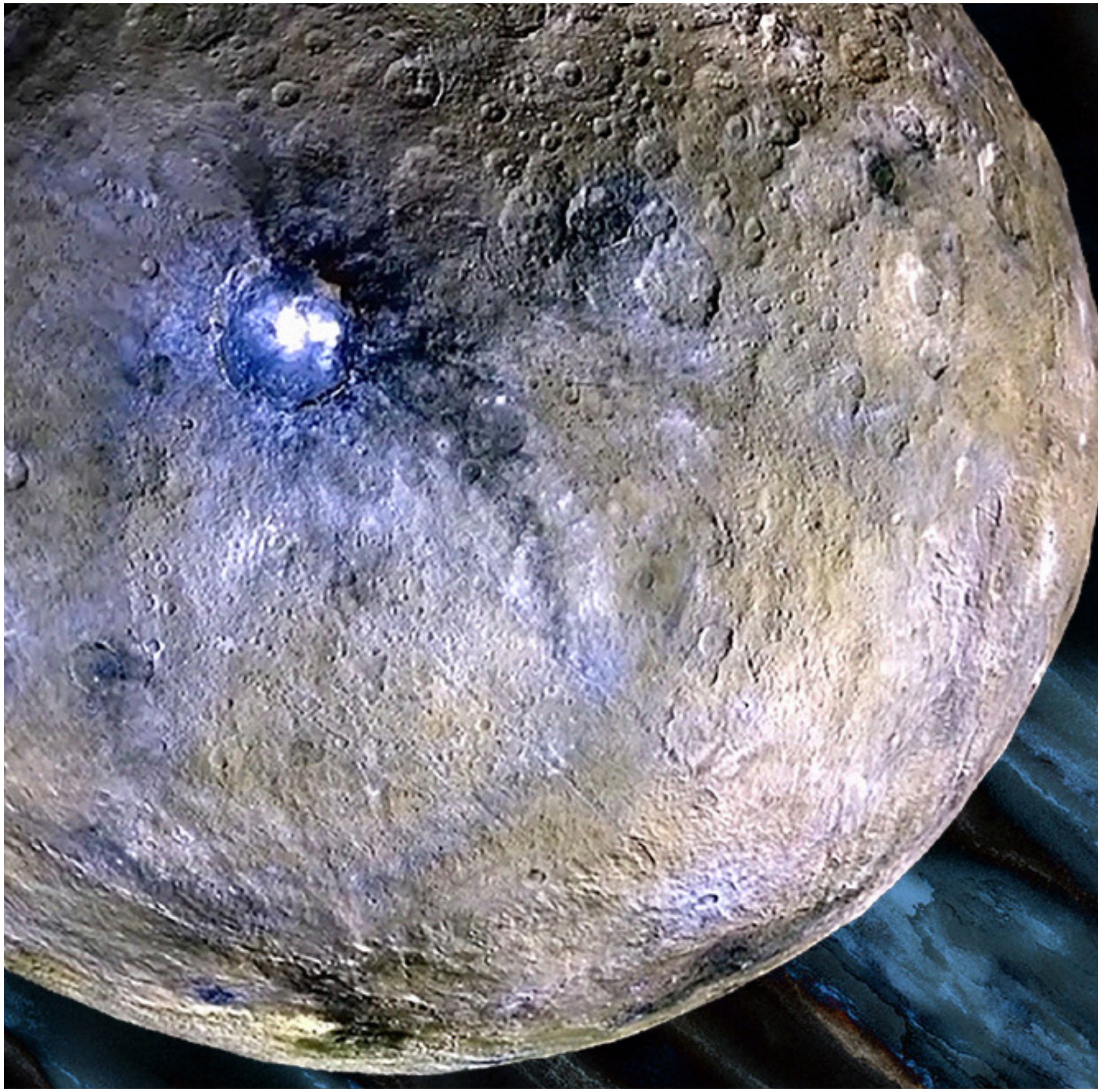

Jet Propulsion Laboratory
California Institute of Technology

sampling brines of an evolved ocean world

CERES

planetary mission concept study

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STUDY LEAD
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- Deployable Space Systems (PoC: B. Spence)

