NASA'S Solar System Exploration Paradigm: the First 50 Years and a Look at the Next 50

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NASA, Planetary Science
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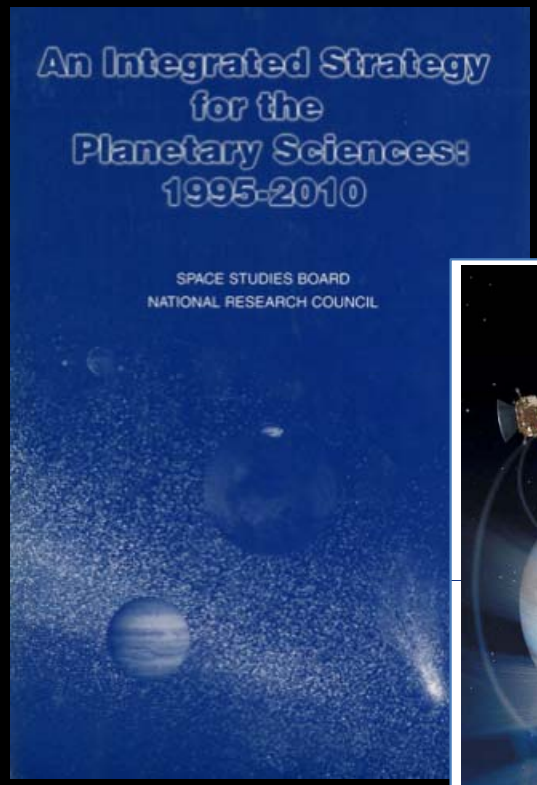
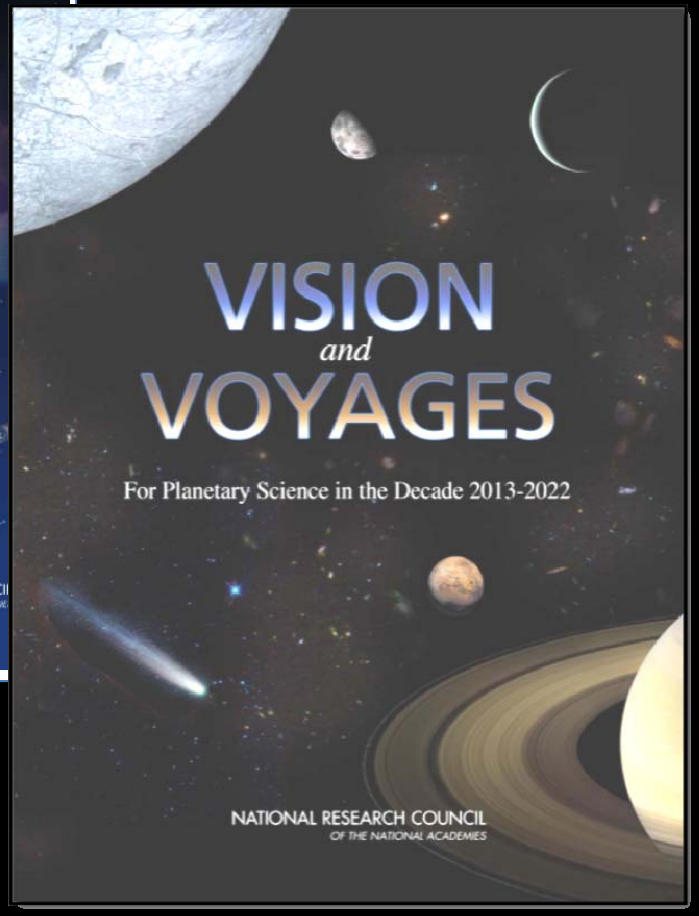
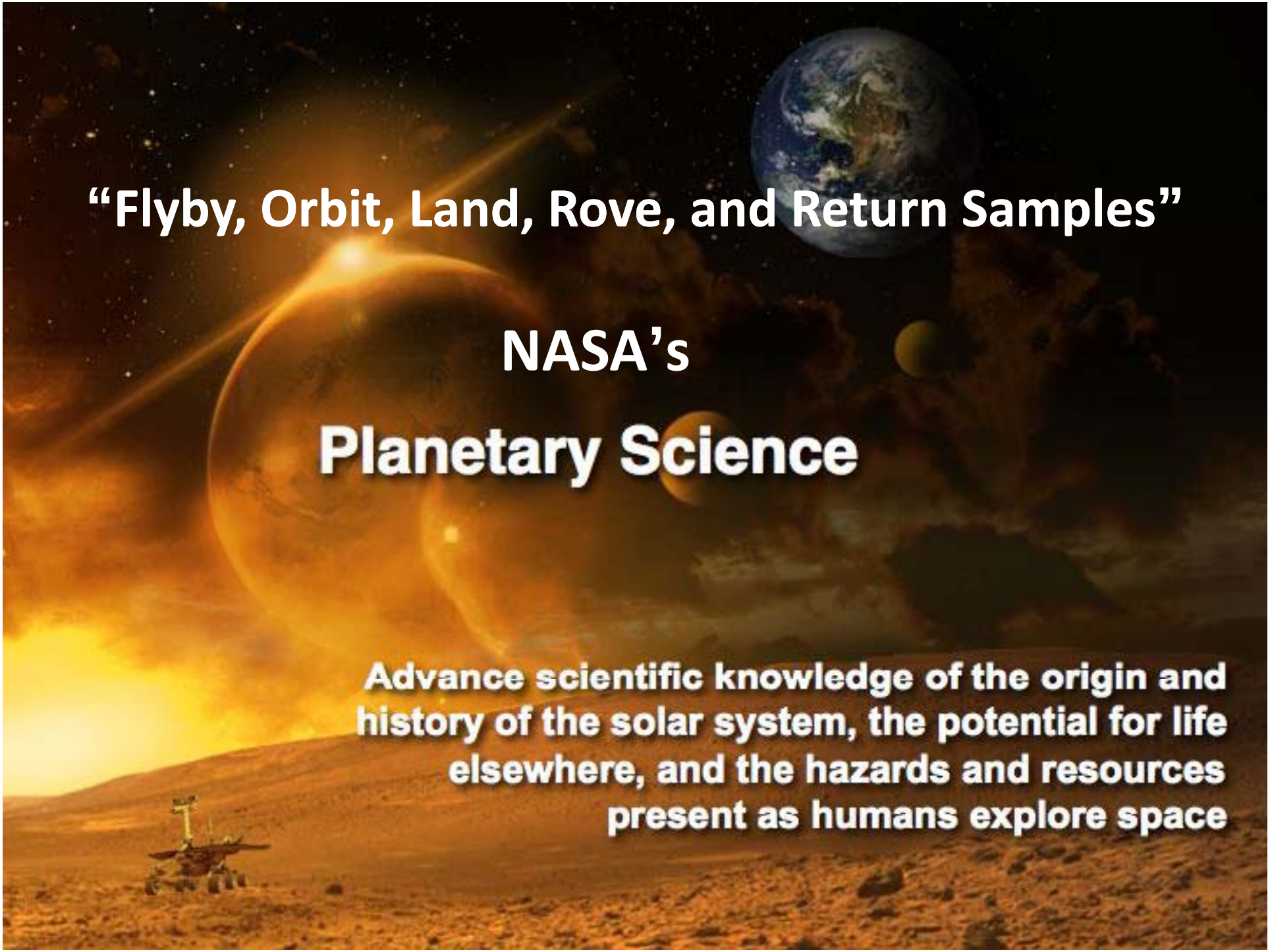
Solar System Exploration @50 Conference

The Revolution in Planetary Science






"Flyby, Orbit, Land, Rove, and Return Samples"
NASA's
Planetary Science
Advance scientific knowledge of the origin and history of the solar system, the potential for life elsewhere, and the hazards and resources present as humans explore space

Year of the Solar System
Planetary Science Mission Events

* Completed

2010

* September 16 – *Lunar Reconnaissance Orbiter*
* November 4 - *EPOXI* encounters Comet Hartley 2
* November 19 - Launch of *O/OREOS*

2011

* February 14 - *Stardust NExT* encounters comet Tempel 1
* March 7 – Planetary Science Decadal Survey released
* March 17 - *MESSENGER* orbit insertion at Mercury
* May 5 – Selection of 3 Discovery-class missions for study
* May – Selection of the next New Frontier mission for flight, *OSIRIS-REx*
* July 16 - *Dawn* orbit insertion at asteroid Vesta
* August 5 - *Juno* launch to Jupiter
* August 9 - *Mars Opportunity Rover* arrives at Endeavour Crater
* September 10 - *GRAIL* (A and B) launch to the Earth's Moon
* November 26 – *Mars Science Laboratory* (Curiosity Rover) launch to Mars
* December 31 – *GRAIL* A (*Ebb*) orbit insertion at Earth's Moon

