# Dawn at Ceres: What Have we Learned?

J. C. Castillo-Rogez, C. A. Raymond, C. T. Russell & Dawn Team

Committee on Astrobiology
and Planetary Science
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DAWN NASA UCLA JPL Jet Propulsion Laboratory California Institute of Technology Orbital ATK DLR MPS

# Most water rich body in the inner solar system after Earth

# Ceres is Large – Geophysically Speaking

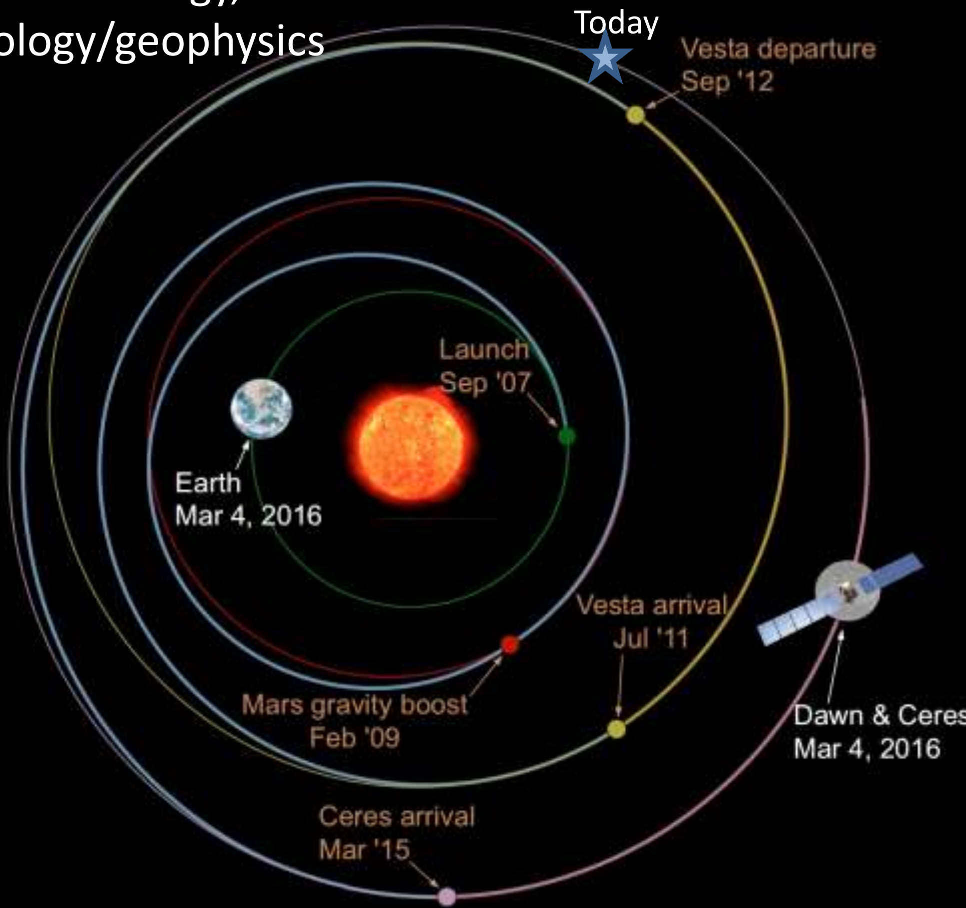
- 940 km diameter
- Rotation period 9.074 hr
- Average albedo of ~0.09
- Surface temperature 110-155K
- Density 2.162 kg $m^{-3}$
  - Rock mass fraction ~73 wt.%
  - Ceres as a whole is ~50 vol.% water

**Pre-Dawn models predicted the preservation of liquid until present**

NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

# Road Map to Vesta and Ceres

First mission to orbit TWO protoplanets with mineralogy, elements, and geology/geophysics






# Dawn at Ceres

| | | |
|---|---|---|
| RC3: | 13500 km alt. | Apr 23 – May 9 2015 |
| Survey Orbit: | 4400 km alt. | Jun 5 – Jul 1 2015 |
| HAMO: | 1470 km alt. | Aug 4 – Oct 8 2015 |
| LAMO: | 385 km alt. | Dec 1 2015 – Mar 6 2016 |
| Extended LAMO | 385 km alt. | Mar 6 – Jun 30 2016 |

Extended Mission various orbits Jul 2016 – Sep 2017

HAMO: High Altitude Mapping Orbit LAMO: Low Altitude Mapping Orbit

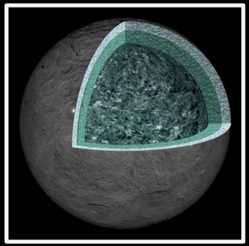
# What Dawn Accomplished at Ceres

- All Prime Mission Level 1 Requirements (all exceeded)
- All XM1 Level 1 Requirements (all exceeded)
- All 2016 PMSR review panel recommendations (during XM1)

Including:

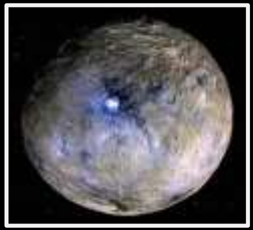
- Global imaging, multi-view-angle, all filters at 140 m/pix
- Global imaging, multi-view-angle at 35 m/pix
- Highest priority targets observed with color filters at 35 m/pix
- Global mapping in VIR
- Highest priority targets observed with VIR at best spatial resolution
- GRaND data for 6 months (>5x requirement) at low altitude, plus 8 months of background calibration

# Outline

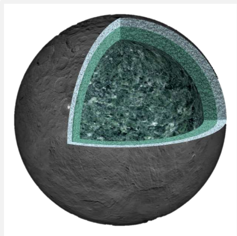


Findings of Broad Implications

Emerging Paradigms and Questions



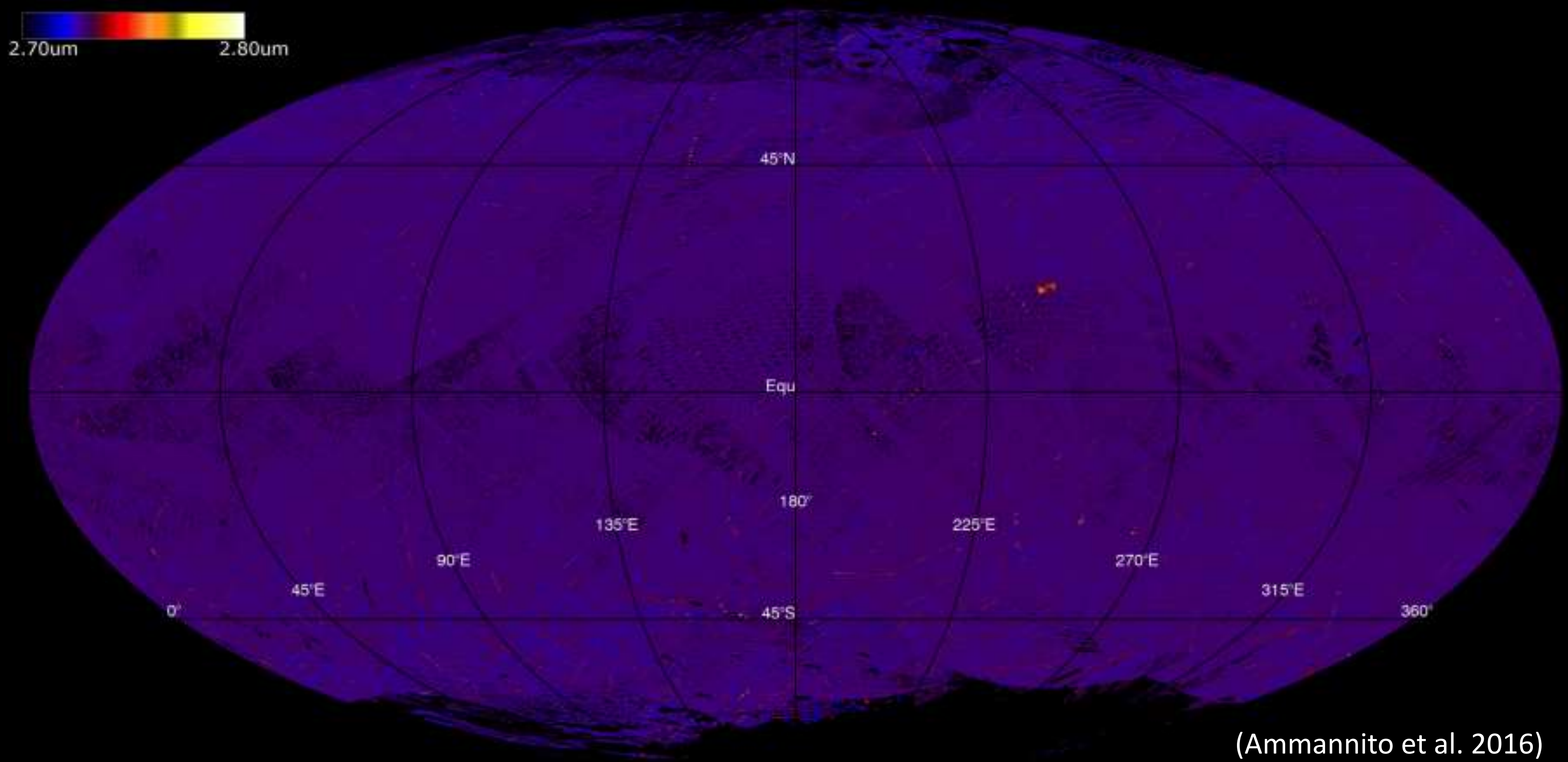
Summary – Importance of Ceres for Understanding Ocean Worlds



