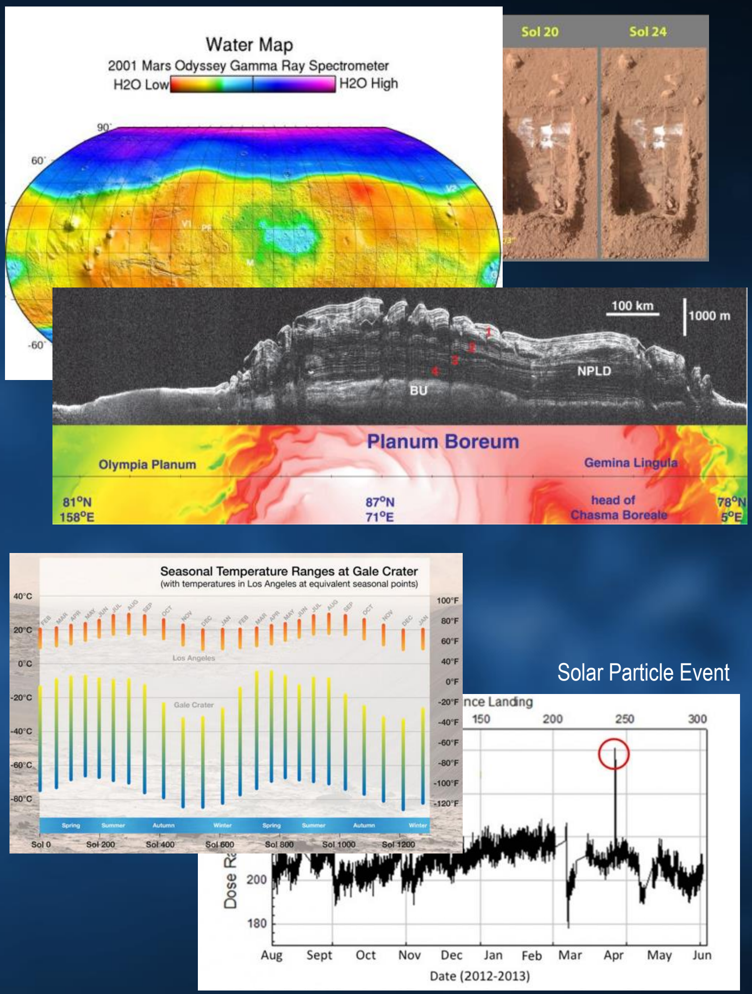


Confirmed Ancient Habitable Environment

- **Mars Orbiter** cameras mapped the remnants of river channels, deltas, lakes[1], and potentially even larger bodies of water billions of years old
- The **Spirit** and **Opportunity** rovers confirmed water with diverse chemistries persisted in the ancient past on the surface, as groundwater, and within hydrothermal systems[2]
- **Curiosity** assessed an ancient lake and groundwater system within Gale Crater; X-ray diffraction and evolved gas analyses of a drilled mudstone sample indicated past water with near-neutral pH and low-salinity[3]; Further analyses detected key chemical elements required by life, nitrates, and simple organic molecules[4]
- Exploration by **Curiosity** determined lakes and groundwater were present for at least millions of years, with variable chemistry, pH, and salinity[5]
- **MAVEN** obtained compelling evidence that the loss of atmospheric gases to space has been a major driver of climate change on Mars
- Upper-atmospheric structure of Ar isotopes indicates ~70% of the atmosphere lost to space by sputtering[6]

1. Fassett and Head, *Icarus*, **198**, 37-56 (2008)
2. Arvidson, R.E., *J. Geophys. Res.*, **121,** 9, (2016)
3. Grotzinger et al., *Science*, **350**, 7575 (2015)
4. Freissinet et al., *J. Geophys. Res.*, **120**, 495-514 (2015)
5. Hurowitz et al., *Science*, **356**, 6849 (2017)
6. Jakosky et al., *Science*, **355**, 1408–1410 (2017)

MARS SCIENCE HIGHLIGHTS



Measured Environment for Human Explorers

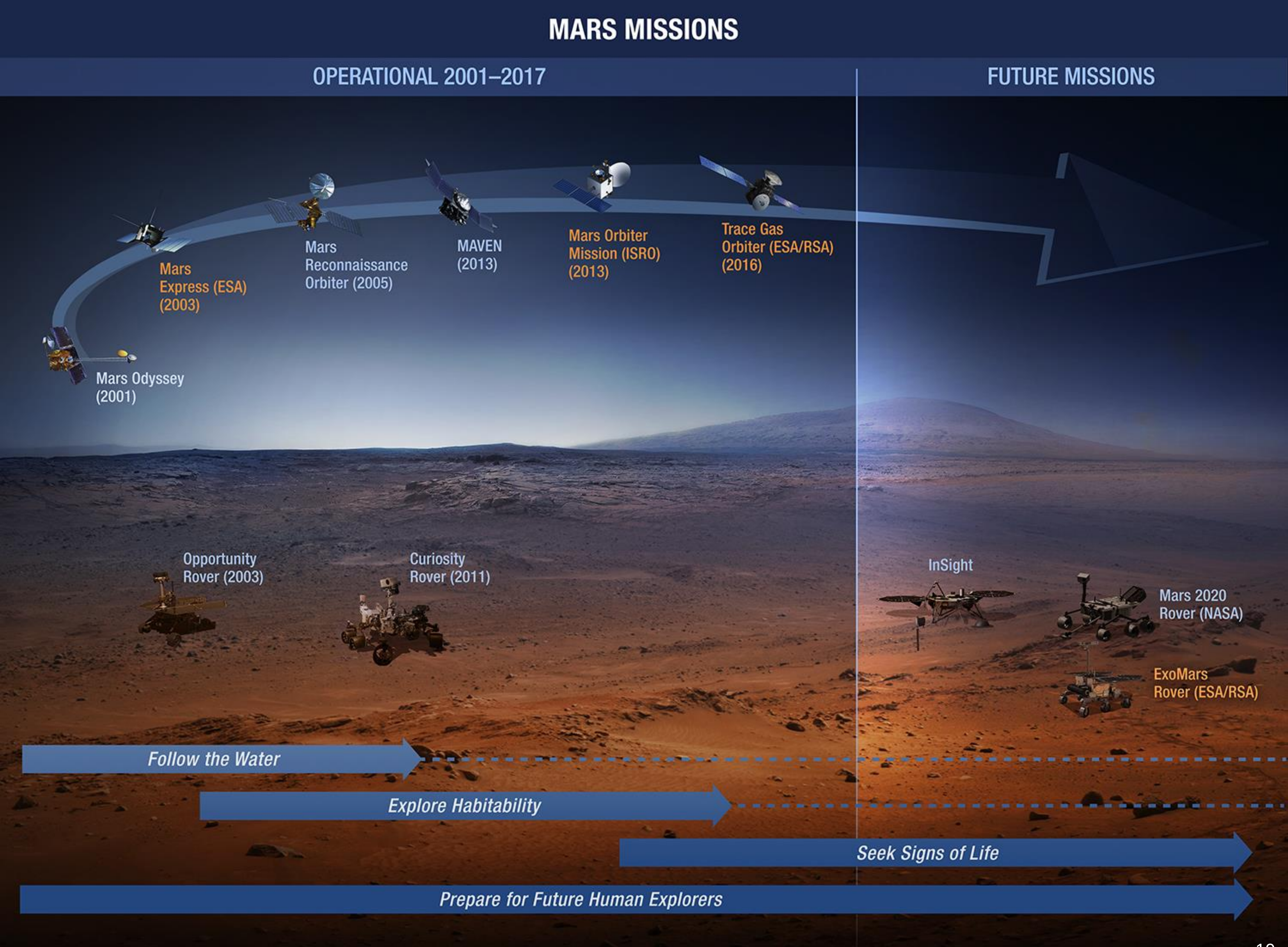
Robotic missions assessed subsurface water ice useful for human explorers

