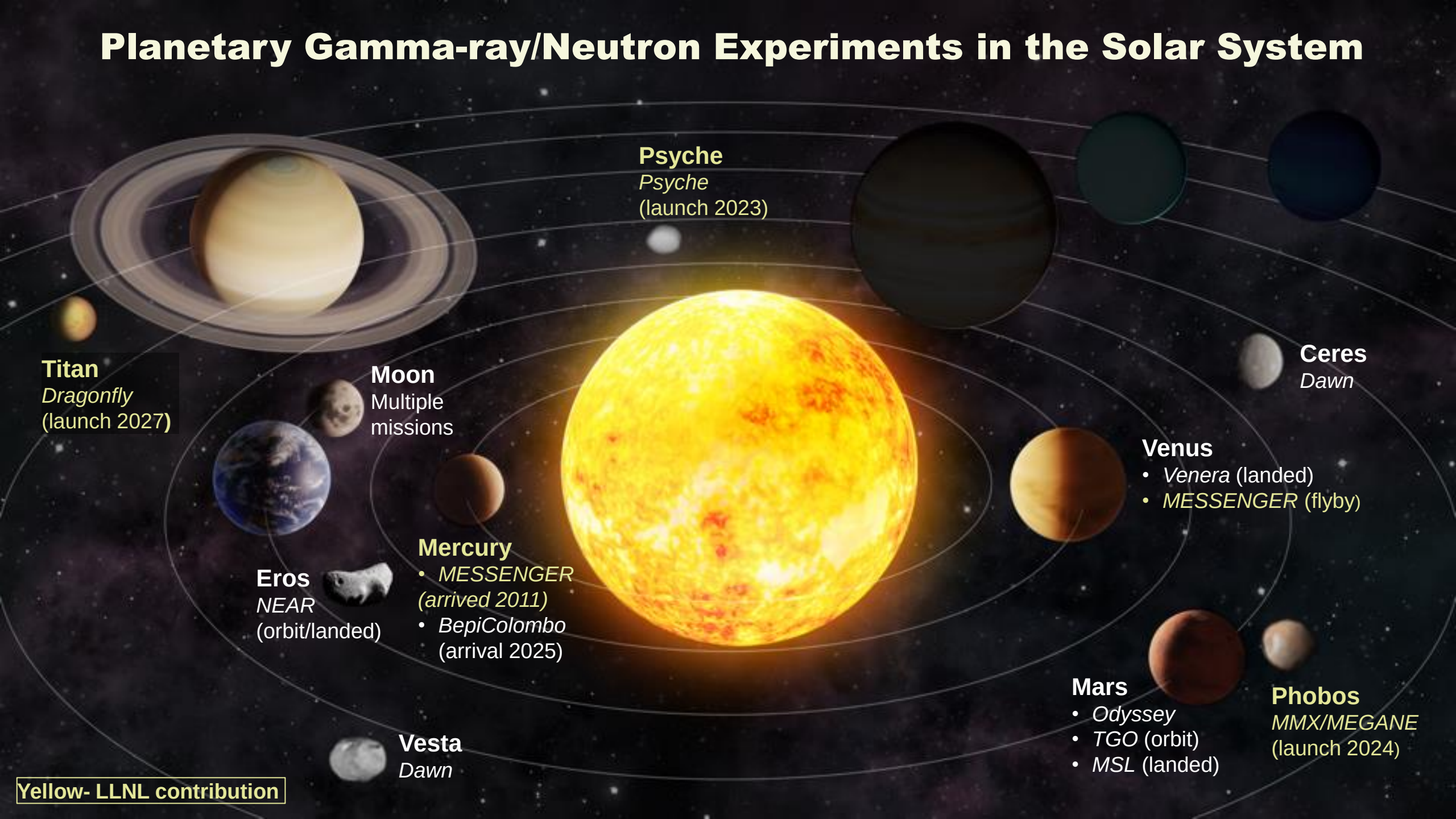
Exploring the Solar System with Gamma Rays

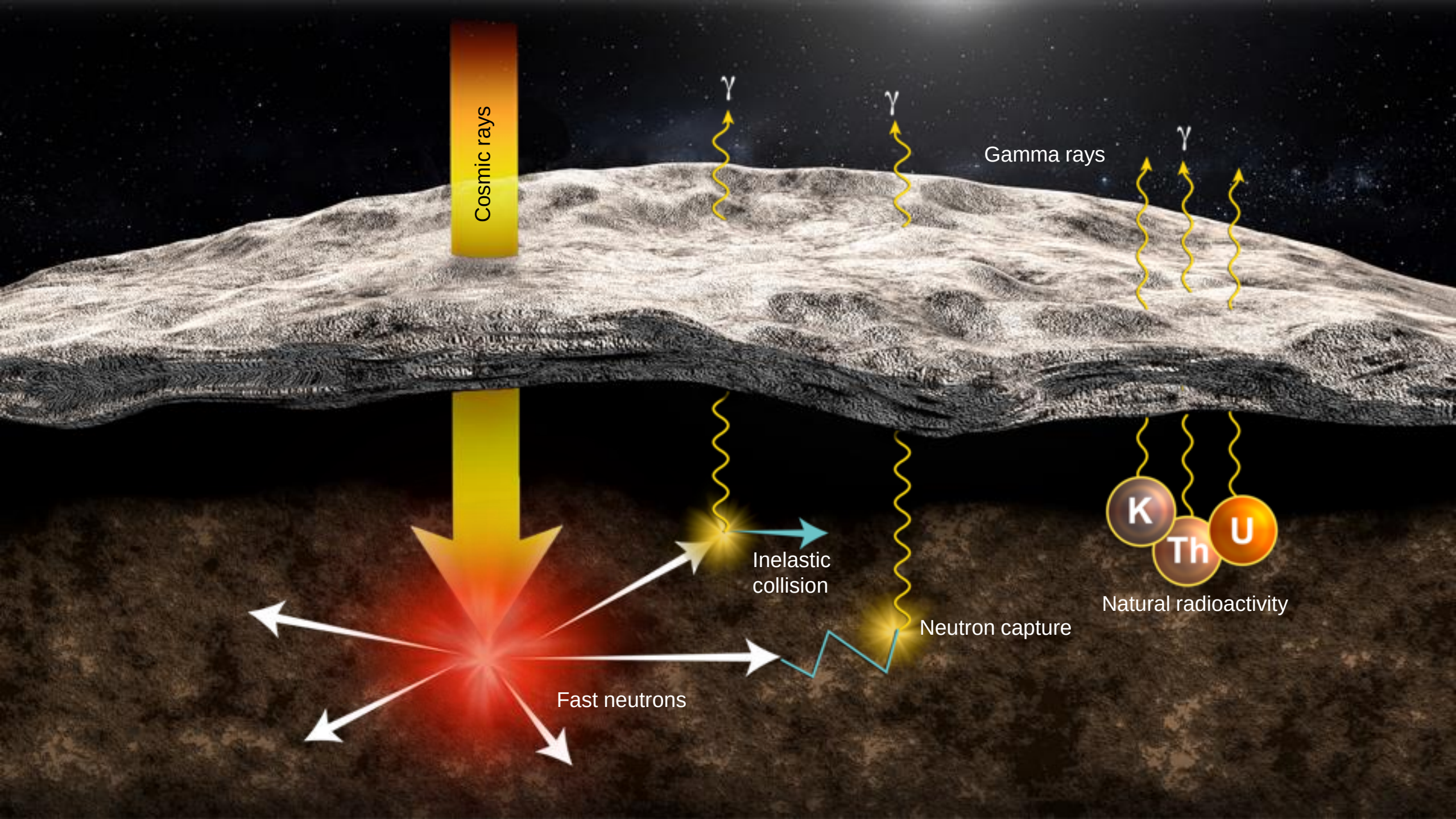


Morgan Burks
Geon-Bo Kim
Nathan Hines
Stephan Friedrich
Vladimir Mozin
Lawrence Livermore National Laboratory
In collaboration with the *Johns Hopkins Applied Physics Laboratory*

LLNL-PRES-744183

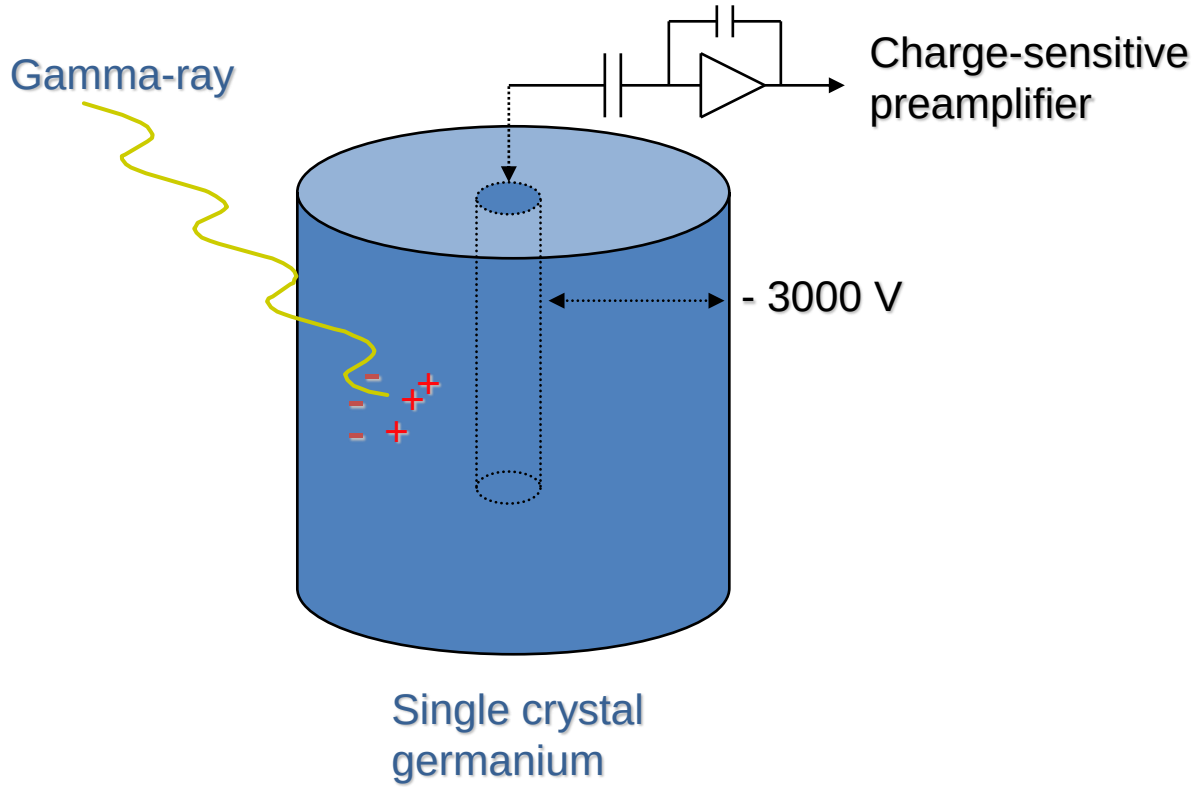
Planetary Gamma-ray/Neutron Experiments in the Solar System



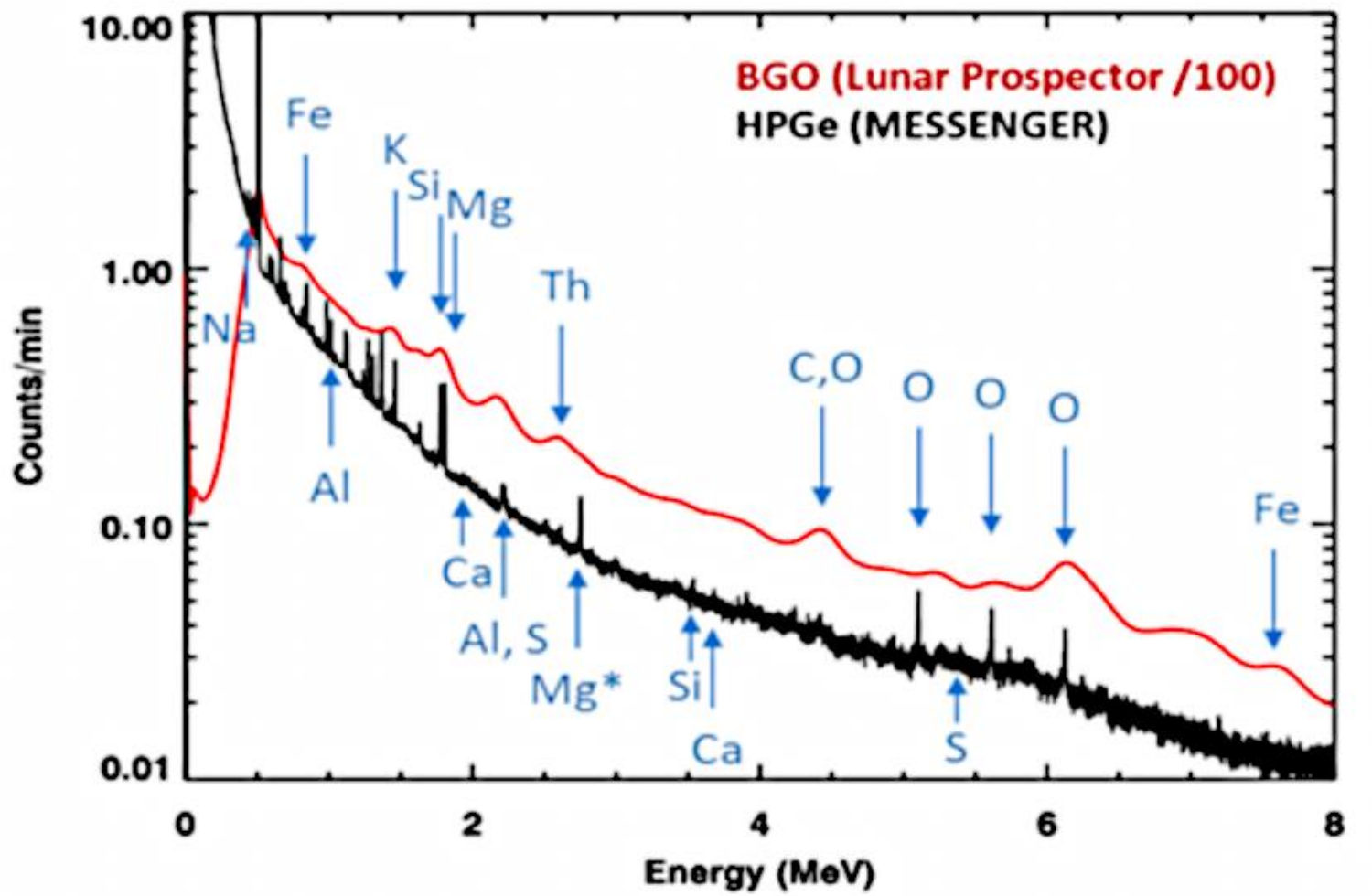

Cosmic rays
γ
γ
γ
Gamma rays
Inelastic
collision
Neutron capture
Fast neutrons
K
Th
U
Natural radioactivity