# Findings of Broad Implications

- Occurrence of global oceans in the early history of large planetesimals
- Thermal evolution and differentiation in a midsize (500-1000 km), ice-rich planetesimal
- Chemical differentiation similar to icy moons
- Geology driven by icy materials and brines

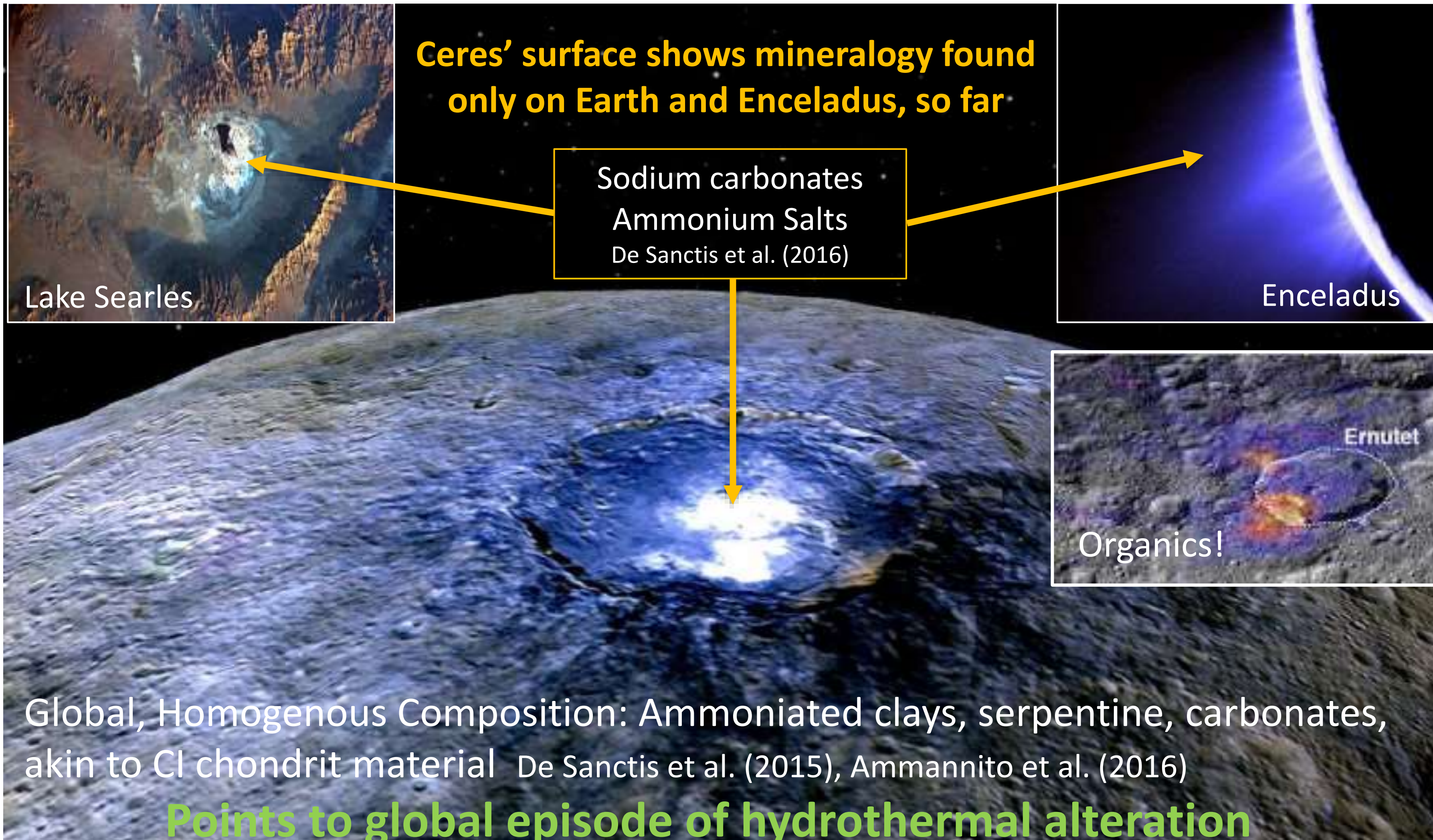
# Ceres' Surface is Globally Homogeneous



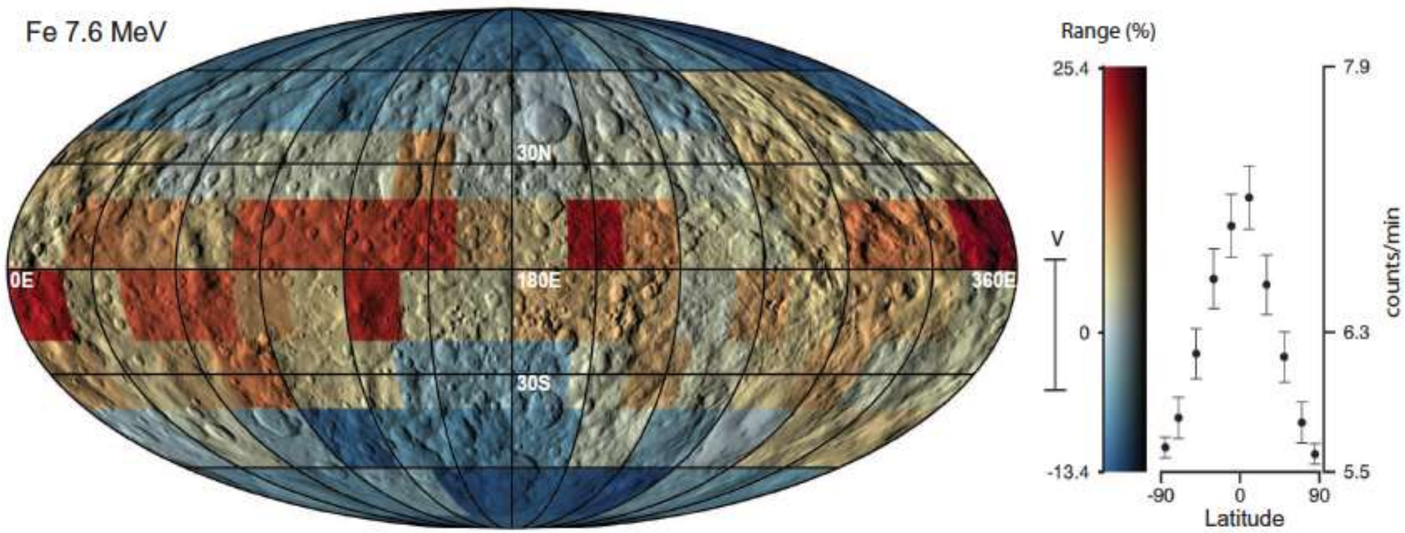

(Ammannito et al. 2016)

Band Center maps at 2.7 and 3.1 microns show ubiquitous presence of phyllosilicates

# Ceres’ Surface Displays Materials Formed at Depth



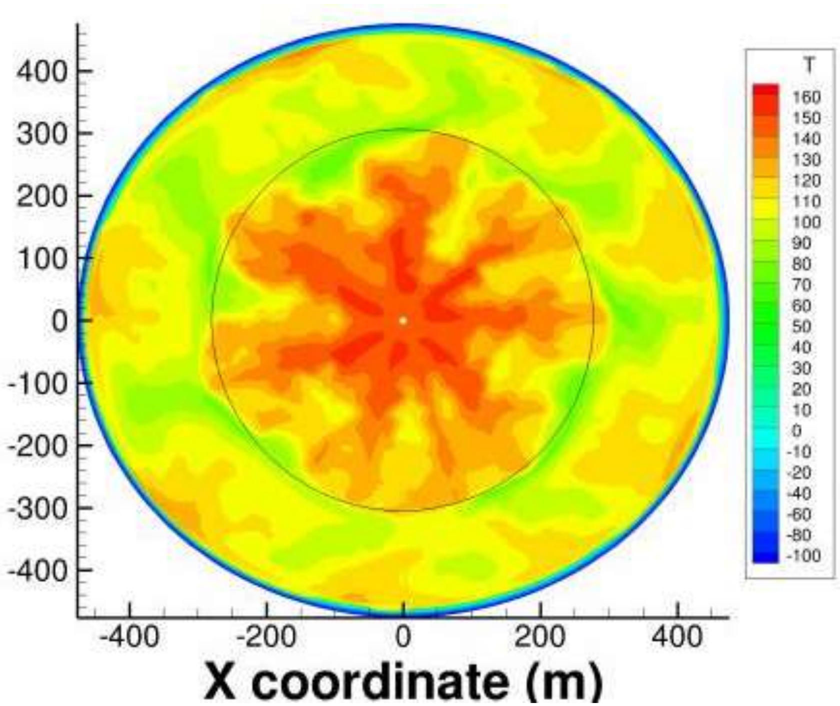
# Ceres' Elemental Composition Indicates Chemical Fractionation