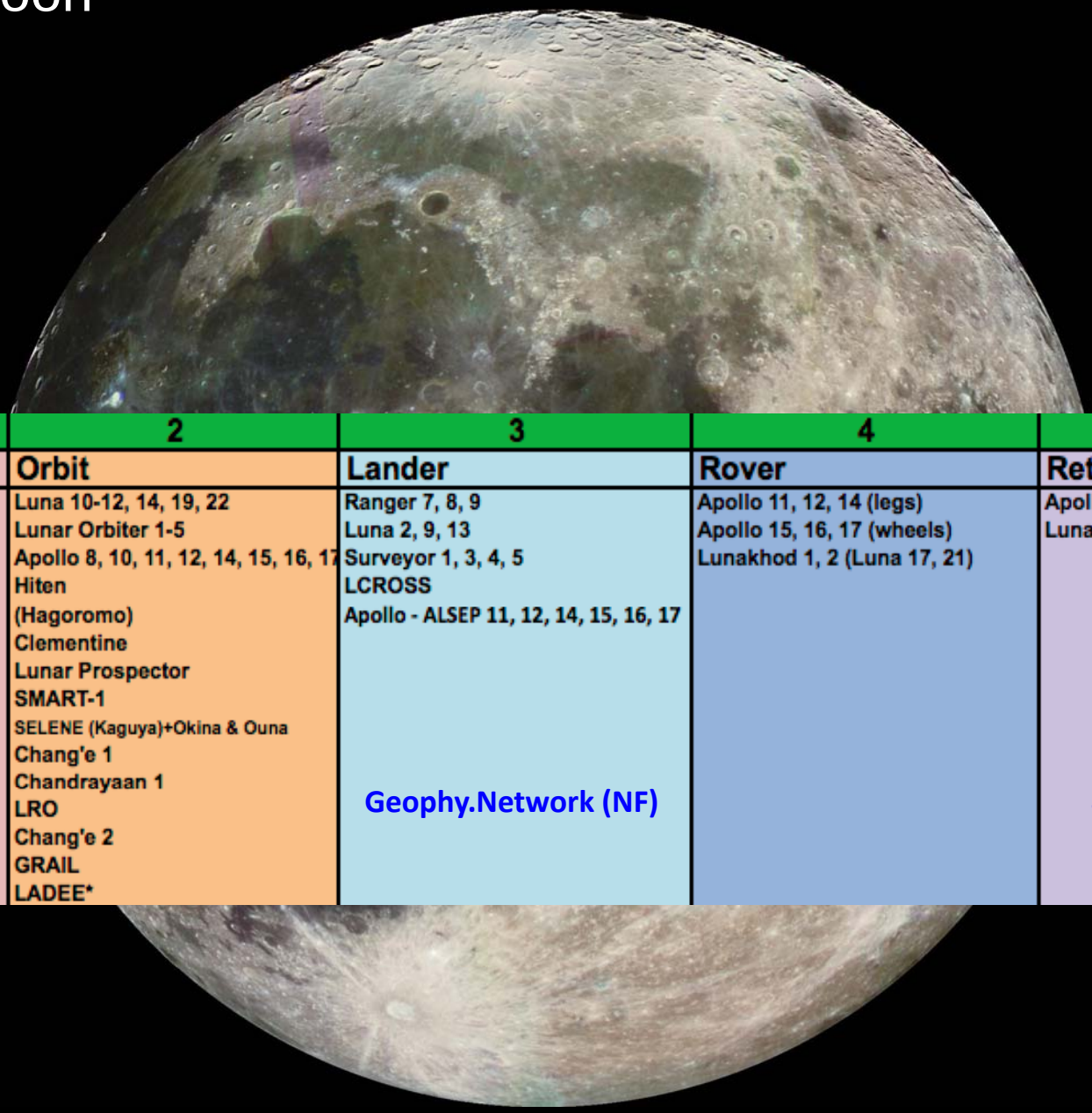
2012

* January 1 – *GRAIL* B (*Flow*) orbit insertion at Earth's Moon
* June 6 – Venus transits Sun (last time this Century)
* August 5 – *Curiosity* Rover successfully lands on Mars
* August 20 – Selection of Discovery 12 Mission *InSight*
* September 5 - *Dawn* leaves Vesta and starts on its journey to Ceres

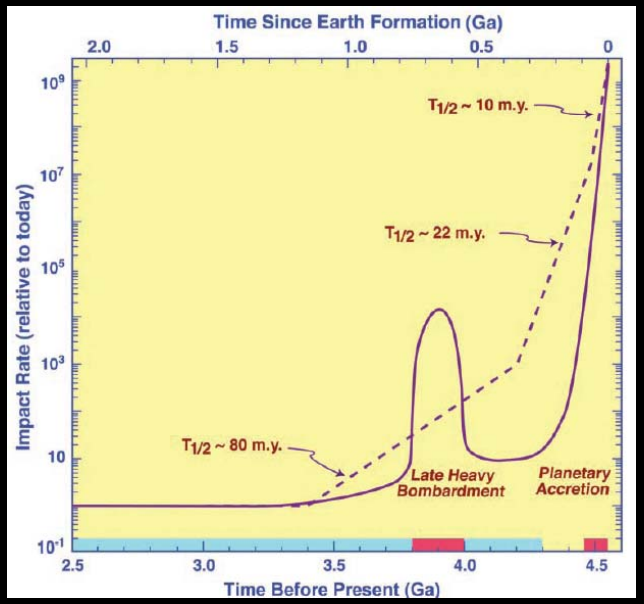
Inner Solar System

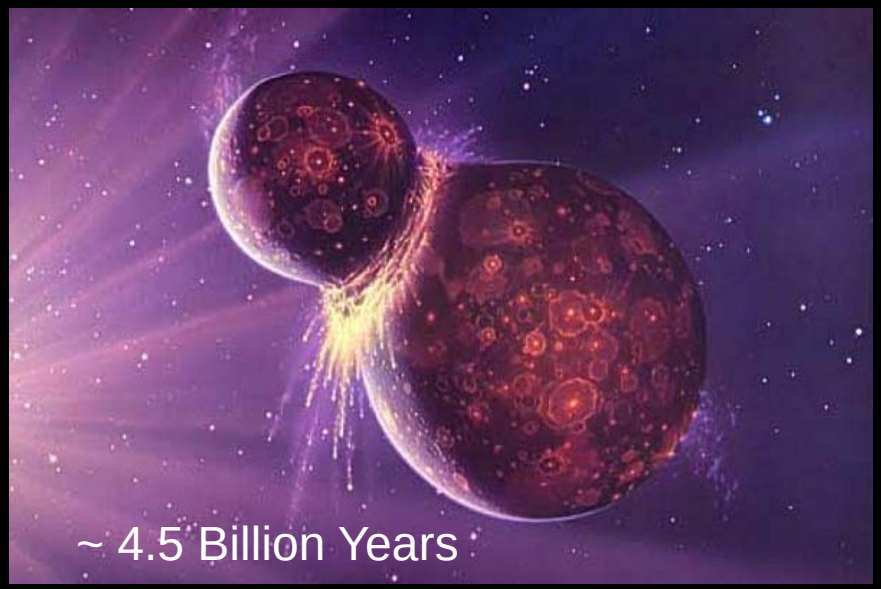
	Mercury	Venus	Earth's Moon	Mars	Phobos	Deimos
Flyby 1	Mariner 10 MESSENGER	Mariner 2, 5, 10 Venera 11-14 Galileo Cassini MESSENGER Akatsuki	Luna 1, 3 Pioneer 4 Zond 3, (5), 6, 7, 8 Apollo 13 Hiten	Mariner 4 Mariner 6, 7 Mars 4 Mars Observer (Rosetta)	Mariner 9 Viking Orbiter 1 & 2 Phobos 2 Mars Global Surveyor Mars Express Mars Recon Orbiter	Mariner 9 Viking Orbiter 1 & 2 Mars Global Surveyor Mars Express Mars Recon Orbiter
Orbit 2	MESSENGER	Venera 9, 10, 15, 16 Pioneer 12 (PV 1) Magellan Venus Express Akatsuki (2016)* **Venus Climate (FS)**	Luna 10-12, 14, 19, 22 Lunar Orbiter 1-5 Apollo 8, 10, 11, 12, 14, 15, 16, 17 Clementine Lunar Prospector SMART-1 Hiten, SELENE (Kaguya)+Okina & Ouna Chang'e 1 & Chang'e 2 Chandrayaan 1 LRO, GRAIL, LADEE*	Mariner 9 Mars 2, 5 Viking 1, 2 Phobos 2 Mars Global Surveyor Mars Odyssey Mars Express Mars Reconnaisance Orbiter MAVEN*		
Lander 3		Venera 3 (crash landing) Venera 7-10, (11, 12), 13, 14 Pioneer 13 (PV 2; 1 entry survivor) VeGa 1, 2 **Venus In-situ (NF)**	Ranger 7, 8, 9 Luna 2, 9, 13 Surveyor 1, 3, 4, 5 LCROSS **Geophysical Network (NF)**	Mars 2 (crash landing) Mars 3 (no useful data) Viking 1, 2 Mars Pathfinder Phoenix **InSight**		
Rover 4			Apollo 11, 12, 14 (legs) Apollo 15, 16, 17 (wheels) Lunakhod 1, 2 (Luna 17, 21)	Sojourner MER Spirit, MER Opportunity MSL Curiosity*		
Return Samples 5			Apollo 11, 12, 14, 15, 16, 17 Luna 16, 20, 24 **SPA – SR (NF)**	**Sample Return (FS)**		

