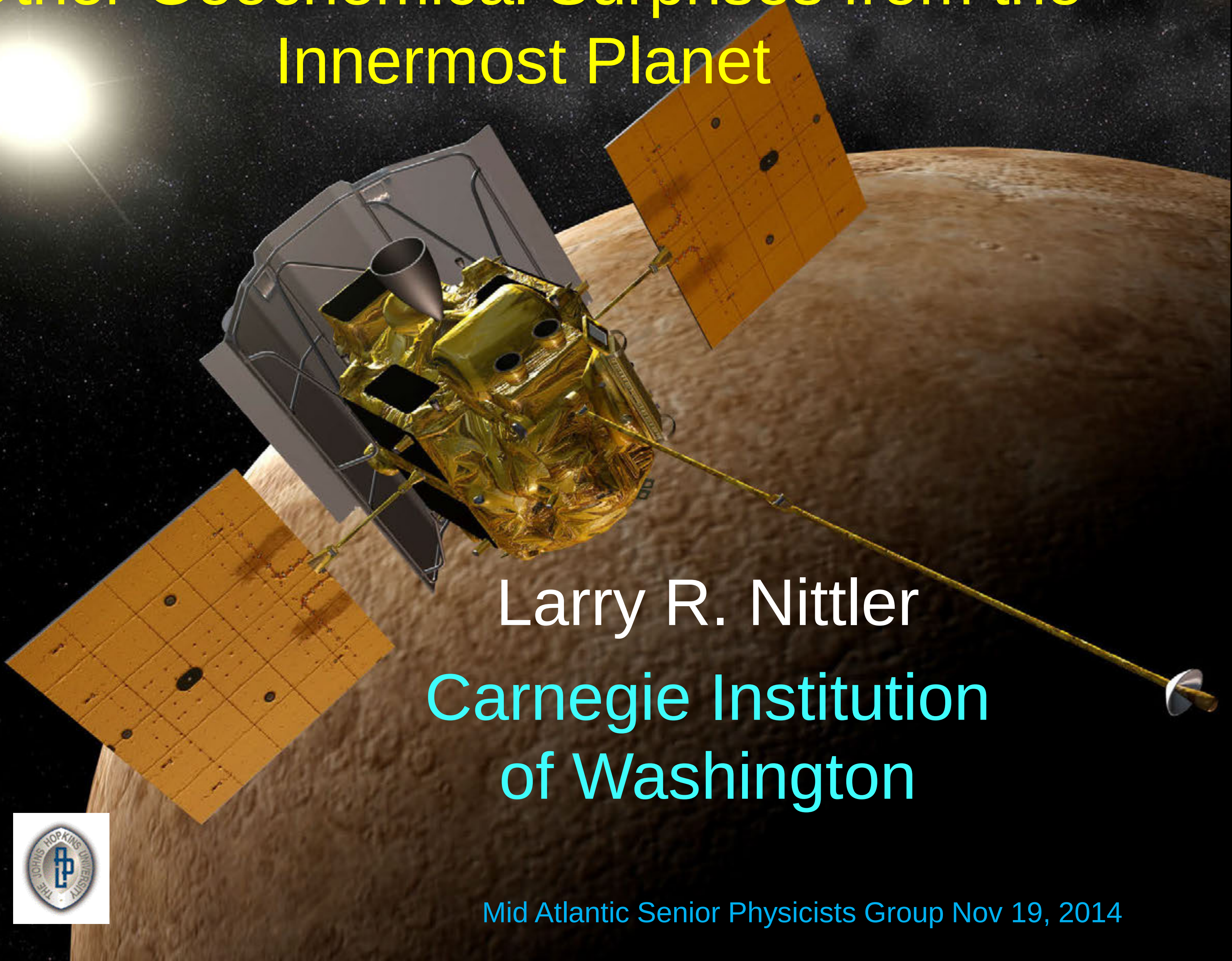
# MESSENGER at Mercury: Water, Sulfur and Other Geochemical Surprises from the Innermost Planet

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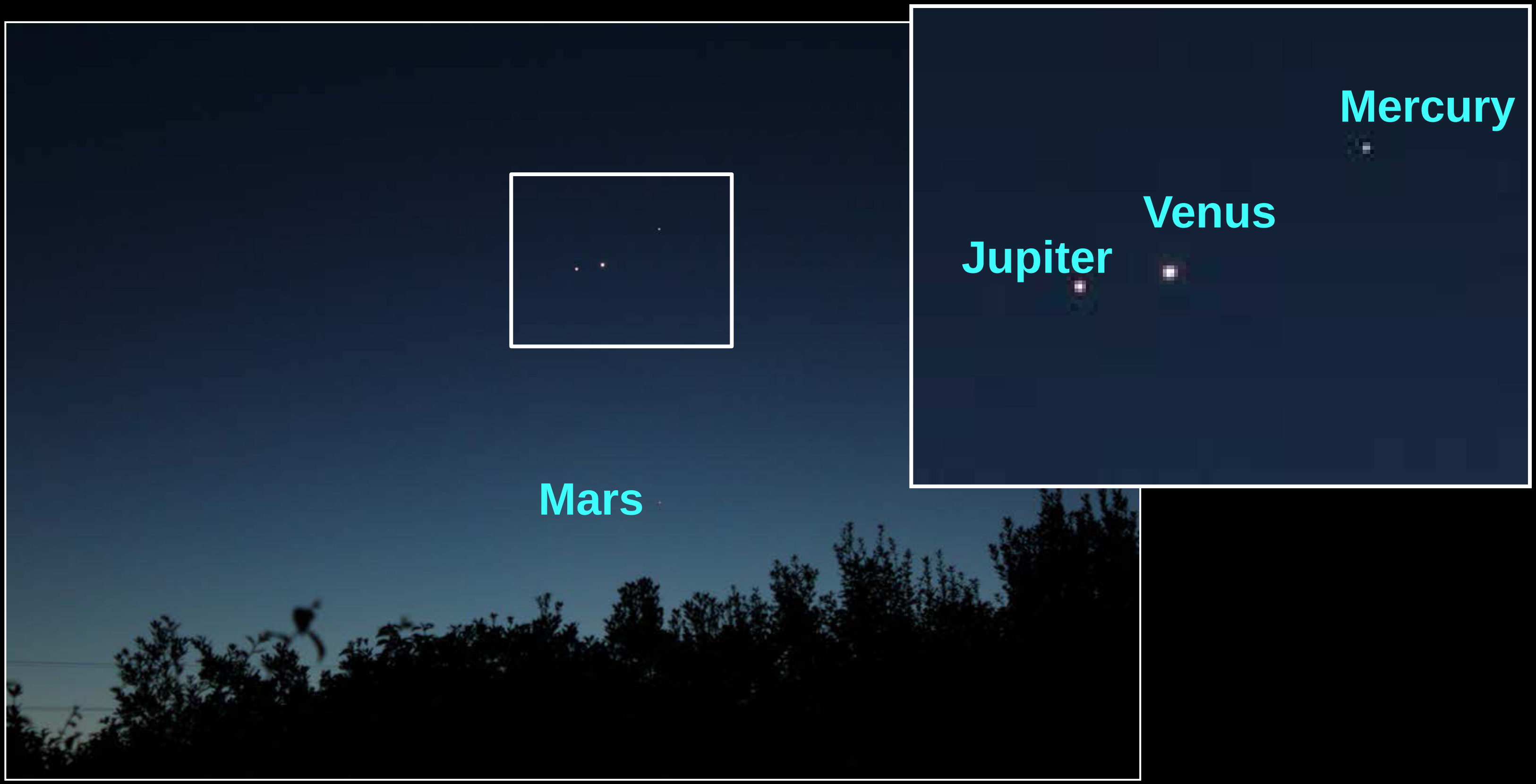
Mid Atlantic Senior Physicists Group Nov 19, 2014

# Acknowledgements


- Richard D. Starr, Shoshana Z. Weider, Patrick N. Peplowski, Ellen Crapster-Pregont, Larry G. Evans, Timothy J. McCoy, William V. Boynton, Paul Byrne, Nancy Chabot, Brett Denevi, Denton S. Ebel, Carolyn M. Ernst, Larry G. Evans, Jeffery J. Gillis-Davis, John O. Goldsten, David K. Hamara, Steven A. Hauck, II, Christian Klimzcak, David J. Lawrence, Ralph L. McNutt, Jr., Louise Prockter, Edgar A. Rhodes, Charles E. Schlemm II, Sean C. Solomon, Ann L. Sprague, Karen R. Stockstill-Cahill, Audrey Vorberger

- MESSENGER Science Team, Engineers, Mission Operations (APL)