High-Purity Germanium Detector





High Resolution Provides Higher Sensitivity

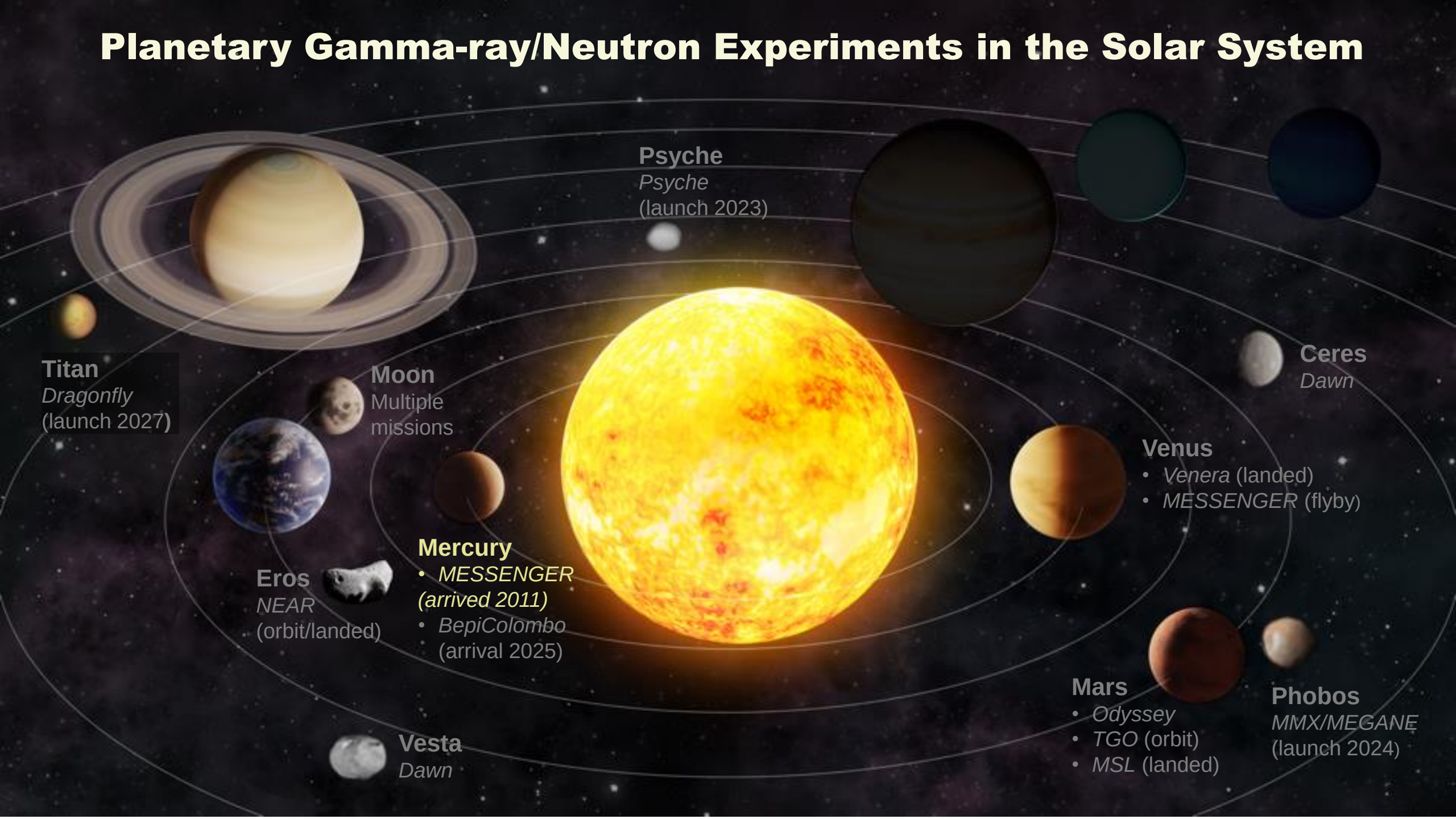


High-Purity Germanium in Space: Technical Challenges

- Cooling
- Mass/Power
- Ruggedness
- Solar Particle Events
- Radiation Damage

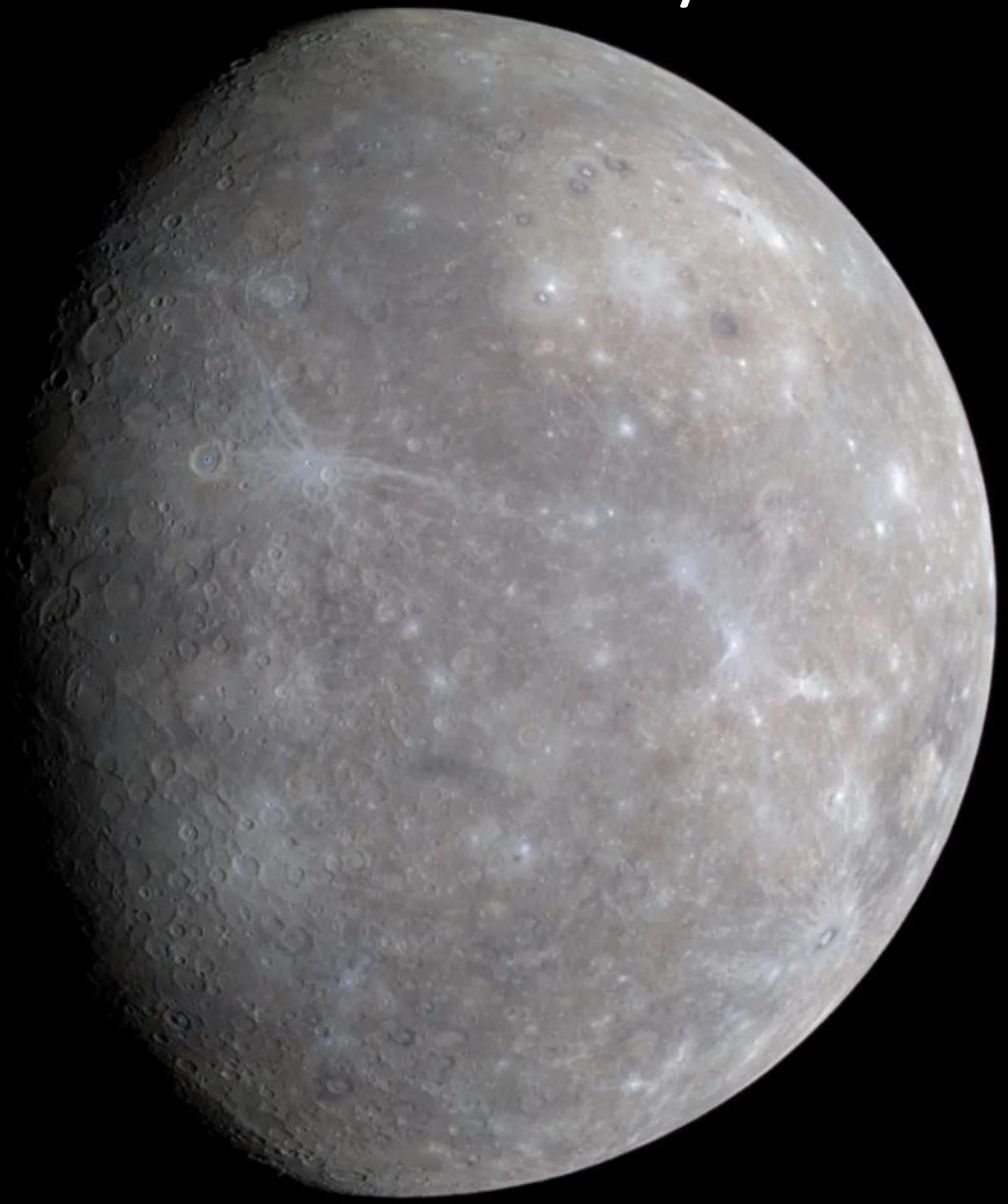


Planetary Gamma-ray/Neutron Experiments in the Solar System



MESSENGER Mission to Mercury

- NASA Discovery-class Mission
- Launched in 2004
- Entered Mercury orbit in 2011
- Primary Science Goals:
  - Study the geology, magnetic field, and chemical composition of Mercury



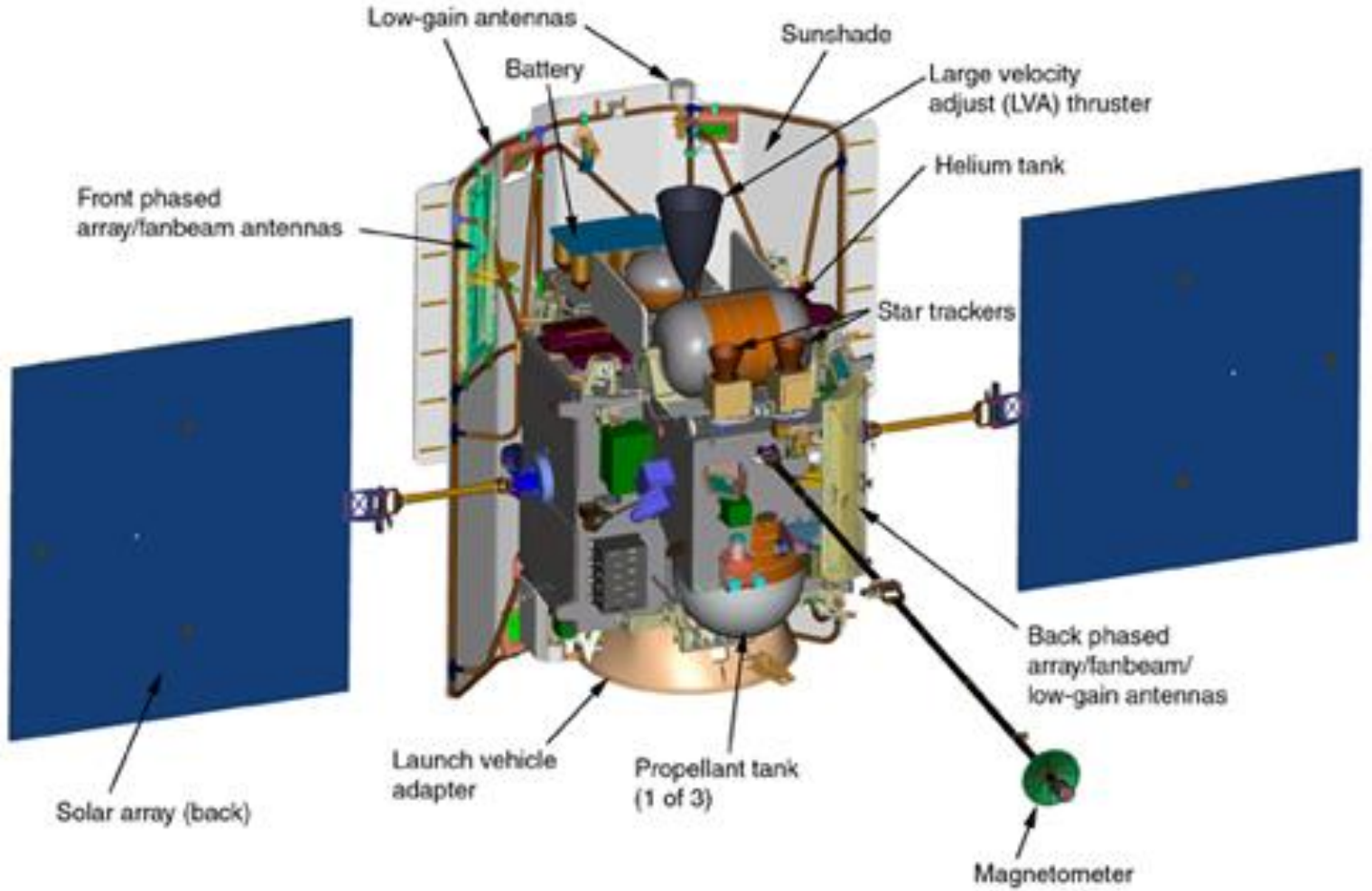
MESSENGER Instrumentation

Spectroscopy Instruments

- Infrared & EUV
- X-ray
- Gamma ray
- Neutron
- Charged particle

Other Instrumentation

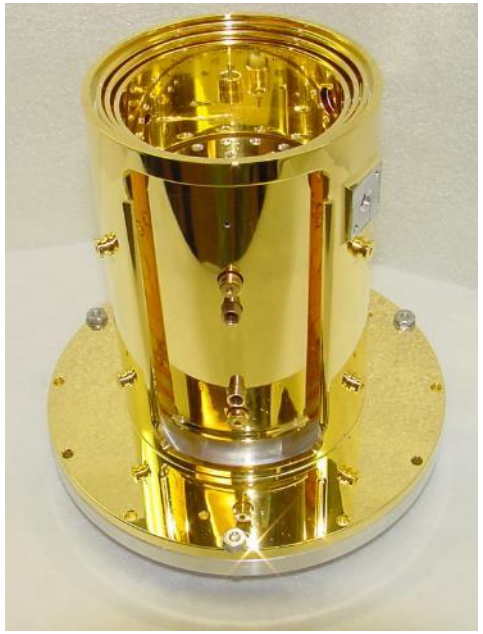
- Magnetometer
- Visible imaging camera
- Laser altimeter
- Radio science



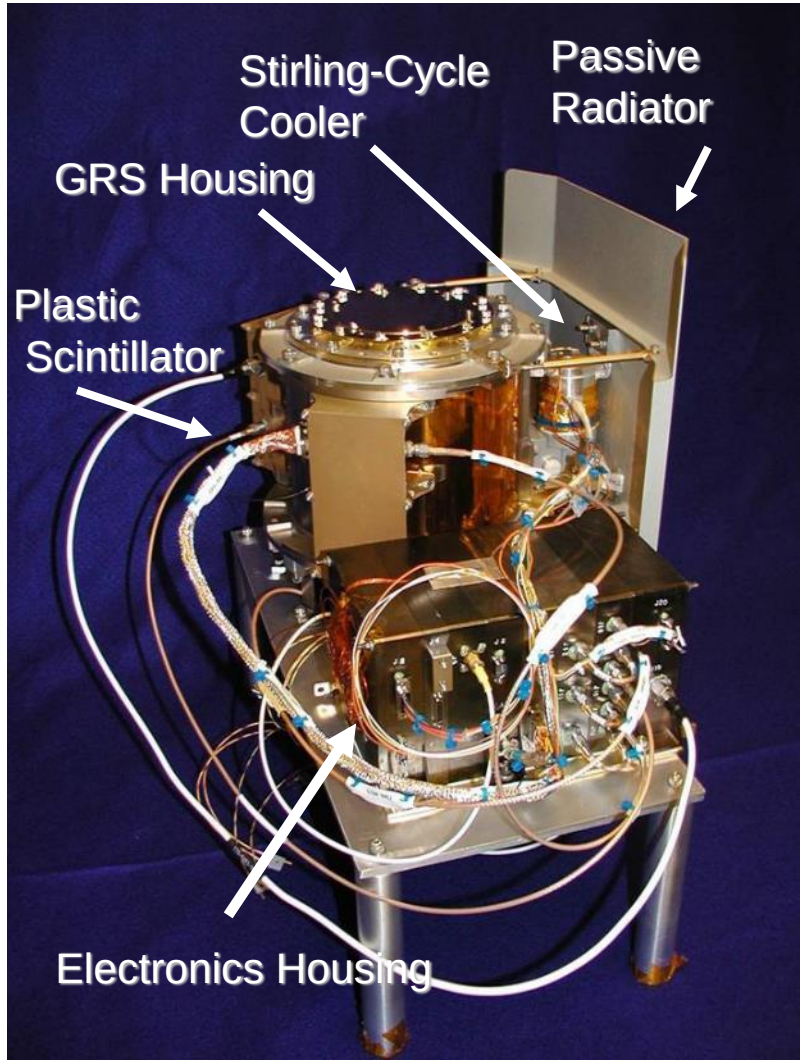
MESSENGER Gamma-Ray Spectrometer



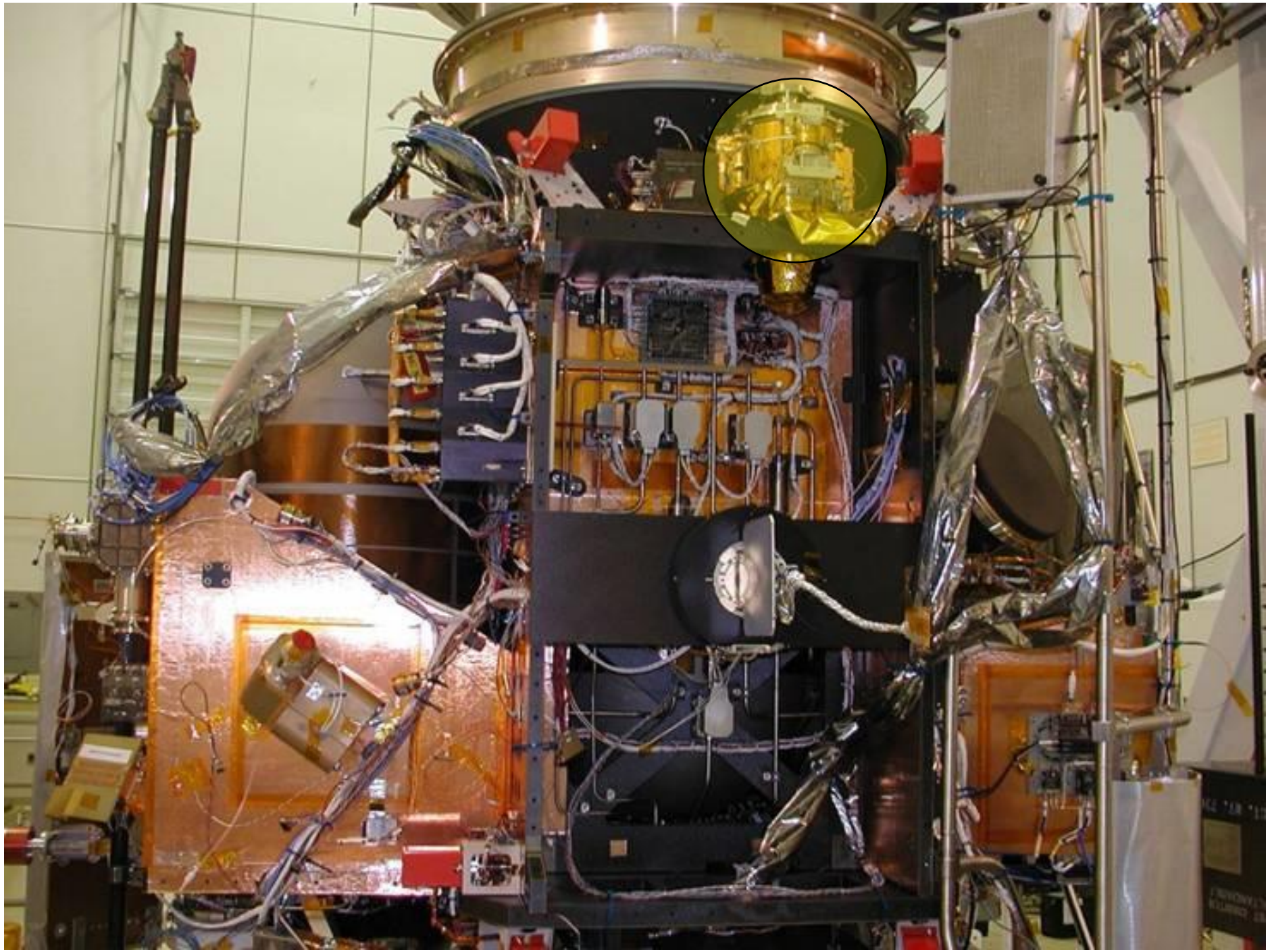
5 cm x 5 cm
germanium crystal



Three nested layers of
infrared shielding



Ready for flight



Major Scientific Contributions

Mapped elemental composition

- K, Th, U
- C, O, Na, Al, Si, S, Cl, Ca, Fe

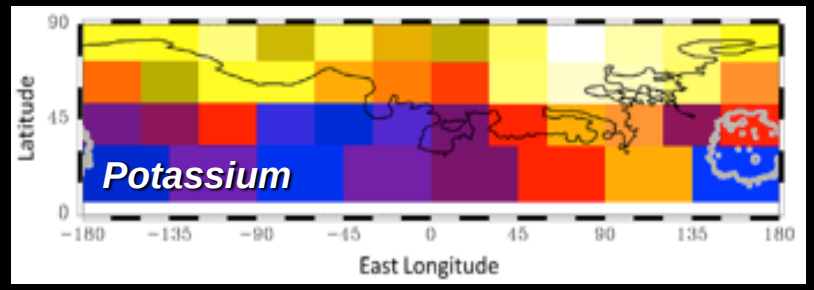
Discovered surprisingly high ratio of volatile elements: K, Na, Cl

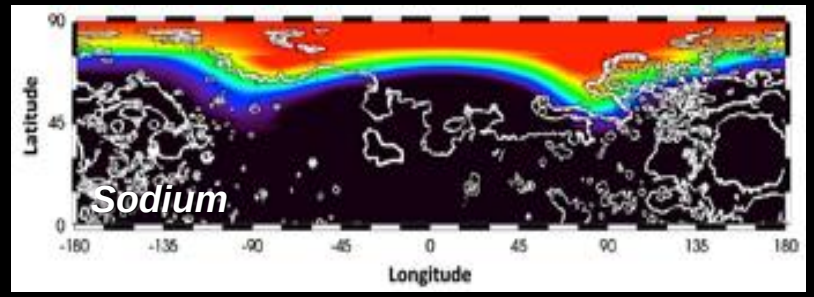
Measured redistribution of volatiles to poles

Discovered signs of volcanic activity

Discovered water ice at the poles!