Earth's Moon



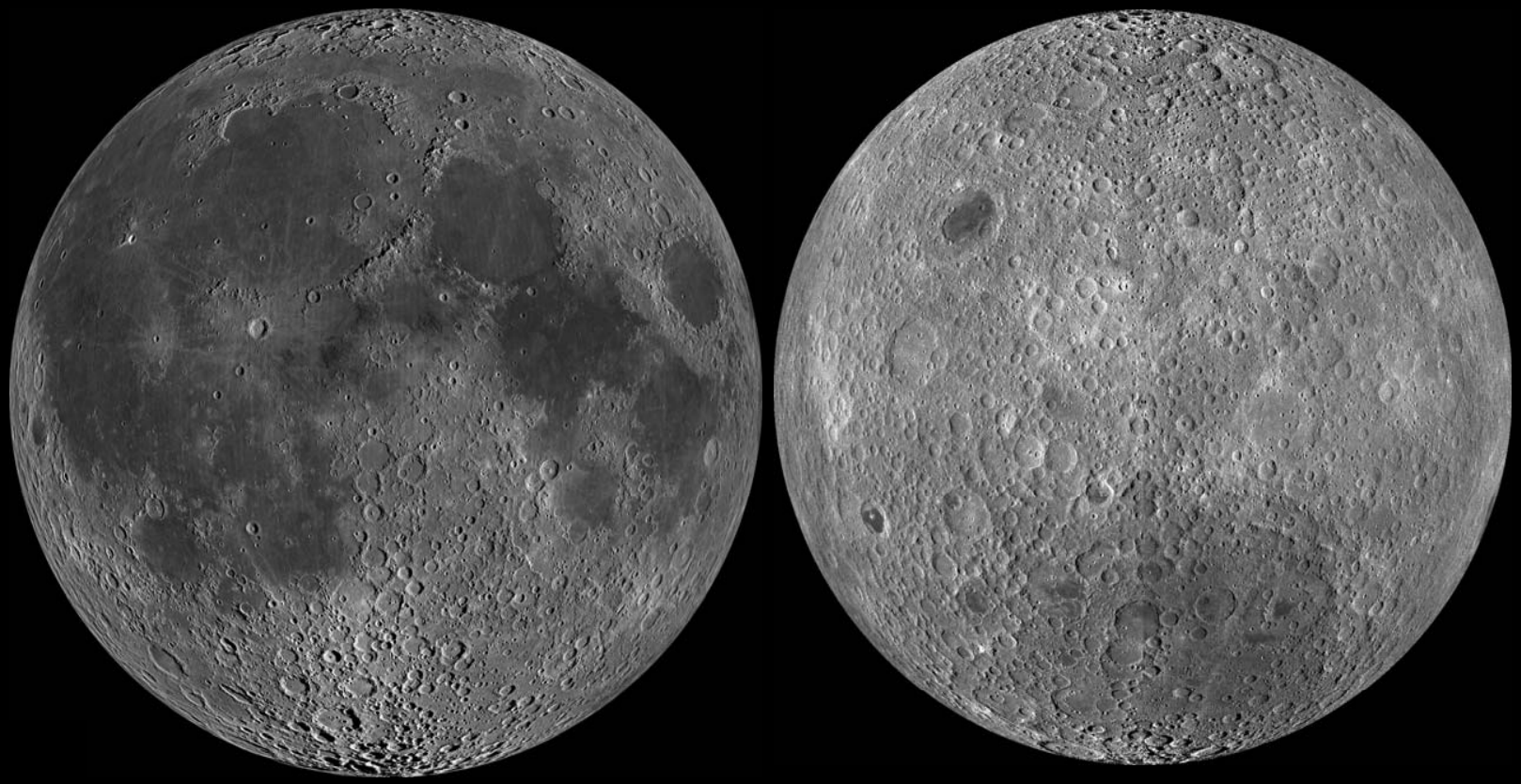
1	2	3	4	5
Flyby	**Orbit**	**Lander**	**Rover**	**Return Samples**
Luna 1, 3 Pioneer 4 Zond 3(, 5), 6, 7, 8 Apollo 13 Hiten	Luna 10-12, 14, 19, 22 Lunar Orbiter 1-5 Apollo 8, 10, 11, 12, 14, 15, 16, 17 Hiten (Hagoromo) Clementine Lunar Prospector SMART-1 SELENE (Kaguya)+Okina & Ouna Chang'e 1 Chandrayaan 1 LRO Chang'e 2 GRAIL LADEE*	Ranger 7, 8, 9 Luna 2, 9, 13 Surveyor 1, 3, 4, 5 LCROSS Apollo - ALSEP 11, 12, 14, 15, 16, 17 **Geophy.Network (NF)**	Apollo 11, 12, 14 (legs) Apollo 15, 16, 17 (wheels) Lunakhod 1, 2 (Luna 17, 21)	Apollo 11, 12, 14, 15, 16, 17 Luna 16, 20, 24 **SPA – SR (NF)**


Time Since Earth Formation (Ga)
2.0
1.5
1.0
0.5
0
Impact Rate (relative to today)
10^9
10^7
10^5
10^3
10
10^{-1}
$T_{1/2}$ ~ 10 m.y.
$T_{1/2}$ ~ 22 m.y.
$T_{1/2}$ ~ 80 m.y.
Late Heavy Bombardment
Planetary Accretion
2.5
3.0
3.5
4.0
4.5
Time Before Present (Ga)

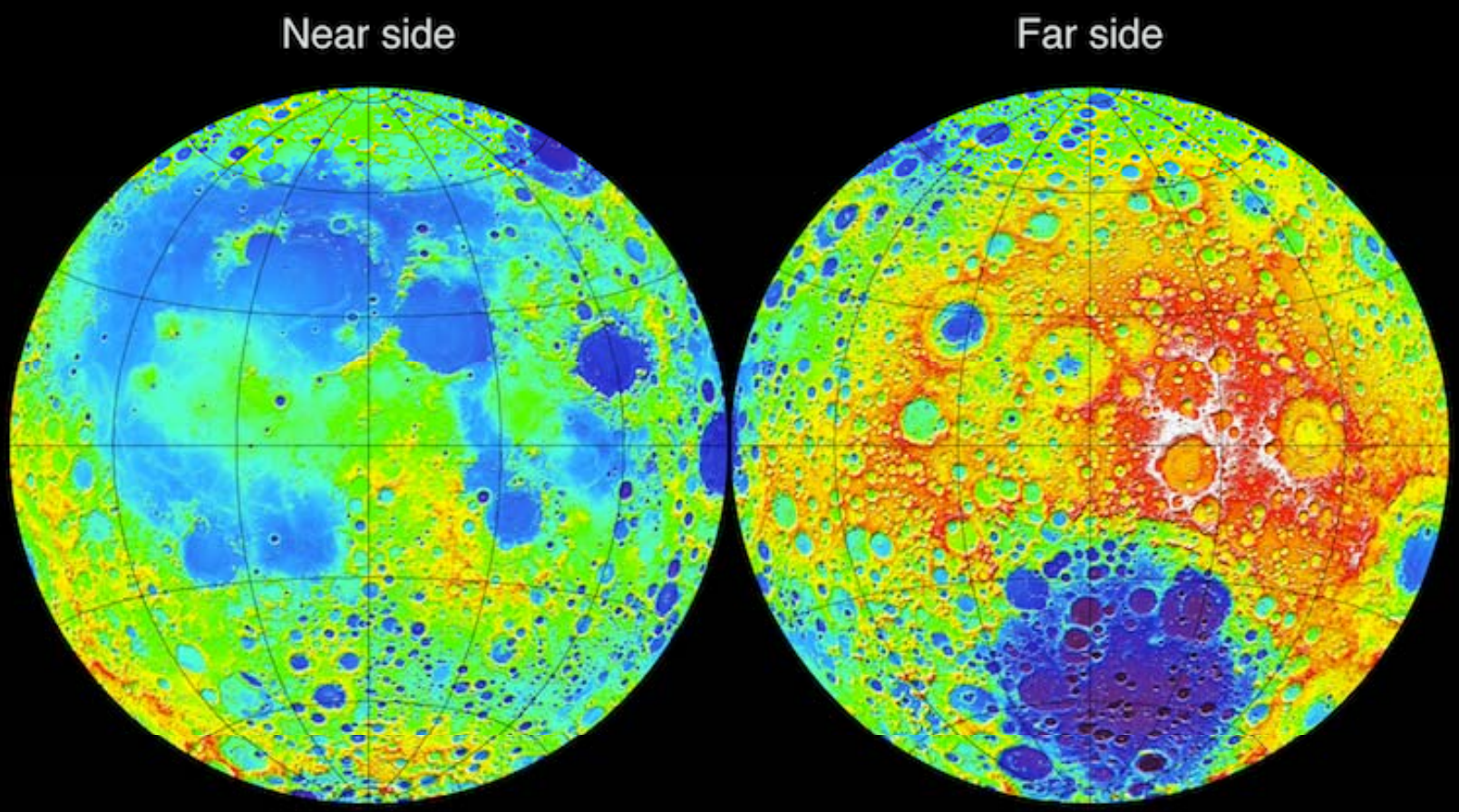

~ 4.5 Billion Years

~ 3.8 Billion Years
"Late Heavy Bombardment"