- **Mars Odyssey** detected and mapped shallow (<1 m) ground ice in both arctic regions[1]
- Mars **Phoenix** Lander directly sampled north high-latitude ground ice[2]
- Radar sounding data from **Mars Reconnaissance Orbiter** and **Mars Express** show massive subsurface ice in polar caps and mid-latitude remnant glaciers[3]
- **Mars Express** and **MRO** mapped the locations of thousands of hydrated mineral deposits with high spatial resolution[4]

Robotic missions are characterizing the environments astronauts will experience on the journey to Mars and at the Martian surface

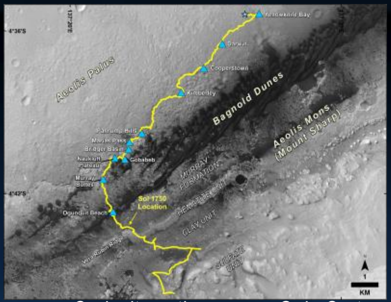
- Orbiters and landers compiled records of temperature, atmospheric pressure, dust, water vapor, wind, and solar visible and UV flux
- **Curiosity** measured the high-energy radiation dose received during cruise and at the Martian surface, and variations with solar cycles and storms[5]

1. Boynton et al., *Science*, **297**, 81-85 (2002)
2. Smith et al., *Science*, **325**, 58-61 (2009)
3. Phillips et al., *Science*, **320**, 1182-1185 (2008)
4. Ehlmann and Edwards, *Annu. Rev. Earth Planet. Sci.*, **42**, 291–315 (2014)
5. Hassler et al., *Science*, **343**, 1244797 (2014)


MARS MISSIONS
OPERATIONAL 2001–2017
FUTURE MISSIONS
Mars Odyssey (2001)
Mars Express (ESA) (2003)
Mars Reconnaissance Orbiter (2005)
MAVEN (2013)
Mars Orbiter Mission (ISRO) (2013)
Trace Gas Orbiter (ESA/RSA) (2016)
Opportunity Rover (2003)
Curiosity Rover (2011)
InSight
Mars 2020 Rover (NASA)
ExoMars Rover (ESA/RSA)
Follow the Water
Explore Habitability
Seek Signs of Life
Prepare for Future Human Explorers

CURIOSITY– MISSION STATUS

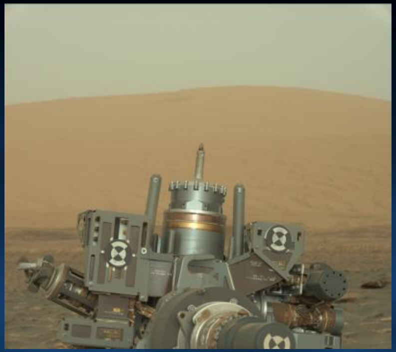
- Drove 17.4 km since 8/5/12 landing
- More than sufficient MMRTG energy available to complete mission objectives



Curiosity pathway map Gale Crater

Drill Feed Status

- Drill feed, used to extend and retract drill bit, exhibiting “stickiness” since 12/1/16, likely due to foreign object
- Successfully extended drill bit to full extent (109mm) on 8/12/17
- Techniques to drill with feed extended (i.e. arm-only without stabilizers) in development since April 2017; testbed results promising; additional development required



Wheel Status

- Wheels accumulating cracks and punctures more rapidly than expected
- Mitigating through strategic terrain assessment and careful selection of local drive paths
- Extensive ground testing suggests >29 km total life (>11.6 km remaining), more than sufficient to complete mission

MRO – MISSION STATUS

- Launched in August 2005, achieved MOI March 2006
- Science Orbit since November 2006
  - Low Altitude = 250 km x 320 km
  - Inclination = 93.3 deg, Sun-Sync at 3:00 pm
  - Instruments nominal
- Success with both scientific and programmatic objectives (relay, reconnaissance, critical event coverage)
  - Over 309 Tb of science data returned
  - Completed imaging of ~95% of requested Mars 2020 landing sites
  - UHF Relay for PHX (past), MER, & MSL
  - Future relay for InSight, Mars 2020, & ESA ExoMars
- Healthy spacecraft with large fuel reserves (> 20 years)
  - Single string telecomm since 2006
  - All-stellar capability developed to preserve IMU life