# Mercury

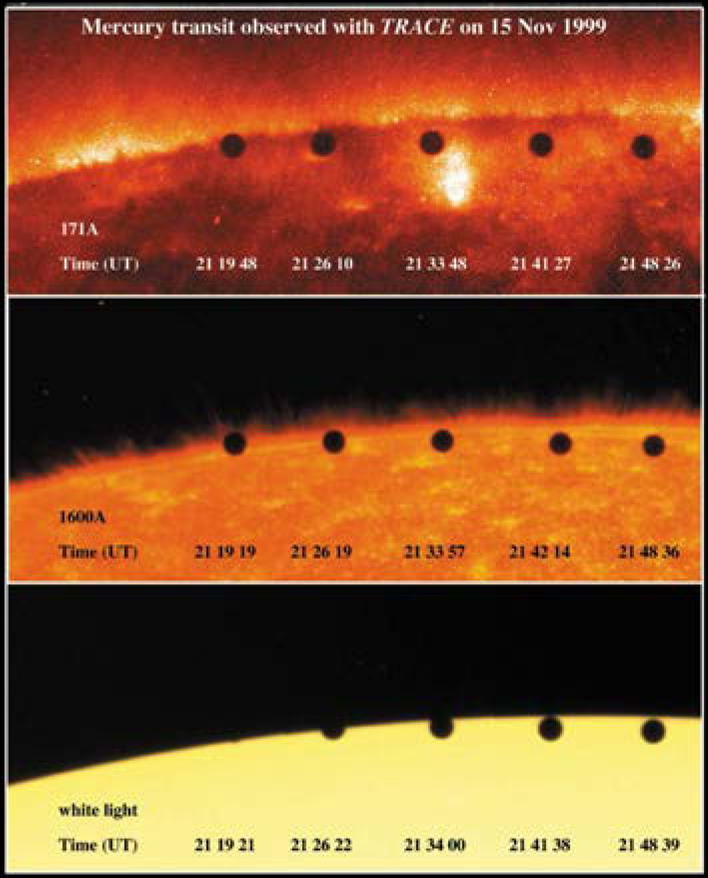


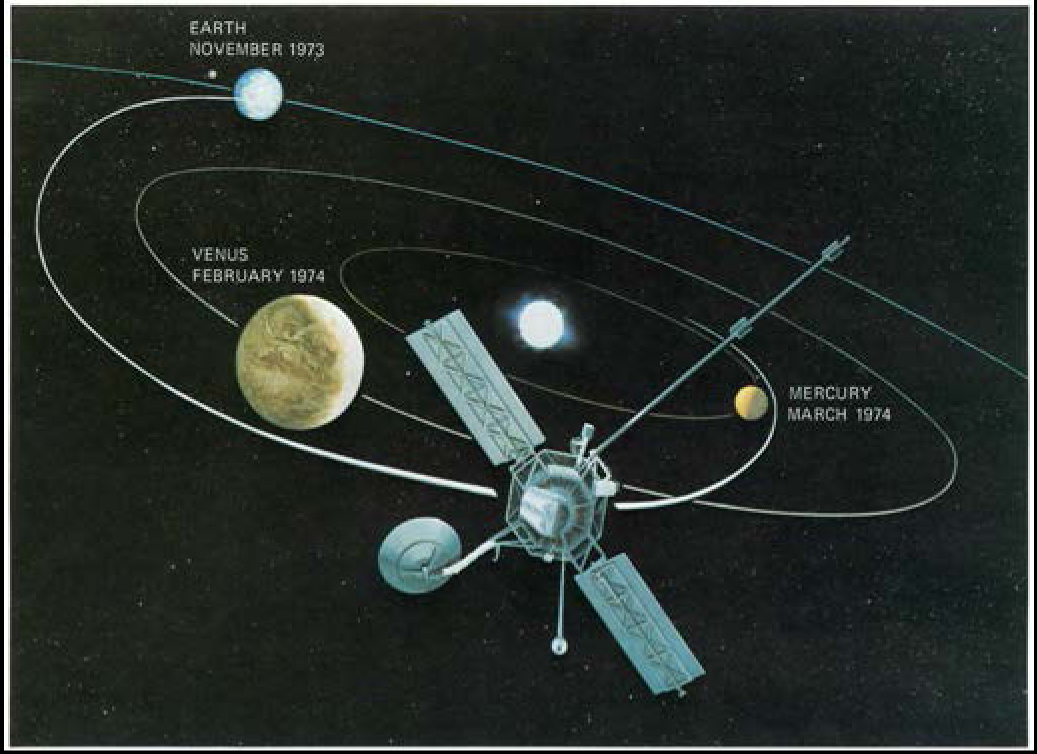

*May 12, 2011, from NZ (M. White, Flickr)*

- Naked-eye planet, but very difficult to observe due to proximity to Sun

# Mercury Is Difficult to Study

…by telescope … …or spacecraft.



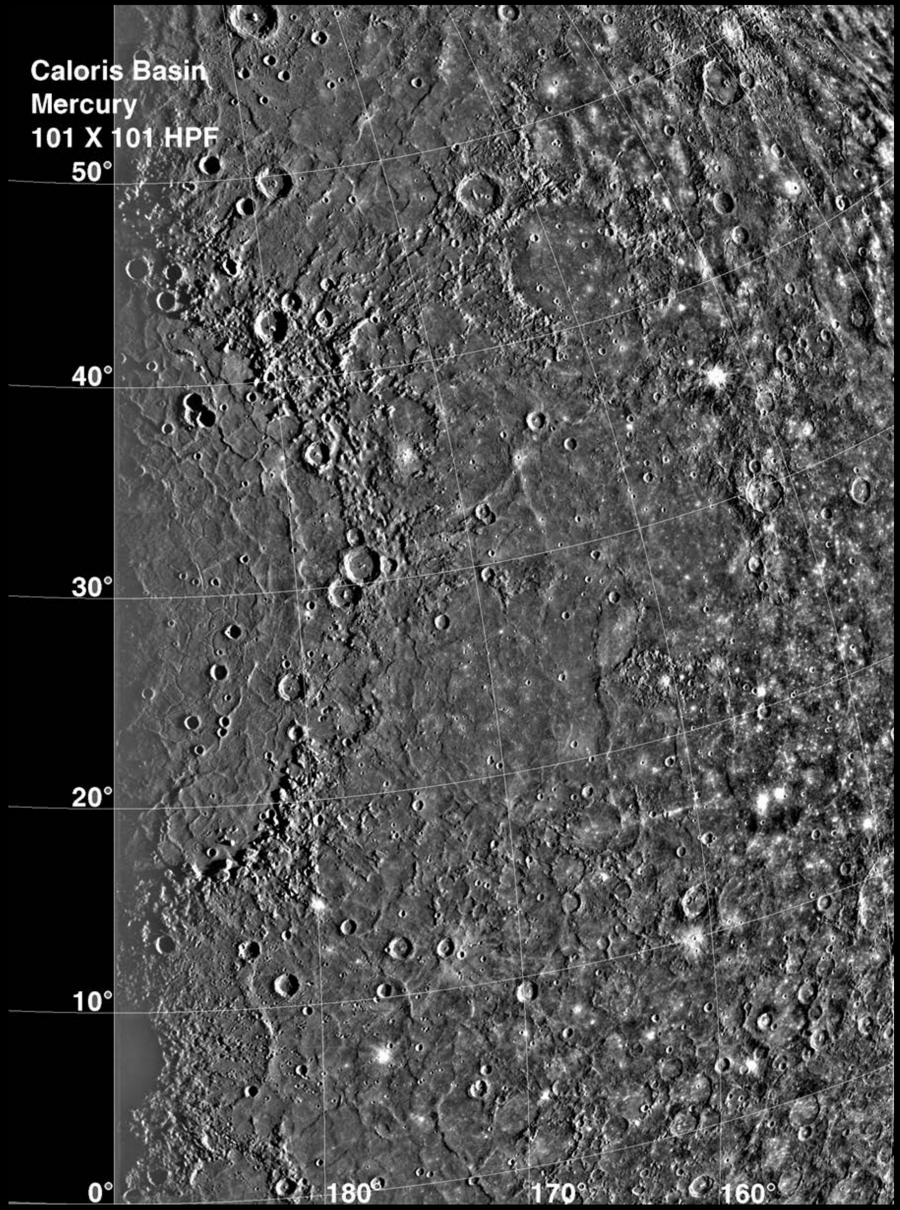

Only prior visit was by

Mariner 10, 1974-1975

# Mercury Exploration

Contributions of Mariner 10 flybys:

- Imaged 45% of Mercury's surface
- Discovered Mercury's magnetic field and dynamic magnetosphere
- Detected H, He, O in Mercury's "exosphere"