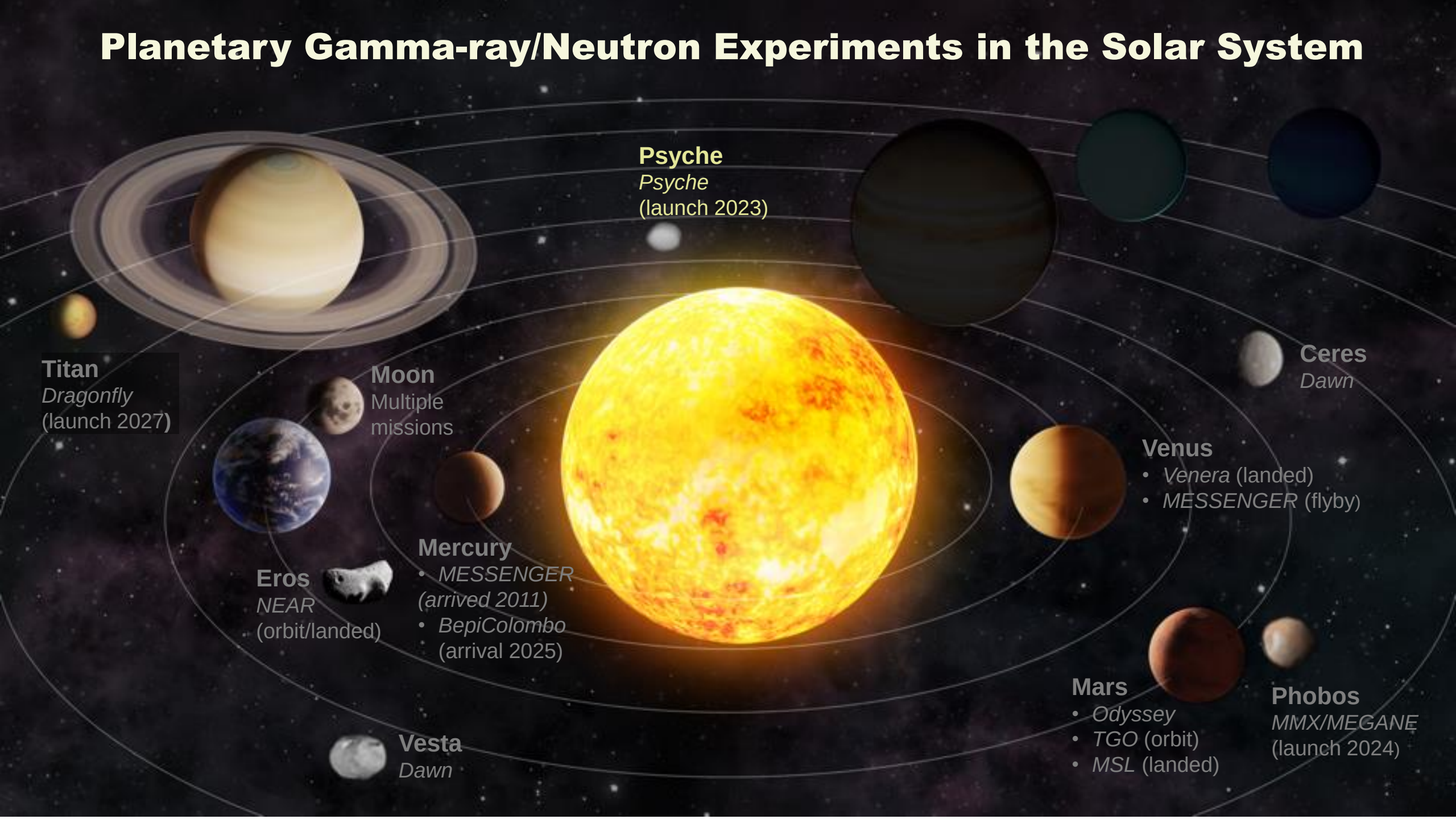
Elemental Maps







Planetary Gamma-ray/Neutron Experiments in the Solar System



16-Psyche

- Discovered in 1852
- ~200 km diameter
- 2.5 to 3.3 A.U. orbit

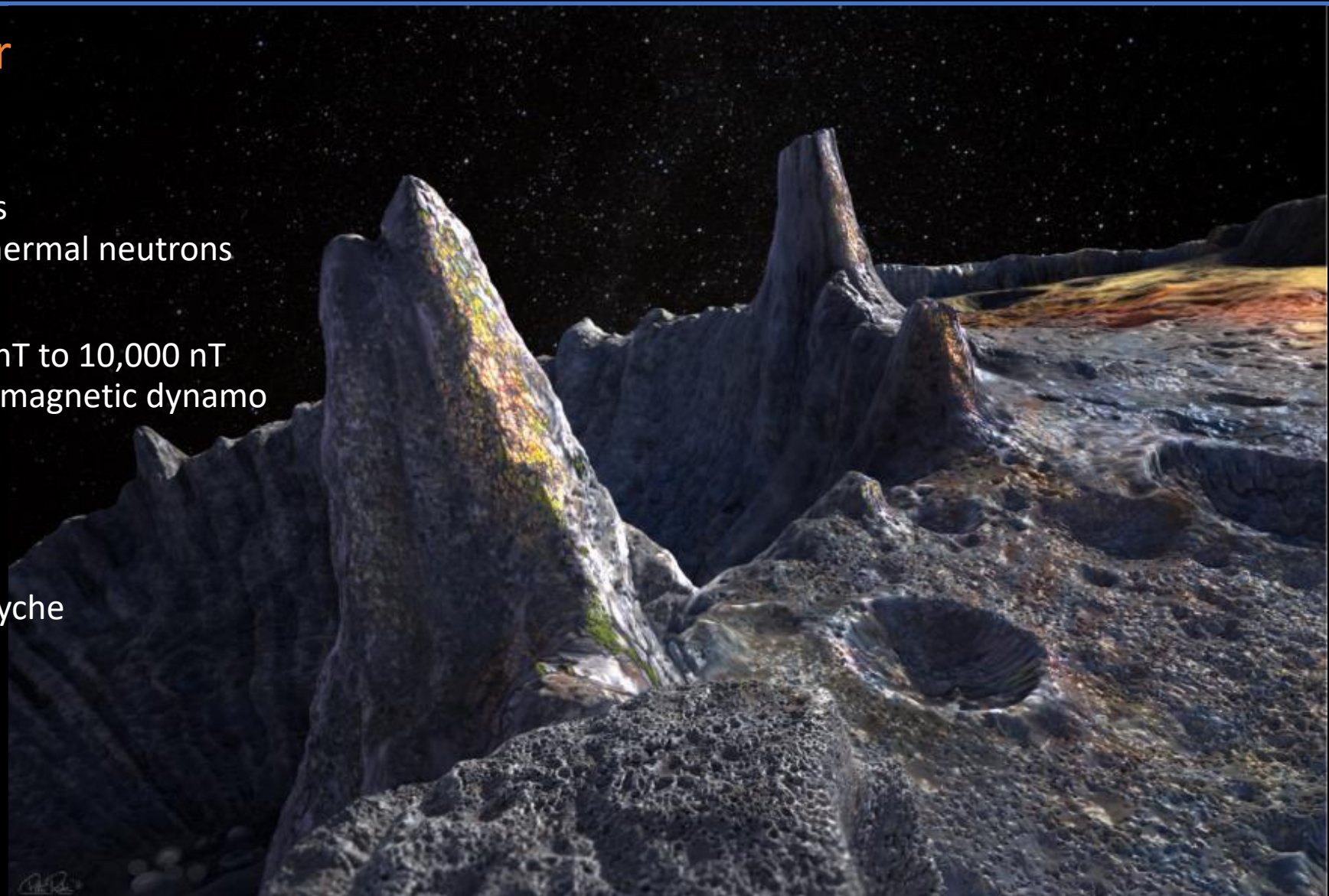
Information Available to date

- Optical imaging: Arecibo Observatory
- Density: ~3.78 g/cm^3
- Radar reflectance
  - ~90% Fe-Ni, ~10% high-Mg silicates (M-class)
  - *Recently confirmed by UV imaging from the Hubble Telescope!*
- *Preliminary shape results: from the JWT*

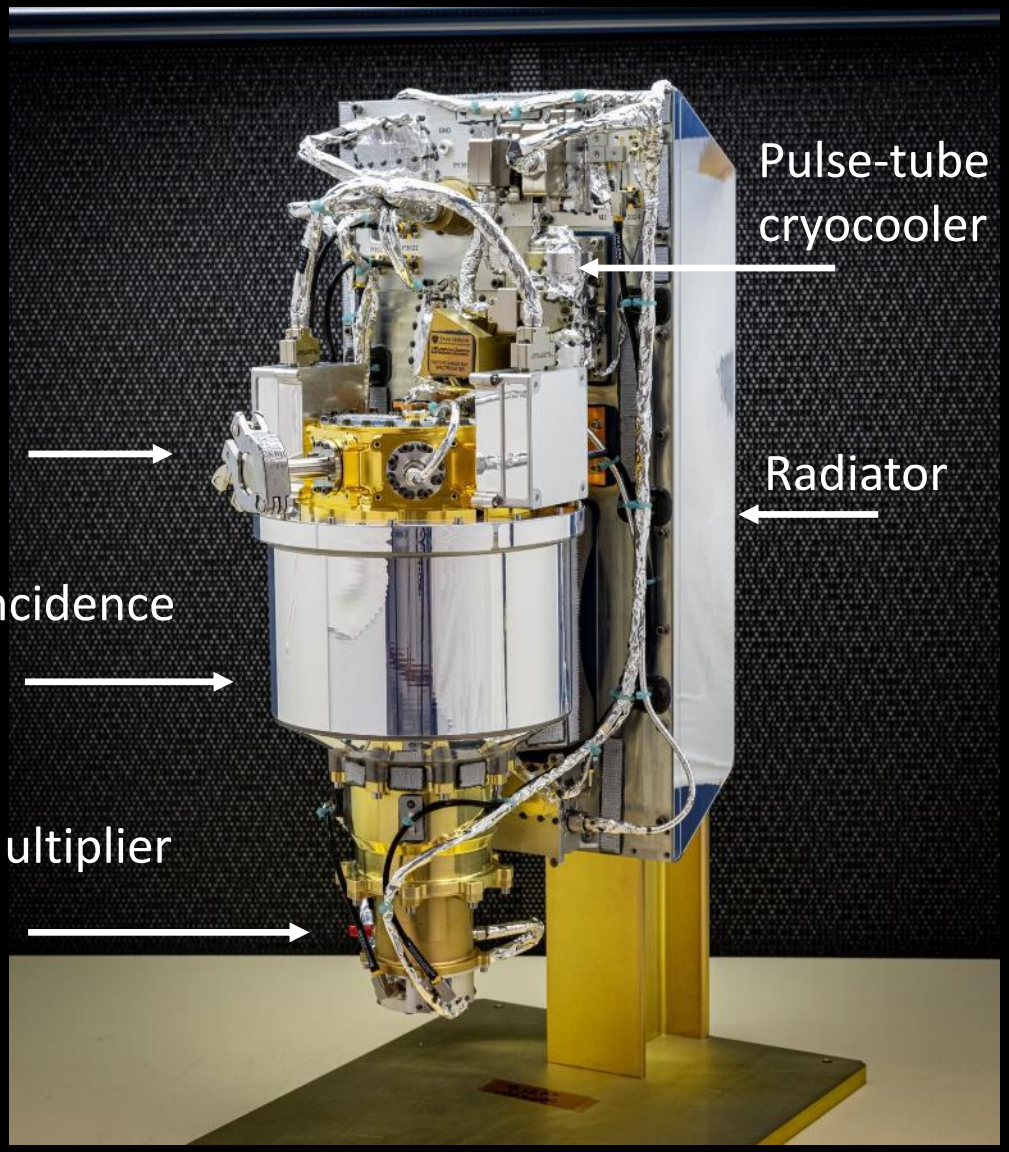


Instrumentation on the Psyche Spacecraft

- Gamma-ray spectrometer
  - Fe, Ni, Si, K, S, Al, Ca, Th, U
- Neutron spectrometers
  - Borated plastic for fast neutrons
  - ^{3}He tubes for thermal and epithermal neutrons
- Magnetometer
  - Map the magnetic field from 1 nT to 10,000 nT
  - Determine if Psyche ever had a magnetic dynamo
- Multi-spectral Imager
  - Mapping silicates
- Radio Science
  - Map gravitation moments of Psyche
  - Find a stable orbit