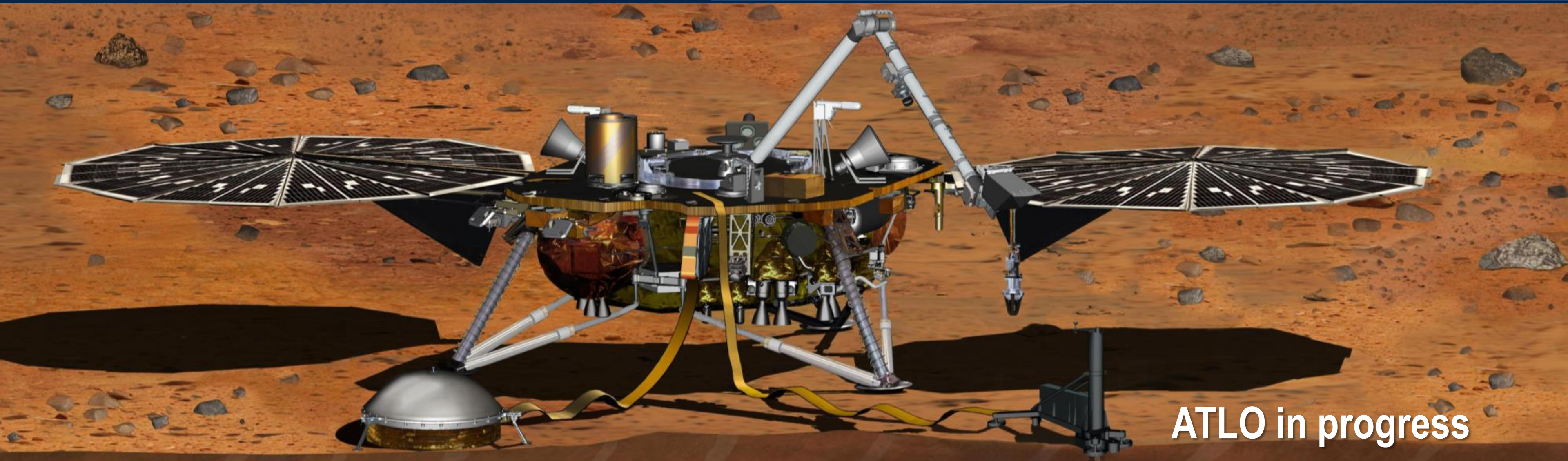
MAVEN – MISSION STATUS

- Launched November 2013, achieved MOI September 2014
- Completed primary mission in November 2015
  - Met all mission success criteria and Level-1 requirements
  - Provided strong evidence for solar wind driven atmospheric loss history
- Currently in second extended mission (EM-2) through September 2018
- Spacecraft is in excellent health, with all instruments operating
- Carries Electra UHF transceiver and UHF antenna
- Plan to reduce apoapsis for improved relay performance
  - Assessing change from 6200 km to 4500 km
  - Exploring approaches to preserve fuel
  - Decision on orbit configuration by end of CY17

TRACE GAS ORBITER – MISSION STATUS

- Launched March 14, 2016, achieved MOI October 19, 2016
- ESA's ExoMars/Trace Gas Orbiter carries two NASA -provided Electra UHF relay payloads
  - Will provide relay services to both NASA and ESA landers/rovers
- Successful post-MOI Relay Checkout w/ MSL, MER: Nov 22, 2016
- Aerobraking in process; plan to reach final 400-km orbit by ~ Apr 2018
- Primary mission science/relay operations planned through Dec 2022
  - Planned fuel reserves for extended mission operations

INSIGHT - MISSION STATUS



ATLO in progress

Spacecraft Full Functional completed, SEIS and other payload elements installed on Lander on August, 3 2017

- Contributed science instruments
  - CNES: SEIS (Seismomemeter)
  - DLR (Heat flow & Physical Properties Package)
- SEIS fully integrated on spacecraft
- Launch May 5 - June 8, 2018
- Landing November 26, 2018

MARS 2020 - MISSION STATUS

- Completed CDR Feb ’17
- System Integration Review scheduled for February ’18
- Spacecraft assembly on target to begin in March ’18; 3 Candidate Landing Sites
- Technical, Programmatic
  - Healthy mass, power, and other technical margins
  - Key challenges in developments of sample caching system, new instruments, maintaining compliance with sample cleanliness, and mission conops
  - MOXIE to continue
  - Good schedule margins (~230 work days) to launch
  - Stable life-cycle costs since inception

Parachute Testing

Flight Cruise Stage

Flight Aeroshell

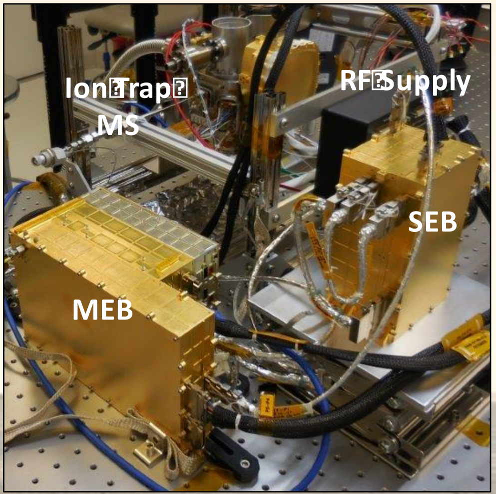
Flight Descent Stage

MOXIE In-Situ Oxygen Generation

NASA CONTRIBUTION TO ESA EXOMARS

Mars Organic Molecule Analyzer (MOMA)

- Led by Max Planck Institute for Solar System Research (MPS)
- NASA/GSFC providing ion trap mass spectrometer and electronics
- Central organic bio-signature analysis experiment on ExoMars Rover
- Gas chromatography and laser desorption sampling to characterize complex organics
- Rover's 2-meter sampling drill provides unique samples, well-protected from cosmic radiation
- On track to deliver to ESA for rover integration
- Launch July 2020; EDL March 2021