GRaND Iron Maps of Ceres
(Prettyman et al., *Science*, 2016)

- Ice-free regolith in equatorial region is similar to CI/CM composition
- Iron abundance is lower than the average value for CI/CM chondrites
- Consistent with sinking of metal-rich particles in a global ocean

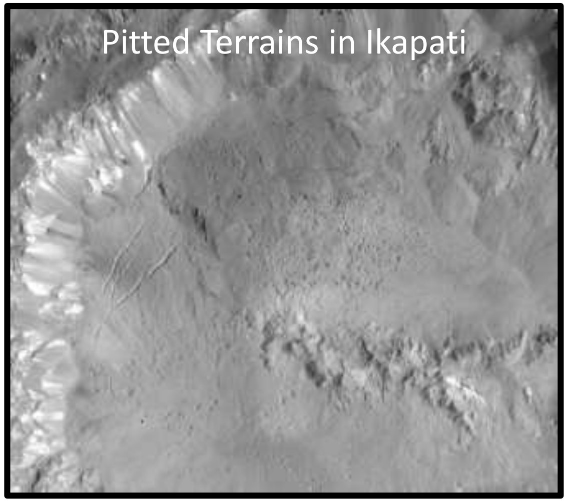
# Mineralogy points to episode of global hydrothermal activity in Ceres' early history

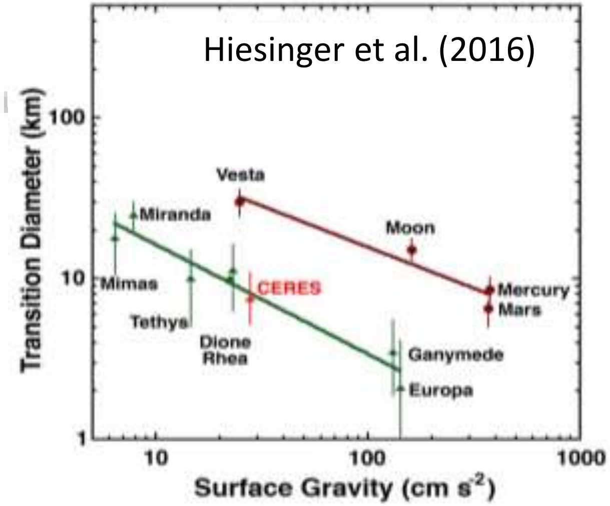



Bland and Travis (2017)

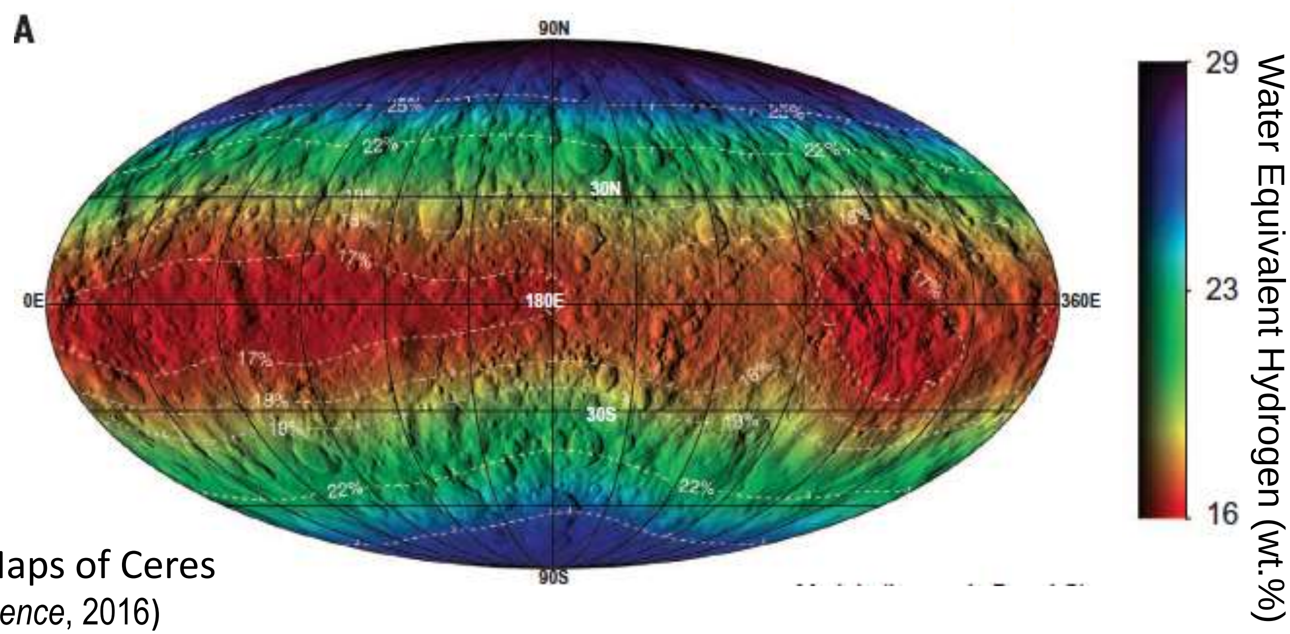
- Activity likely fueled by $^{26}Al$ decay heat
  - Formation within a few My after CAIs
- Water-to-rock ratio is > 2 (Castillo-Rogez et al., submitted)
  - Release of huge amounts of $H_2$
  - Leaching of soluble elements from rock, yields ~5 wt.% salinity (average)
- Nature of early liquid environment is to be further studied
  - Giant, long-lived mudball?
  - Rapid sinking of rock to form core?
  - Important to understand scale of chemical activity