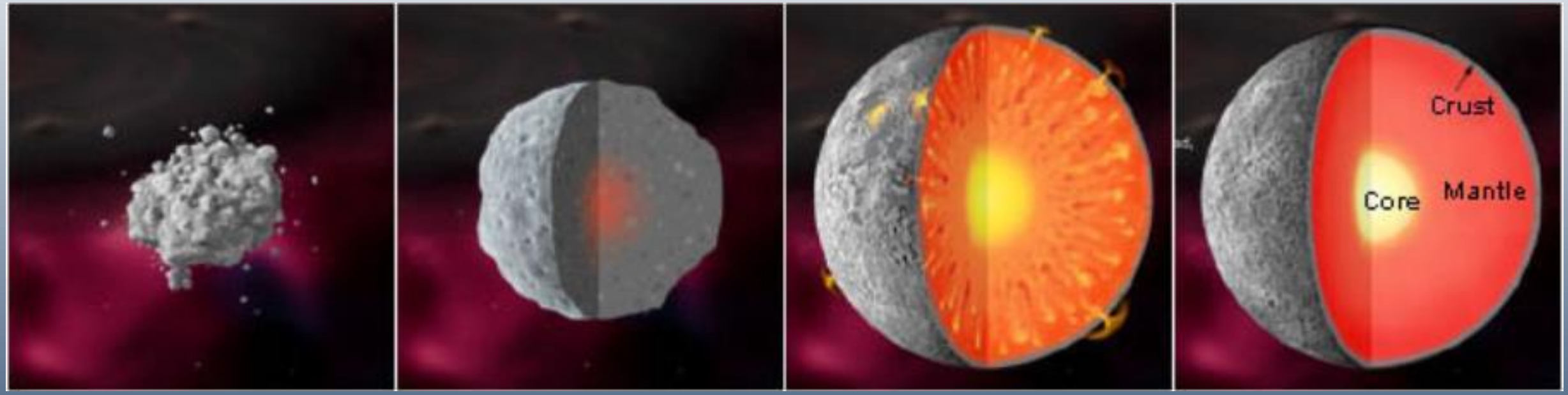
Psyche Gamma-Ray Spectrometer



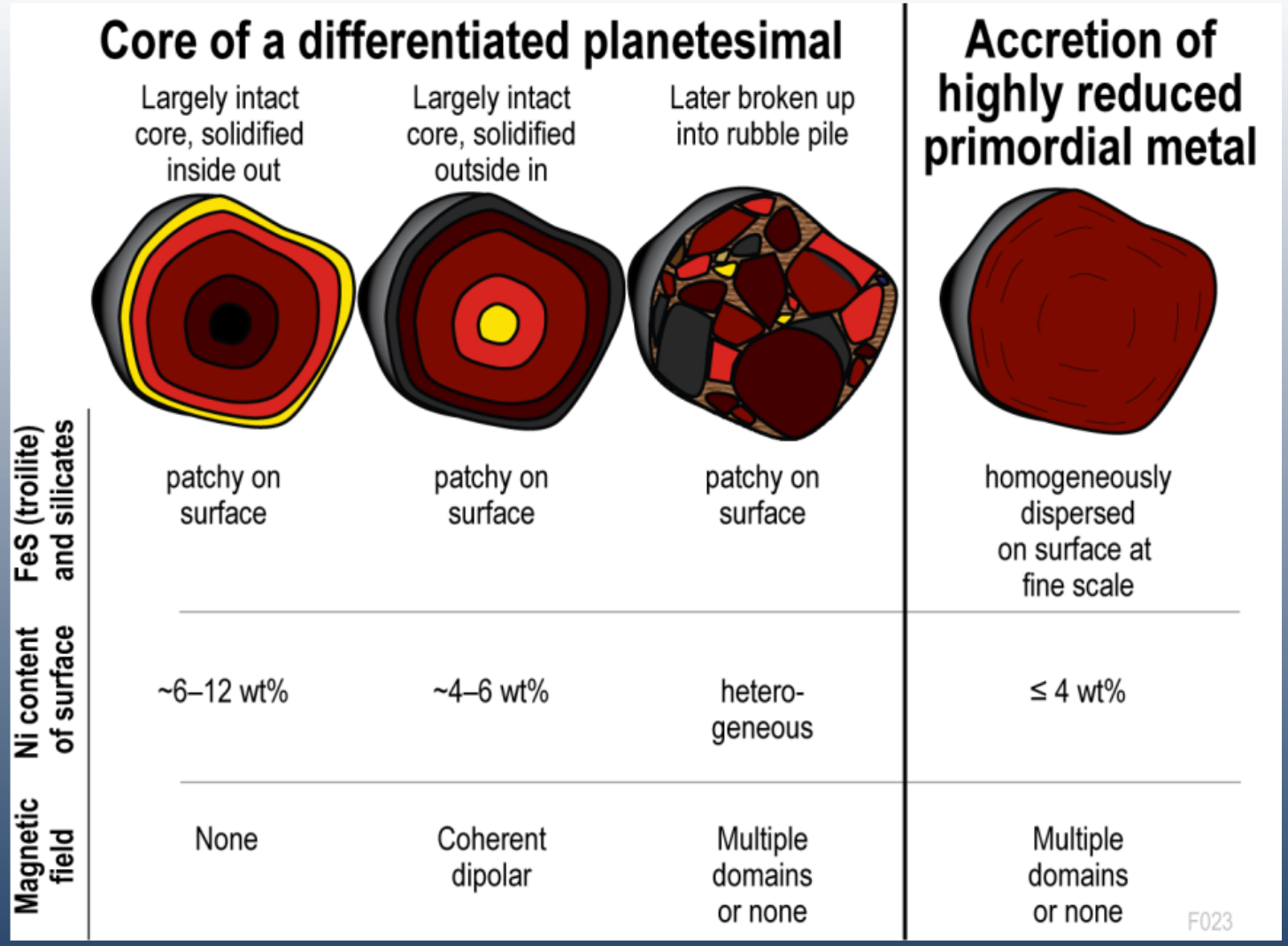
Installing the Psyche Gamma Ray Spectrometer at NASA's Jet Propulsion Laboratory



Psyche May be the Remnant Core of a Planetesimal



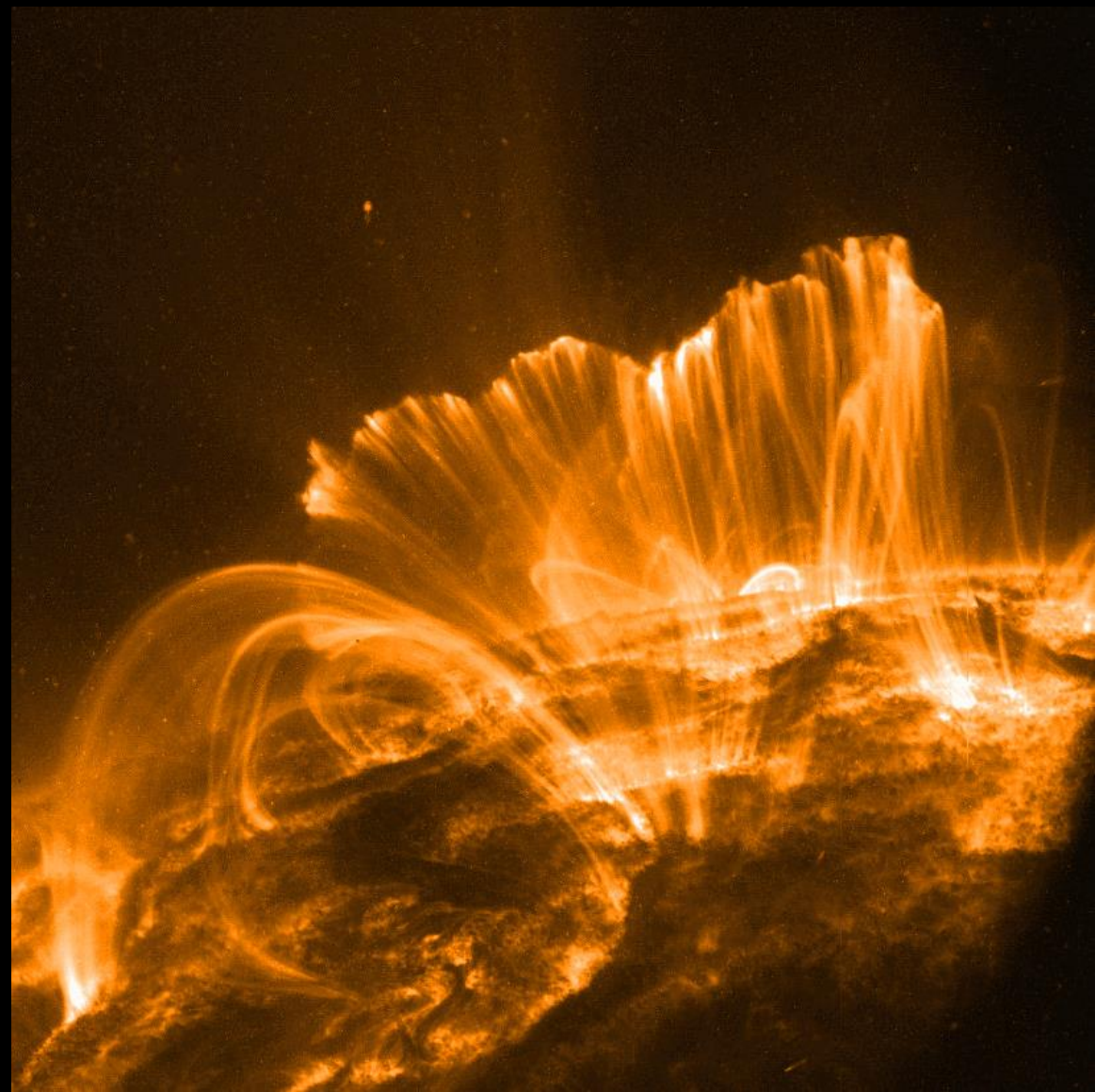
The Ni/Fe reveals how Psyche formed



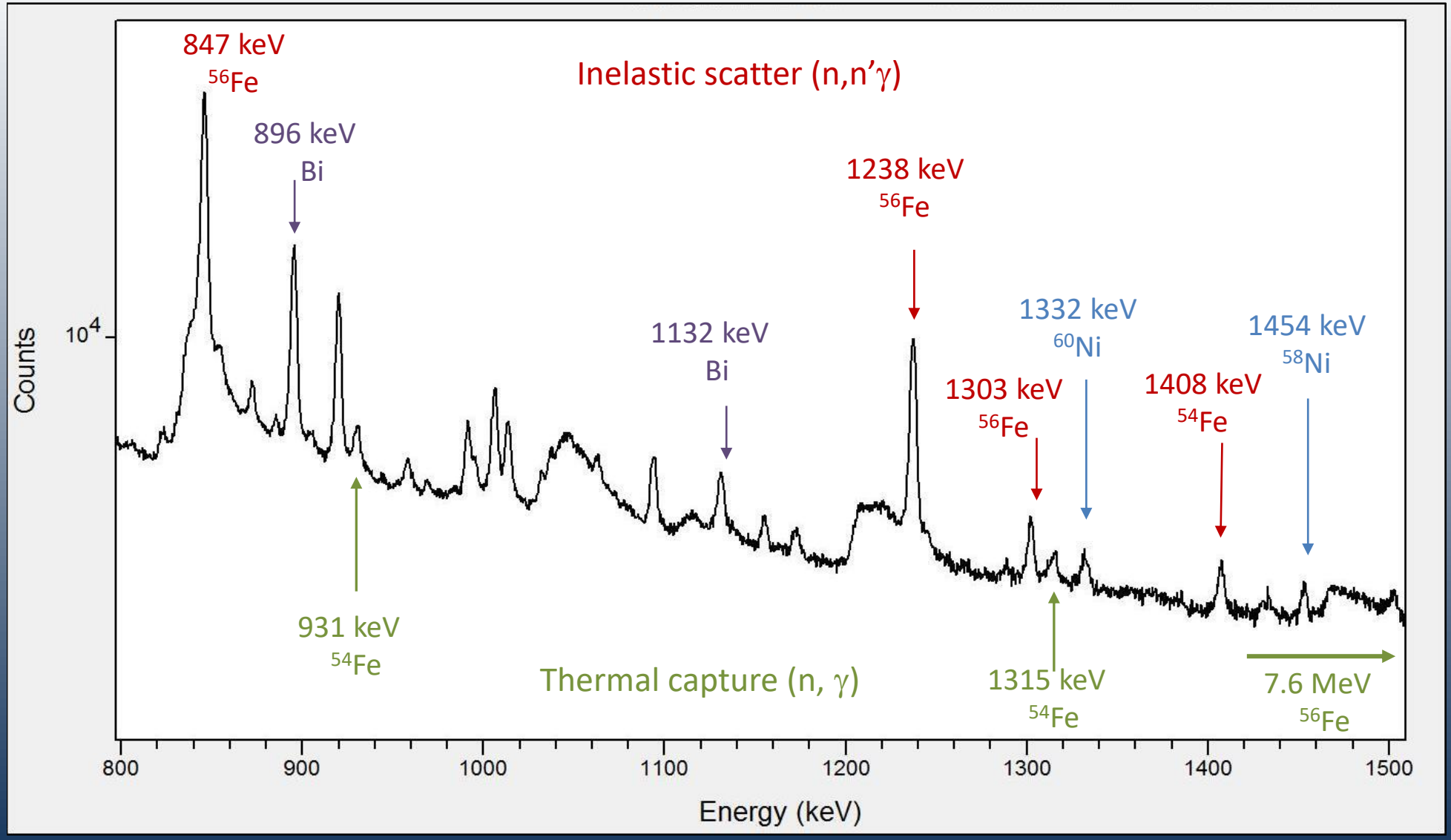
Nickel accumulates in *liquid* iron ⇒ Fe/Ni ratio indicates *Psyche's* evolution

Gamma-Ray Measurements in the Presence of Solar Particle Events

- Solar Particle events (SPE)
  - Solar Flares or coronal mass ejections
  - Mostly protons: 10 to 150 MeV
- SPE activate the iron in the spacecraft
  - ^{56}Fe (p,n) ^{56}Co
    - 56Co → 56Fe + γ (847.8 keV)
    - 77.2 day half-life
- A large SPE hit MESSENGER spacecraft
  - Prevented the further mapping of iron for the remainder of the mission



Meteorite bombardment by 14 MeV neutrons

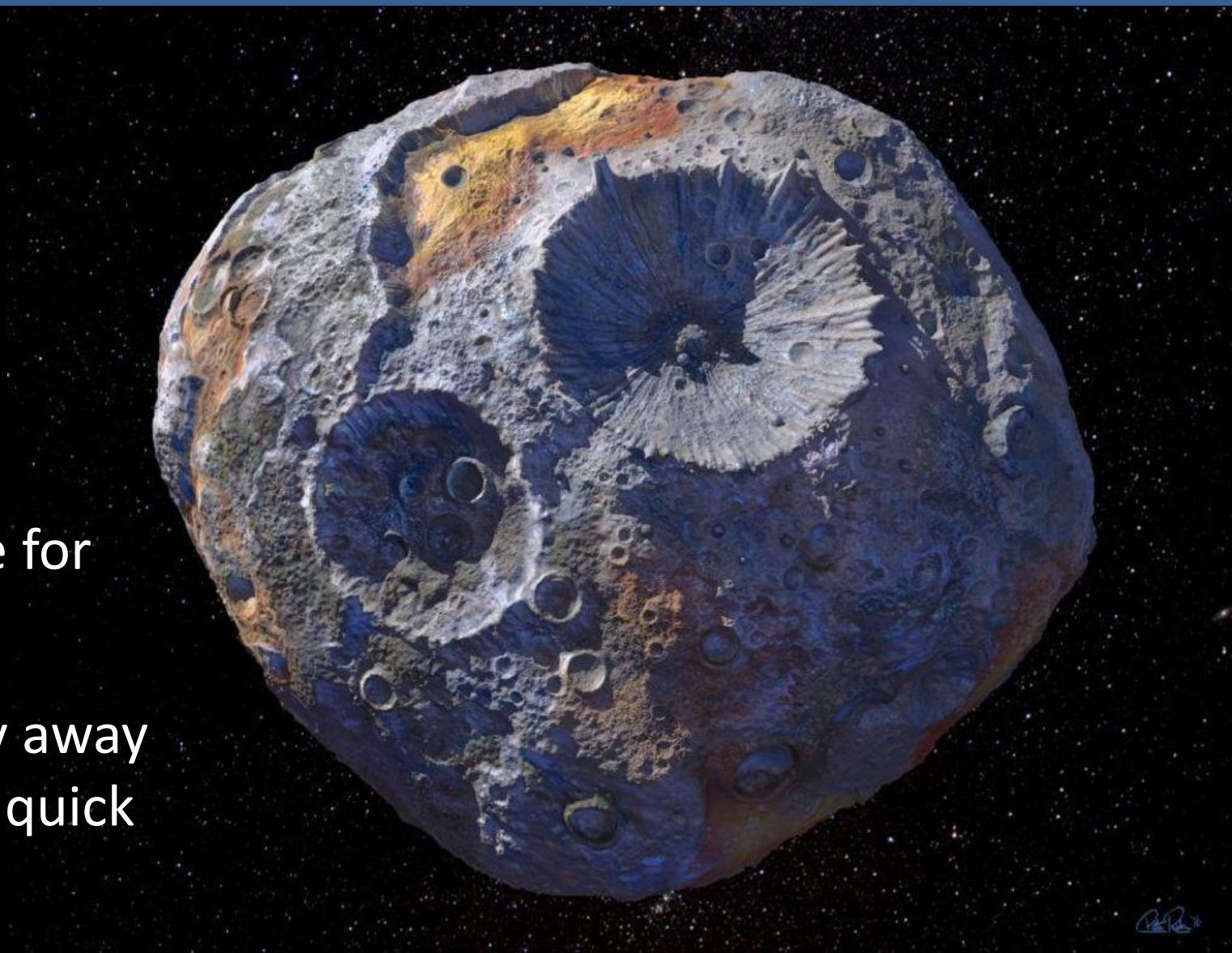




Odessa meteorite
92% Fe
7% Ni
Trace: P, S, C, Ga, Ge, Ir

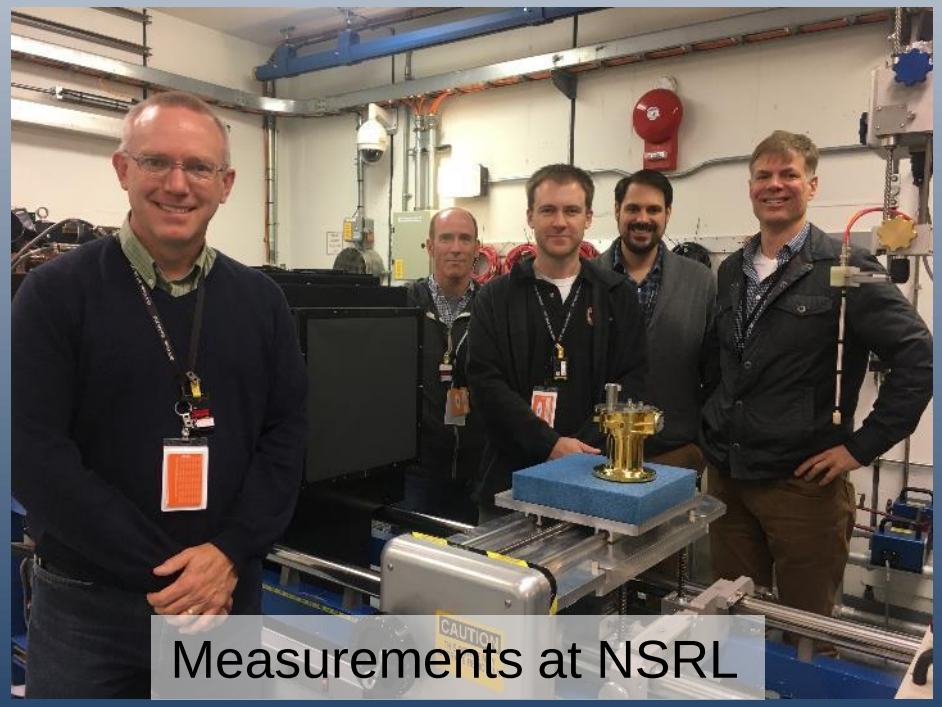
^{54}Fe gamma-ray line (1408.5 keV) is robust against Solar Particle Events