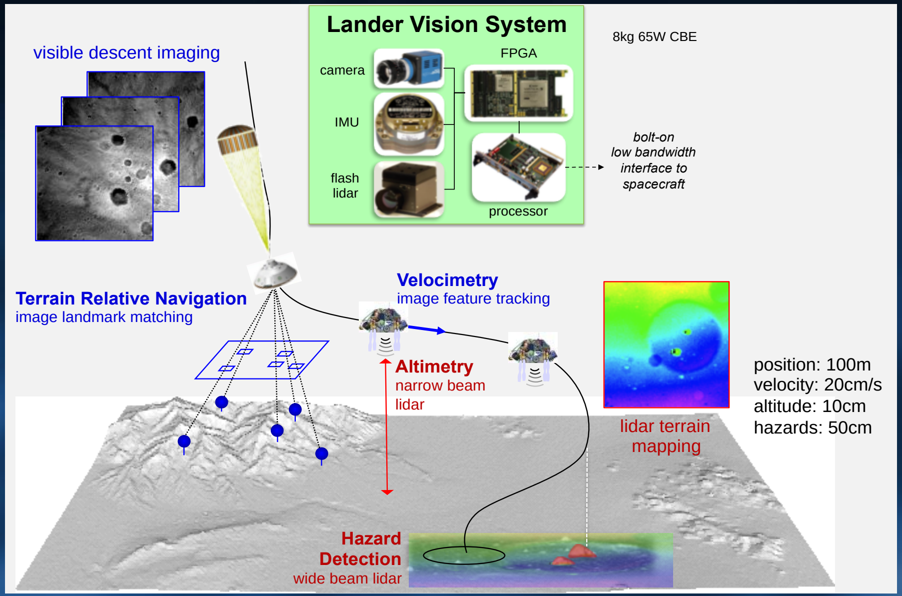


NASA-developed MOMA mass spectrometer

TRN - TECHNOLOGY DEVELOPMENT

Objective

- Enable access to wider range of landing sites through descent image analysis to identify/avoid patches of hazardous terrain
  - Determines location relative to pre-stored map
  - Determines optimal direction for divert maneuver to avoid hazardous terrain
- Incorporated on Mars 2020
  - Key enabler for 2 of 3 top priority landing sites (Jezero Crater and NE Syrtis)



Terrain-Relative Navigation (TRN) uses real-time descent imagery to guide M2020 to a safe landing area

Technology Maturation Progress

- Demonstrated performance on helicopter flights
  - 20 m error at 2 km altitude
- Vision Compute Element and associated algorithms developed
- M2020 system now in manufacture

MARS HELICOPTER - TECHNOLOGY DEVELOPMENT

Objective

- Explore utility of Mars aerial mobility
  - Regional-scale high-resolution reconnaissance to facilitate surface operations of future robotic missions
  - Access to extreme terrains, Scouting

Full-scale free flight testing in JPL Space Simulator

Technology Maturation Progress

- Controlled-flight feasibility demonstration – June 2016
- Engineering Model in-work: Mass < 2 kg, solar powerd,300 m range on one charge, autonomous, dual cameras

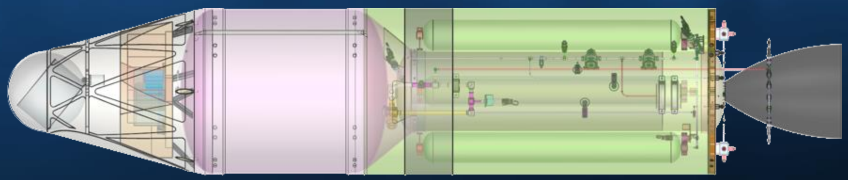
MAV - TECHNOLOGY DEVELOPMENT

Objective

- Achieve stable orbit @ 18 deg, 350 km circular
- Minimize thermal survival power
- Constrain mass/volume

Technology Maturation Progress

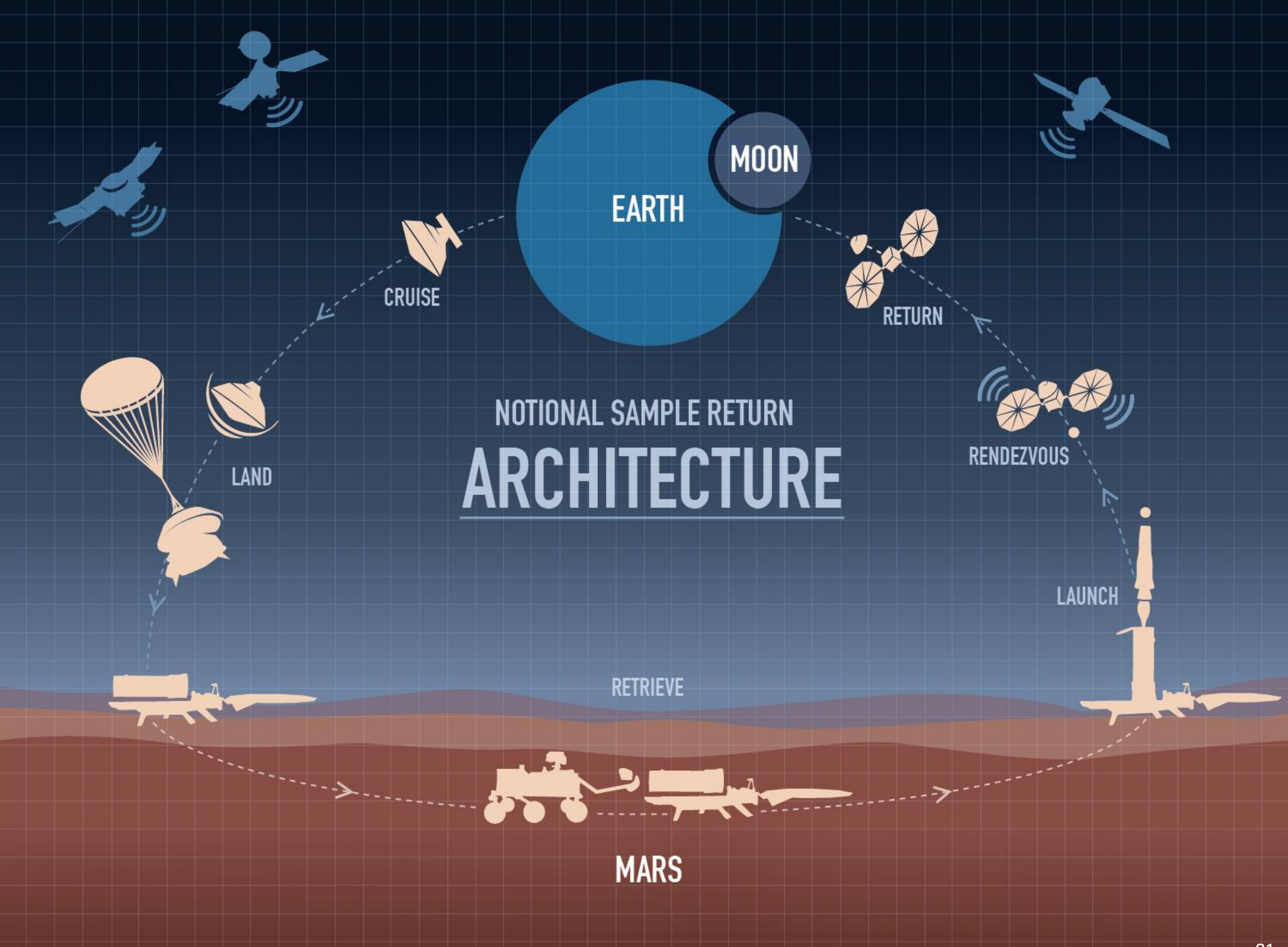
- Pursuing hybrid propulsion SSTO approach
  - Paraffin based fuel has superior cold temperature properties (-90 C)
  - Inert fuel grain and low temp MON3 oxidizer
- Full scale motor test firings in-work