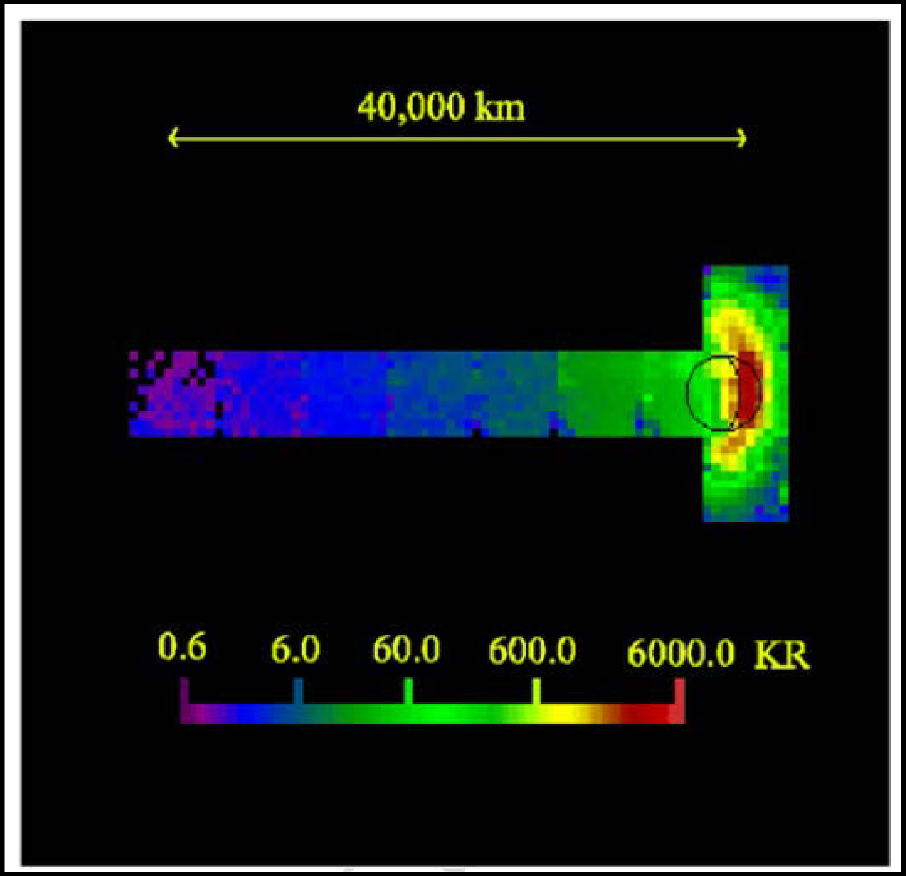



Mariner 10 mosaic of the Caloris basin

# Mercury Exploration

Contributions of Earth-based astronomy

- Discovery of Mercury's 3:2 spin-orbit resonance (1965)
  - 3 days in 2 years
- Discovery of sodium (1985), potassium (1986), and calcium (2000) in Mercury's exosphere

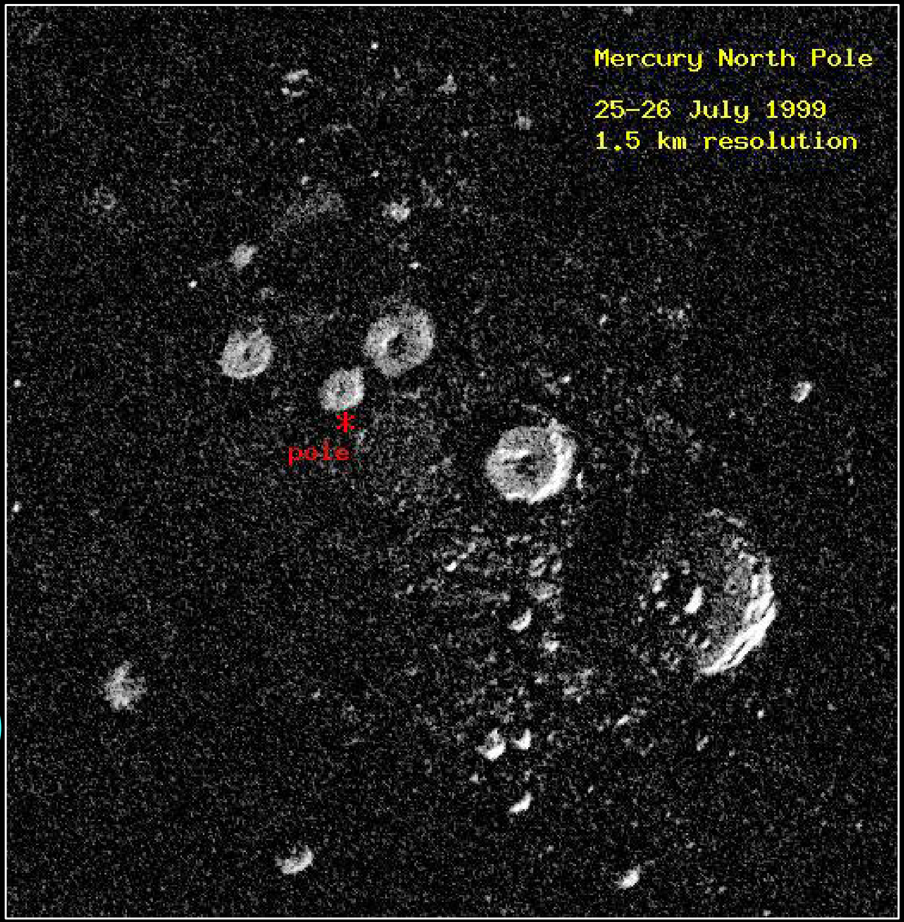



Na emission
Potter et al. 2002

# Mercury Exploration

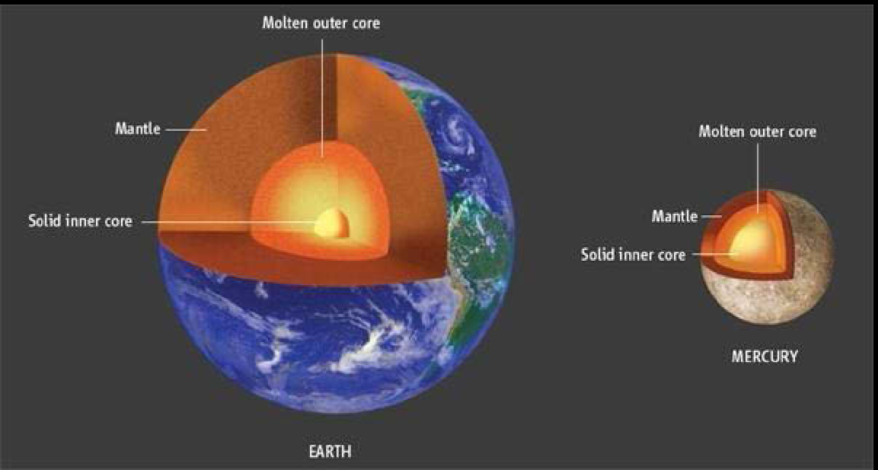
Contributions of Earth-based astronomy

- Discovery of Mercury's polar deposits (1992)
- Discovery of Mercury's molten outer core (2007)