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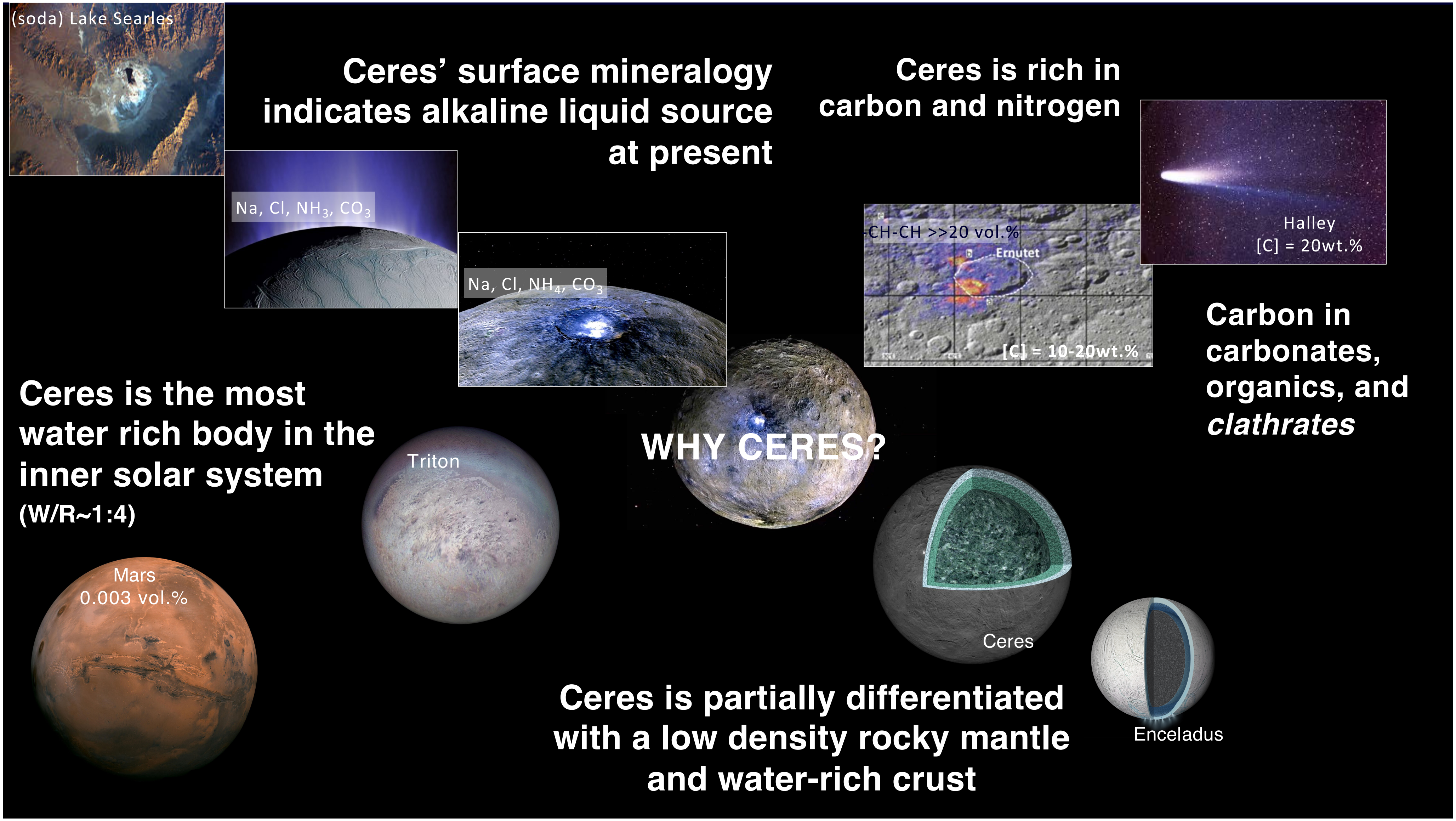
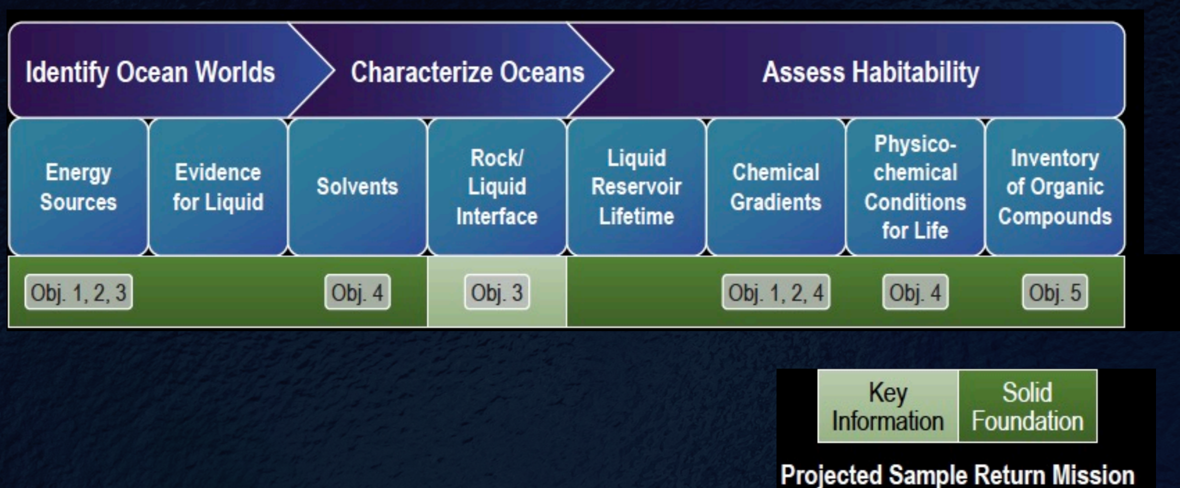

(soda) Lake Searles
Ceres' surface mineralogy indicates alkaline liquid source at present
Ceres is rich in carbon and nitrogen
Na, Cl, NH_3, CO_3
Na, Cl, NH_4, CO_3
CH-CH >>20 vol.%
Ernutet
[C] = 10-20wt.%
Halley
[C] = 20wt.%
Carbon in carbonates, organics, and *clathrates*
Ceres is the most water rich body in the inner solar system
(W/R~1:4)
Triton
WHY CERES?
Mars
0.003 vol.%
Ceres
Enceladus
Ceres is partially differentiated with a low density rocky mantle and water-rich crust

CERES A POTENTIAL HABITABLE WORLD CLOSE TO HOME



Obj. 1: Test if extrusion from a brine-rich mantle occurred during Ceres' recent history