Mars Ascent Vehicle (MAV)
~2.4m length/~ 300 kg mass

Full-scale hybrid motor test at Whittinghill Aerospace

Full-scale hybrid motor test at Space Propulsion Group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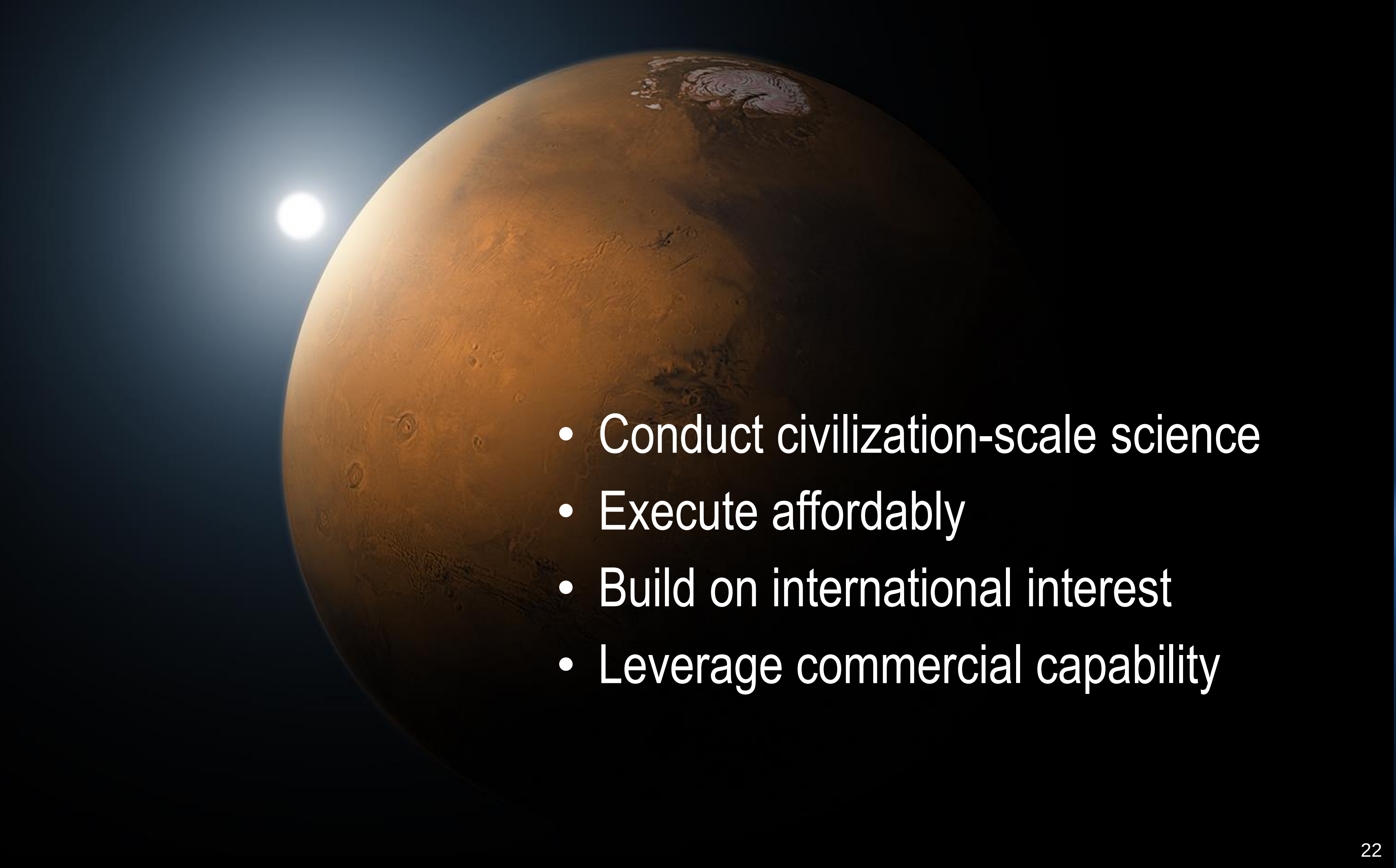
REALIZING MSR: GUIDING PRINCIPLES