Harmon et al. 1999

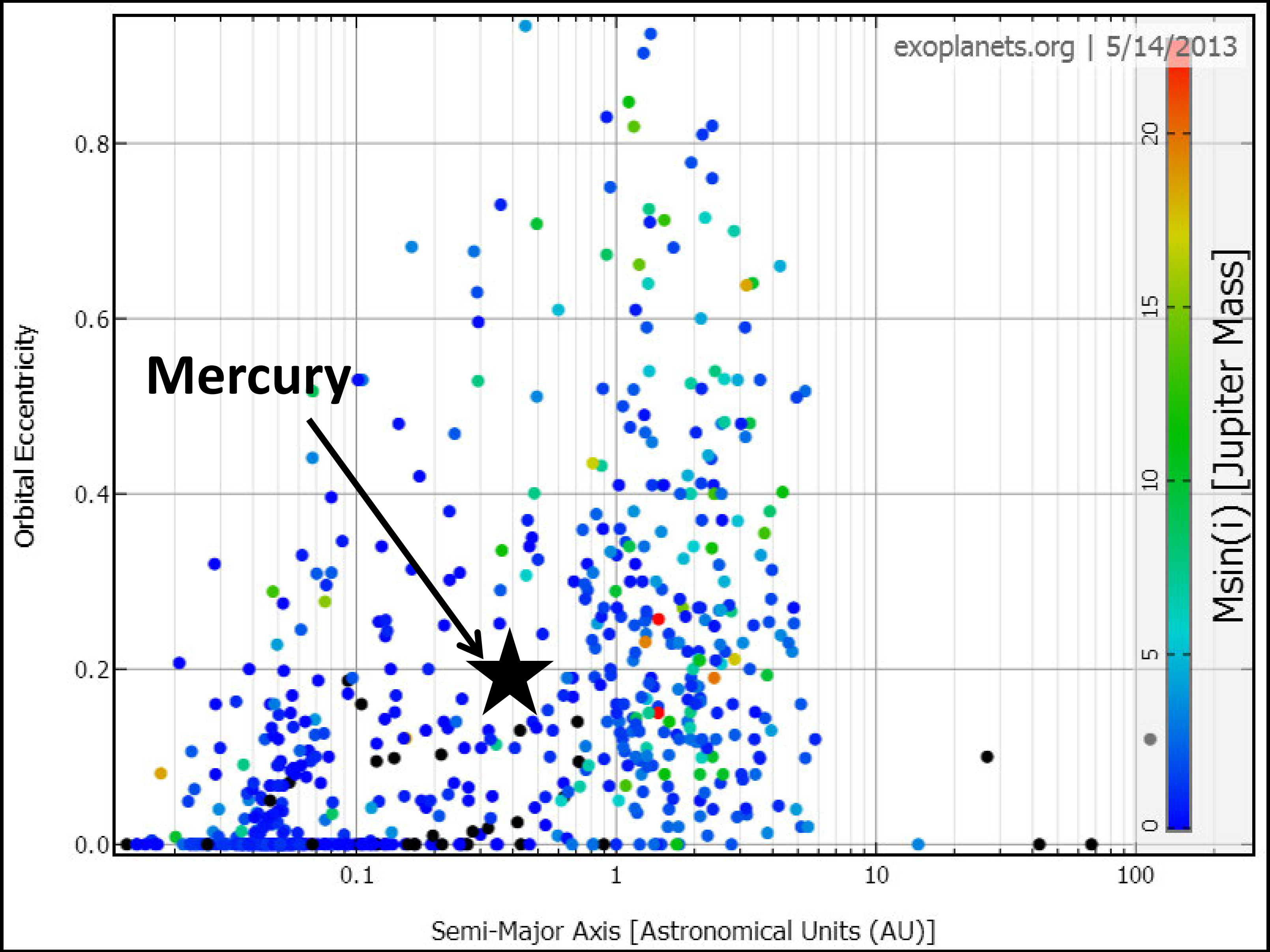
# Mercury: planet of extremes



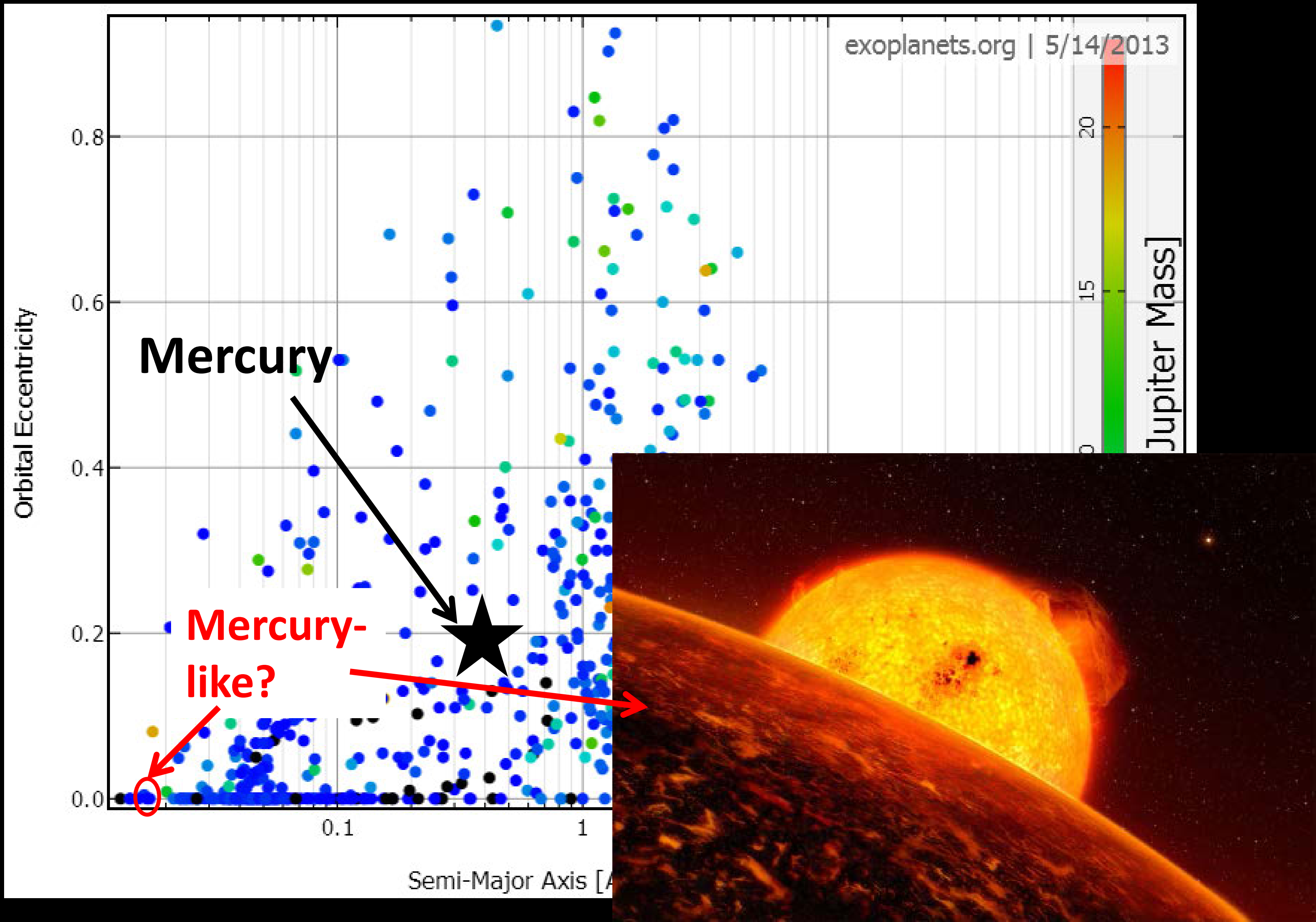

- Smallest, densest planet
- Closest to Sun
- Highest diurnal variation in temperature
  - −170 ºC to +430 ºC
- Very high Fe:silicate ratio
  - Core ~70% of mass, 80% radius
- Magnetic field: dynamic magnetosphere
- Low FeO in surface silicates

“end-member of planet formation”