Obj. 2: Test if endogenic activity is ongoing at Occator crater

Obj. 3: Map the distribution of brines below Occator crater

Obj. 4: Characterize Ceres' deep brine environment at Occator crater

Obj. 5: Characterize the evolution of organic matter in long-lived ocean

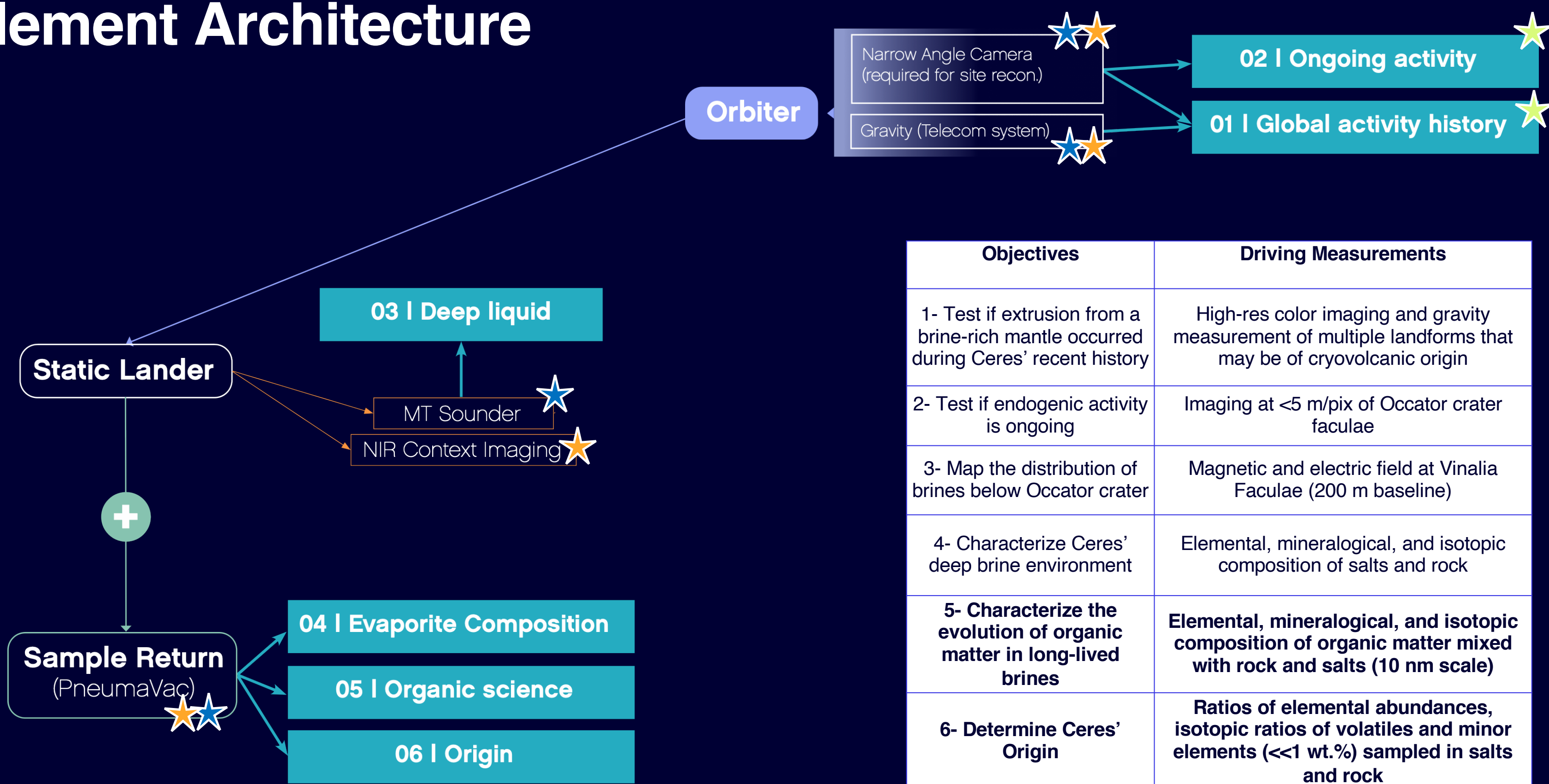
Obj. 6: Determine Ceres' accretional environment

SAMPLE RETURN OPTION

New Frontiers $FY25 (50% reserves)

Single Element Architecture

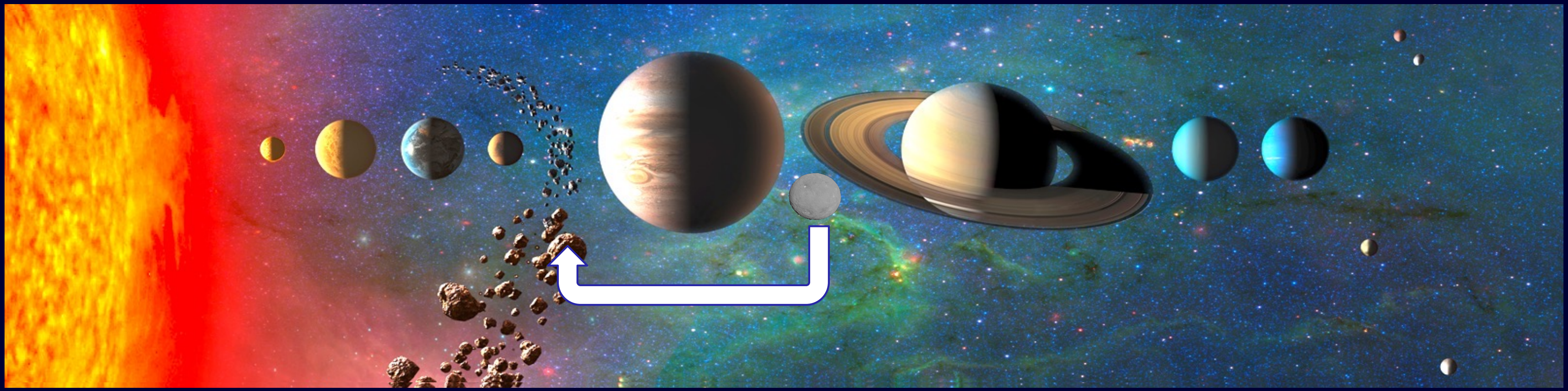
Low cost objective
Contribution possible
High-heritage subsystem



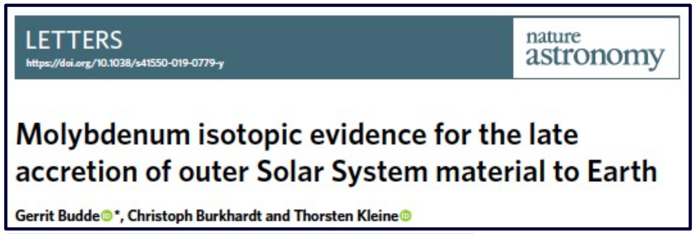
Objectives	Driving Measurements
1- Test if extrusion from a brine-rich mantle occurred during Ceres' recent history	High-res color imaging and gravity measurement of multiple landforms that may be of cryovolcanic origin
2- Test if endogenic activity is ongoing	Imaging at <5 m/pix of Occator crater faculae
3- Map the distribution of brines below Occator crater	Magnetic and electric field at Vinalia Faculae (200 m baseline)
4- Characterize Ceres' deep brine environment	Elemental, mineralogical, and isotopic composition of salts and rock
5- Characterize the evolution of organic matter in long-lived brines	**Elemental, mineralogical, and isotopic composition of organic matter mixed with rock and salts (10 nm scale)**
6- Determine Ceres' Origin	**Ratios of elemental abundances, isotopic ratios of volatiles and minor elements (<<1 wt.%) sampled in salts and rock**