# Ceres' Crust is Ice Rich

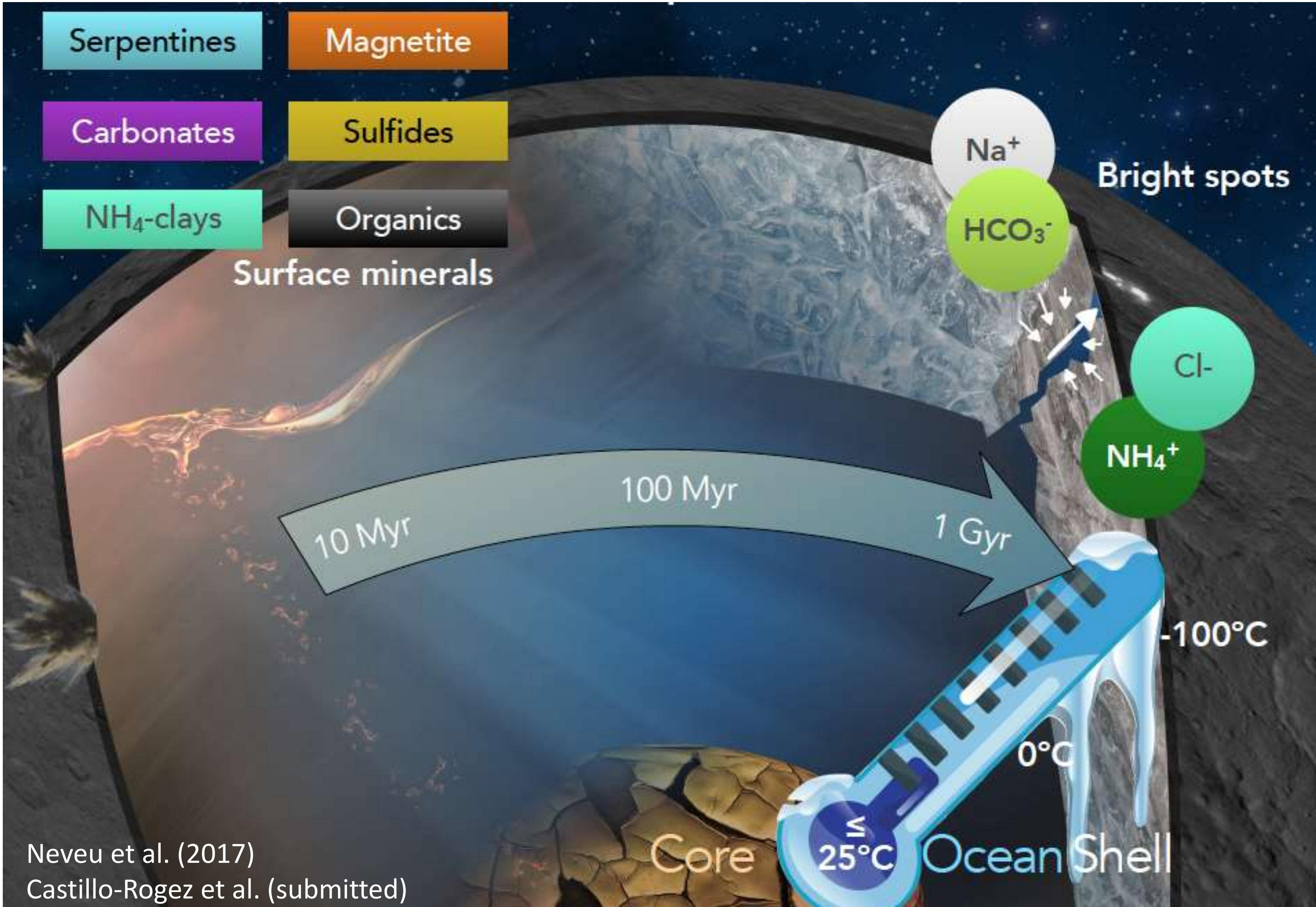

Water ice table near surface at poles, receding deeper at the equator




GRaND Hydrogen Maps of Ceres
(Prettyman et al., *Science*, 2016)

# Na-Carbonates Found in Many Sites, Likely Abundant in Ceres' Crust

# Background and Bright Spot Compositions are Complementary

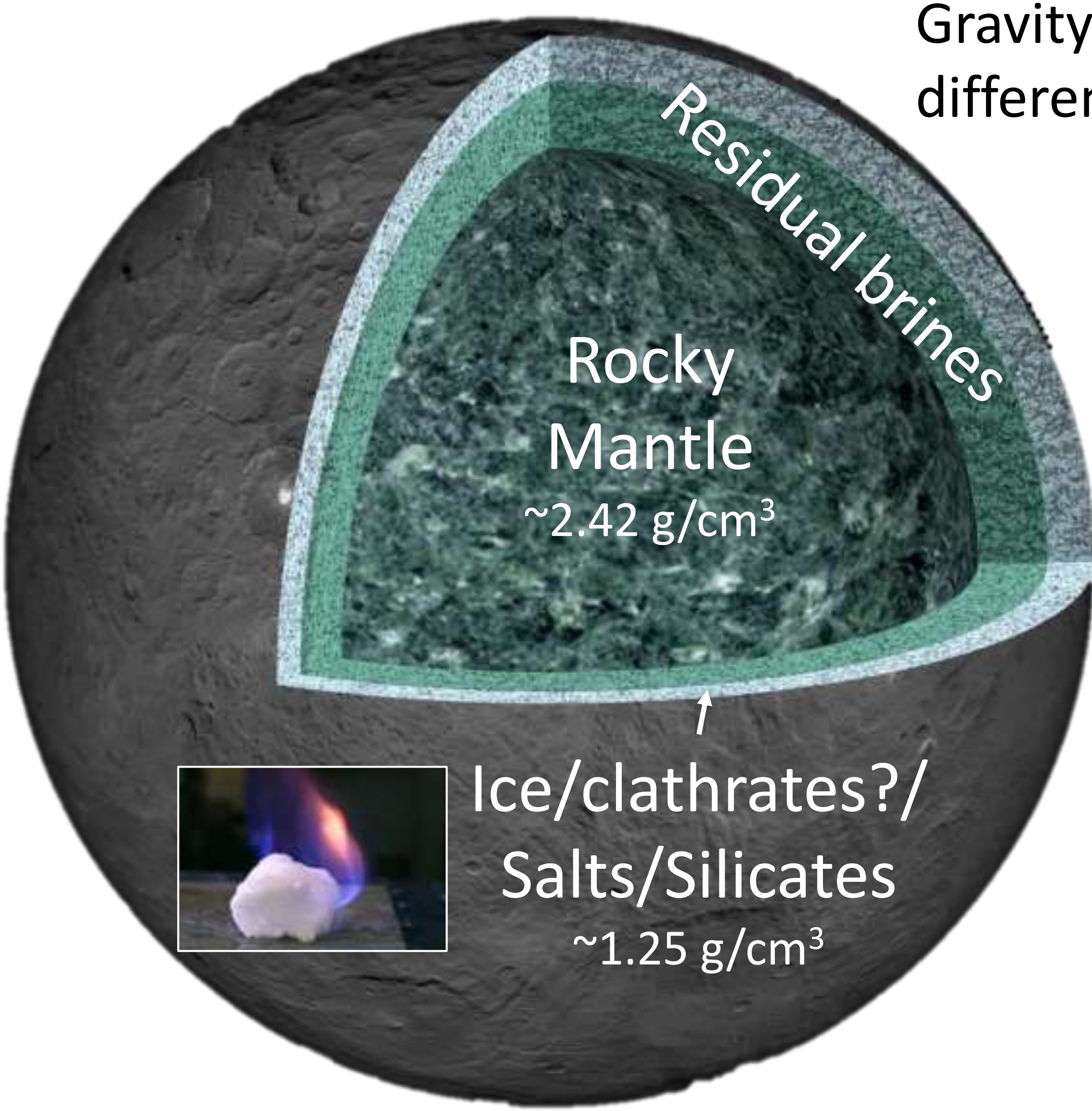



Neveu et al. (2017)
Castillo-Rogez et al. (submitted)

# Evidence for Local Brine-Driven Geology

- The emplacement of 4-km high Ahuna Mons *requires* a **partially molten source** (Ruesch et al., 2016),
- Indicates subsurface brine pockets
- Bright streaks are rich in Na-carbonate (Zambon et al., 2017)
- **Activity is recent** – 10s My
- Brine mixture eutectic is about 245K, possibly lower if ammonia remains

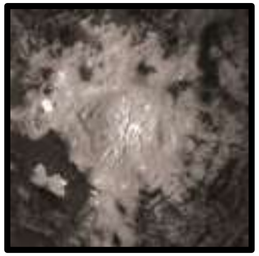
# Interior Structure of a Midsize, Ice-Rich Dwarf Planet




Gravity data confirm partial differentiation (Park et al. 2016)

Crater morphologies indicate ice content <30% (Bland et al. 2016)

**Topography is explained by strong shell (<40 km) over soft, muddy interior**
Ermakov et al. (submitted), Fu et al. (2017)

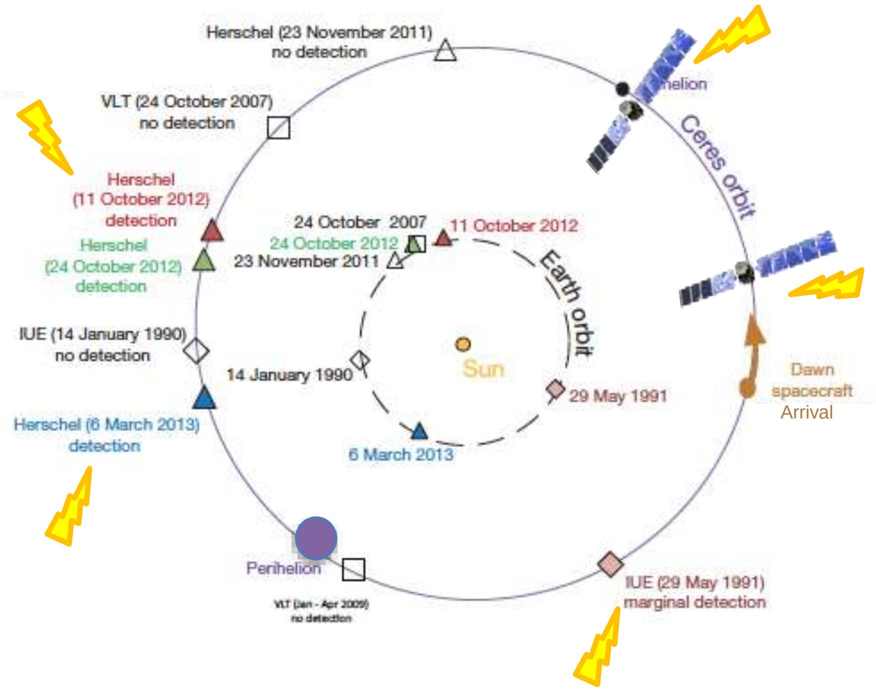


# Emerging Paradigms/Questions

- Role of solar wind in driving outgassing
- Origin of Ceres in the outer solar system?
- Production of organics in Ceres?
- Global occurrence of brines?
- Beyond coolness: what is Occator telling us?
- Origin and nature of Ceres' surface?