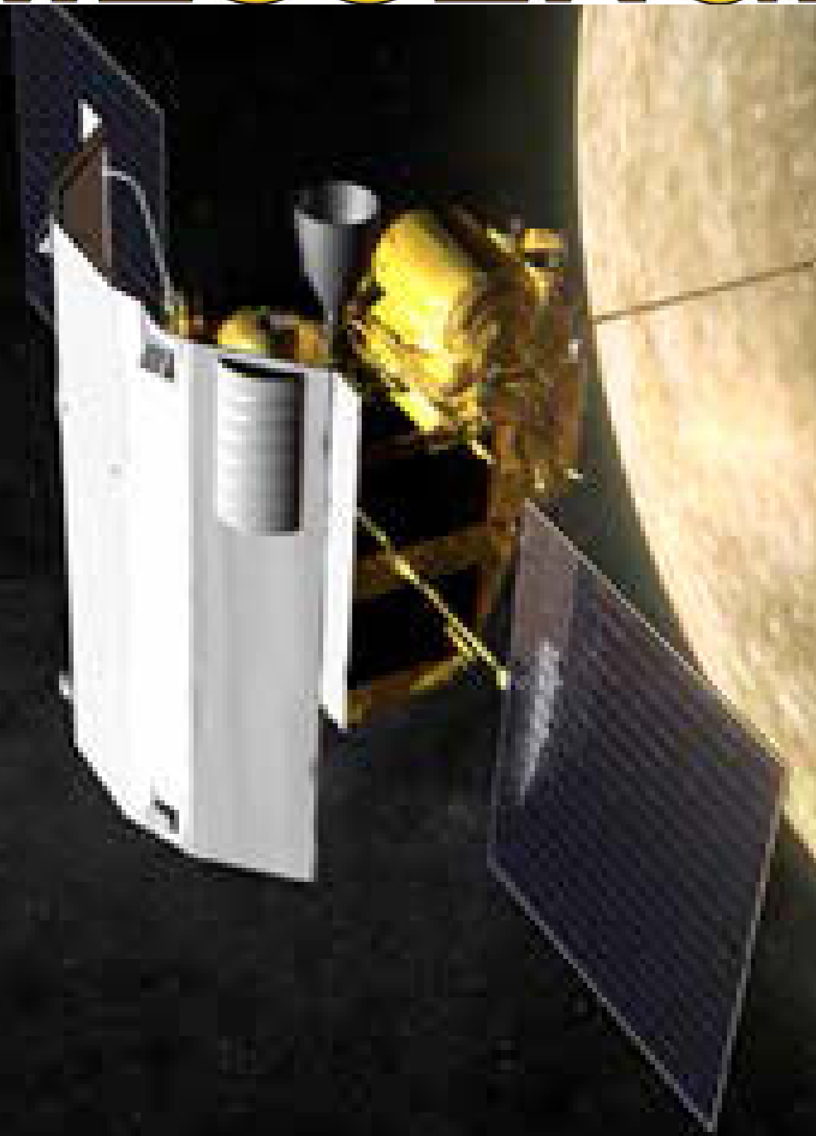
# Extrasolar Planetary Context



# Extrasolar Planetary Context

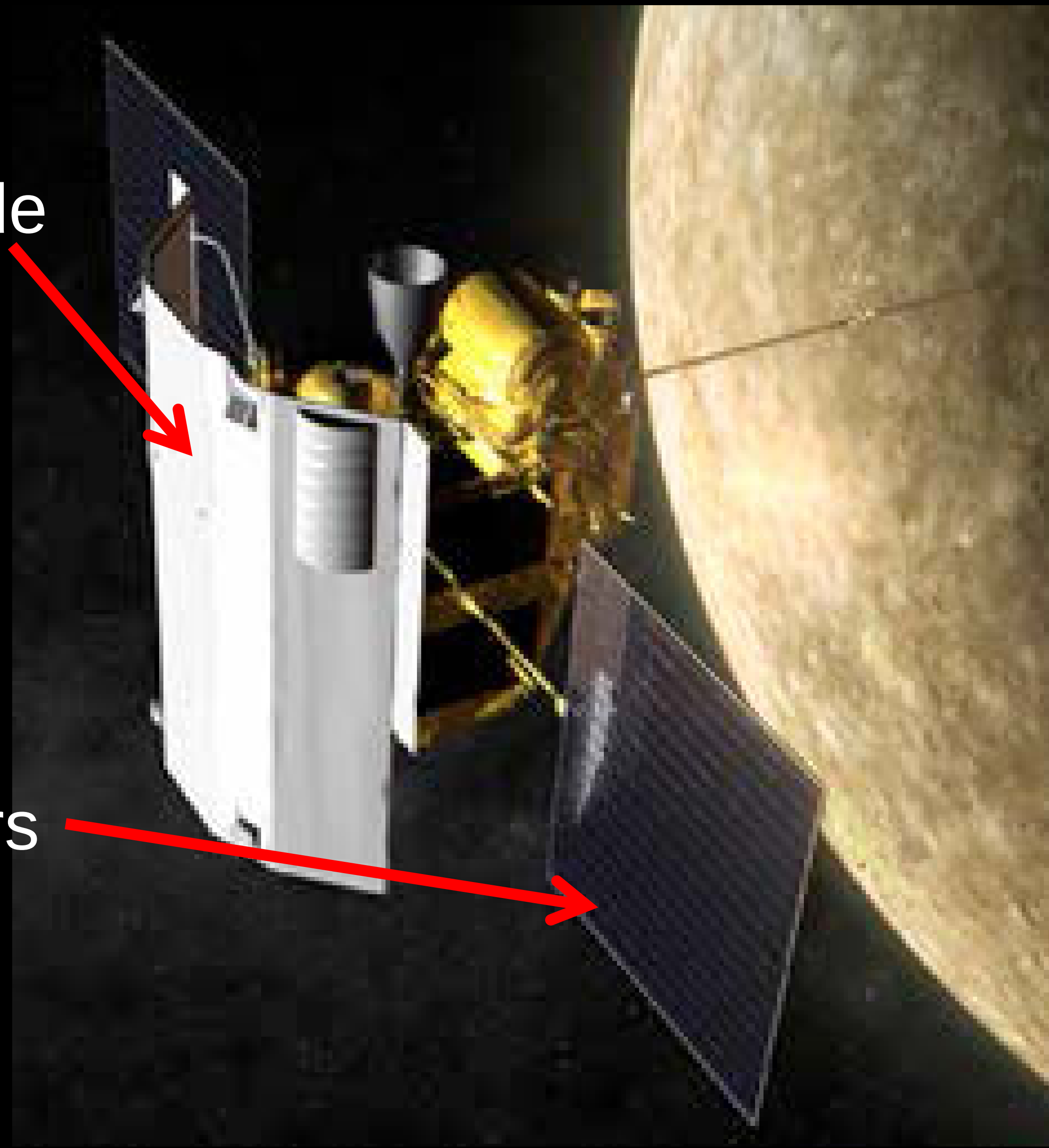


# MESSENGER

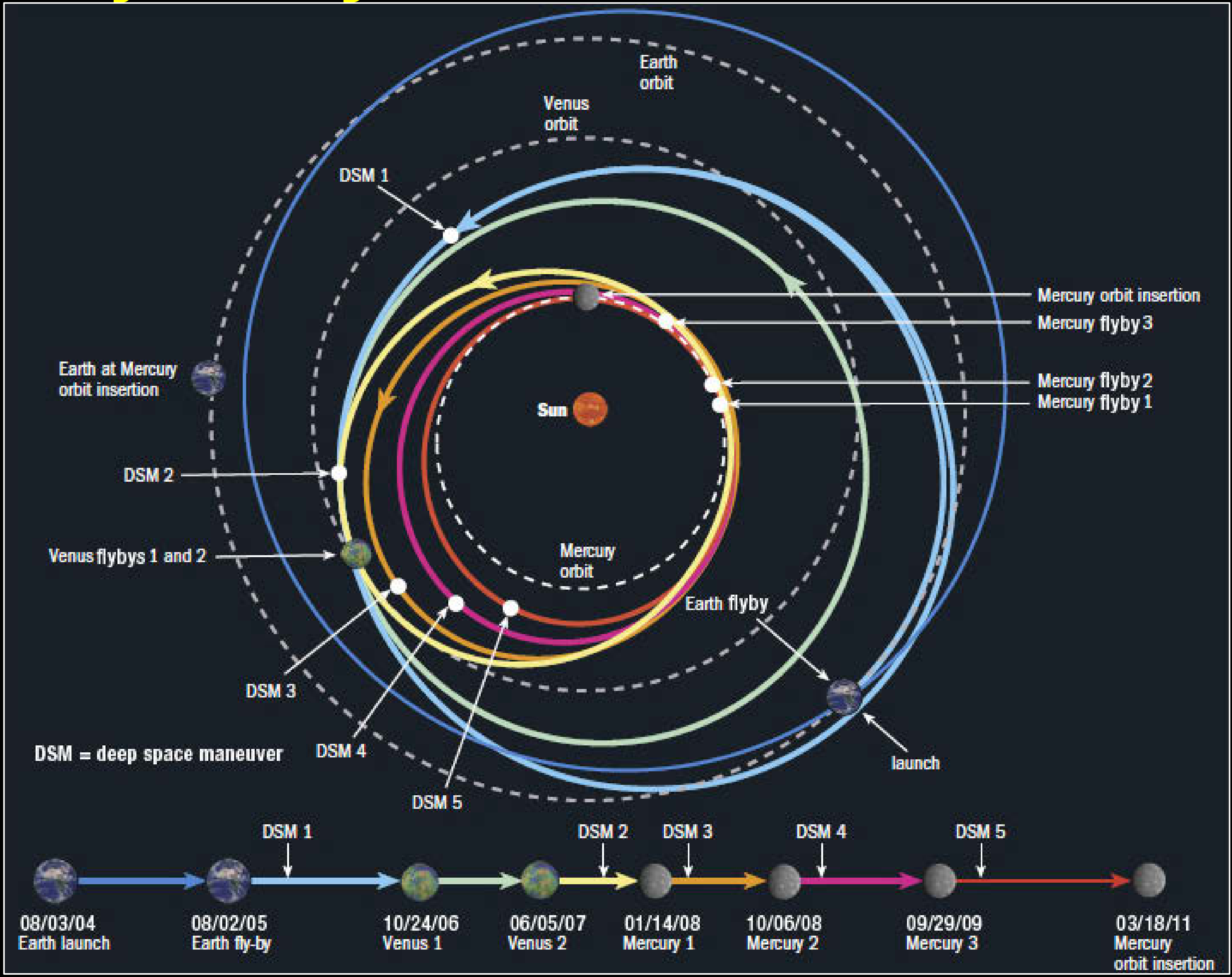


- First spacecraft to orbit Mercury
- 7th NASA *Discovery* mission
  - PI: Sean C. Solomon