- ^{56}Fe (p,n) ^{56}Co
  - ^{56}Co → ^{56}Fe + γ (847.8 keV)
  - 77.2 day half-life
- ^{54}Fe (p,γ) ^{55}Co
  - ^{55}Co → ^{55}Fe + γ (1408.5 keV)
  - 17.5 hour half-life
- 1408.5 keV is a useful signature for iron
- Activation of this line will decay away within a few days, allowing the quick resumption of measurements

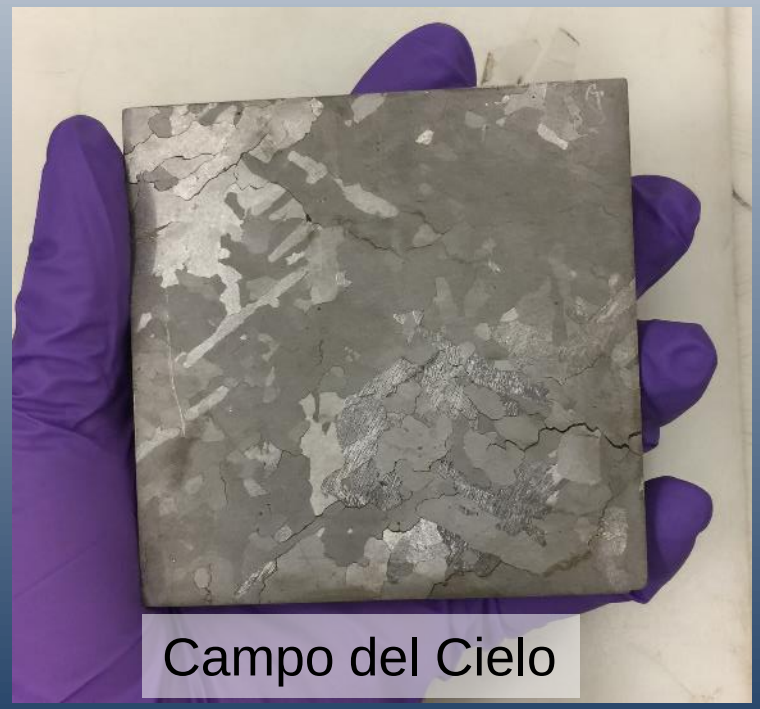


Irradiation tests at Brookhaven: NASA Space Radiation Laboratory (NSRL)

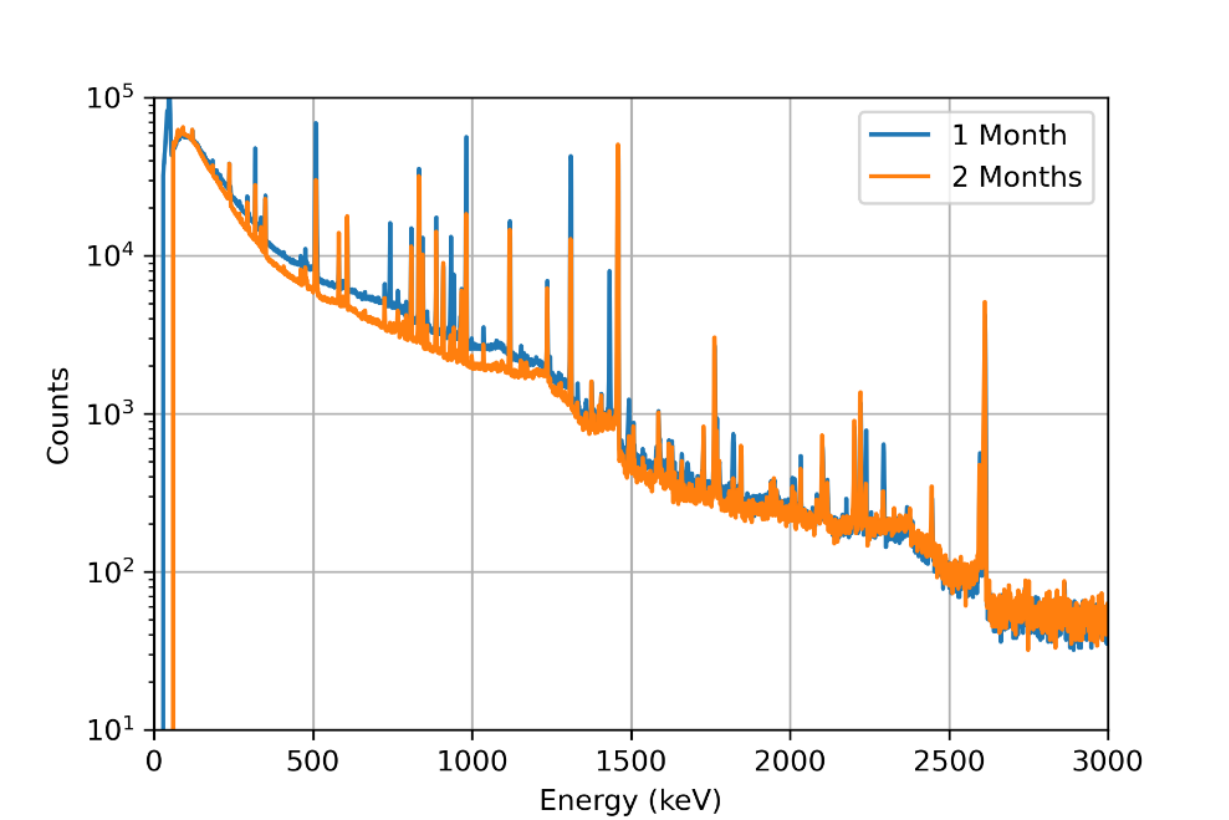
- Irradiate iron-nickel meteorite with proton beam at NSRL
- Proton beam energy spectrum mimics Solar Particle Event
- Measured activation lines