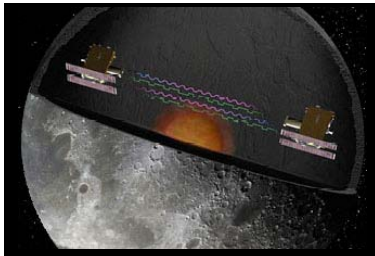
Earth’s Moon



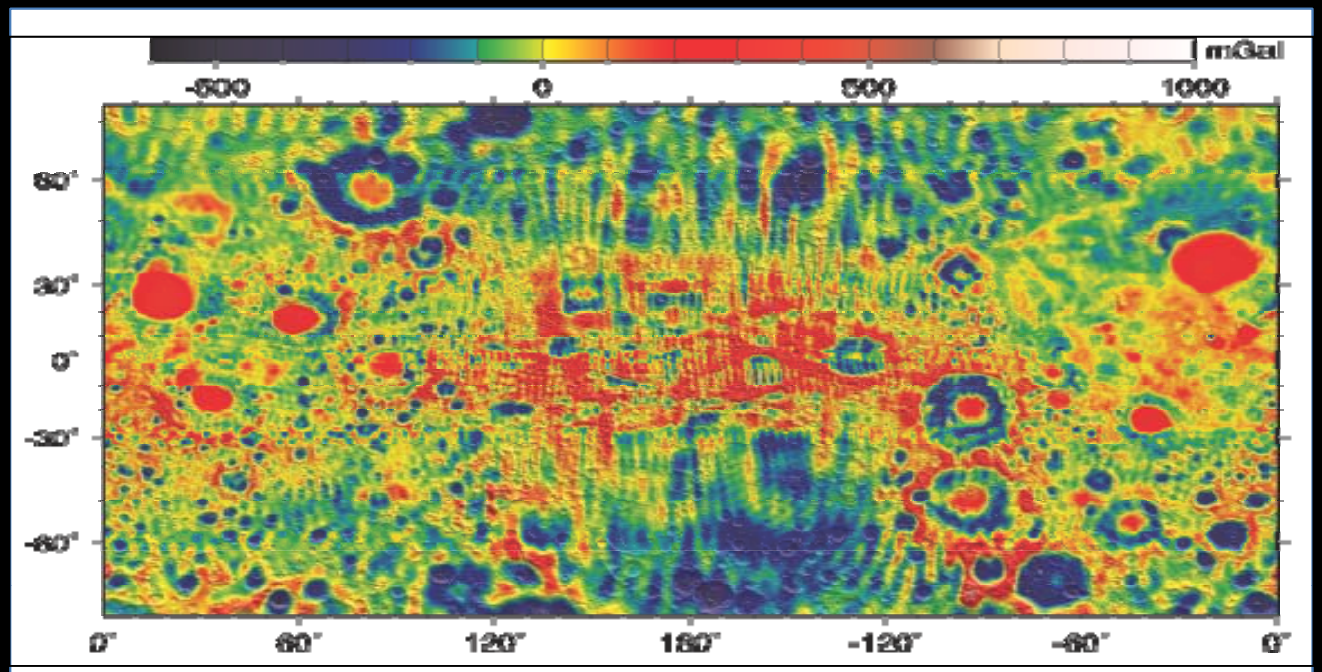
Earth's Moon



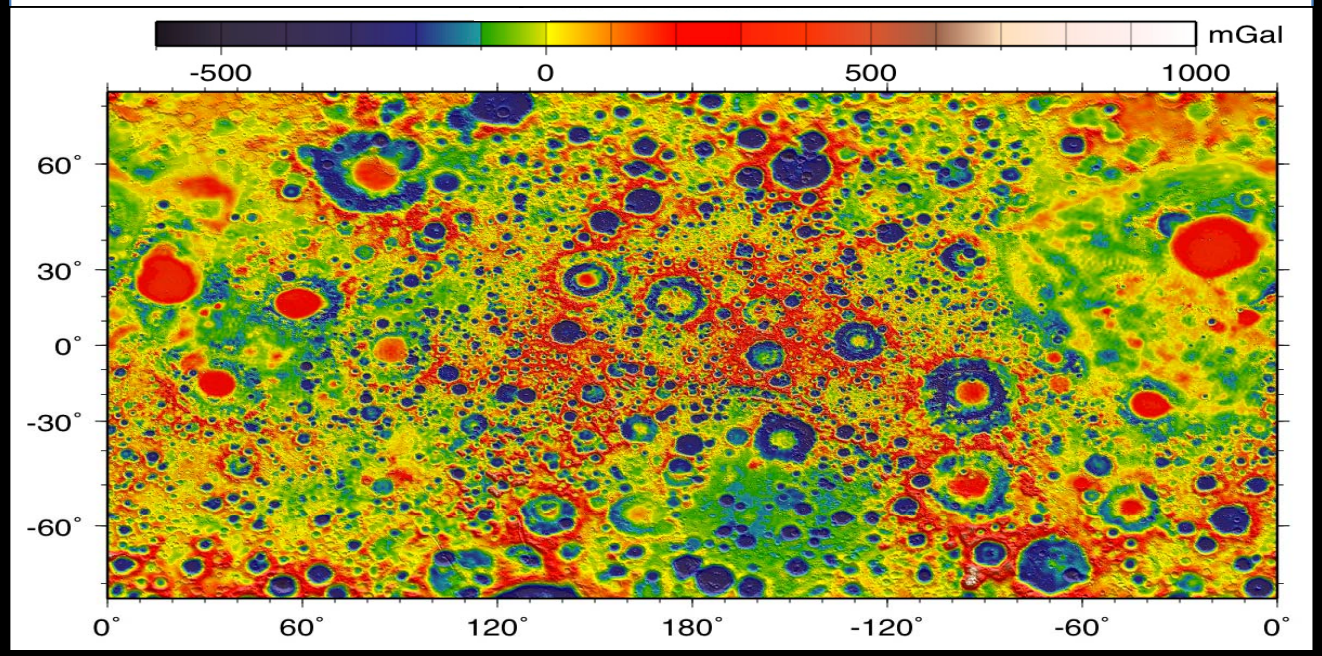
- New Frontiers future missions:
  - South Pole Aiken Basin Sample Return
  - Geophysical Network Lander