INVESTIGATING THE ONLY DWARF PLANET IN THE INNER SOLAR SYSTEM RETIRES KNOWLEDGE GAPS ON THE FORMATION OF HABITABLE WORLDS

SCIENCE THEME	EXAMPLES OF TESTABLE HYPOTHESES	SIGNIFICANCE / PROJECTED IMPACT
Genetic Relationships with icy moons and inner solar system volatiles	Test if Ceres originated from between giant planet orbits, Kuiper Belt, in situ (pebble accretion)	▪ Retires knowledge gap on the origin of volatiles and **organics** in inner ss ▪ Narrows down likely early ss evolution scenarios → exoplanet science ▪ Potentially provides information on Ocean Worlds accretional environment

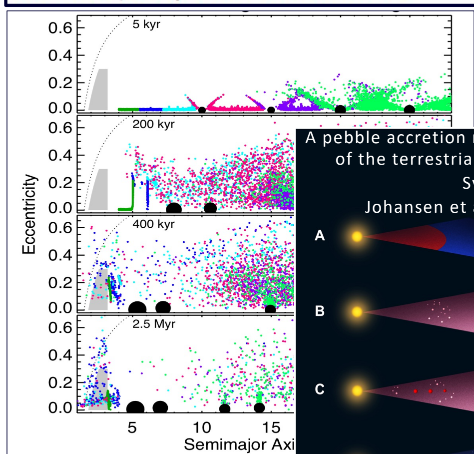


V&V – What governed the accretion, supply of water, chemistry (organics), and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?

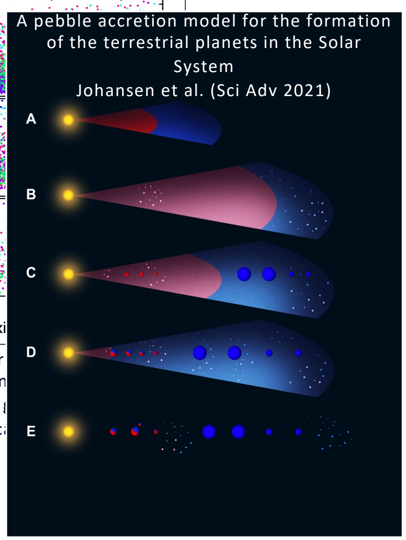

LETTERS
https://doi.org/10.1038/s41550-019-0779-y
nature astronomy

Molybdenum isotopic evidence for the late accretion of outer Solar System material to Earth

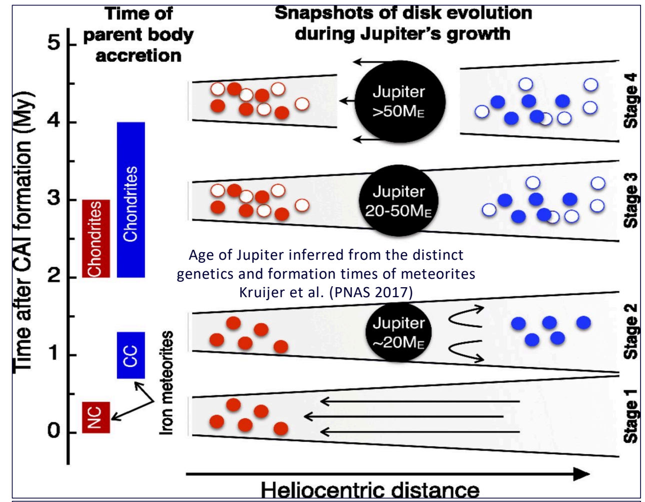
Gerrit Budde*, Christoph Burkhardt and Thorsten Kleine

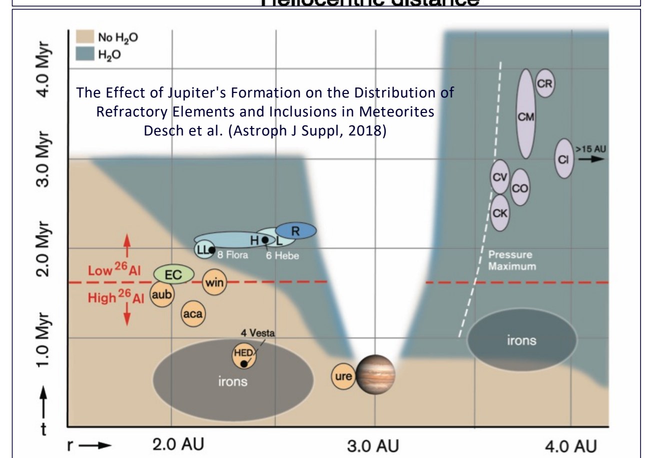


Origin of water in the inner
planetesimals scattered in
Jupiter and Saturn's rapid
Raymond and Izidoro (Ic