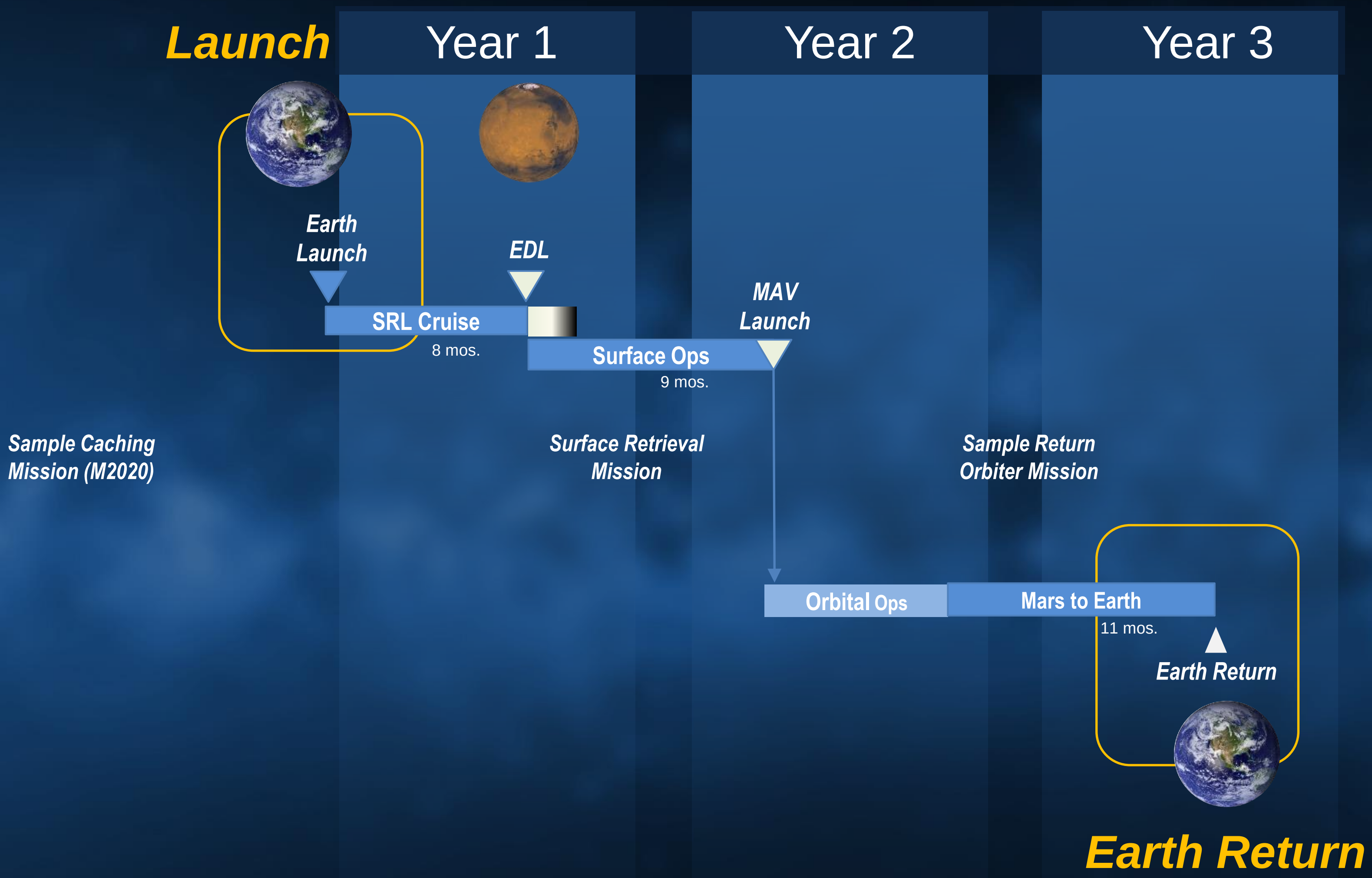


- Conduct civilization-scale science
- Execute affordably
- Build on international interest
- Leverage commercial capability

STRATEGIC APPROACH FOR MSR IMPLEMENTATION

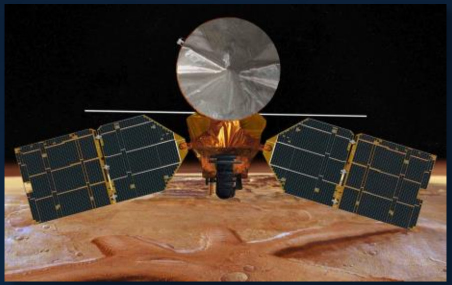
- Flexible requirements
- Focused scope
- Capitalize on experience base
- Limit new development
- Make early technology investments to mature readiness and minimize cost risks
- Leverage partnerships
- Strong programmatic discipline in execution

NOTIONAL MSR TIMELINE

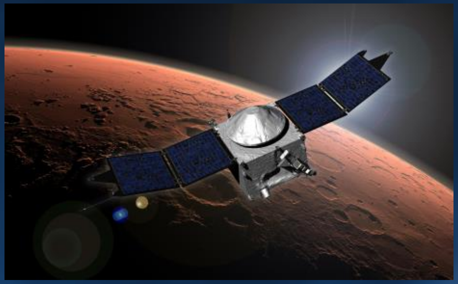


MARS ORBITAL INFRASTRUCTURE

- Current relay assets (MRO/MAVEN/TGO) are healthy, with adequate propellant for ops through M2020 prime mission and beyond
  - MAVEN will transition greater comm support in extended mission operation
  - MRO site reconnaissance for M2020 fulfills SRL recon needs
- ESA's ExoMars/TGO (w/NASA Electra radio) provides additional relay services to NASA landers/rovers
- SRO mission will serve as prime relay for SRL, augmented by existing assets
- Possibility to leverage future commercial capabilities would add additional robustness



MRO (2005)



MAVEN (2013))

ExoMars/TGO (2016)