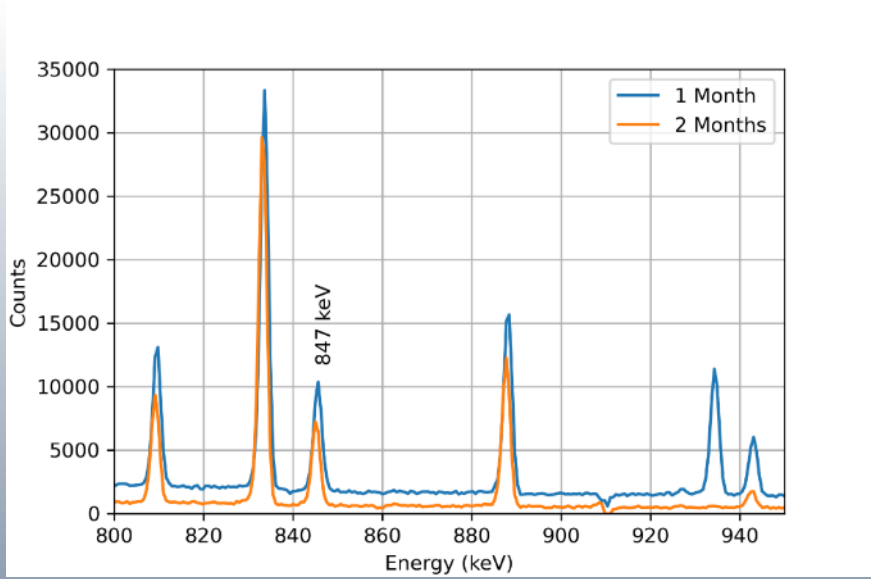


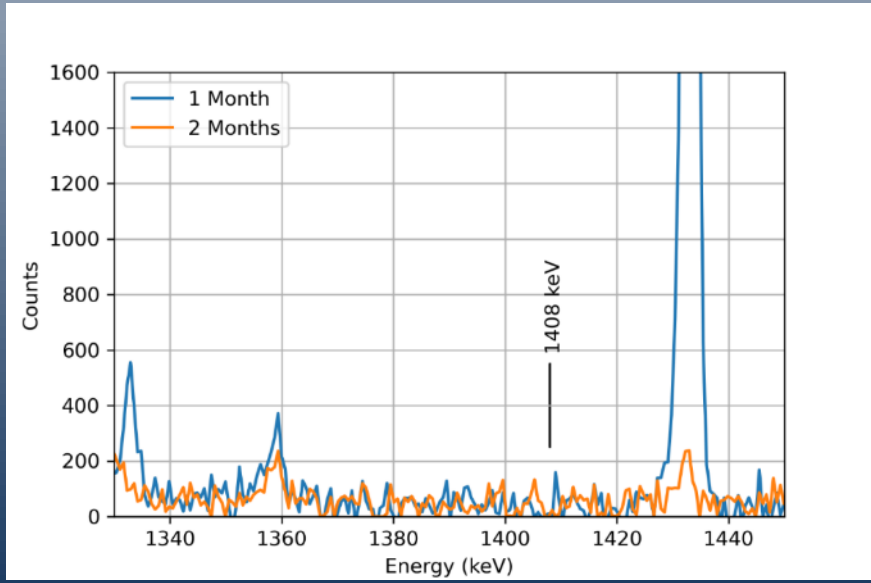
Measurements at NSRL


Campo del Cielo

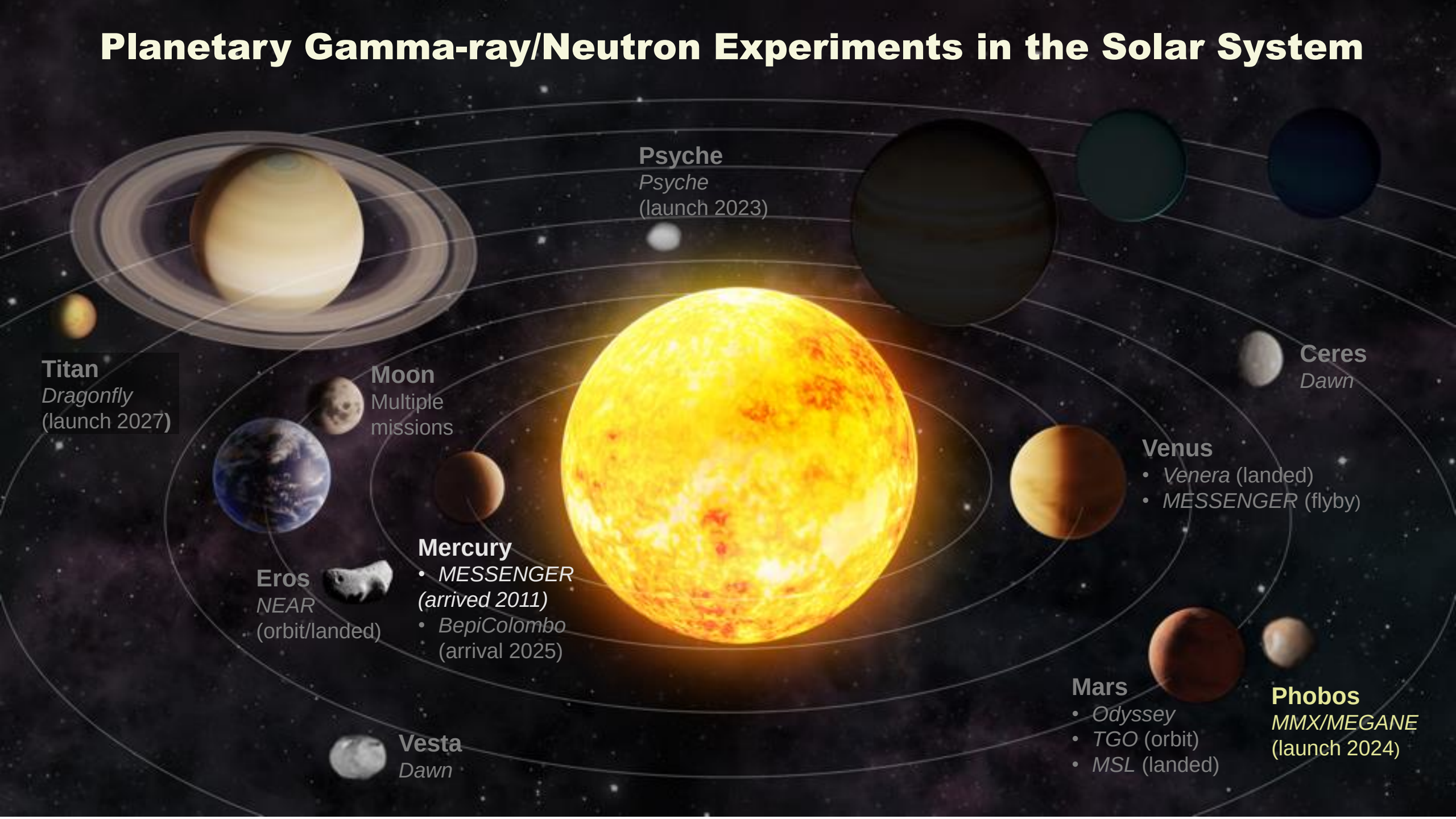
Meteorite Activation by proton beam





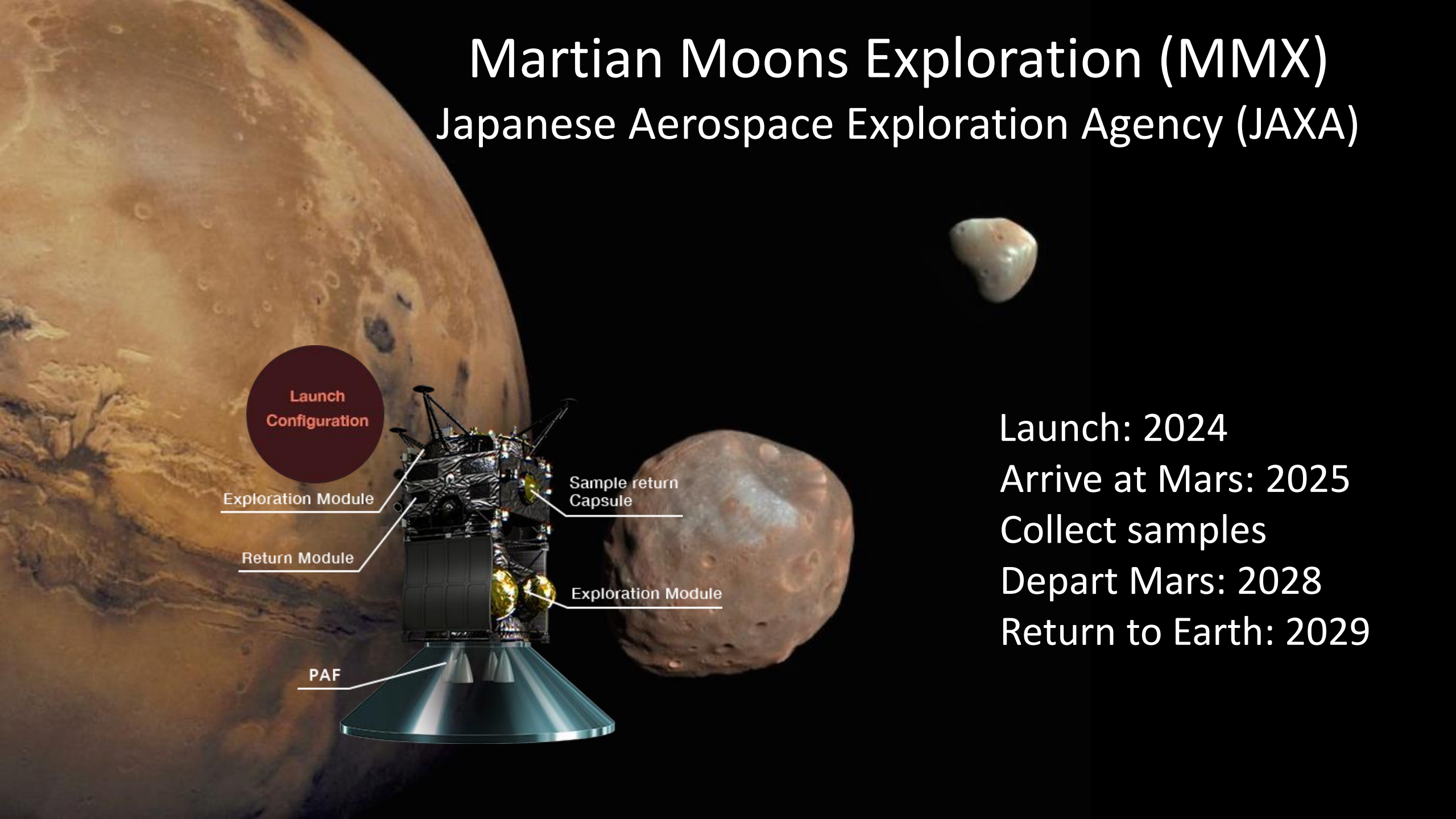


Planetary Gamma-ray/Neutron Experiments in the Solar System

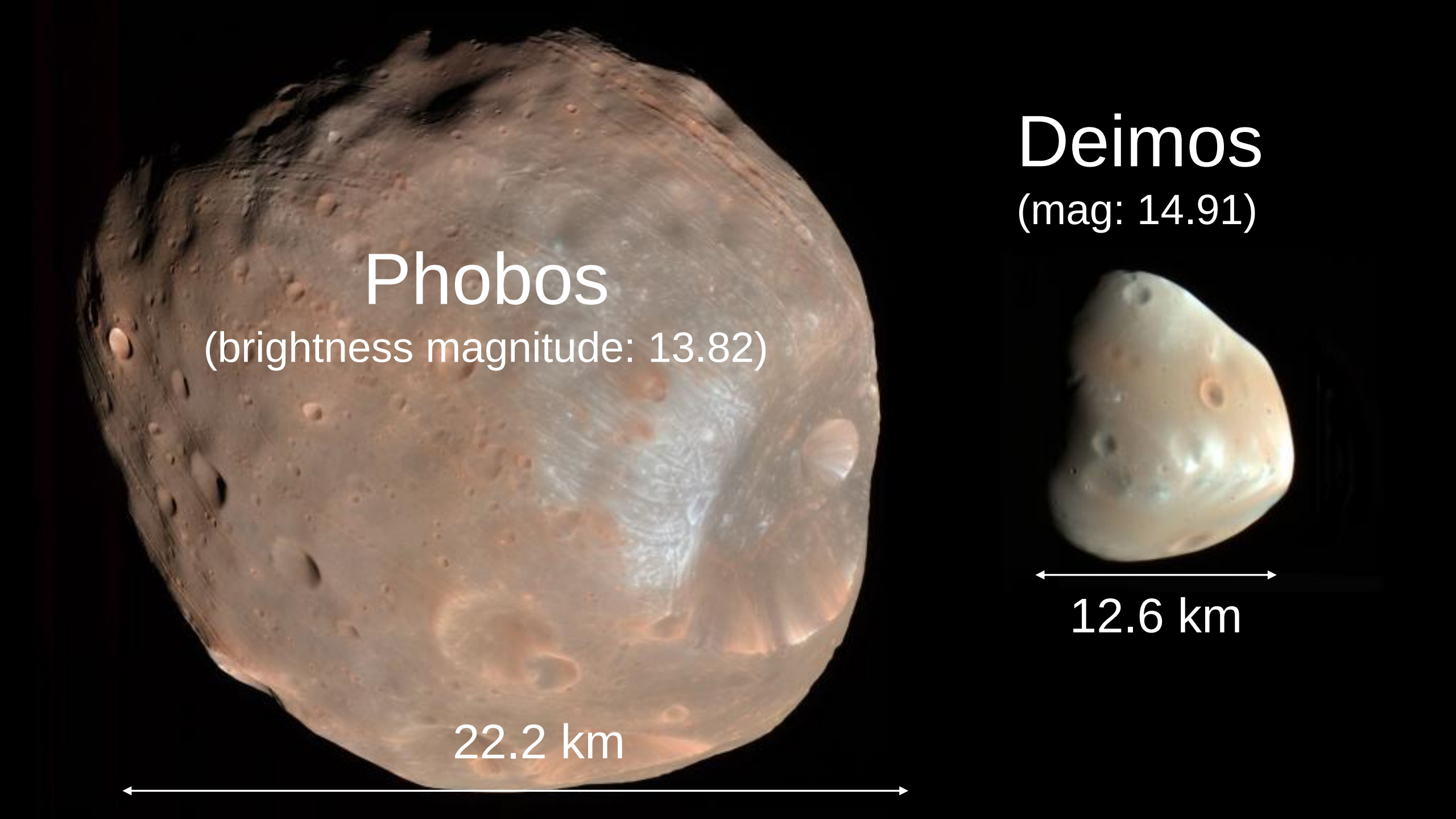


Martian Moons Exploration (MMX)

Japanese Aerospace Exploration Agency (JAXA)



Launch: 2024
Arrive at Mars: 2025
Collect samples
Depart Mars: 2028
Return to Earth: 2029


Phobos
(brightness magnitude: 13.82)
22.2 km
Deimos
(mag: 14.91)
12.6 km

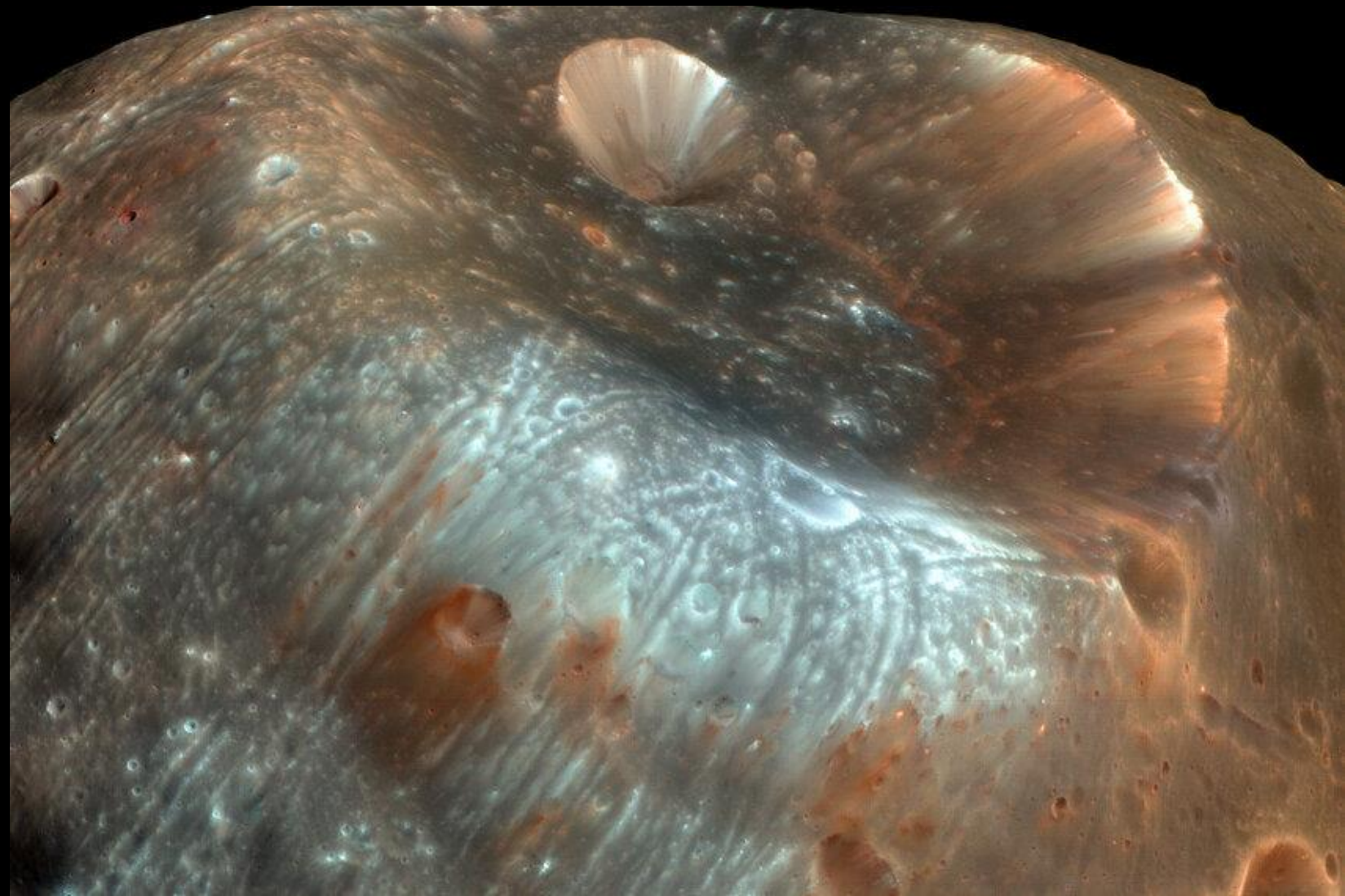
Martian Moons Exploration
Science Investigation

Mysterious origins of Phobos and Deimos

- Captured asteroids
- Remnant of collision with Mars

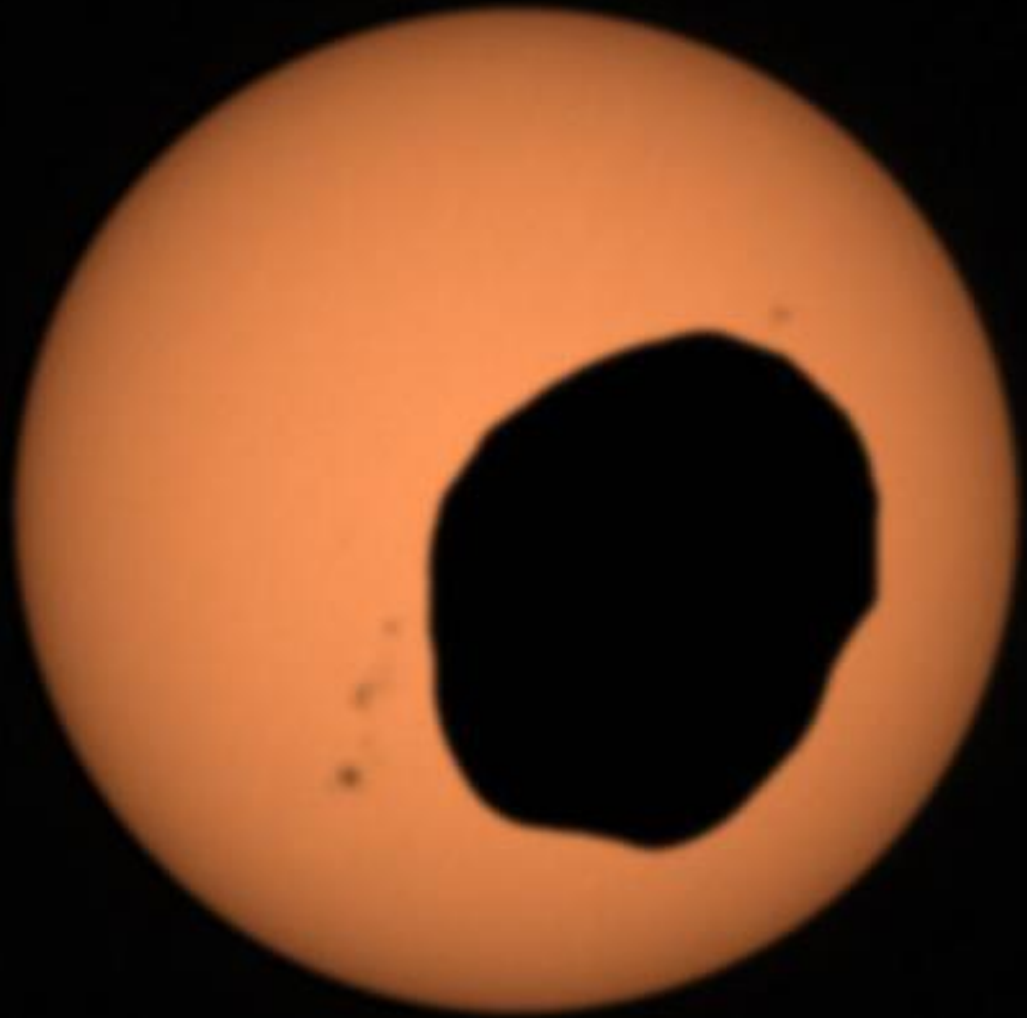
Origin of Blue/Red IR spectral features

- Compositional difference
- Space weathering



Phobos Captured by Perseverance

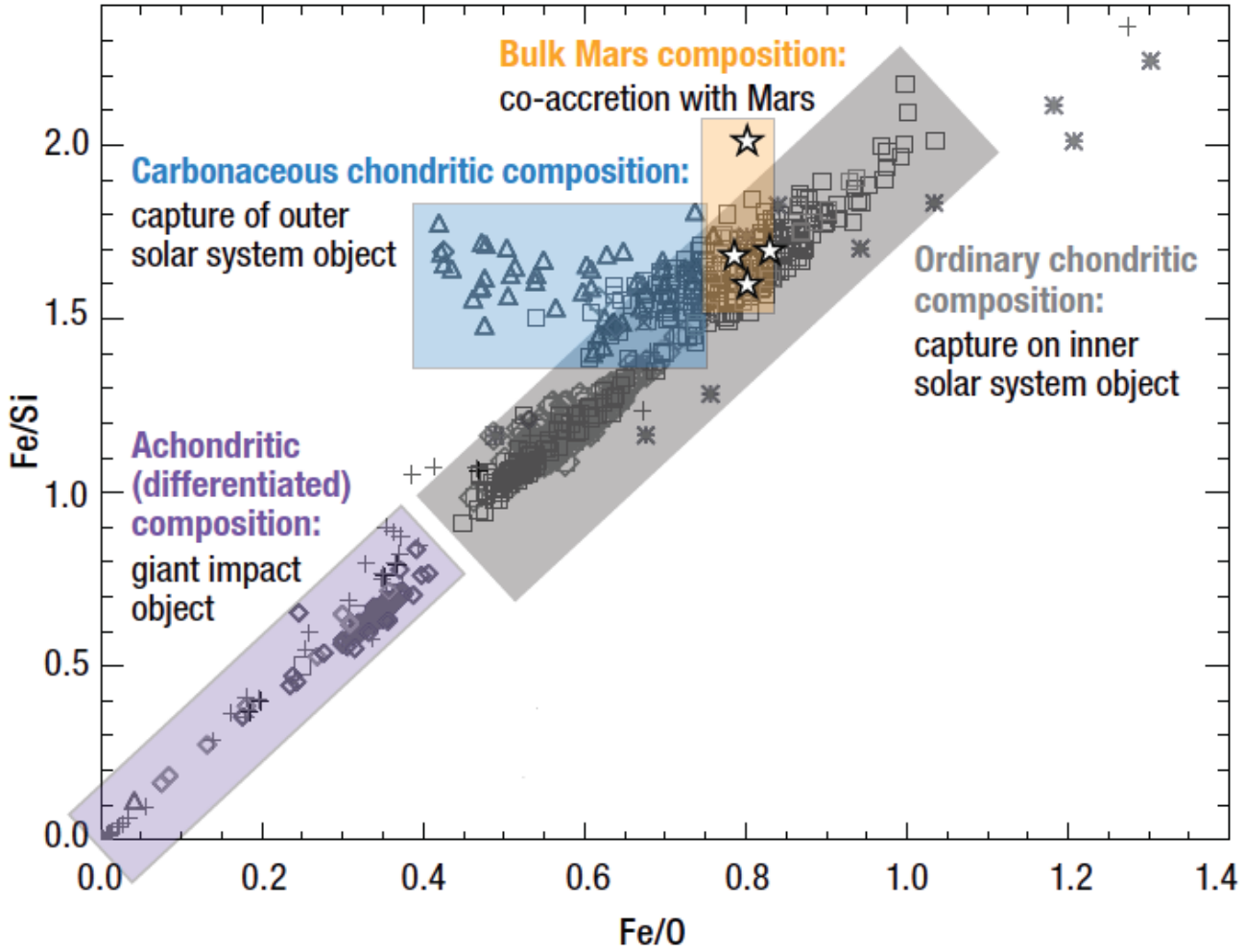




The MMX GRS will help distinguish between origin theories

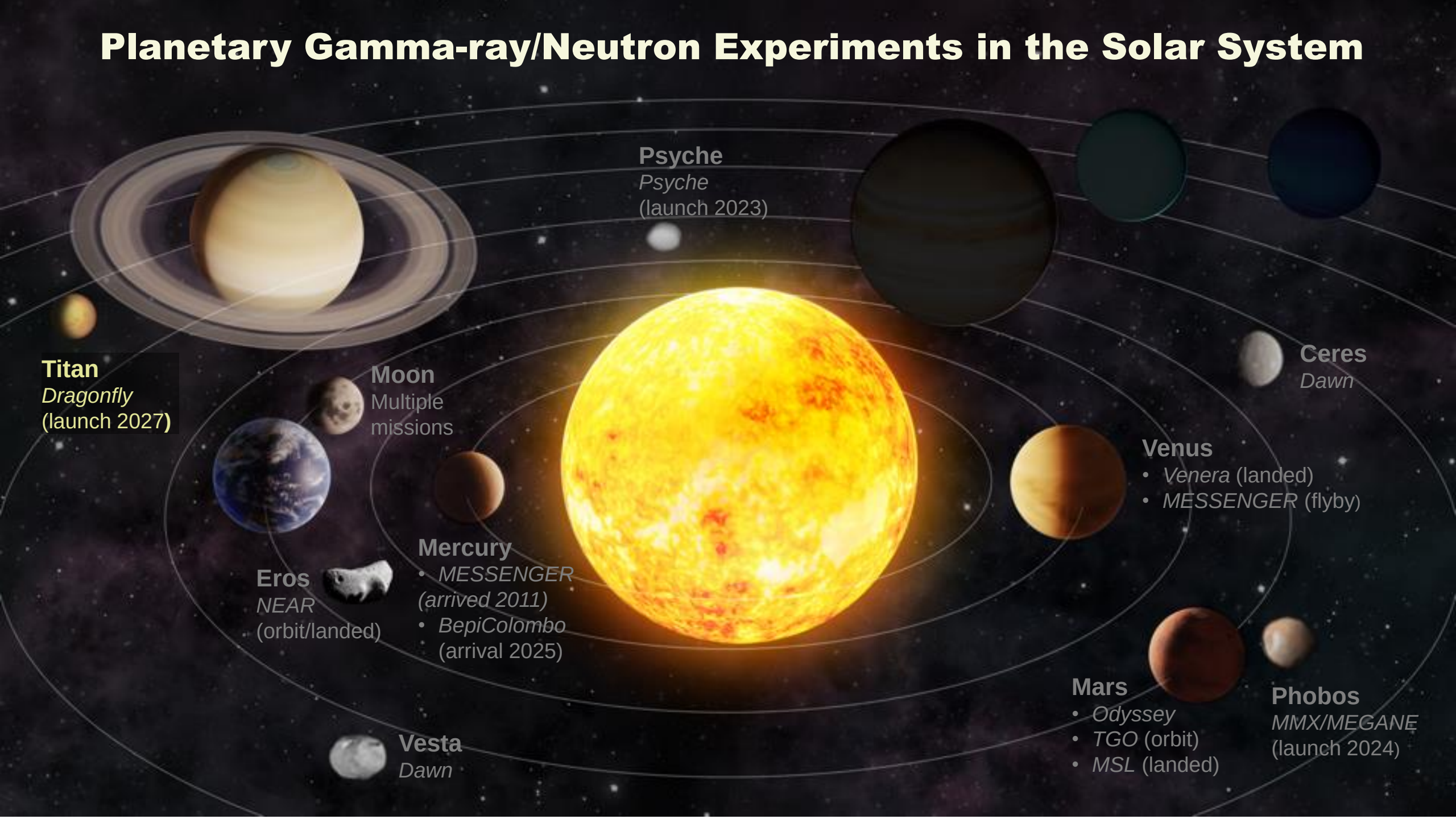
Correlate composition to the known composition of

- meteorites,
- asteroids,
- surface of Mars



Elemental abundances can be used to classify the surface of Phobos/Deimos and compare to the known composition of Mars' surface, asteroids, and meteorites.