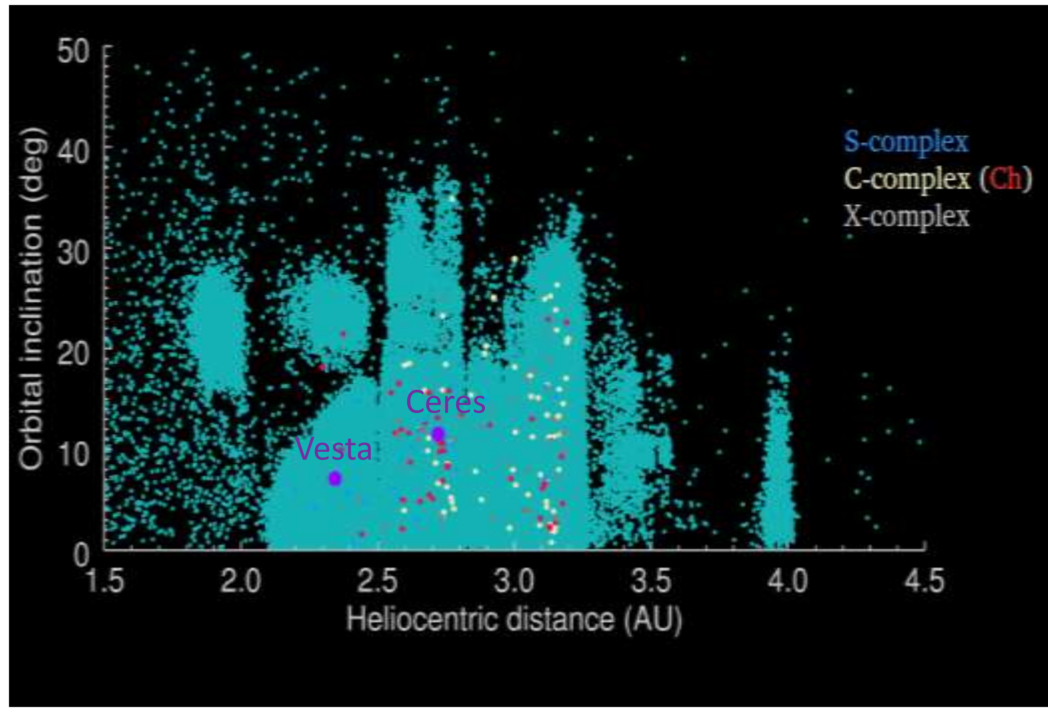
# Solar Wind Drives Outgassing

- Solar energetic protons events may explain the transient nature of the Cerean exosphere
  - GRaND recorded electrons reflected on transient atmosphere in two occasions
  - Correlation between solar activity and vapor detection events shown by Villarreal et al. (2017)



# Where Does Ceres Come From?

- Formation in situ – snowline "fine-tuning"
  - Not consistent with observed mixing of dry and wet asteroids in the main belt
  - Ceres and Vesta could not form in the same timeframe




- Abundance of water, carbon, and nitrogen points to an origin in the outer solar system

# Migration Options for Ceres (1/3)

- Formation in situ with accretion of migrated icy planetesimals (Mousis and Alibert 2005; Grazier et al. 2014)
- Difficult to explain how planetesimals preserved hyper-volatiles when crossing Jupiter's gap (Turner et al. 2013)

# Migration Options for Ceres (2/3)

- Ceres' migration from the transneptunian region
- Difficult to reconcile from a dynamical and geophysical standpoint
  - Large KBOs/TNOs have high-porosity/little heat

# Migration Options for Ceres (3/3)

- Ceres’ migration from between the giant planet orbits (esp. Jupiter/ Saturn)
- Is supported by accretion models (Johansen et al. 2015), dynamical models (Kretke et al. 2017), and cosmochemical studies (Kruijer et al. 2017)

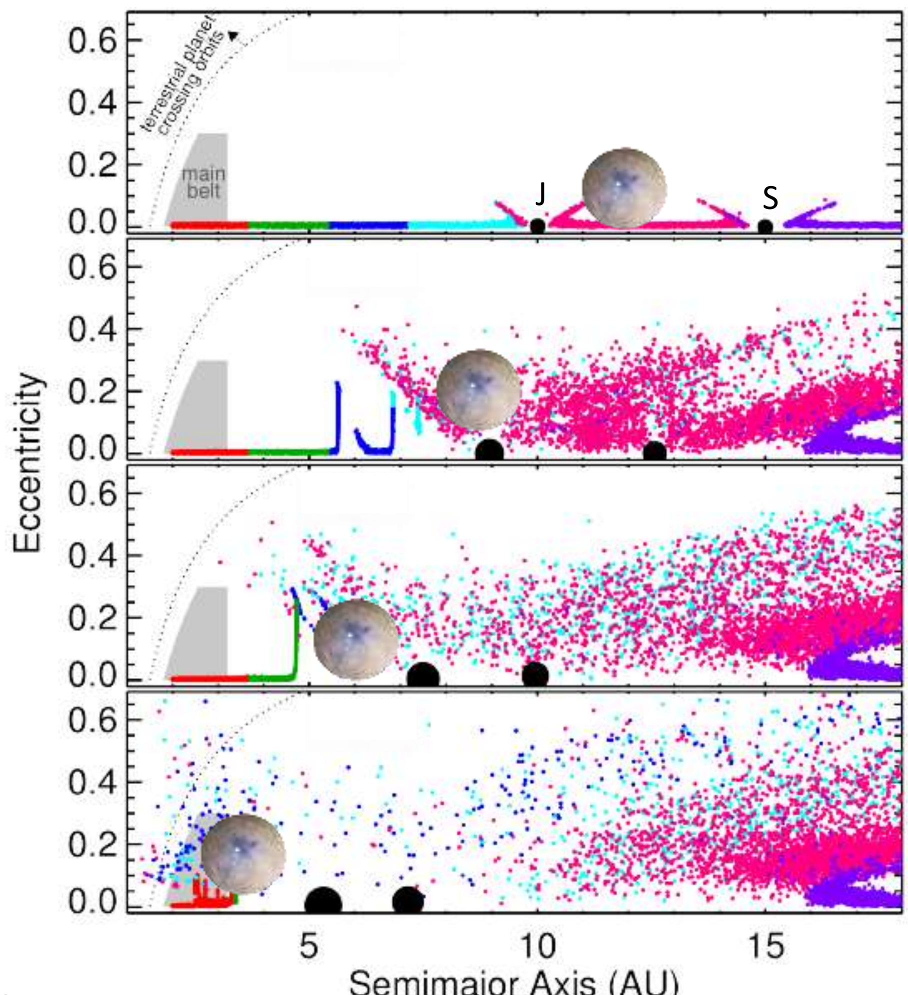
# Two Emerging Models for Ceres' Origin

1. Formation between the orbits of the giant planets with other C-type asteroids, scattered by planetary growth and migration

   ➔ *Other C-type asteroids should share similar volatile composition with Ceres*

2. Formation between the orbits of the giant planets but with efficient accretion of pebbles from the far outer solar system

   ➔ *Pebble accretion less efficient on small C-types; should show a different composition*




**Importance investigate the chemistry of 100-200 km C-type asteroids to gain context for Ceres**

Raymond and Izodoro (2017)
Kretke et al. (2017)
Johansen et al. (2015)

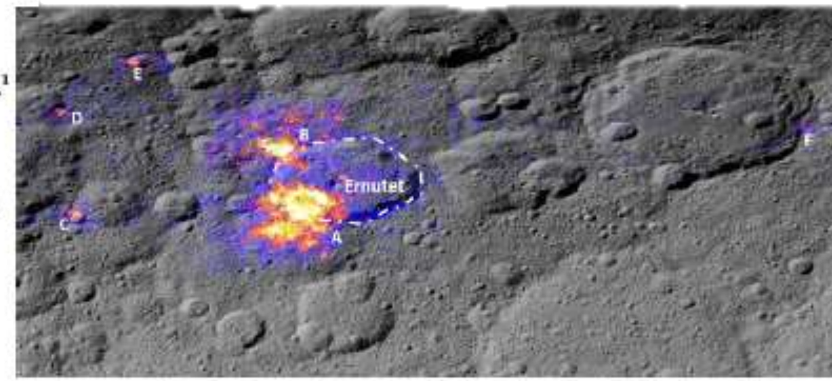
# Organics Found on Ceres' Surface!