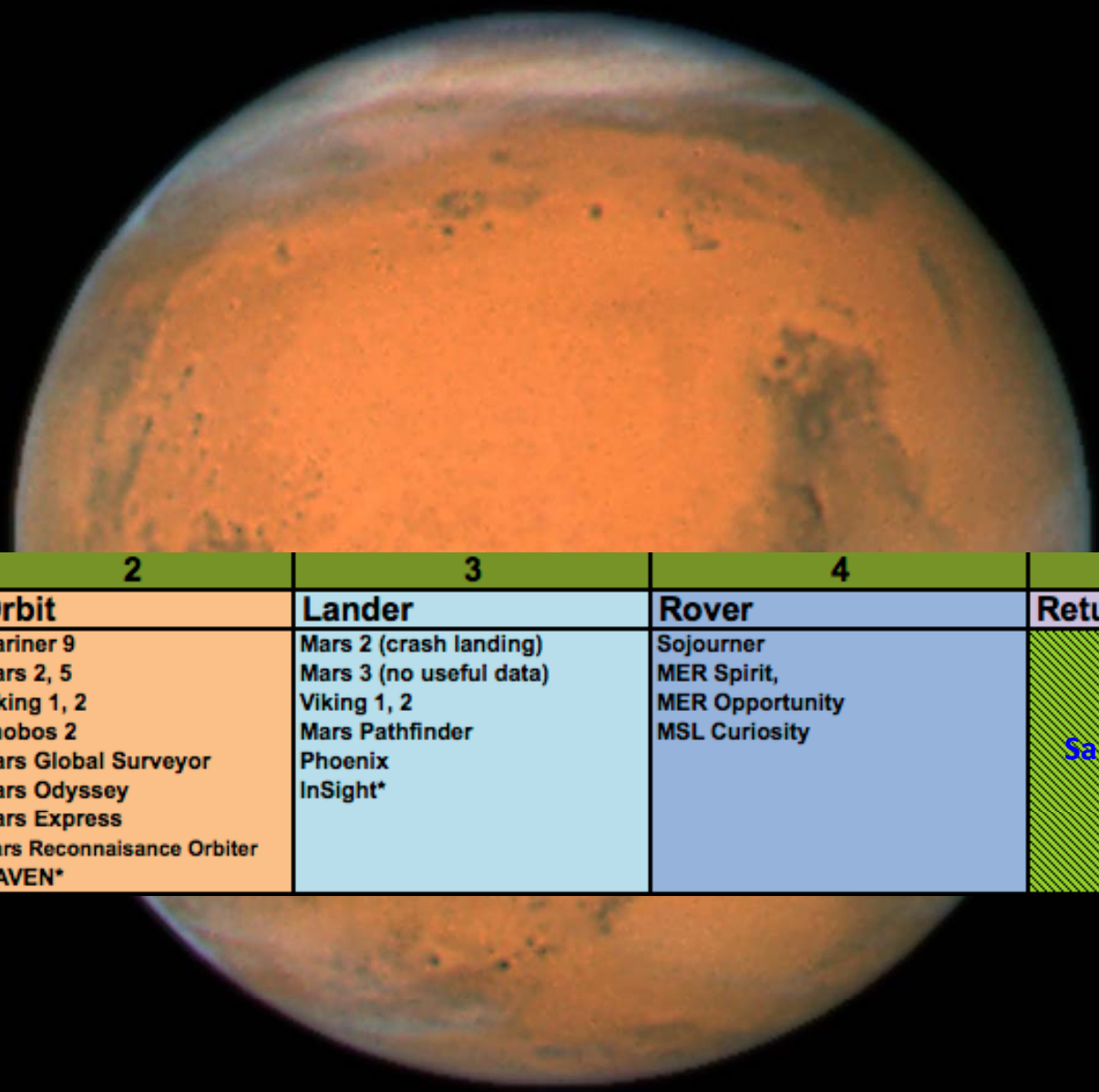
Lunar Gravity



GRAIL after 1 month

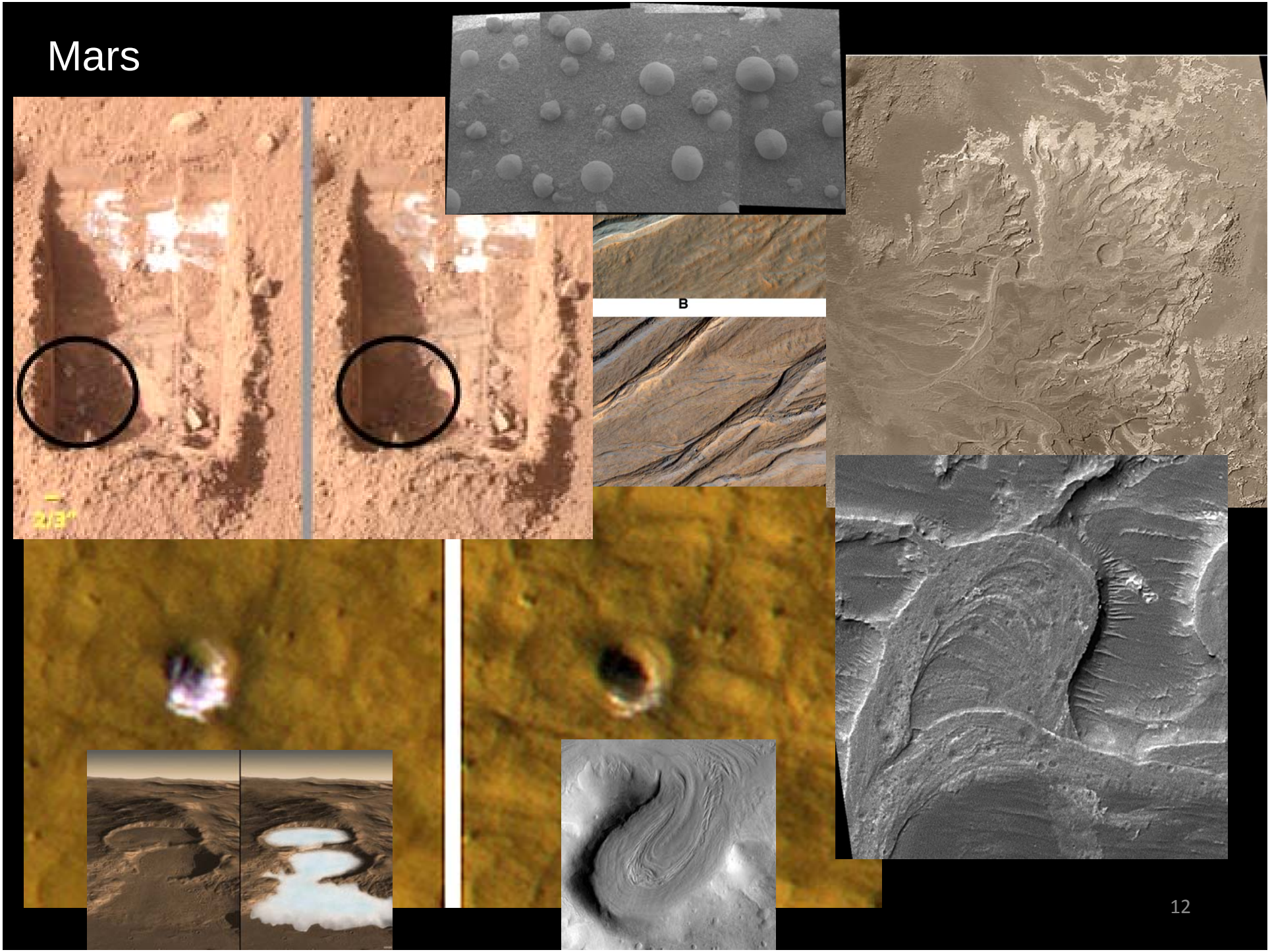


Mars

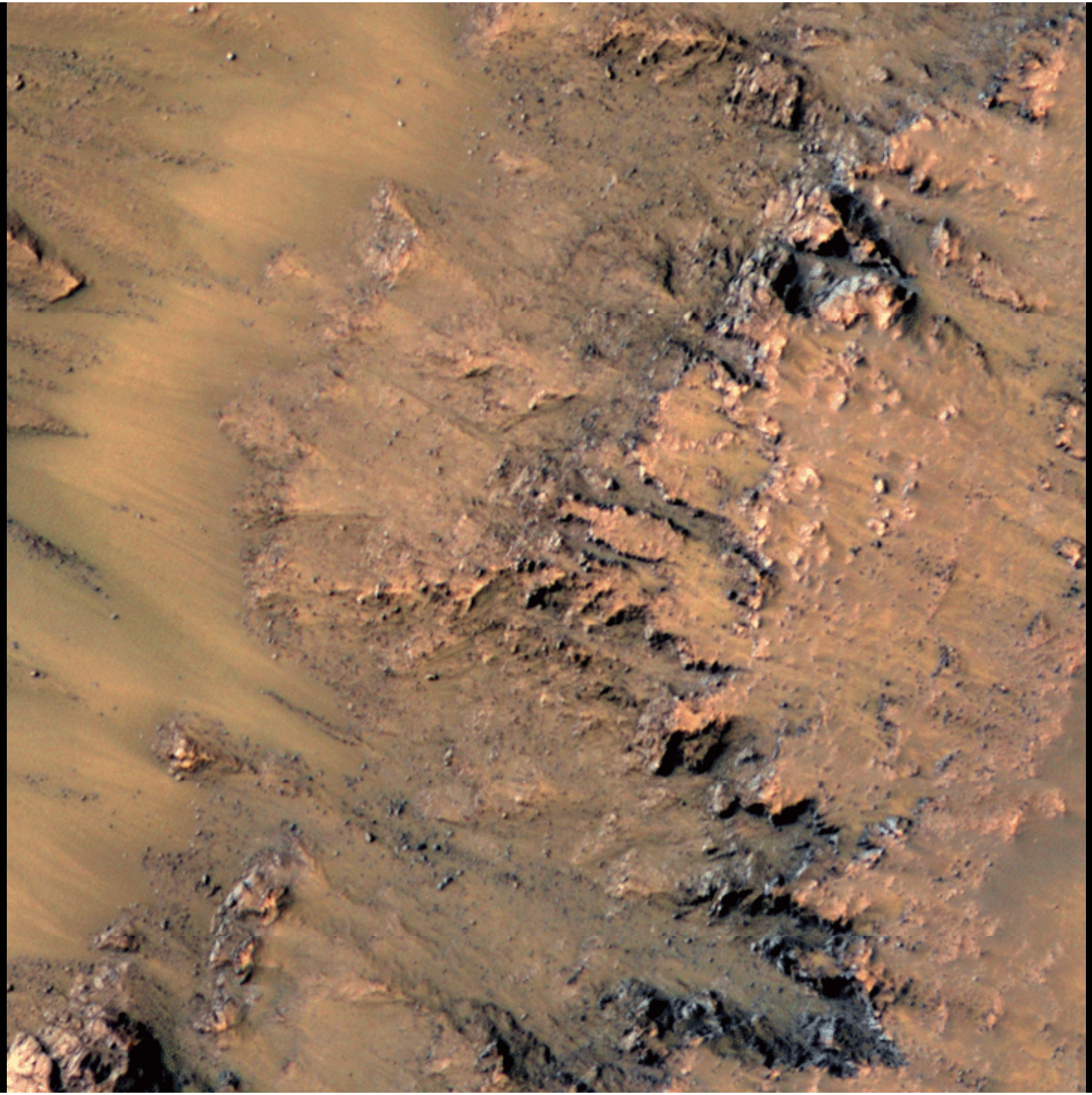


1	2	3	4	5
Flyby	**Orbit**	**Lander**	**Rover**	**Return Samples**
Mariner 4 Mariner 6, 7 Mars 4 Mars Observer (Rosetta)	Mariner 9 Mars 2, 5 Viking 1, 2 Phobos 2 Mars Global Surveyor Mars Odyssey Mars Express Mars Reconnaisance Orbiter MAVEN*	Mars 2 (crash landing) Mars 3 (no useful data) Viking 1, 2 Mars Pathfinder Phoenix InSight*	Sojourner MER Spirit, MER Opportunity MSL Curiosity	Sample Return (FS)