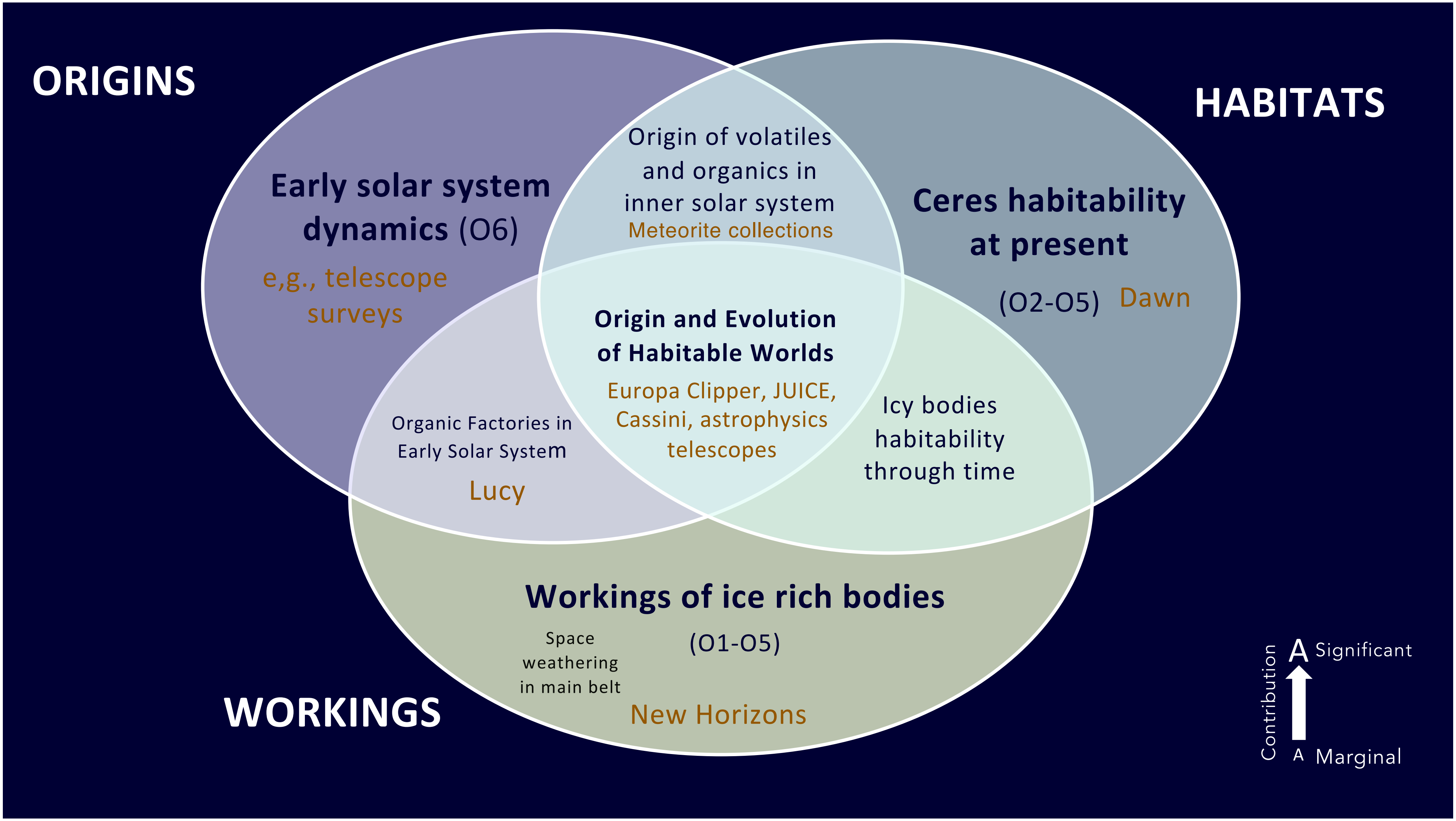


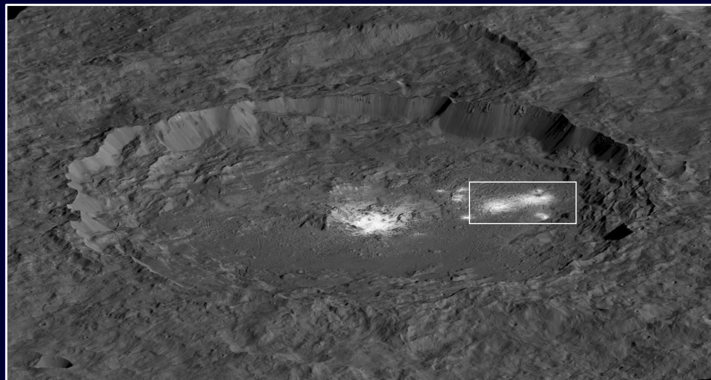
WHAT FORMED WHERE AND WHEN?





V&V – How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions?

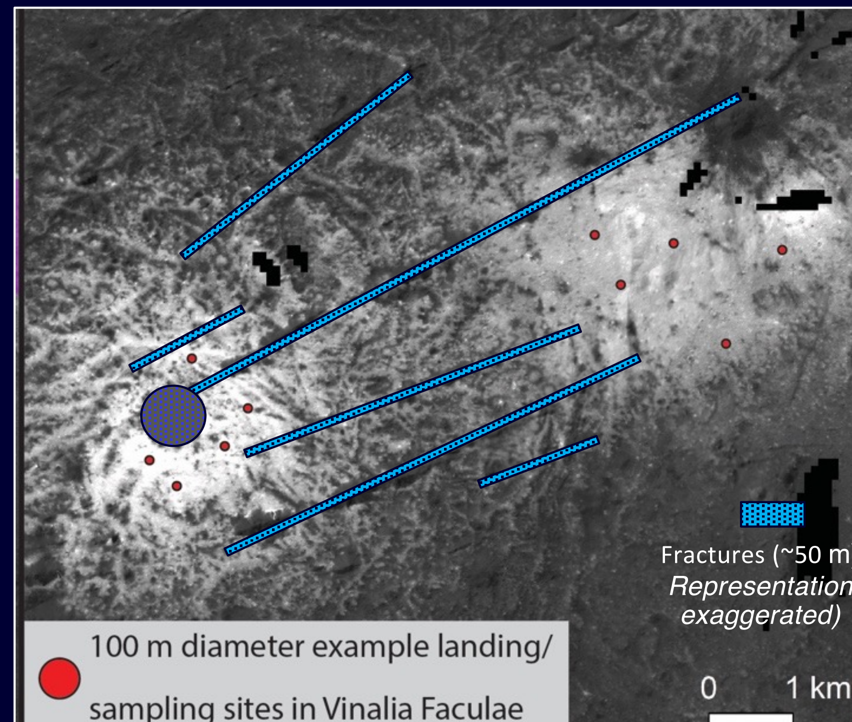

ORIGINS
HABITATS
WORKINGS
Early solar system dynamics (O6)
e,g., telescope surveys
Origin of volatiles and organics in inner solar system
Meteorite collections
Ceres habitability at present
(O2-O5)
Dawn
Origin and Evolution of Habitable Worlds
Europa Clipper, JUICE, Cassini, astrophysics telescopes
Organic Factories in Early Solar System
Lucy
Icy bodies habitability through time
Workings of ice rich bodies
(O1-O5)
Space weathering in main belt
New Horizons
Contribution
A Significant
A Marginal