PLANETARY SCIENCE

## Localized aliphatic organic material on the surface of Ceres

M. C. De Sanctis,[1*] E. Ammannito,[2,1] H. Y. McSween,[3] A. Raponi,[1] S. Marchi,[4,1] F. Capaccioni,[1] M. T. Capria,[1] F. G. Carrozzo,[1] M. Ciarniello,[1] S. Fonte,[1] M. Formisano,[1] A. Frigeri,[1] M. Giardino,[1] A. Longobardo,[1] G. Magni,[1] L. A. McFadden,[5] E. Palomba,[1] C. M. Pieters,[6] F. Tosi,[1] F. Zambon,[1] C. A. Raymond,[7] C. T. Russell[2]

Organic compounds occur in some chondritic meteorites, and their signatures on solar system bodies have been sought for decades. Spectral signatures of organics have not been unambiguously identified on the surfaces of asteroids, whereas they have been detected on cometary nuclei. Data returned by the Visible and InfraRed Mapping Spectrometer on board the Dawn spacecraft show a clear detection of an organic absorption feature at 3.4 micrometers on dwarf planet Ceres. This signature is characteristic of aliphatic organic matter and is mainly localized on a broa ~1000 square kilometers close to the ~50-kilometer Ernutet crater. The co presence on Ceres of ammonia-bearing hydrated minerals, water ice, carbo and organic material indicates a very complex chemical environment, sugge environments to prebiotic chemistry.



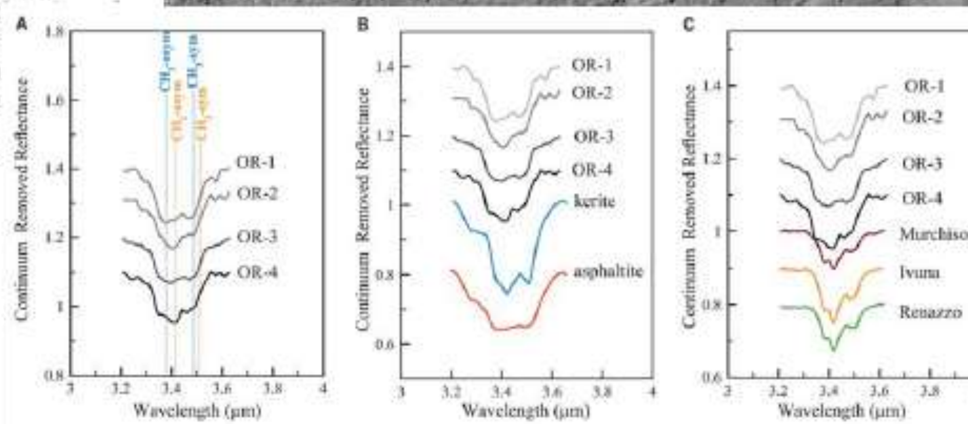
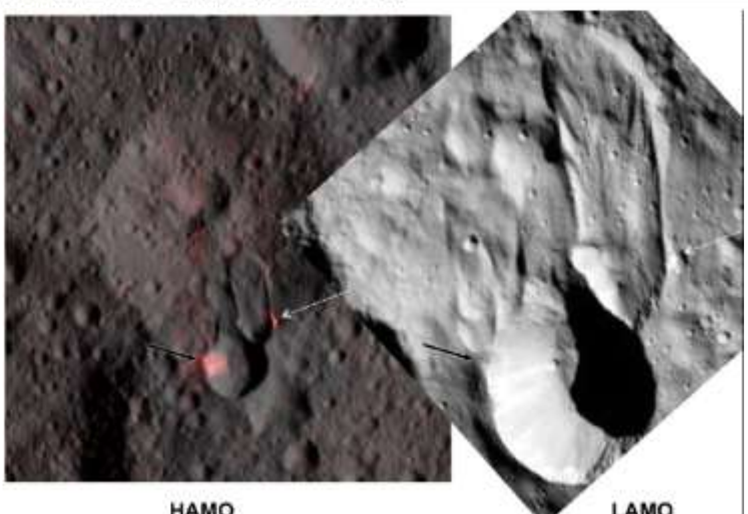



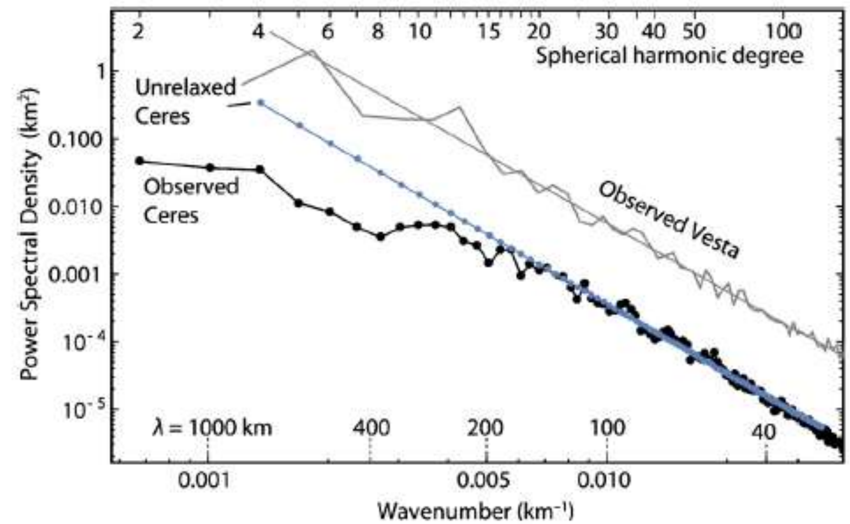

Fig. 2. Spectra of organic-rich pixels. Spectra of organic-rich pixels (OR-1 to OR-4, 450 m/pixel taken from area a in Fig. 4) compared with (A) methyl ($CH_3$) and methylene ($CH_2$) functional groups, (B) terrestrial hydrocarbons, and (C) IOM in carbonaceous chondrites. The spectra are offset for clarity.

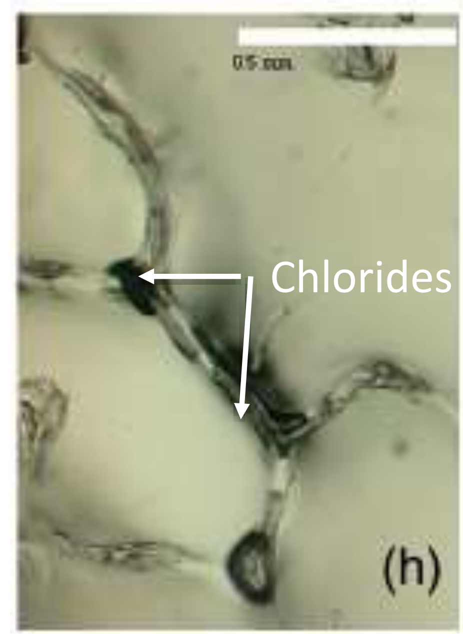



**Endogenic vs. exogenic origin of organics is work in progress.**

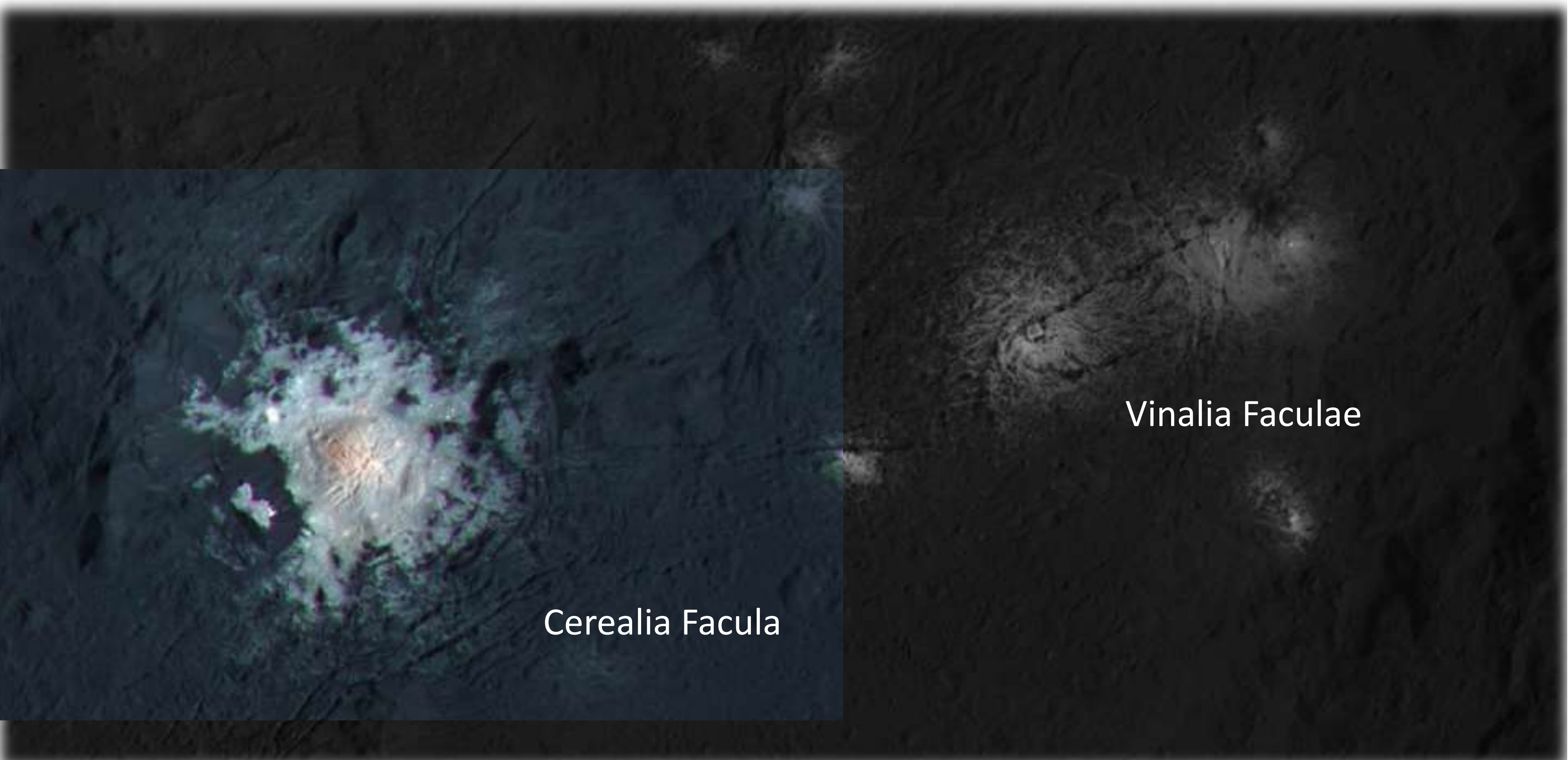
# Global Occurrence of Brines at Present?