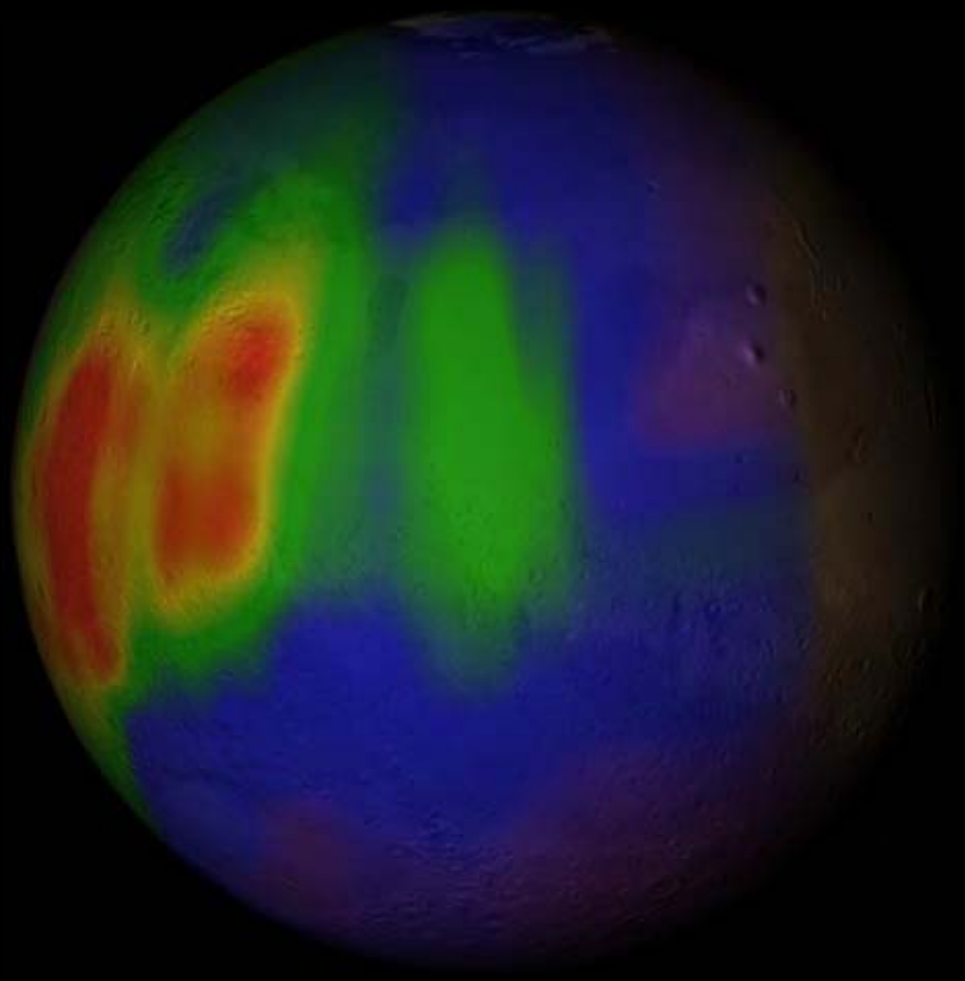
Mars



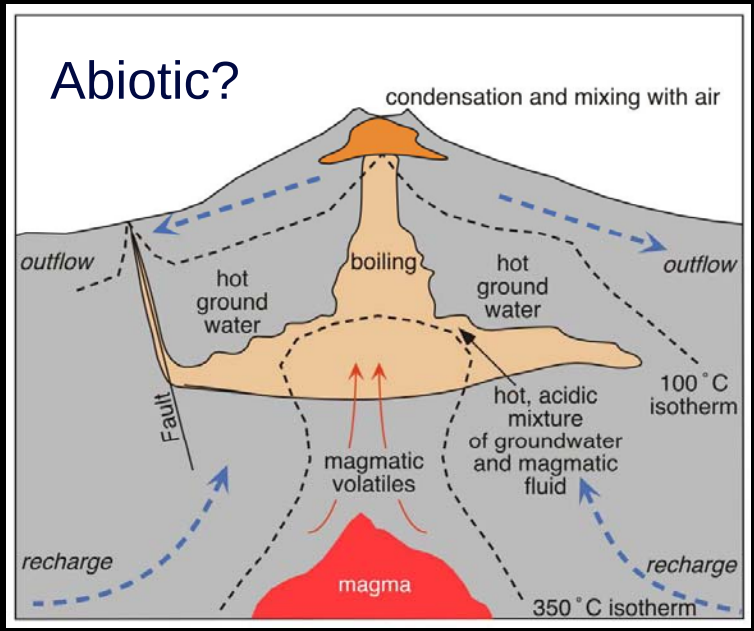
Mars



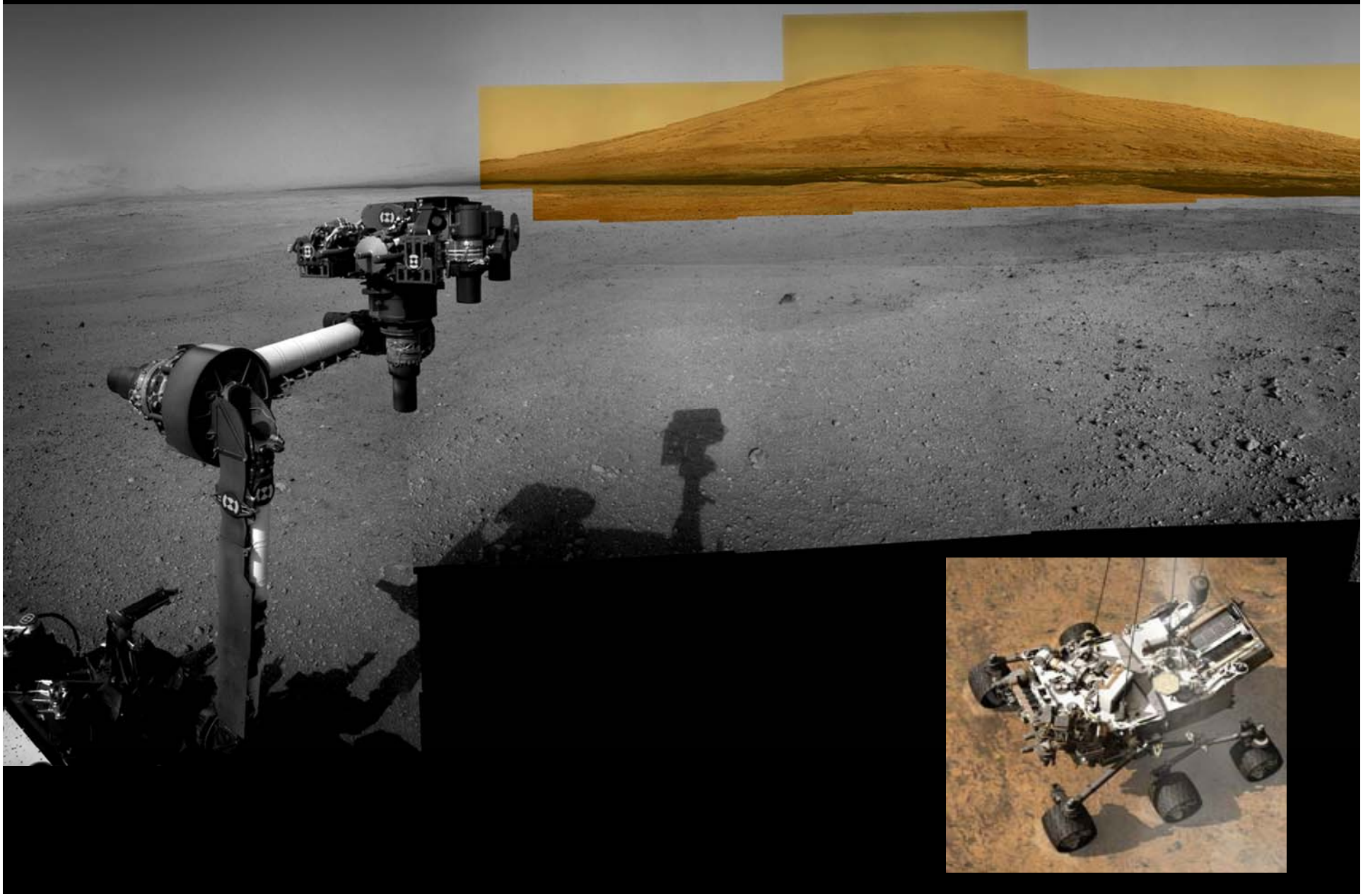
Mars



Biotic?


Abiotic?
condensation and mixing with air
outflow
hot
ground
water
boiling
hot
ground
water
outflow
100 °C
isotherm
Fault
hot, acidic
mixture
of groundwater
and magmatic
fluid
magmatic
volatiles
recharge
magma
recharge
350 °C isotherm

Curiosity’s Landing Site: Gale Crater



Outer Solar System & Small Bodies

	Jupiter	Io	Europa	Ganymede	Saturn	Enceladus	Titan	Uranus	Neptune	Triton	Plutoid Pluto	Asteroids	Comets
Flyby 1	Pioneer 10 Pioneer 11 Voyager 1 Voyager 2 Cassini New Horizons	Galileo	Galileo JUICE (ESA)	Galileo	Pioneer 11 Voyager 1 Voyager 2 Cassini	Voyager 2	Voyager 2 Cassini	Voyager 2	Voyager 2	Voyager 2	New Horizons*	NEAR Shoemaker Rosetta Galileo (Cassini) Deep Space 1 Rosetta New Horizons (KBO)	ICE (ISEE-3) VeGa 1, 2 Sakigake, Suisei Giotto Deep Space 1 Stardust & Stardust-NeXT Deep Impact & EPOXI (Galileo, Ulysses)
Orbit 2	Galileo Juno	Io Obs (NF)	Orbiter (FS)	JUICE (ESA)	Cassini	Orbiter (FS)		Orbiter (FS)				NEAR Shoemaker Hayabusa Dawn	Rosetta
Lander 3	Galileo Probe				Probes (NF)		Huygens					NEAR Shoemaker	Deep Impact Philae (2014)*
Rover 4													
Return Samples 5												Hayabusa Hayabusa 2* OSIRIS REx*	Stardust Surface SR (NF)

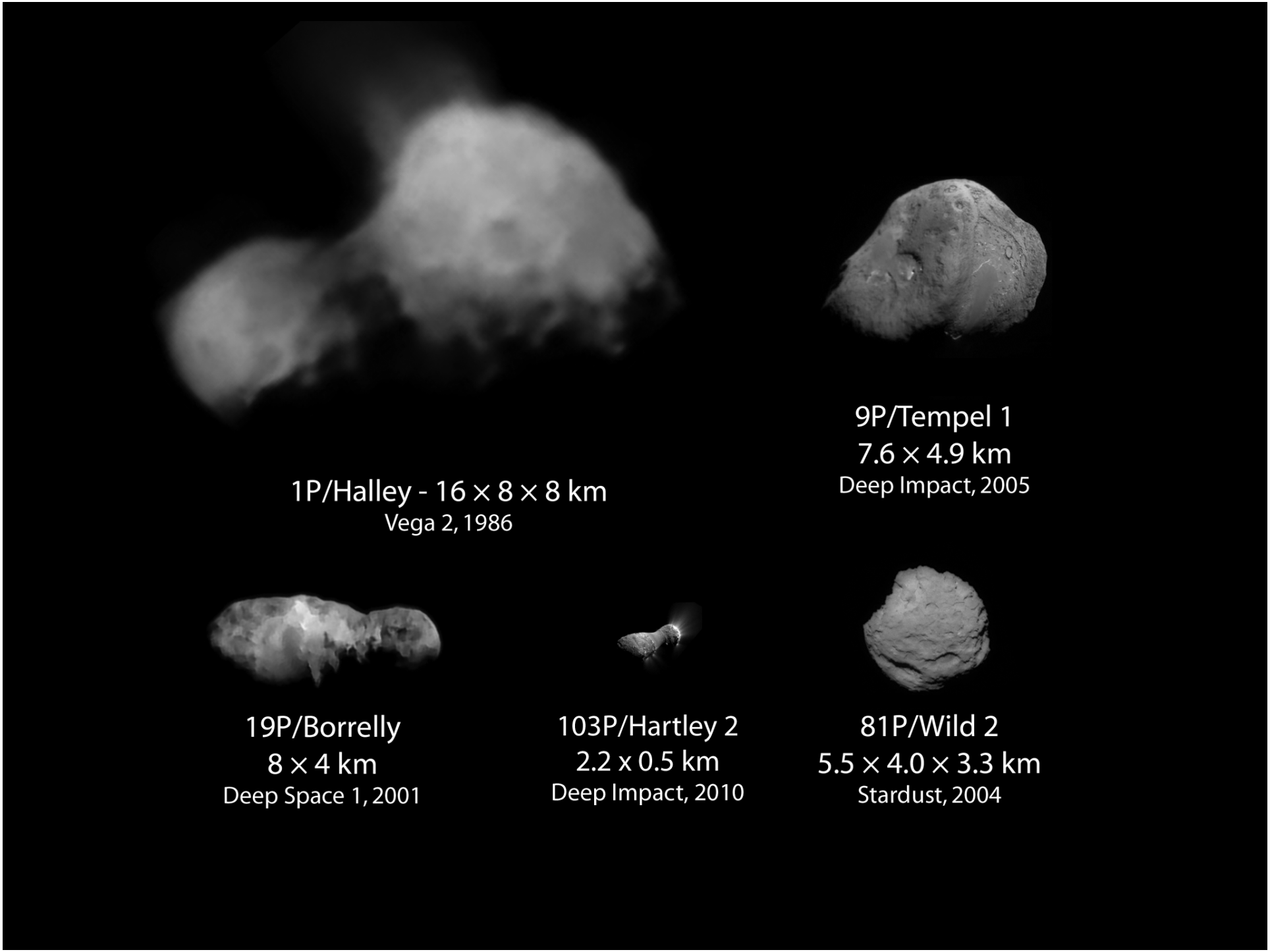
Comets

1	2	3	4	5
Flyby	**Orbit**	**Lander**	**Rover**	**Return Samples**
ICE (ISEE-3) VeGa 1, 2 Sakigake Suisei Giotto Deep Space 1 Stardust Stardust - NeXT Deep Impact Deep Impact - EPOXI (Galileo) (Ulysses)	Rosetta	Deep Impact Philae (2014)*		Stardust **Surface Sample Return (NF)**