Occator crater – 92 km diameter

TARGET IS <2 Ma VINALIA EVAPORITES

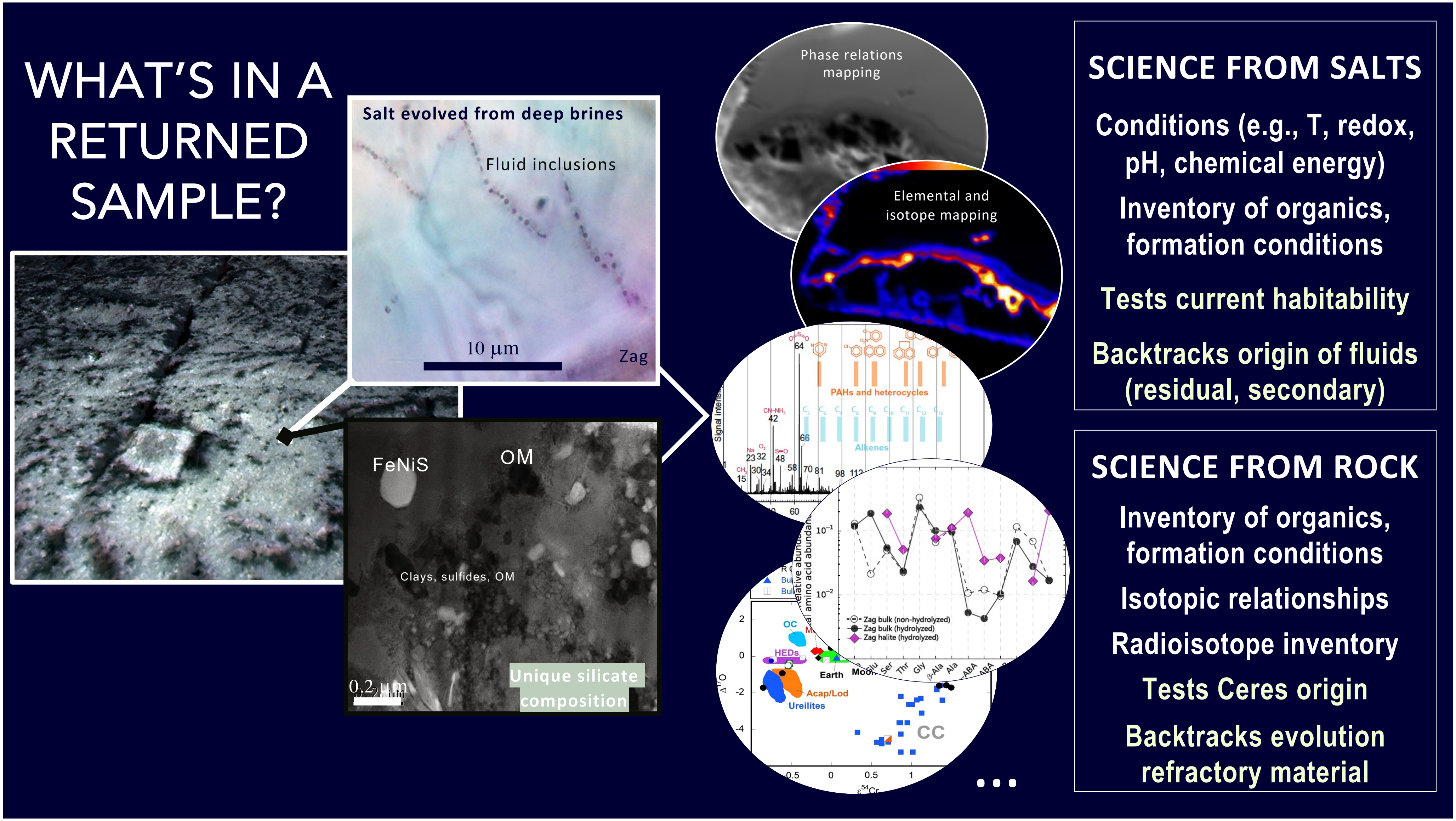
Allows sampling both bright and dark materials associated with vents and/or fractures from a static lander



State of knowledge:
- Dawn (<5 m/px) indicate many possible safe sites adequate for science
- Analysis indicates loose material

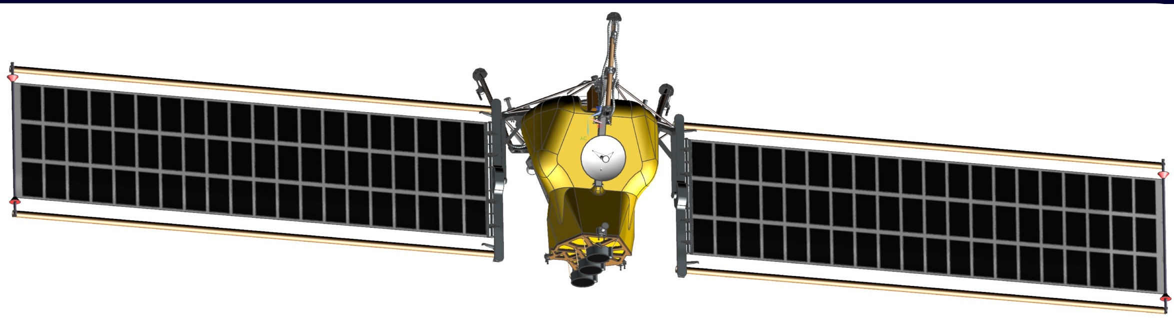
Approach to Landing
- Landing site imaging at <30 cm/pix
- Requirement to land outside of large fractures (<5% of surface area)
- TRN allows <20 m landing ellipse – input from M2020 TRN Lead A. Johnson