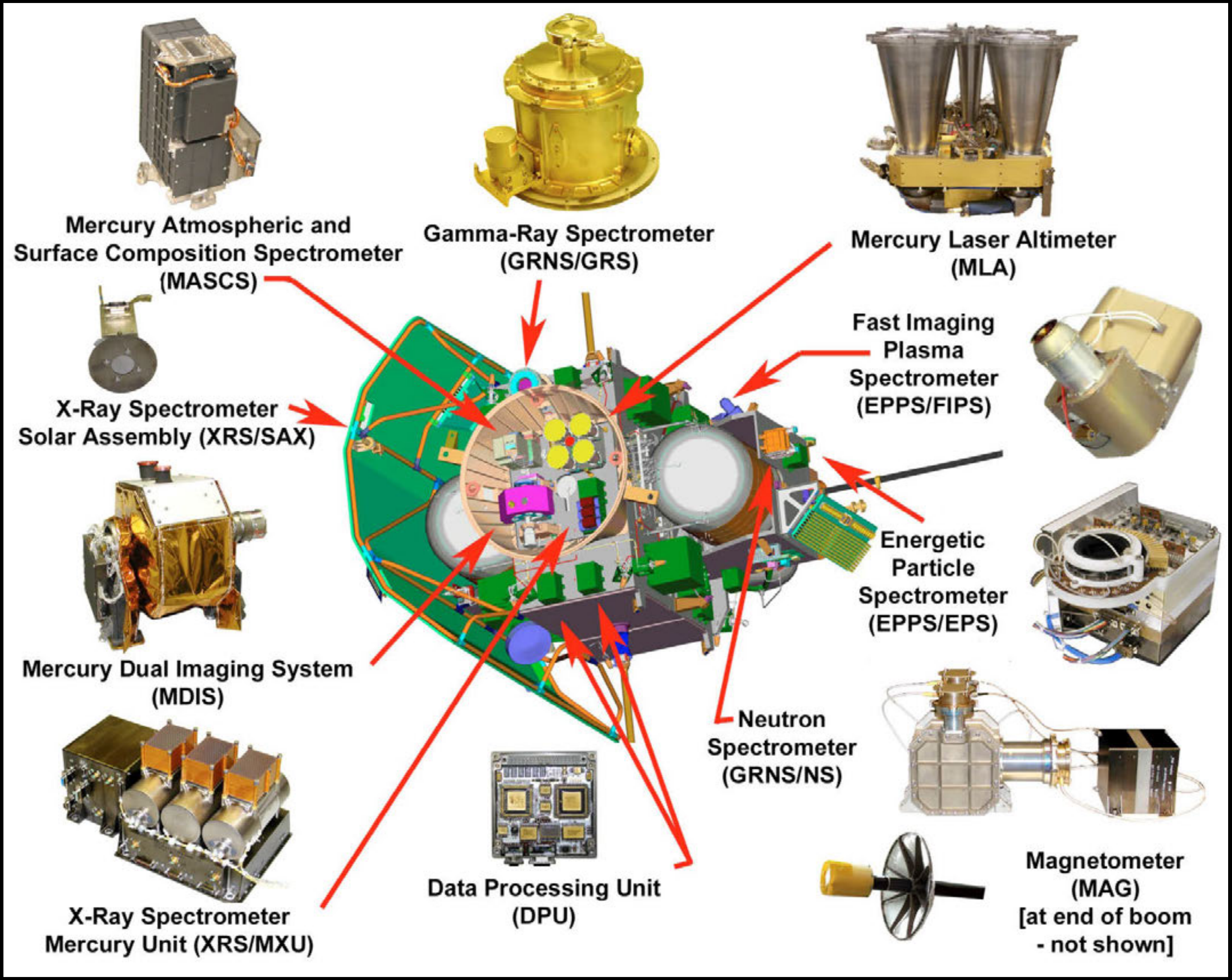
# Challenge: Surviving at Mercury



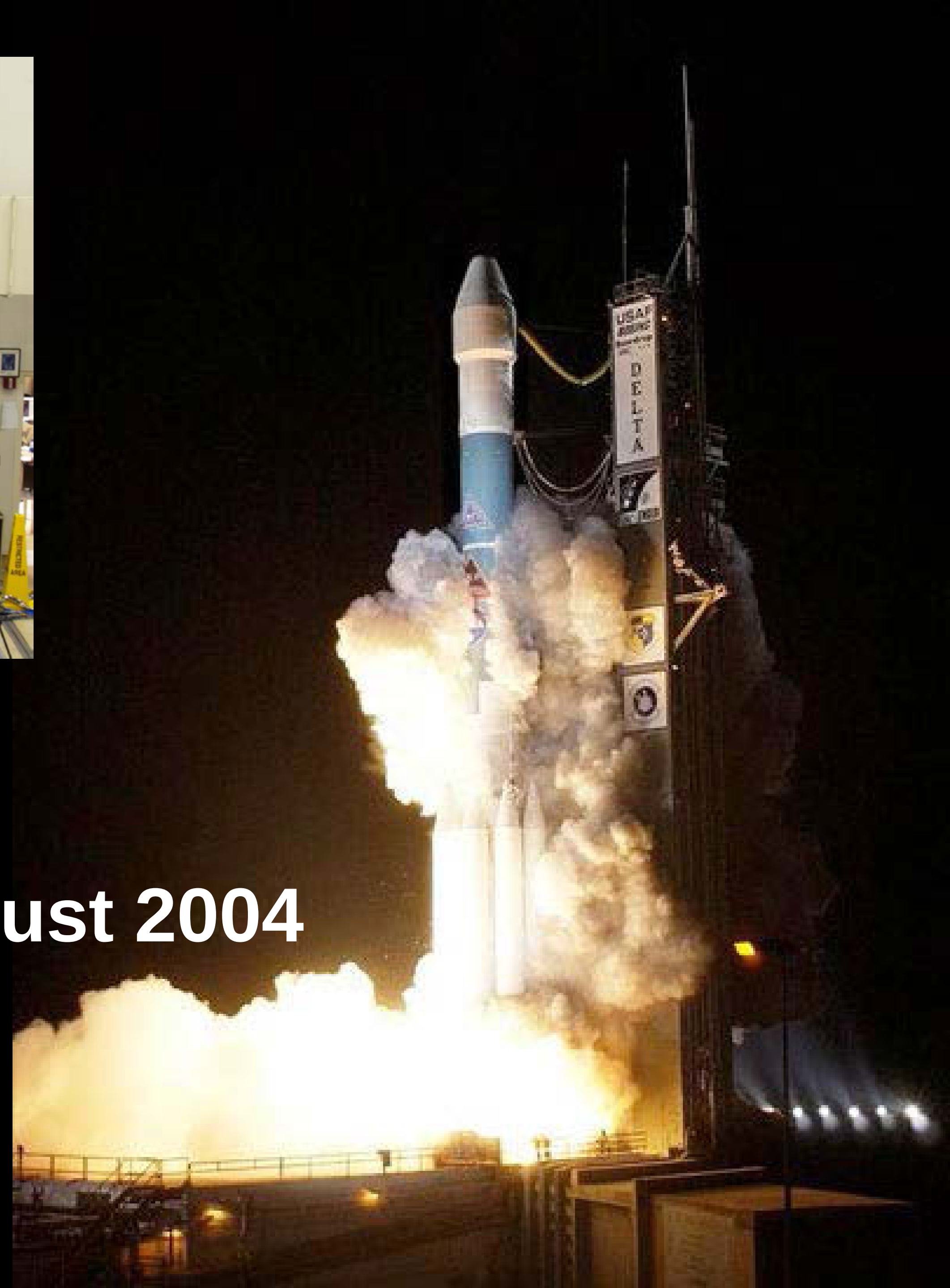
# Trajectory allows orbit insertion



# Scientific Payload



**Vibration test, December 2003**




**Launch, August 2004**

# Getting to Mercury

Earth (August 2005)

Venus (October 2006)

# Mercury Flybys (2008-2009)


M1 (Jan 2008)

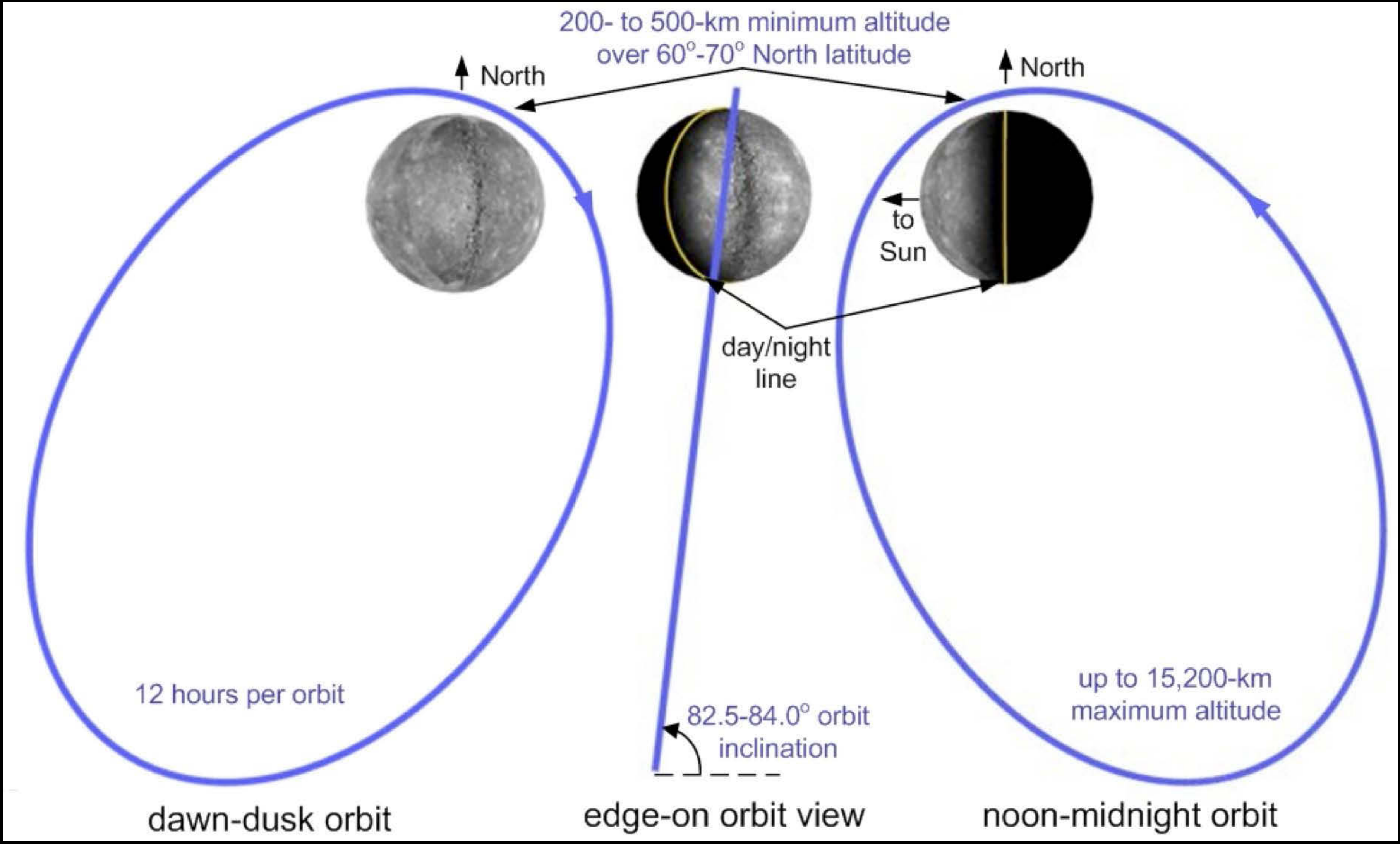

M2 (Oct 2008)