Planetary Gamma-ray/Neutron Experiments in the Solar System



Titan
Dragonfly
(launch 2027)

Moon
Multiple missions

Psyche
Psyche
(launch 2023)

Ceres
Dawn

Venus
- *Venera* (landed)
- *MESSENGER* (flyby)

Eros
NEAR
(orbit/landed)

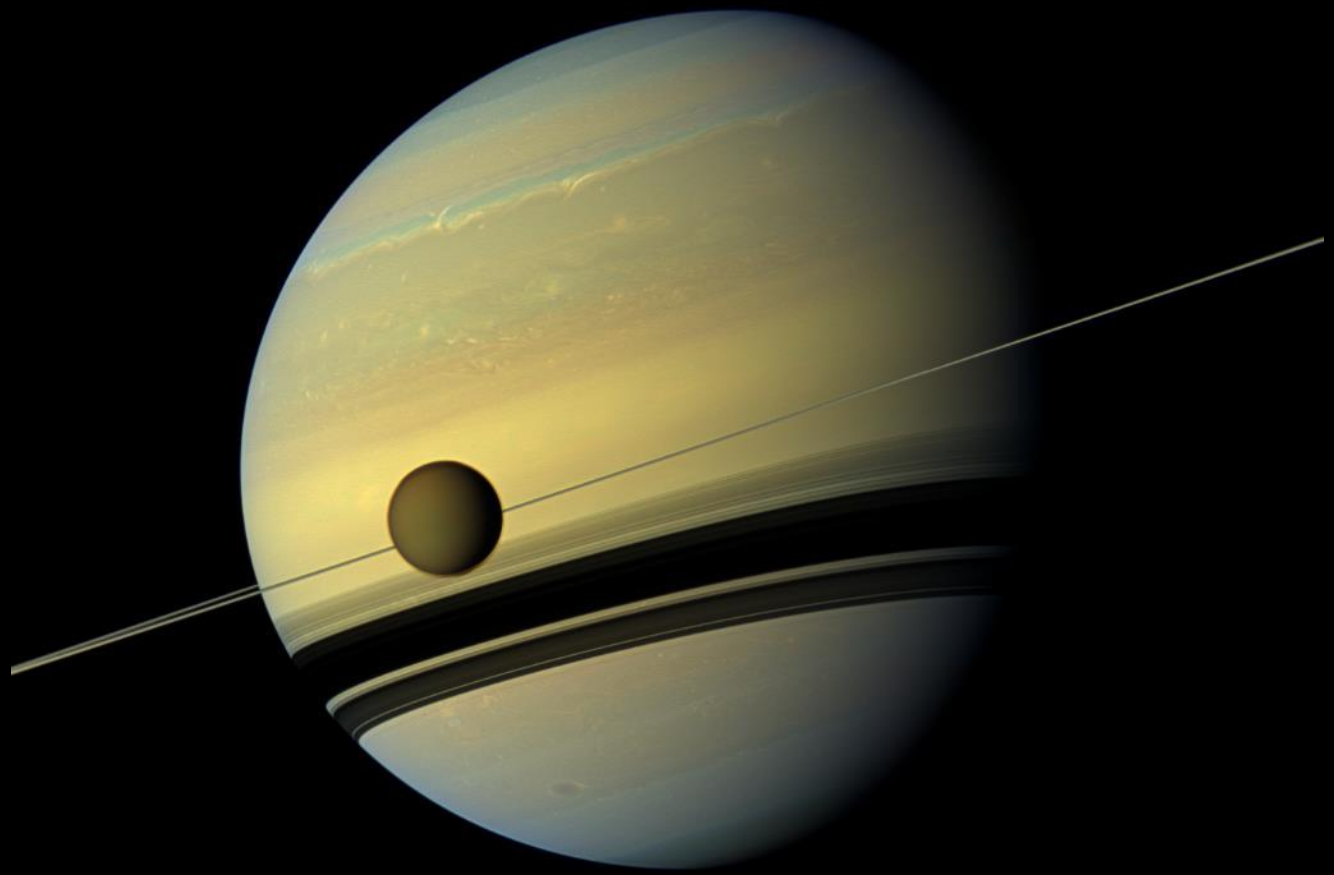
Mercury
- *MESSENGER (arrived 2011)*
- *BepiColombo* (arrival 2025)

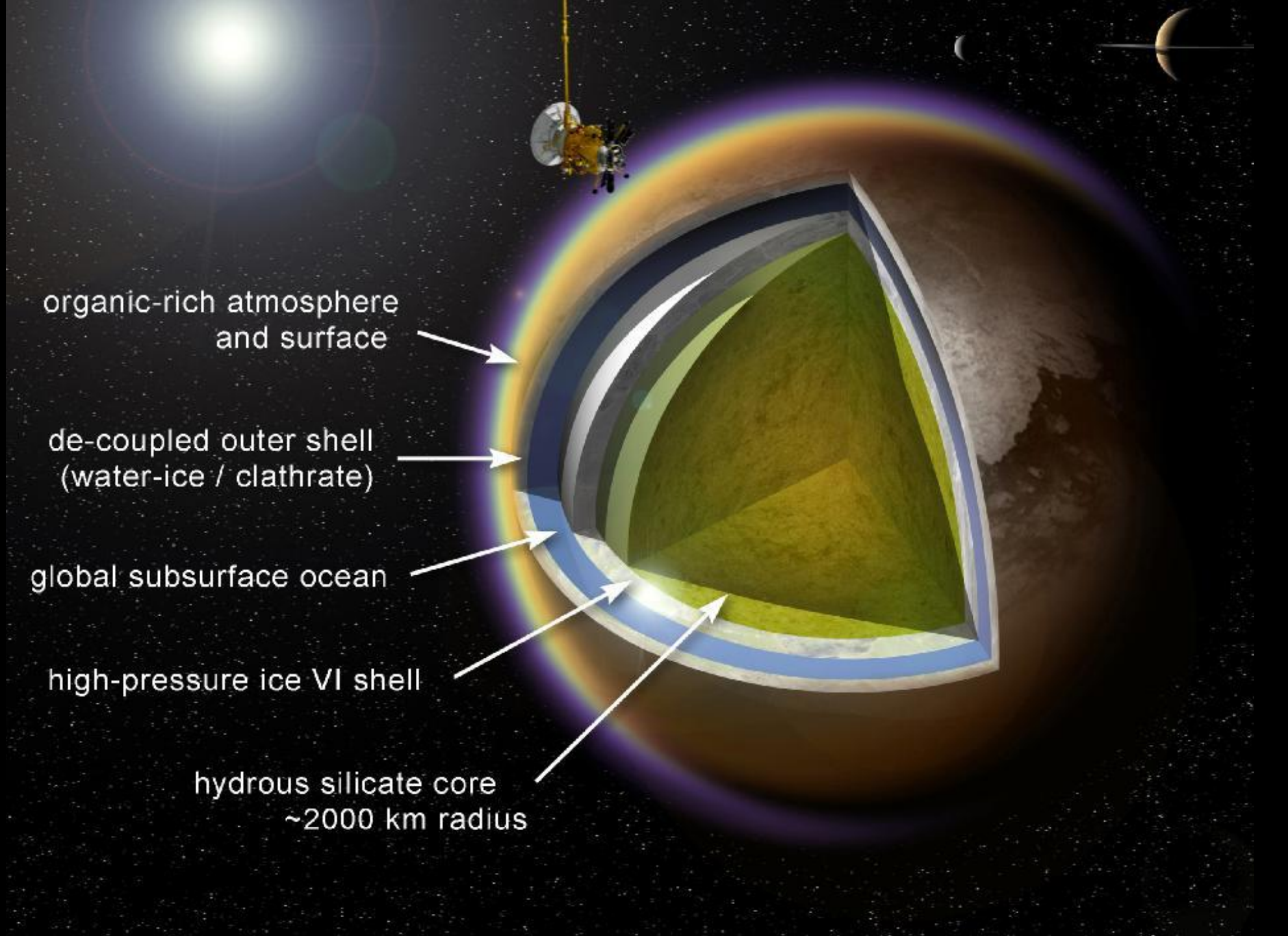
Vesta
Dawn

Mars
- *Odyssey*
- *TGO* (orbit)
- *MSL* (landed)

Phobos
MMX/MEGANE
(launch 2024)

Dragonfly Mission to Titan Launches in 2027




organic-rich atmosphere
and surface
de-coupled outer shell
(water-ice / clathrate)
global subsurface ocean
high-pressure ice VI shell
hydrous silicate core
~2000 km radius