- Fu et al. (2017) inferred a sharp drop in viscosity at about 40 km depth
  - Fraction of melt is work in progress
  - A few vol.% necessary for Ahuna mons
  - Interpreted as evidence for structural liquid
  - Extent is at least 60 km
- Low core density suggests ~10% porosity – would be consistent with mudball model, which suggests large volume of mud at present (Travis et al. submitted)

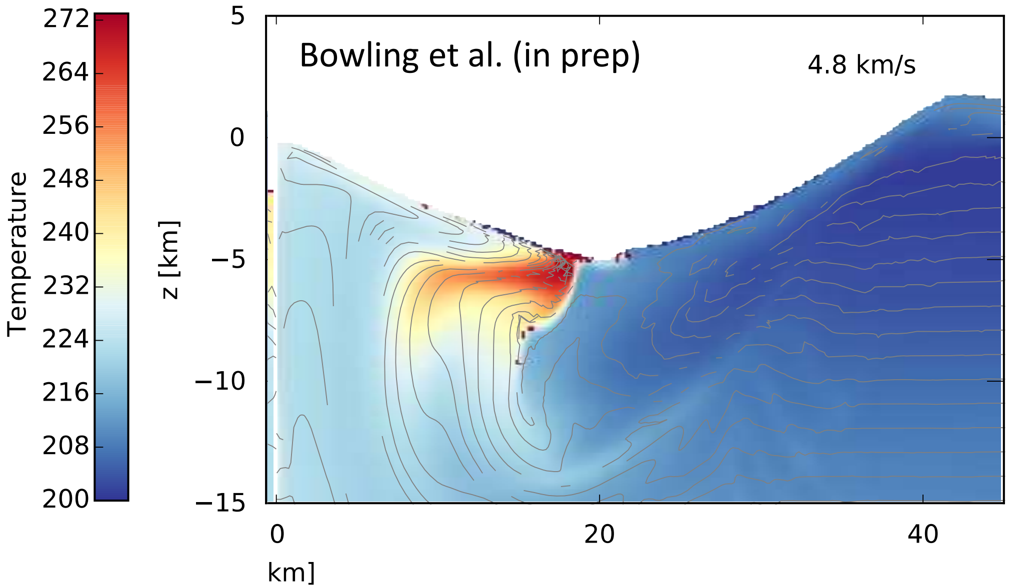


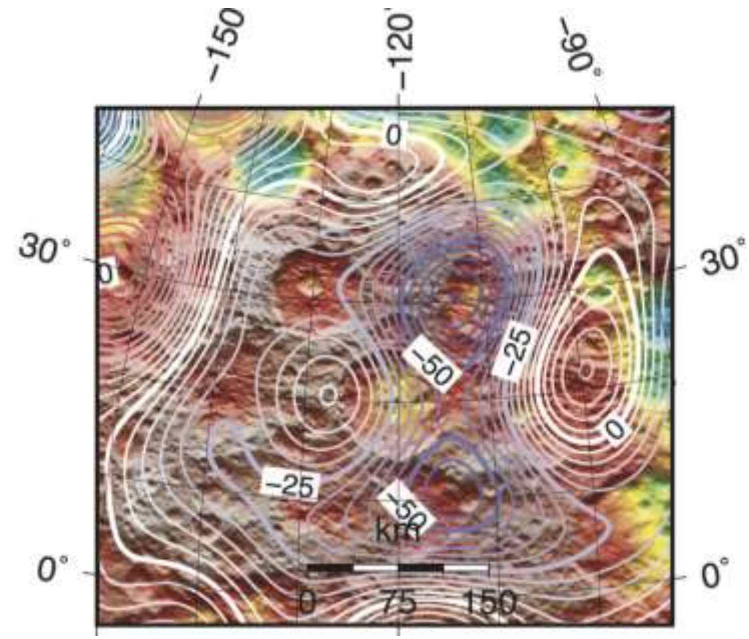



# Beyond the Coolness, What is Occator Telling us?



# Did the Faculae Come from a Magma Chamber?



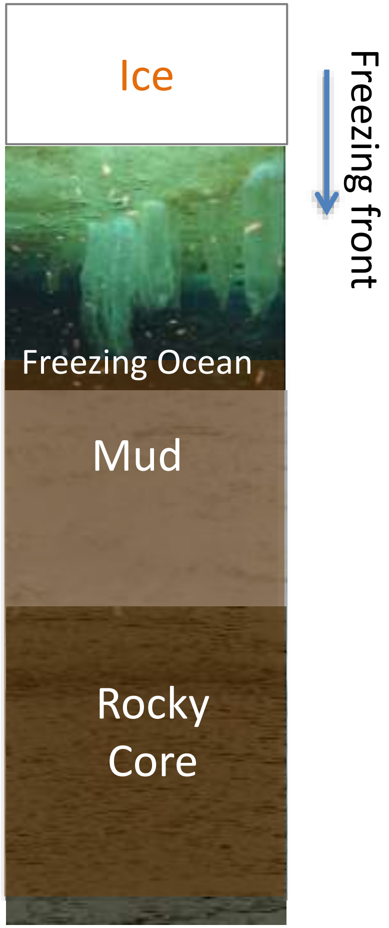




Hanami Planum

- Volume of low-eutectic material melted upon impact is significant
- Clathrate destabilization may promote buoyancy
- Material exposed when reservoir is freezing (quick, submitted)
- Negative gravity anomaly supports magma reservoir
- But freezing timescale is fast in comparison to derived ages