- >90% of surface imaged

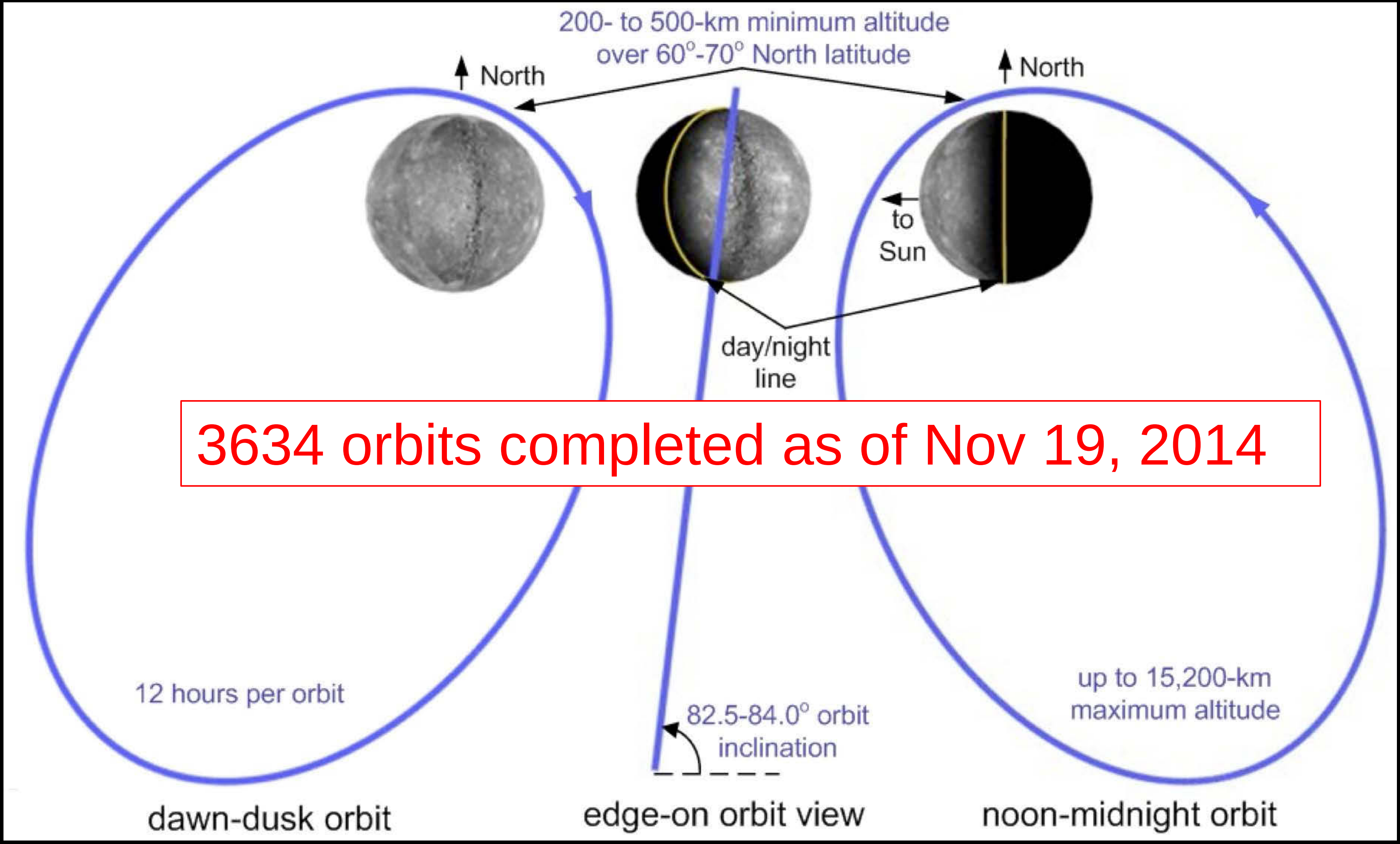

M3 (Sep 2009)

- Flyby results:
  - Extensive volcanism, color/albedo variations
  - Dynamic magnetosphere
  - Na, Mg, Ca variability in exosphere