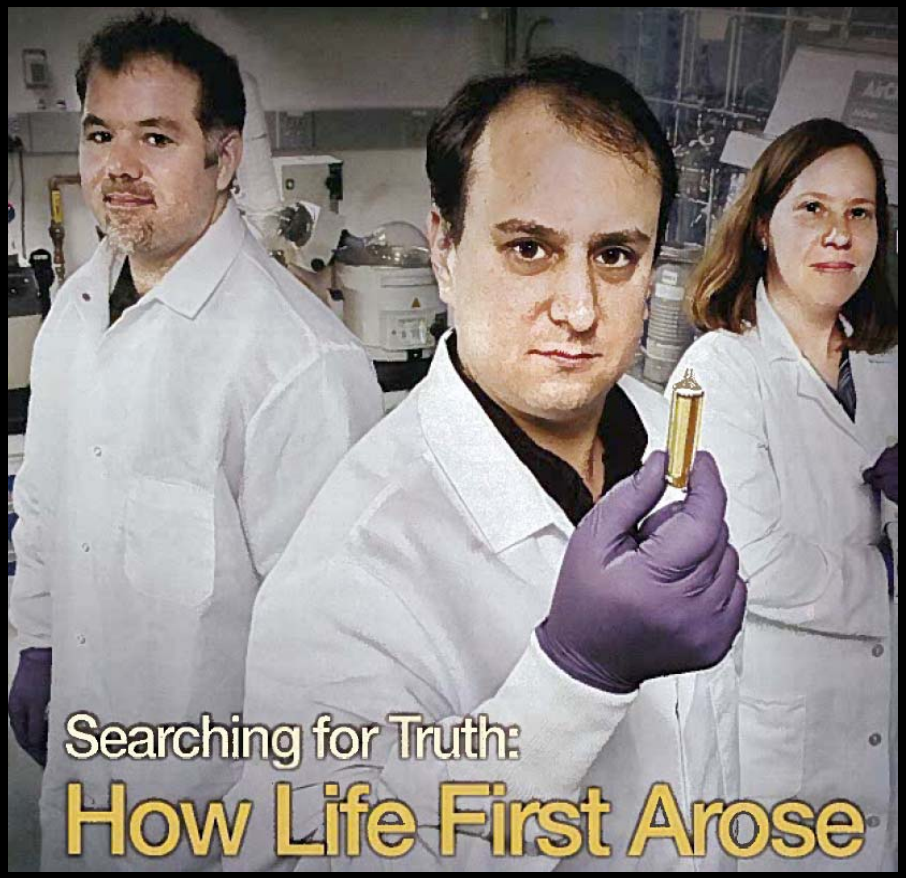
Comets

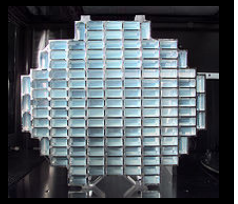
Next Year – Comet ISON!

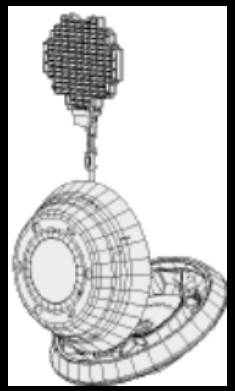
1	2	3	4	5
Flyby	**Orbit**	**Lander**	**Rover**	**Return Samples**
ICE (ISEE-3) VeGa 1, 2 Sakigake Suisei Giotto Deep Space 1 Stardust Stardust - NeXT Deep Impact Deep Impact - EPOXI (Galileo) (Ulysses)	Rosetta	Deep Impact Philae (2014)*		Stardust **Surface Sample Return (NF)**

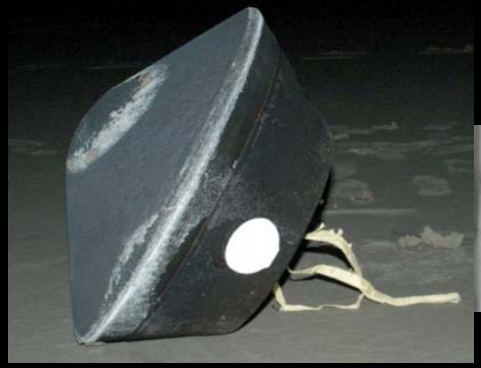

1P/Halley - 16 × 8 × 8 km
Vega 2, 1986
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
103P/Hartley 2
2.2 x 0.5 km
Deep Impact, 2010
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004

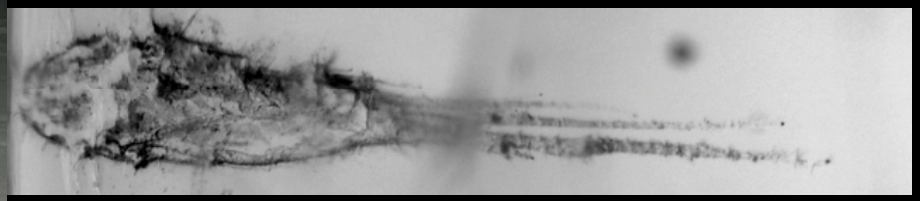
Glycine Discovered in Comet Coma







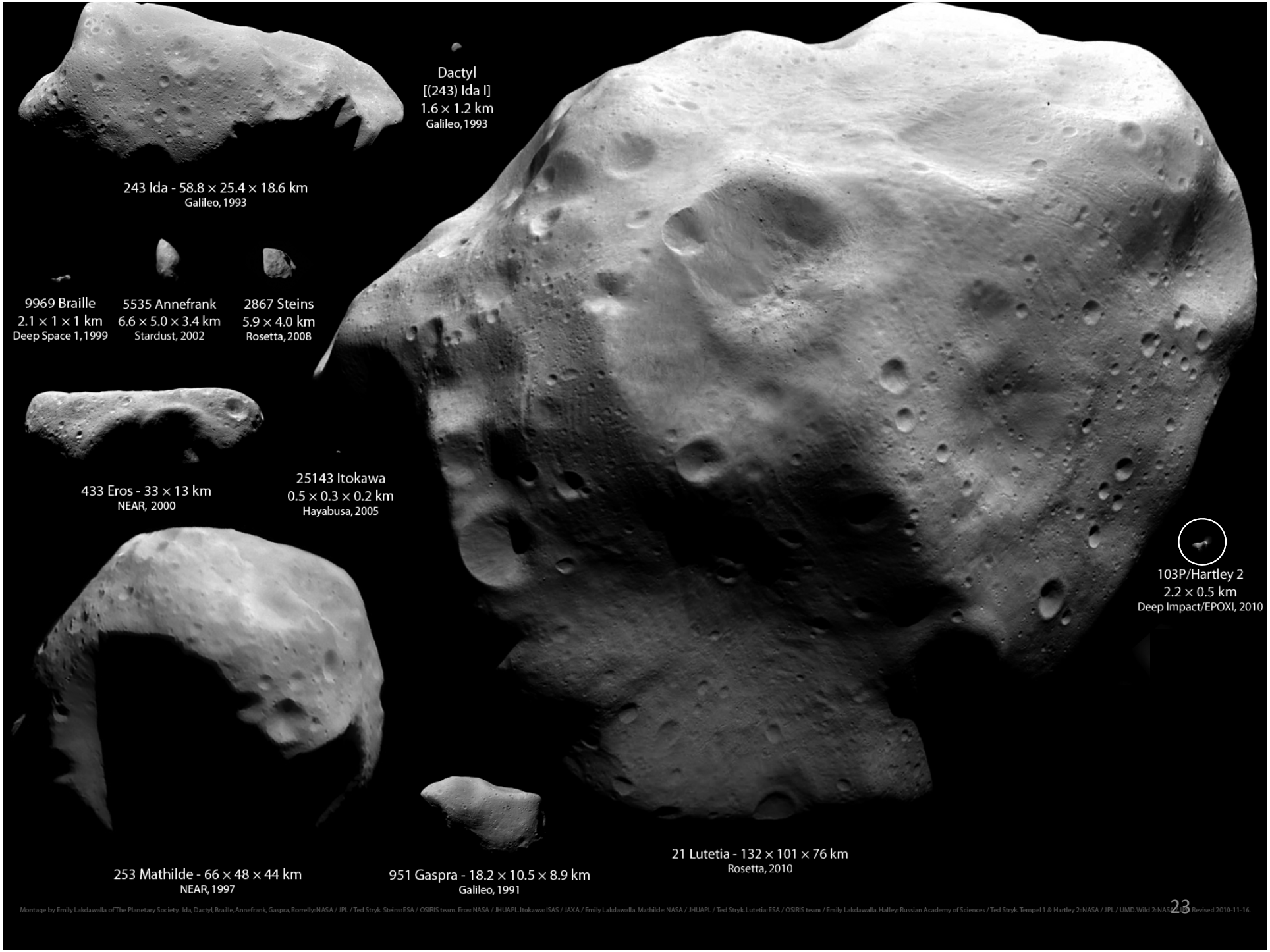




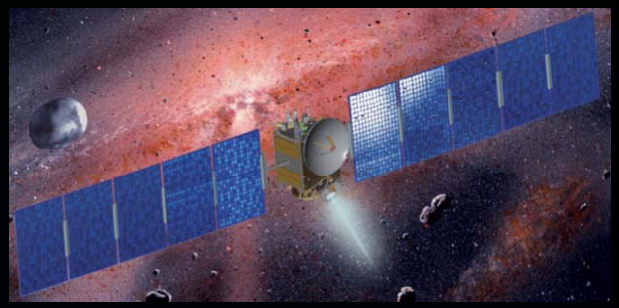
Comet Hartley 2

Near-Earth Objects

1	2	3	4	5
Flyby	**Orbit**	**Lander**	**Rover**	**Return Samples**
NEAR Shoemaker Rosetta Galileo (Cassini) Deep Space 1 Rosetta	NEAR Shoemaker Hayabusa Dawn	NEAR Shoemaker		Hayabusa Hayabusa 2* OSIRIS -REx*


Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993
243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993
9969 Braille
2.1 × 1 × 1 km
Deep Space 1, 1999
5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002
2867 Steins
5.9 × 4.0 km
Rosetta, 2008
433 Eros - 33 × 13 km
NEAR, 2000
25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005
103P/Hartley 2
2.2 × 0.5 km
Deep Impact/EPOXI, 2010
253 Mathilde - 66 × 48 × 44 km
NEAR, 1997
951 Gaspra - 18.2 × 10.5 × 8.9 km
Galileo, 1991
21 Lutetia - 132 × 101 × 76 km
Rosetta, 2010
Montage by Emily Lakdawalla of The Planetary Society. Ida, Dactyl, Braille, Annefrank, Gaspra, Borrelly: NASA / JPL / Ted Stryk. Steins: ESA / OSIRIS team. Eros: NASA / JHUAPL. Itokawa: ISAS / JAXA / Emily Lakdawalla. Mathilde: NASA / JHUAPL / Ted Stryk. Lutetia: ESA / OSIRIS team / Emily Lakdawalla. Halley: Russian Academy of Sciences / Ted Stryk. Tempel 1 & Hartley 2: NASA / JPL / UMD. Wild 2: NASA. Revised 2010-11-16.