Approach to Sampling
- Use PneumaVac system (Honeybee Robotics, e.g., Dragonfly): sample loose material with drilling capability as backup
- Preliminary analysis indicates that sample mass requirement (~100 gm) is met with margin from 2 PneumaVac



WHAT'S IN A RETURNED SAMPLE?
Salt evolved from deep brines
Fluid inclusions
10 μm
Zag
FeNiS
OM
Clays, sulfides, OM
0.2 μm
Unique silicate composition
Phase relations mapping
Elemental and isotope mapping
PAHs and heterocycles
Alkenes
Signal intensity
Zag bulk (non-hydrolyzed)
Zag bulk (hydrolyzed)
Zag halite (hydrolyzed)
OC
HEDs
Earth
Moon
Acap/Lod
Ureilites
CC
...
SCIENCE FROM SALTS
Conditions (e.g., T, redox, pH, chemical energy)
Inventory of organics, formation conditions
Tests current habitability
Backtracks origin of fluids (residual, secondary)
SCIENCE FROM ROCK
Inventory of organics, formation conditions
Isotopic relationships
Radioisotope inventory
Tests Ceres origin
Backtracks evolution refractory material

BASELINE FLIGHT SYSTEM — CRUISE CONFIGURATION

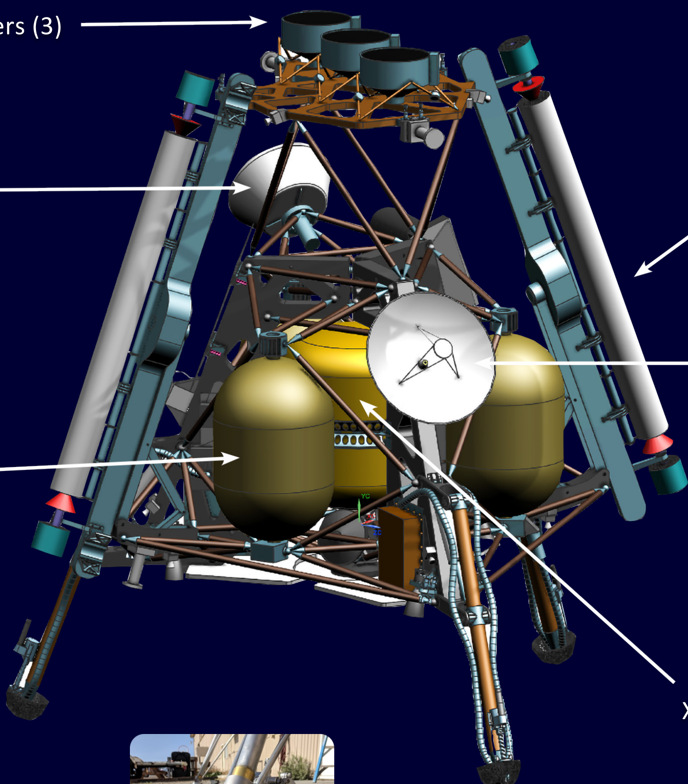


- 27.5-kW solar array (BoL at 1 au)
- 1.5-m dia. high gain antenna
- 3 NEXT gridded ion thrusters
- Hydrazine monopropellant system for deorbit, landing, and takeoff

• Launch Mass:	4669 kg
• Earth Return Mass:	2269 kg
• Xenon Mass (with margin):	1320 kg
• Hydrazine Mass (with margin):	1200 kg

- Option 4: 5-meter fairing, with high performance range, equivalent to the Falcon Heavy reusable
- Regular launch opportunities permitted by solar electric prop
- Mars gravity assist in most cases
- ~6.5 yr trip inbound and 4.7 yr outbound
- Total mission duration ~12.5 yrs including 500 d stay at Ceres

BASELINE – STOWED CONFIGURATION

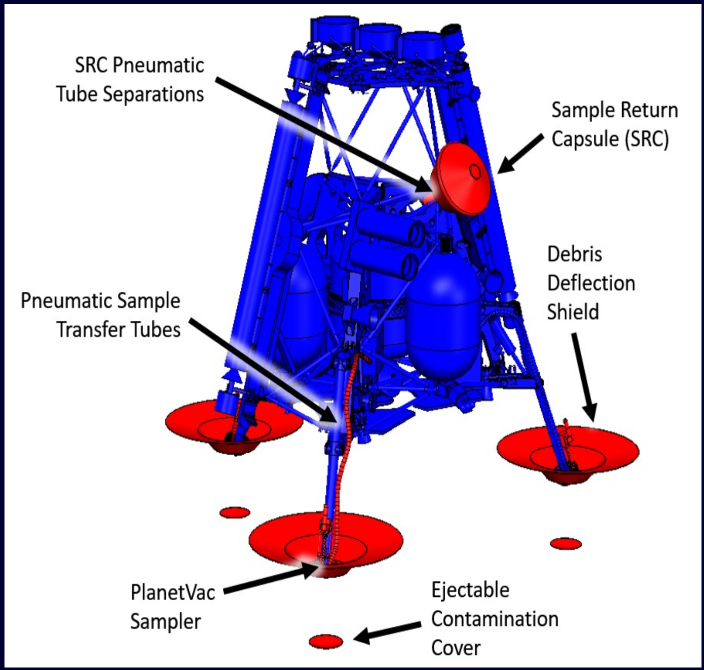


1-m ground clearance, consistent with landing site reconnaissance and certification

Preliminary planetary protection categorization of outbound mission IVb-like (PPO)

Not shown:
Multi-layer insulation

PneumaVac Sampling system in three feet (Honeybee Robotics, based on Dragonfly)