Cassini Dropped the Huygens Probe onto Titan in 2005





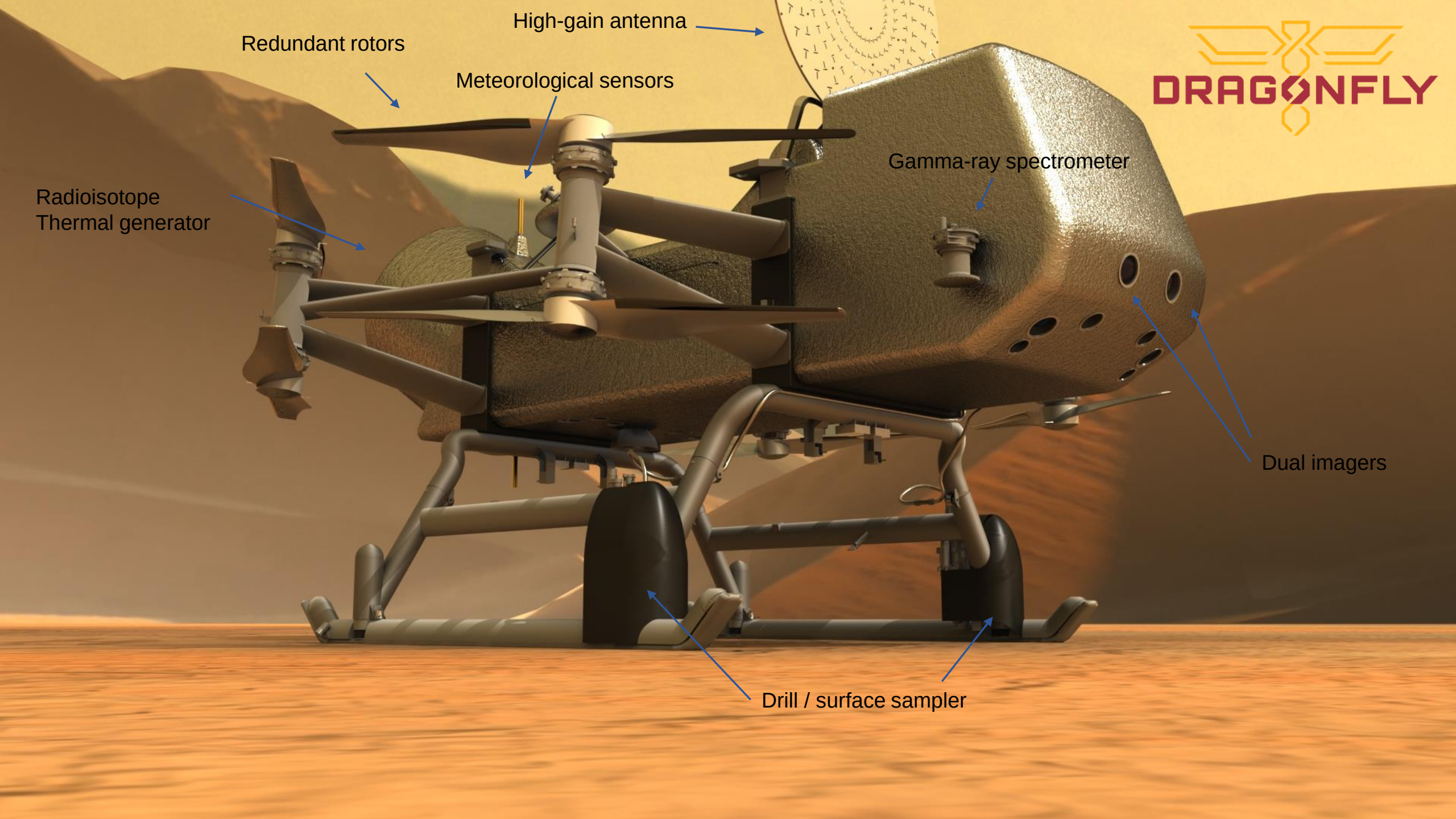


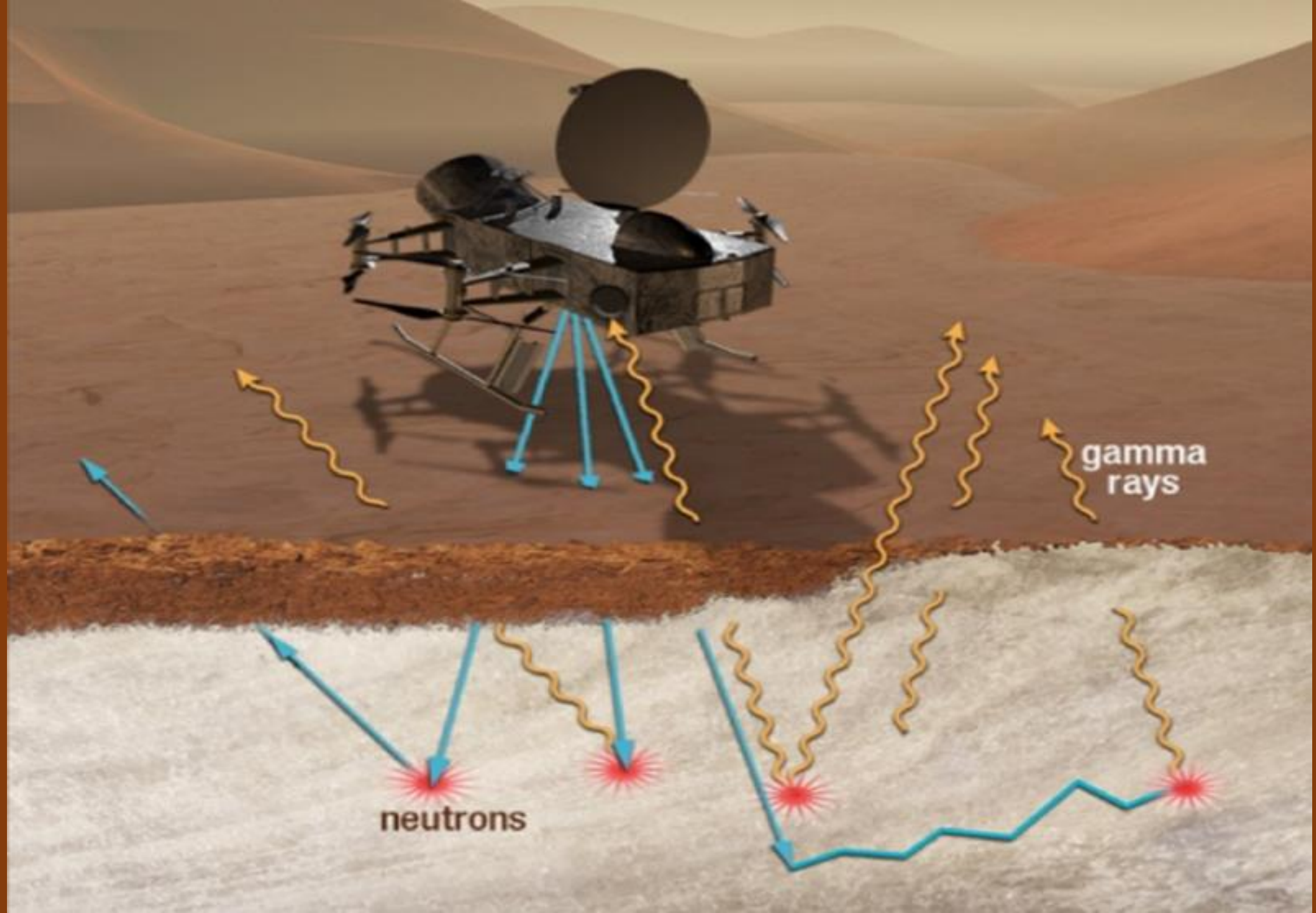


Launch: 2027, Arrival: 2034
3-year surface ops
Dual-quadcopter

Scientific payload

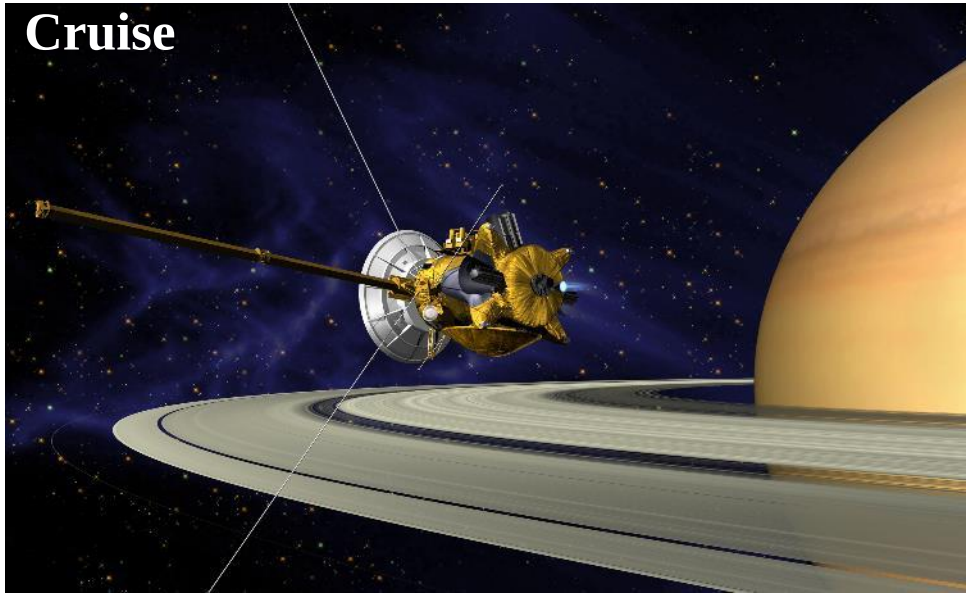
- Mass spectrometer (DragMS)
- Meteorology/seismology equipment (DraGMet)
- Cameras suite (DragonCam)
- **Gamma-ray & neutron spectrometer (DraGNS)**


High-gain antenna
Redundant rotors
Meteorological sensors
Gamma-ray spectrometer
Radioisotope
Thermal generator
Dual imagers
Drill / surface sampler
DRAGONFLY

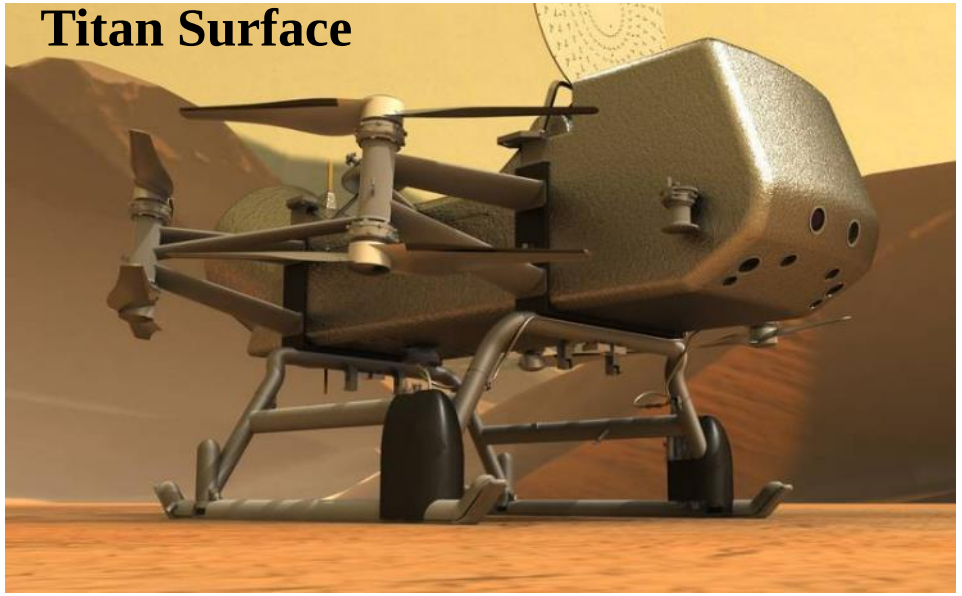

gamma
rays
neutrons

Dragonfly will experience unique radiation damage





- **2.6 MeV neutrons**: MMRTG
- **GeV protons**: GCR + Solar events

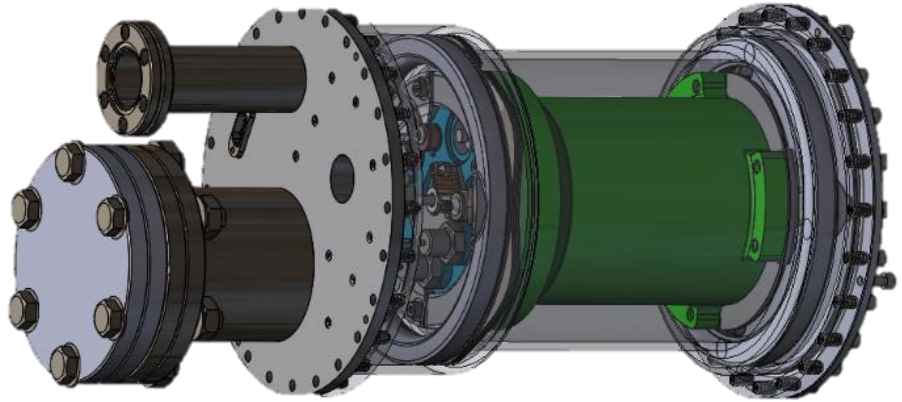


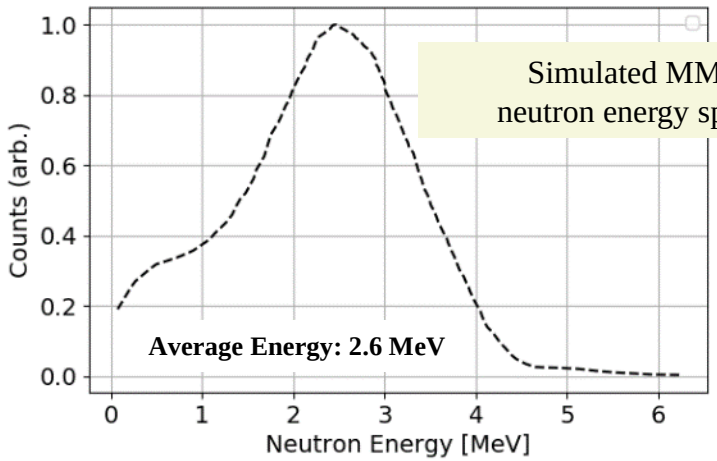
- **2.6 MeV neutrons**: MMRTG
- **14 MeV neutrons**: Neutron generator

DraGNS Radiation Damage: Simulate MMRTG spectrum

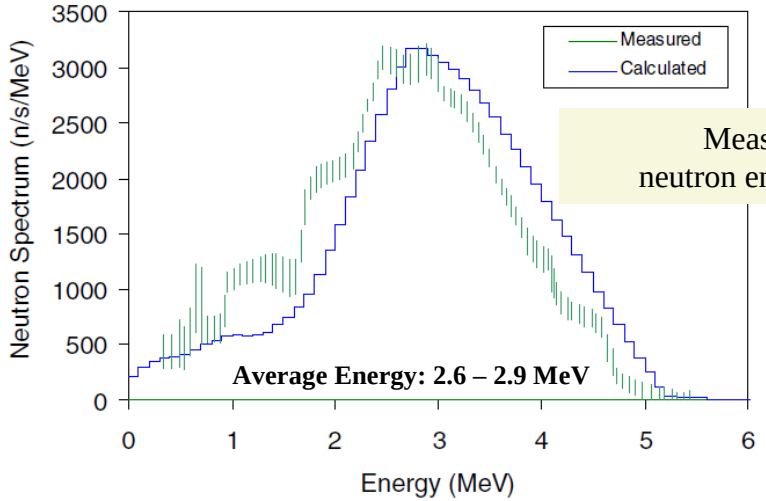


- Irradiate prototype Dragonfly HPGe detector
- Plutonium-boron: $5 * 10^6 \frac{n}{s}$
- Detector temperature: 93K, 101K , 111K
- Post-radiation anneal: 105 °C and 115 °C (378K and 388K)





Simulated MMRTG
neutron energy spectrum

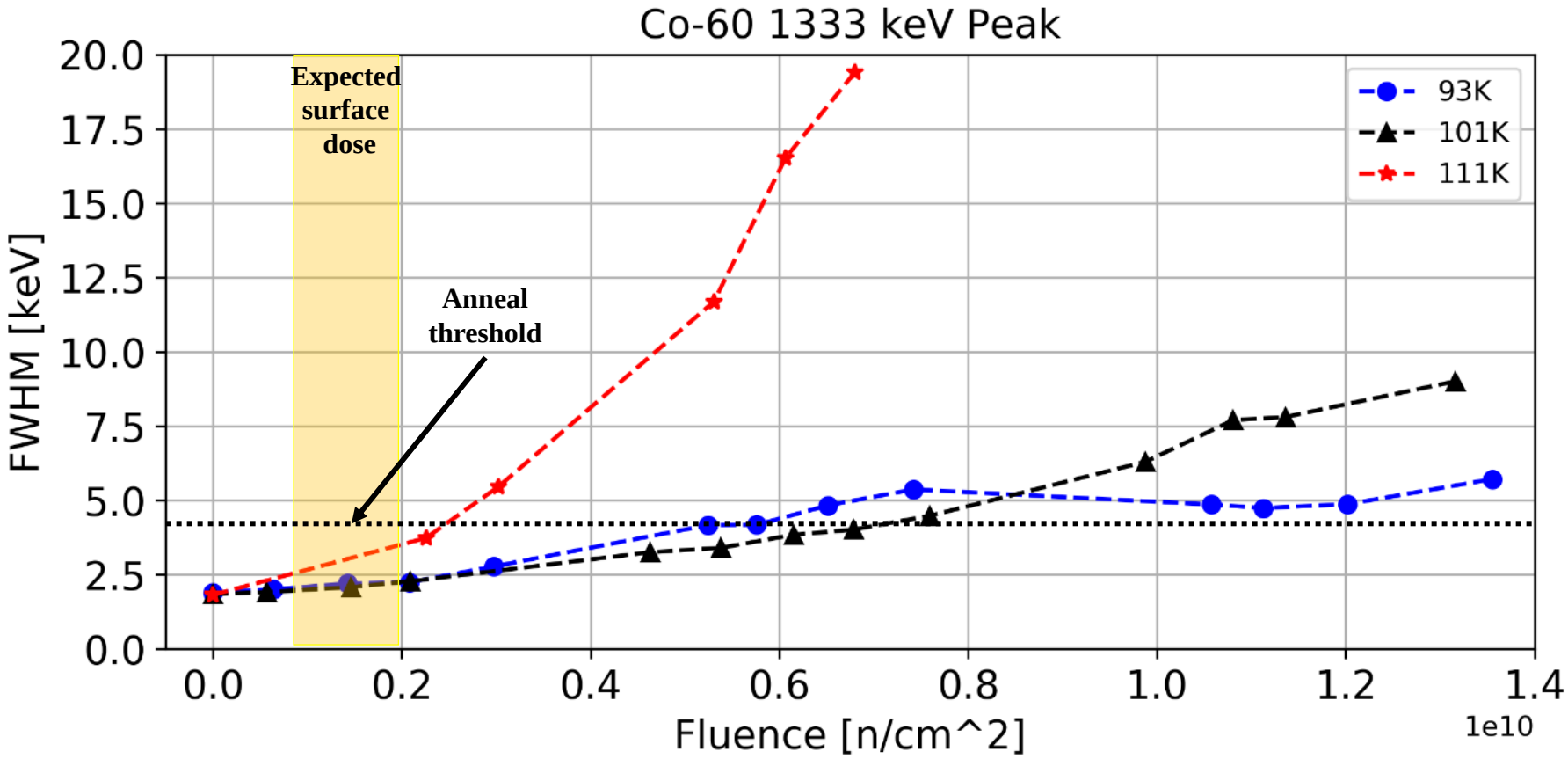


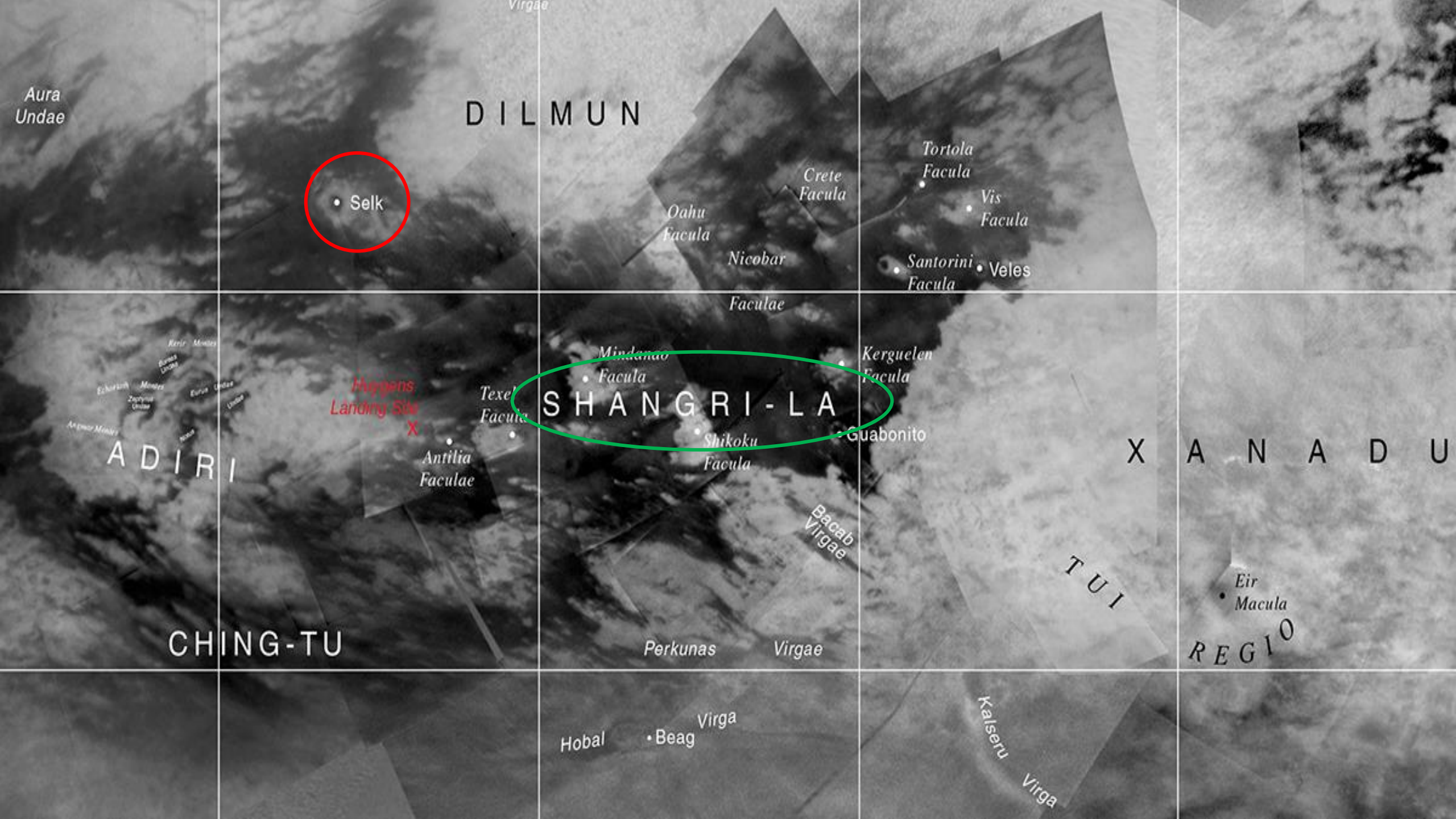
Measured PuB
neutron energy spectrum

Nathan Hines dissertation: *Designing and Testing the High-Purity Germanium Gamma-ray Spectrometer for the Dragonfly Mission to Titan*

Radiation Damage Experiment






Virgae
Aura Undae
DILMUN
Selk
Crete Facula
Oahu Facula
Nicobar Faculae
Tortola Facula
Vis Facula
Santorini Facula
Veles
Kerguelen Facula
Mindanao Facula
SHANGRI-LA
Shikoku Facula
Guabonito
Huygens Landing Site
X
Antilia Faculae
Texel Facula
ADIRI
CHING-TU
XANADU
TUI REGIO
Eir Macula
Bacab Virgae
Perkunas
Virgae
Hobal
Beag
Virga
Kalseru
Virga