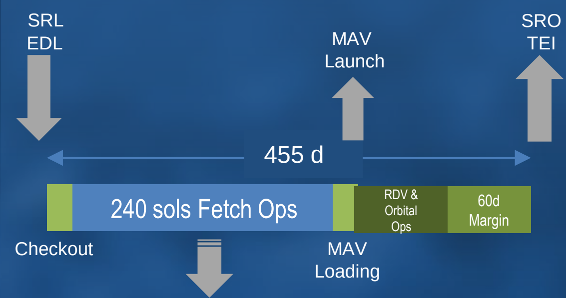
SAMPLE RETURN: KEY REQUIREMENTS

LAND in the right place

Land in small landing error ellipse (≤10 km) to access M2020 sites

COLLECT samples fast

Long traverse with tight timeline



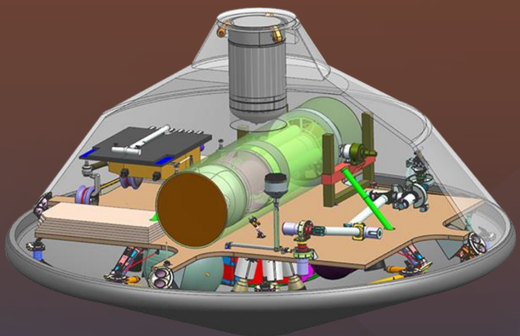
- 130 sols for driving km (rover odometry)
- 20 sols for tube pickup (1 tube/sol)
- 90 sols for faults/anomalies/engineering activities

Get it BACK

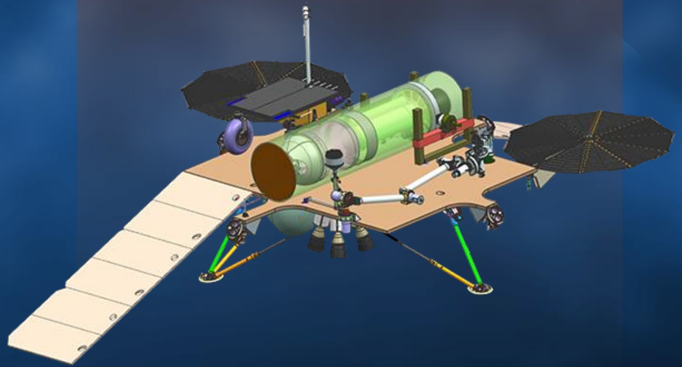
Launch, rendezvous and return

TWO LANDER CONCEPTS

2017 Highly Integrated Concept



***Propulsive Platform Lander (PPL)** Concept*
Packaged in MSL 4.5m Aeroshell

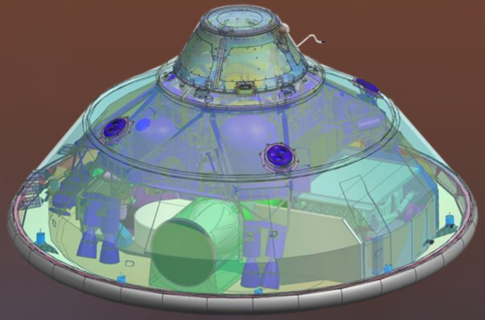


Propulsive Platform Lander
Concept Deployed

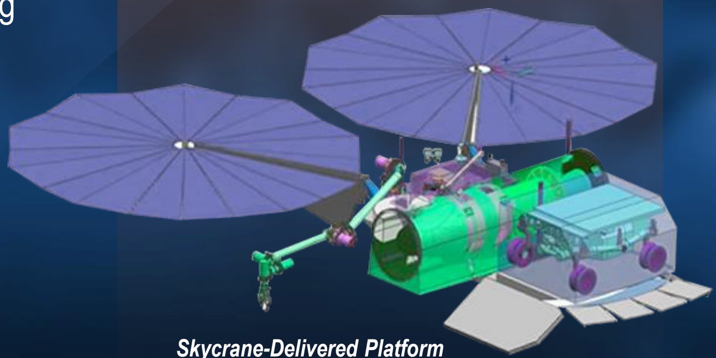
Common Attributes

- Identical cruise and entry architecture
- ~ 10 km landing ellipse
- ~ 900-1000 kg landed useful mass
- Accommodates ~ 600 kg MAV and Fetch Rover

Evolved 2011 Decadal Concept



Skycrane-Delivered Platform Concept
Packaged in MSL 4.5m Aeroshell



Skycrane-Delivered Platform
Concept Deployed

Two concepts that leverage Mars program legacy system capabilities

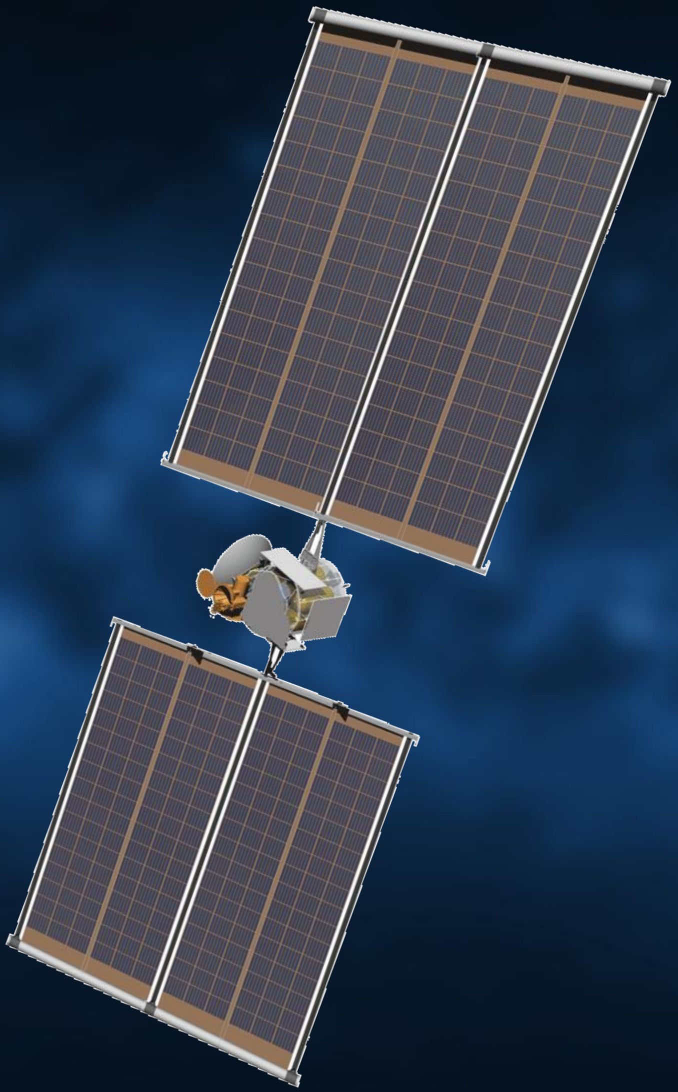
NOTIONAL SAMPLE RETURN ORBITER

Design for Orbital Rendezvous & Fast Sample Return

- Rendezvous & Capture
- Containment and Earth Planetary Protection
- Communication Relay Support for Surface Ops and Critical Events
- Return to Earth, either via
  - Direct return to Earth
  - Deliver to cis-lunar space for human-assisted returns