Vesta and Ceres Size



Lutetia

Vesta

Ceres

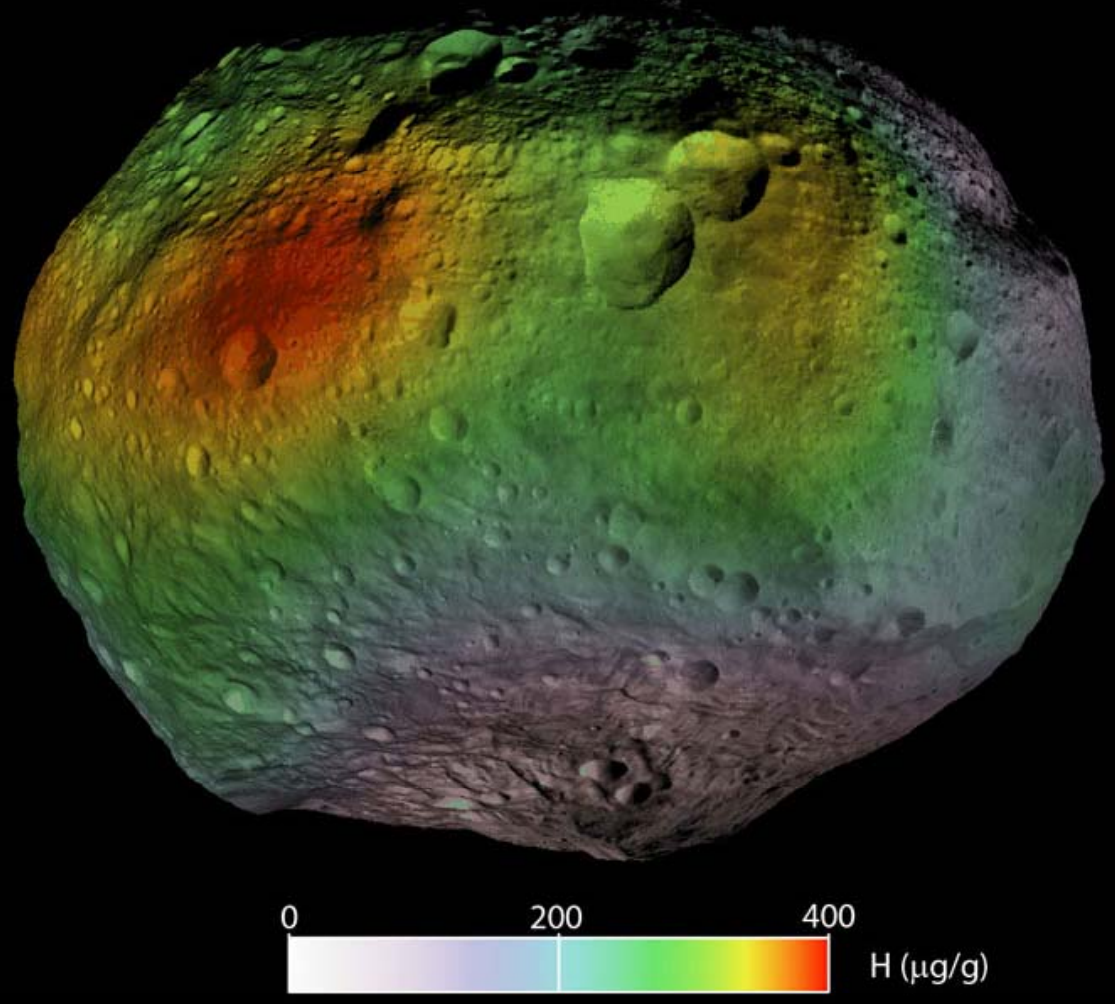
Pluto

California

Texas

Earth's moon

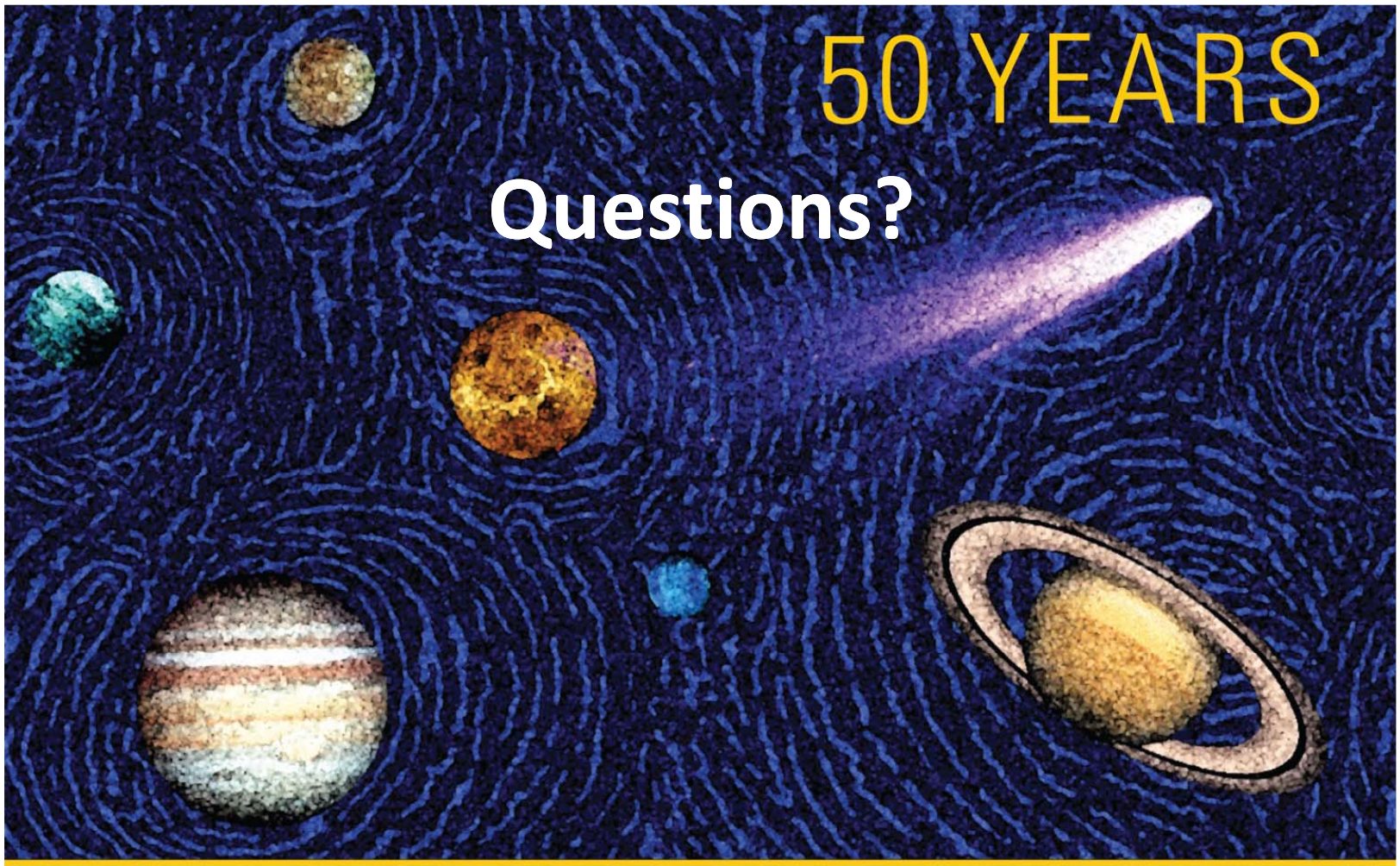
Dawn Observations of Vesta



Future Planetary Missions

	Mercury	Venus	Earth's Moon	Mars	Jupiter	Io	Europa	Ganymede	Saturn	Enceladus	Titan	Uranus	Neptune	Triton	Plutoid Pluto	Asteroids	Comets
Flyby 1	Mariner 10 MESSENGER	Mariner 2, 5, 10 Venera 11-14 Galileo Cassini MESSENGER Akatsuki	Luna 1, 3 Pioneer 4 Zond 3, (5), 6, 7, 8 Apollo 13 Hiten	Mariner 4 Mariner 6, 7 Mars 4 Mars Observer (Rosetta)	Pioneer 10 Pioneer 11 Voyager 1 Voyager 2 Cassini New Horizons	Galileo	Galileo	Galileo	Pioneer 11 Voyager 1 Voyager 2 Cassini	Voyager 2	Voyager 2 Cassini	Voyager 2	Voyager 2	Voyager 2	New Horizons*	NEAR Shoemaker Rosetta Galileo (Cassini) Deep Space 1 Rosetta New Horizons (KBO)	ICE (ISEE-3) VeGa 1, 2 Sakigake, Suisei Giotto Deep Space 1 Stardust & Stardust-NeXT Deep Impact & EPOXI (Galileo, Ulysses)
Orbit 2	MESSENGER*	Venera 9, 10, 15, 16 Pioneer 12 (PV 1) Magellan Venus Express Akatsuki (2016)*	Luna 10-12, 14, 19, 22 Lunar Orbiter 1-5 Apollo 8, 10, 11, 12, 14, 15, 16, 17 Clementine Lunar Prospector SMART-1 Hiten, SELENE (Kaguya)+Okina & Ouna Chang'e 1 & Chang'e 2 Chandrayaan 1 LRO, GRAIL, LADEE*	Mariner 9 Mars 2, 5 Viking 1, 2 Phobos 2 Mars Global Surveyor Mars Odyssey Mars Express Mars Reconnaisance Orbiter MAVEN*	Galileo Juno				Cassini							NEAR Shoemaker Hayabusa Dawn	Rosetta
Lander 3		Venera 3 (crash landing) Venera 7-10, (11, 12), 13, 14 Pioneer 13 (PV 2; 1 entry survivor) VeGa 1, 2	Ranger 7, 8, 9 Luna 2, 9, 13 Surveyor 1, 3, 4, 5 LCROSS	Mars 2 (crash landing) Mars 3 (no useful data) Viking 1, 2 Mars Pathfinder Phoenix	Galileo Probe						Huygens					NEAR Shoemaker	Deep Impact Philae (2014)*
Rover 4			Apollo 11, 12, 14 (legs) Apollo 15, 16, 17 (wheels) Lunakhod 1, 2 (Luna 17, 21)	Sojourner MER Spirit, MER Opportunity MSL Curiosity*													
Return Samples 5			Apollo 11, 12, 14, 15, 16, 17 Luna 16, 20, 24													Hayabusa Hayabusa 2* OSIRIS REx*	Stardust

- Next 50 years of solar system missions will occur in the *green*
- Interdisciplinary approaches – we've come full circle



Questions?

solar system exploration