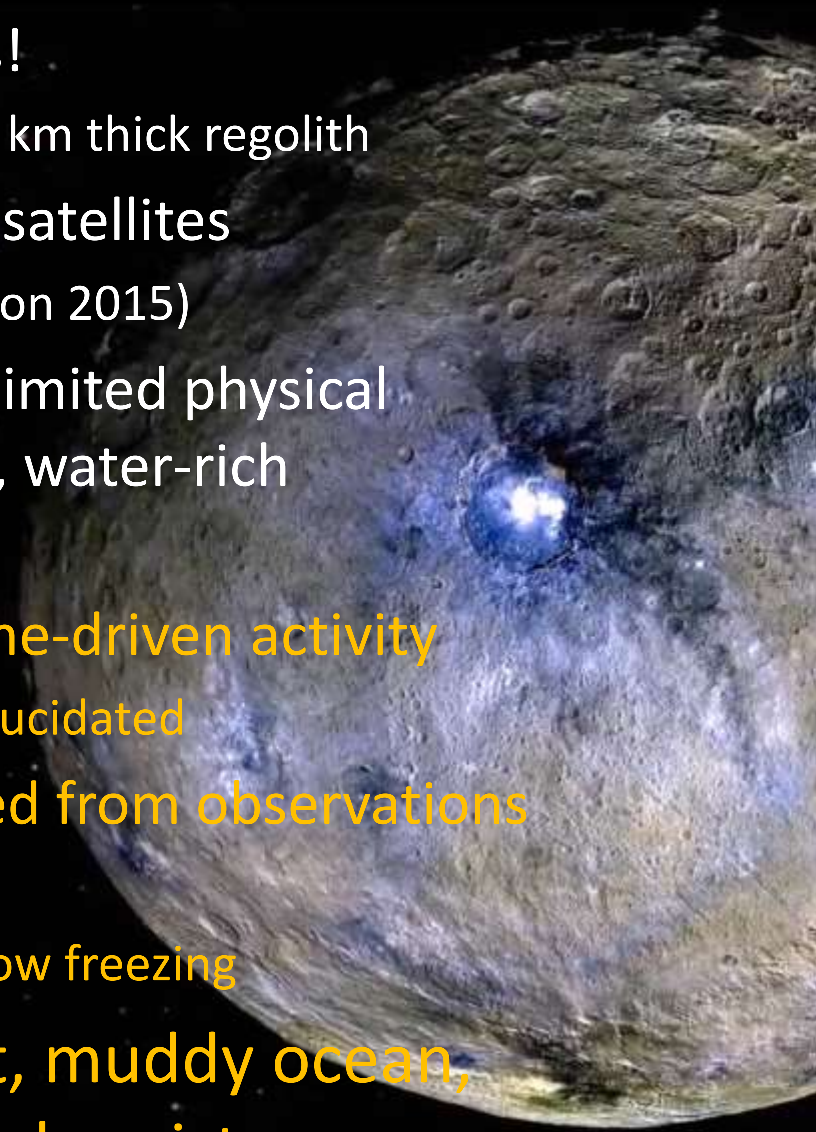
# Did Ceres Lose a Significant Amount of Water?

- Slow freezing over ocean leads to mostly pure ice shell
  - Rock particles cannot be accommodated at ice grain boundaries
  - Salts also rejected during growth (cf. lakes, sea ice)
- Ceres' crust contains <30vol.% ice so it is possible that the ice-rich layer has been lost
- Impact induced sublimation can lead to the loss of 10s km ice (Castillo-Rogez et al. 2016)
- **Frozen oceanic material readily accessible below the regolith**
- Regolith could be lag deposit or exposed via ocean communication with the surface early on (Neveu and Desch 2015)



# Importance of Ceres for Understanding OW

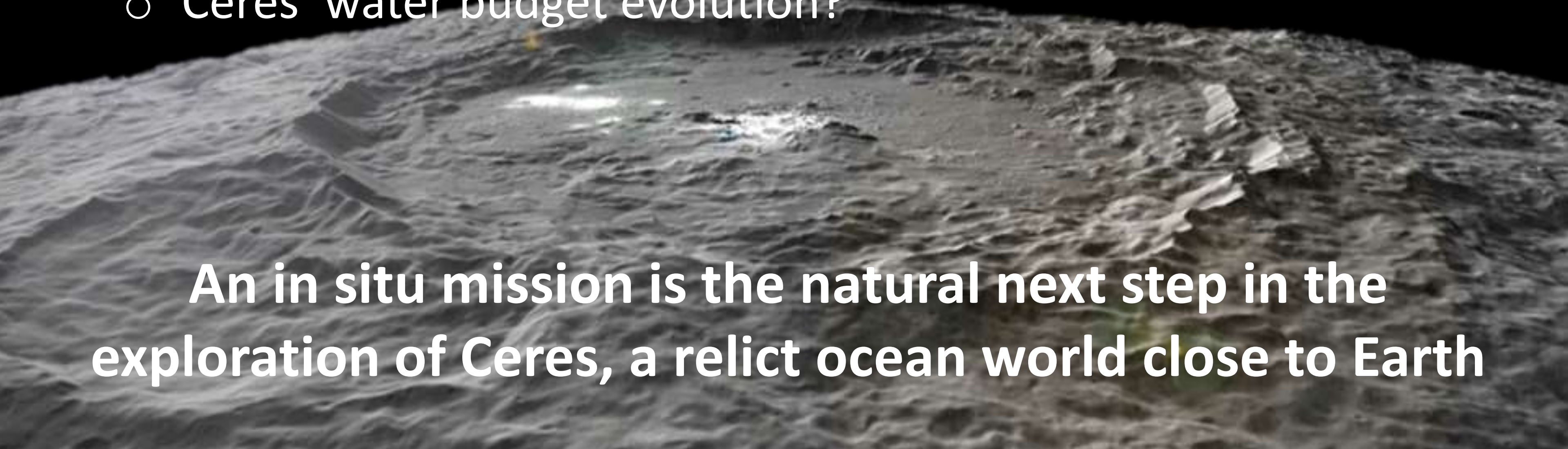
- Ceres is akin to icy satellites, not Mars!
  - A volatile-rich crust is present below a <1 km thick regolith
- Ceres displays chemistry found on icy satellites
  - Na-carbonates, chlorides (Hand and Carlson 2015)
- Advanced chemical fractionation but limited physical differentiation may be typical of large, water-rich planetesimals
- Geology indicates recent (10s My) brine-driven activity
  - Passive or ”active” origin remains to be elucidated
- Current occurrence of brines suggested from observations and supported by modeling
  - Abundance of hydrated material led to slow freezing
- Not a classical ocean, but a relict, muddy ocean, important medium for prebiotic chemistry



# The Next Step in Ceres’ Exploration Requires In Situ Investigations

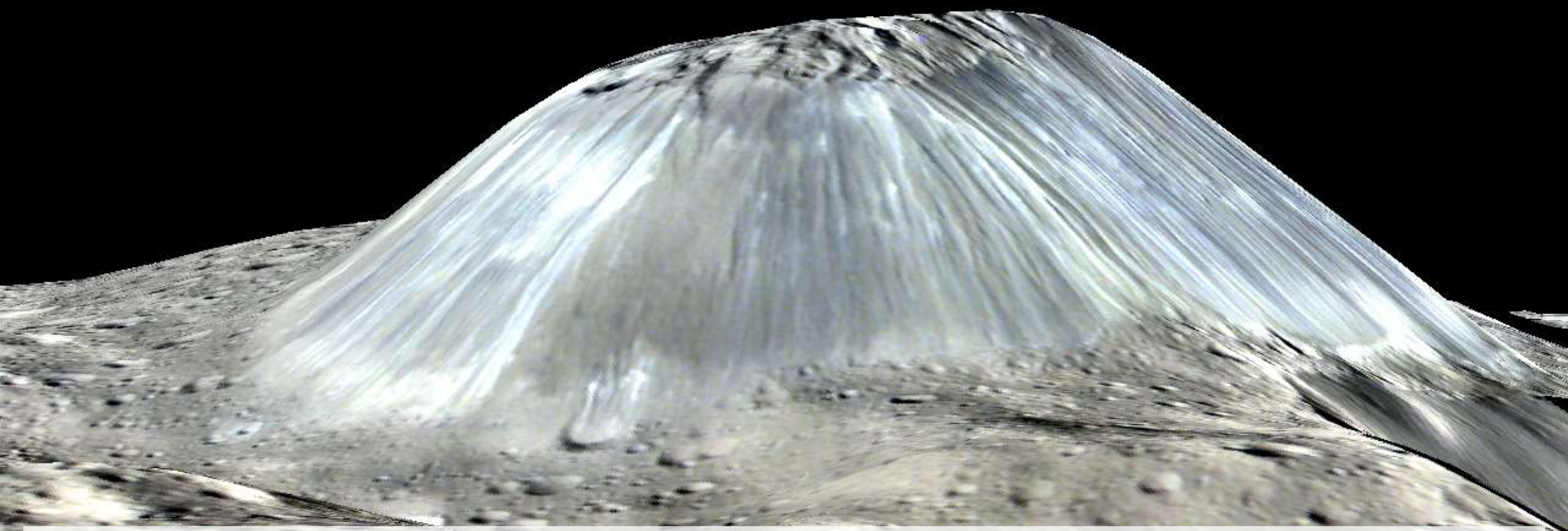
**KEY OPEN QUESTIONS:**

- Confirmation, thickness and extent of mud layer?
- Conditions of past and current liquid environments?
- Past and present extent of geochemical gradients?
- Origin of organics observed on the surface?
- Potential for ongoing “active” geology?
- Origin of Ceres in the outer solar system?
- Ceres’ water budget evolution?



**An in situ mission is the natural next step in the exploration of Ceres, a relict ocean world close to Earth**

# Thank you for your attention!



Dawn's mission is managed by JPL for NASA's Science Mission Directorate in Washington. Dawn is a project of the directorate's Discovery Program, managed by NASA's Marshall Space Flight Center in Huntsville, Alabama. UCLA is responsible for overall Dawn mission science. Orbital ATK Inc., in Dulles, Virginia, designed and built the spacecraft. The German Aerospace Center, Max Planck Institute for Solar System Research, Italian Space Agency and Italian National Astrophysical Institute are international partners on the mission team.