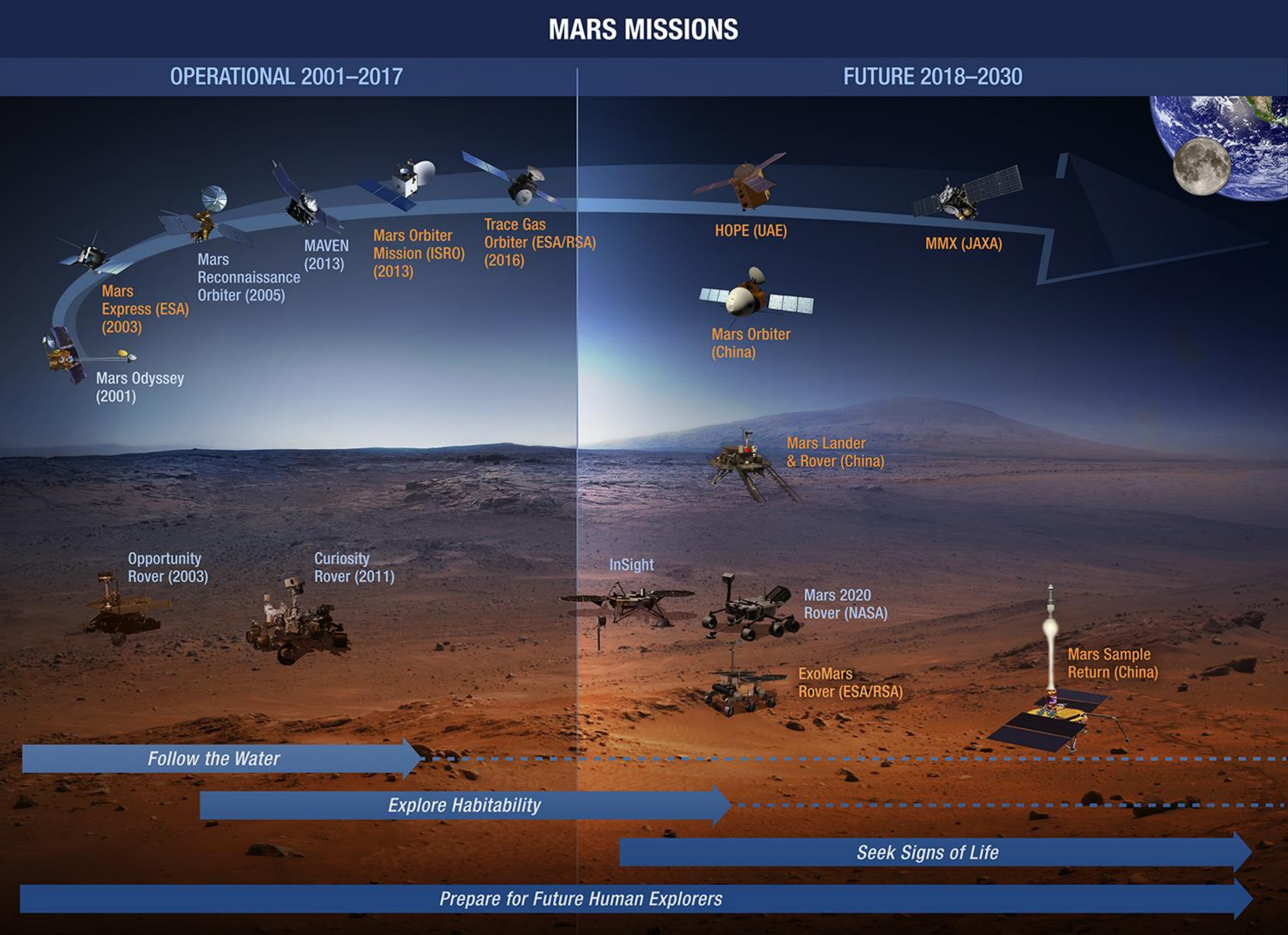
Implementation Options

- NASA provided
- Partner provided



PARTNERSHIP OPPORTUNITIES

- **International**
  - Enduring scientific/technical and programmatic interests
  - Multiple space agencies headed to Mars
- **Growing commercial interest in Mars**
  - Potential to leverage commercial offerings of capability
- **Exploration benefits from MSR**
  - Feed-forward into preparation, planning and development
  - First round trip demonstration
  - Samples inform environmental uncertainties [biological, physical, toxicity]
  - Potential opportunity for early leverage of cis-lunar capabilities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HOPE (UAE)
MMX (JAXA)
Mars Orbiter (China)
Mars Lander & Rover (China)
Opportunity Rover (2003)
Curiosity Rover (2011)
InSight
Mars 2020 Rover (NASA)
ExoMars Rover (ESA/RSA)
Mars Sample Return (China)
Follow the Water
Explore Habitability
Seek Signs of Life
Prepare for Future Human Explorers

NEXT STEPS

- Continue pre-formulation studies on SRL concepts
- Explore additional opportunities for partnership
- Continue and expand technology maturation efforts
- Engage ESA and other international partner interest in a joint study on approaches for collaborative MSR

MSL Gale Crater Mount Sharp Soil Layers

KEY QUESTIONS

- How do we prioritize large, strategic planetary missions among themselves?
- What is the right balance in the planetary program between large, strategic missions and competed missions, technology development and research & analysis?
- What is the capacity of the enabling workforce within NASA and beyond to implement our planetary program?

MSL Gale Crater Mount Sharp Soil Layers

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