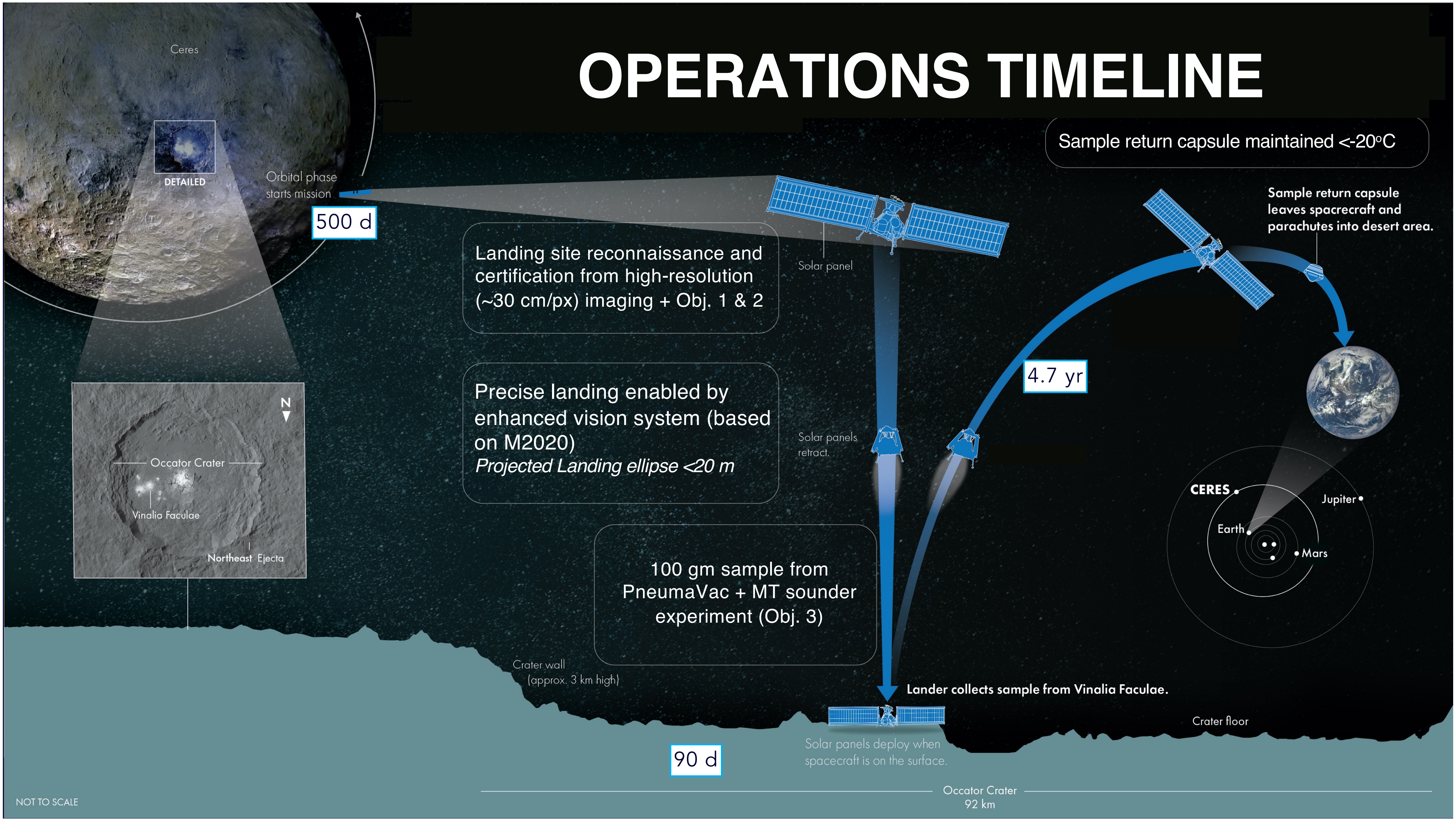


Sample Canister
Hold up to sample mass of: 200 g (100 g and 100% margin)
Particulate contamination control to >ISO 5 and non-volatile organic residue limited to level A/2
Return at ≤-20ºC to prevent reaction between anhydrous material and liquid water in the spacecraft.
Prevent atmospheric leakage into the SRC during and after Earth entry until SRC recovery;
Maintain internal pressure < 10^{-7} torr after SRC closure through SRC recovery

SAMPLING REQUIREMENTS

- Vinalia evaporites likely to have been emplaced recently
  - Not subject to sufficient TID for sterilization (>500kyr for 2.5 MRad)
  - If backcontamination concerns lead to Cat V restricted mission, then would leverage Mars Sample Return infrastructure investments
  - Alternative option is to seek salt deposits that are older – impact on Objective 5 to be assessed
- No requirement on stratigraphy preservation
- 100 gm sample mass requirement (~50 cm^3) based on the diversity of techniques (esp. destructive and semi-destructive) involved for addressing Obj. 4-6

OPERATIONS TIMELINE



OPEN ITEMS AND TECHNOLOGY DEVELOPMENTS

- **CML 4 Concept**
  - **Open trades: thruster location, drop altitude, SRC**
  - **Up to $150M of possible contributions and descopes (e.g., point spectrometer, shorter orbital/in situ ops, target older brine region, SRC)**
- **Standard Engineering: Sample transfer from sampling system to return capsule needs to be refined**
- **Technology Maturation: ROSA partially demonstrated on ISS and lunar conditions; needs to be assessed in Ceres' conditions**
- **Needs formal planetary protection categorization**

CERES IS A COMPELLING NEW FRONTIERS TARGET

- **Sample return from Ceres' evaporites is high science return per $$**
  - **OW Science, Origins, Processes in a single mission**
  - **Complementary to OW missions planned in next decade**
- **Close distance to Earth and low gravity → single element architecture**
  - **Feasible with TRL5+ technologies**
  - **13-yr roundtrip; 3 objectives achieved at Ceres**
- **Leverages NASA's >$100M investments in ground-based facilities and benefit from decade-long analyses**