# Mercury Orbit Insertion (March 18, 2011)

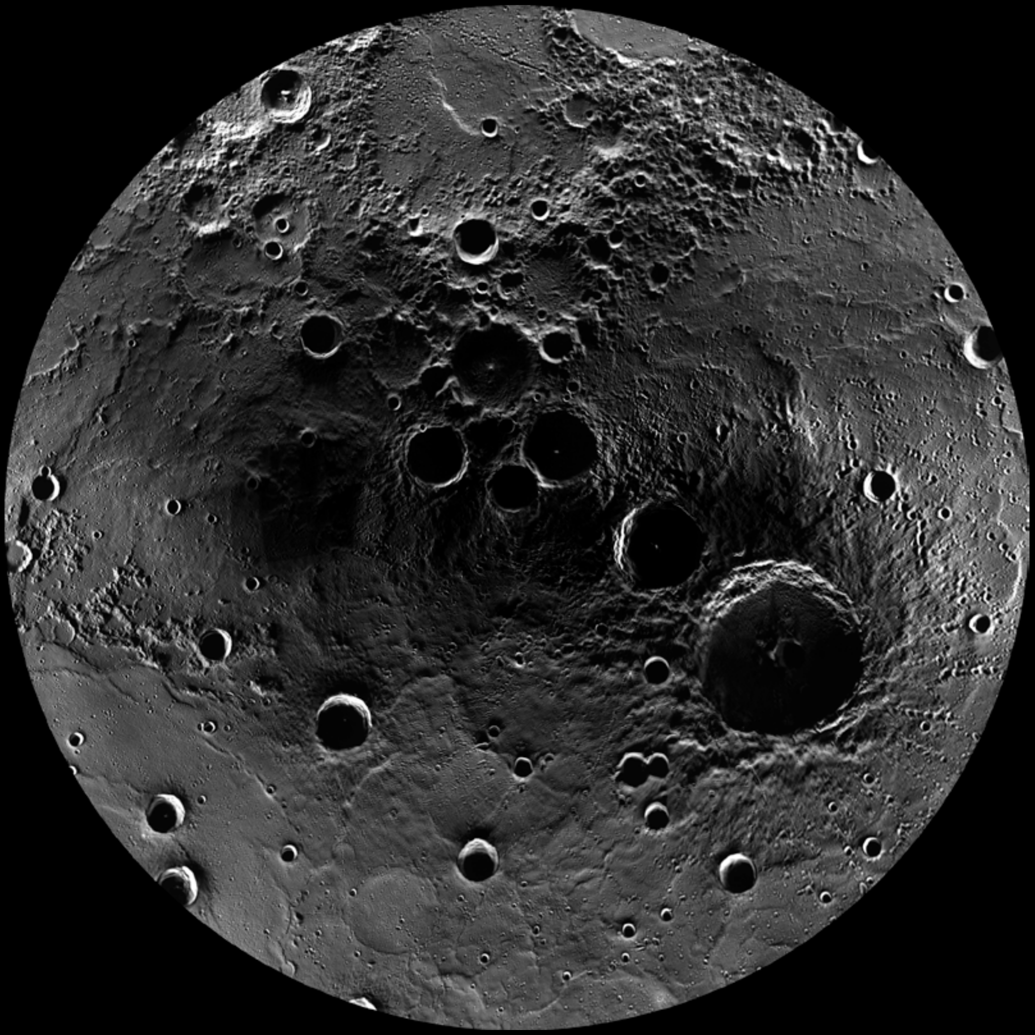


# Mercury Orbit Insertion (March 18, 2011)



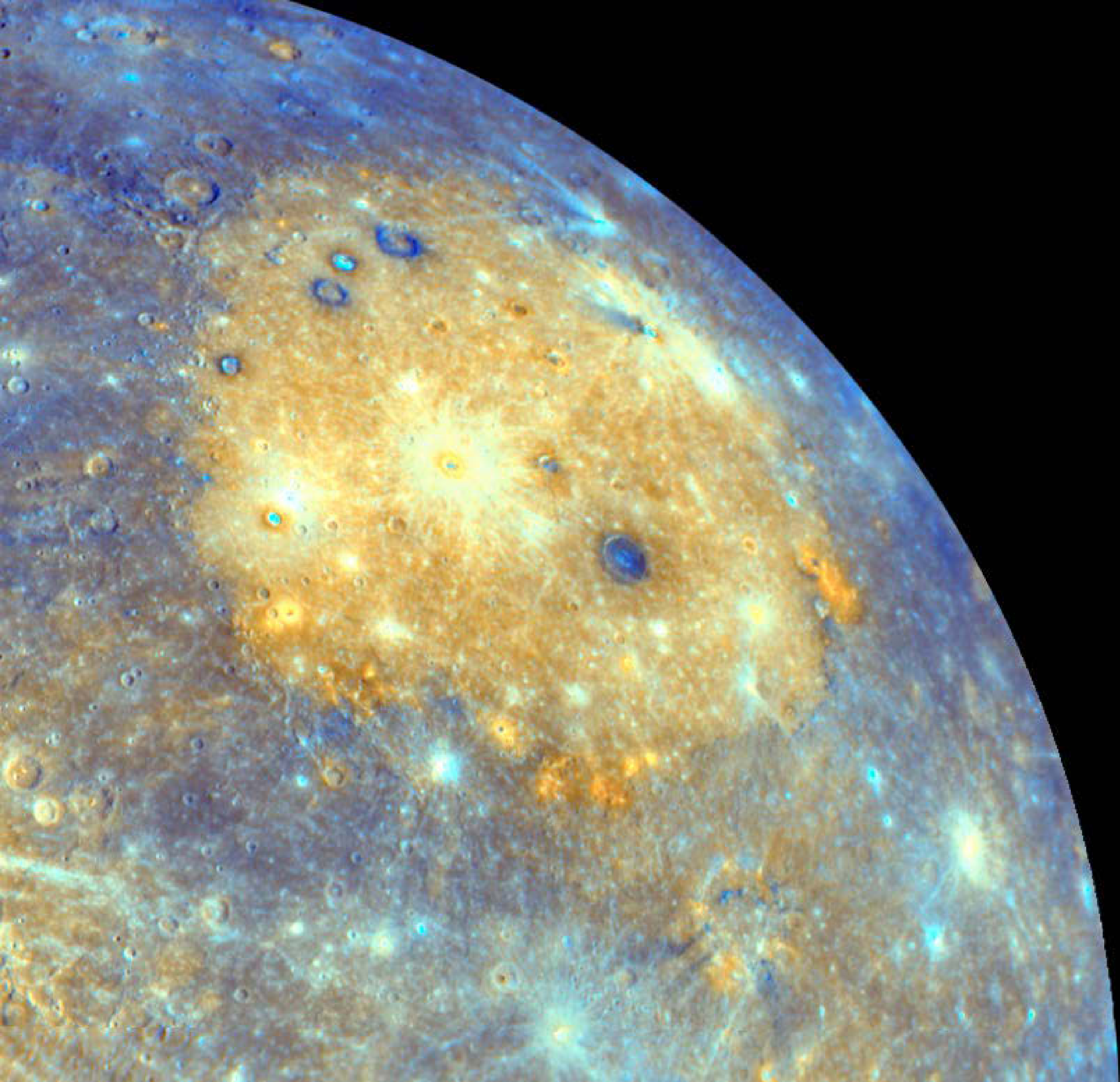

3634 orbits completed as of Nov 19, 2014

# After 3 flybys +2 years orbit, MESSENGER increased imaging coverage to 100%!



Mercury in “true” color – RGB: 630, 560, 480 nm

**Mercury in “enhanced” color – RGB: PC2, PC1, 430/1000**



**Caloris basin:**
**1550 km diameter**
**Mercury radius:**
**2440 km**
**RGB: PC2, PC1,**
**430/1000**

# Formation of Mercury

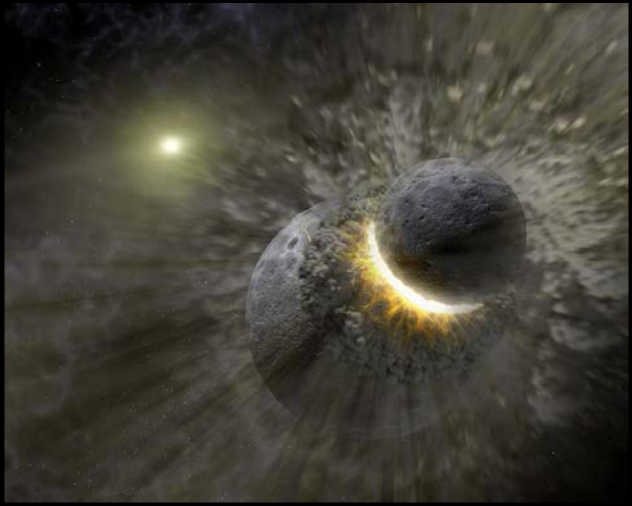
- Terrestrial planets shared common formation process:
  *accretion*

Dust -> Rocks -> Planetesimals -> Planets

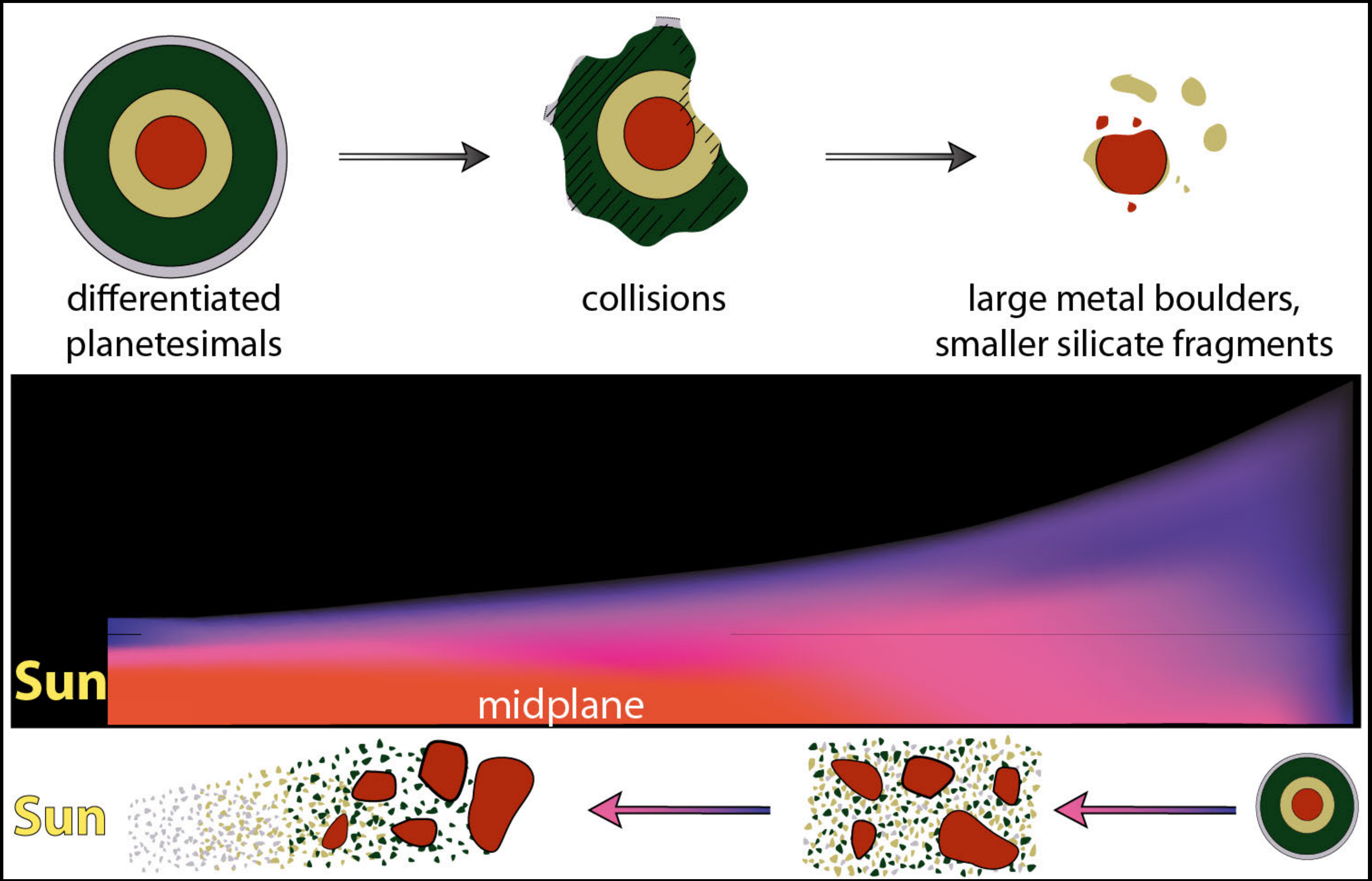
- Why is Mercury so iron-rich, relative to other planets?

# (pre-MESSENGER) Mercury Formation Models

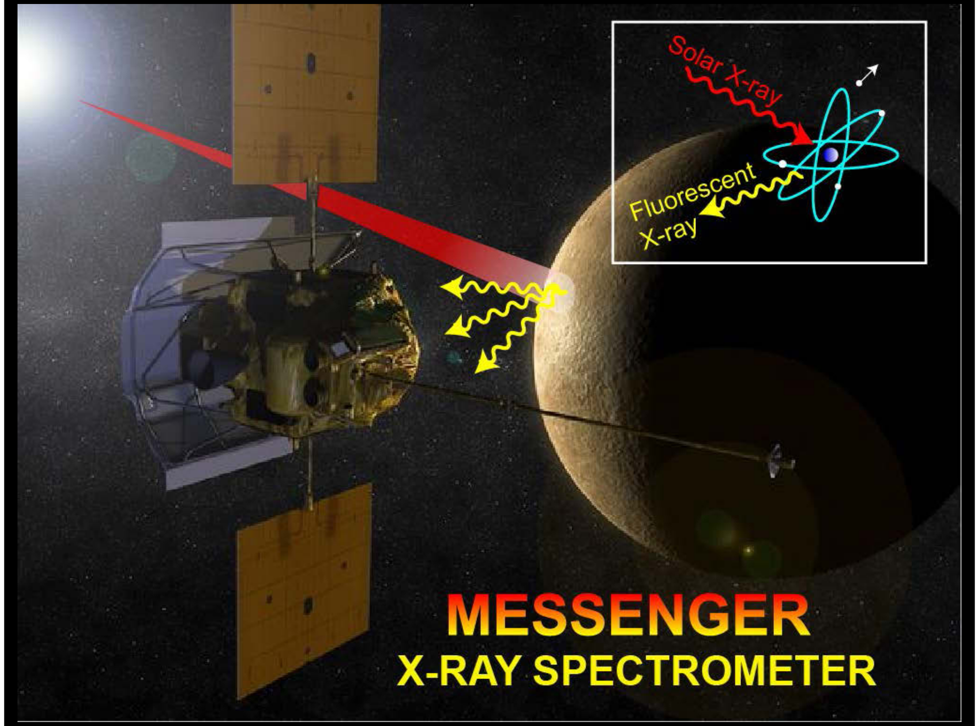
- Accretion at high-T? (Lewis 1973)
- Evaporation by hot Sun? (Cameron 1985)
- Giant impact stripping? (Wetherill, Benz 1988)



# Aerodynamic sorting (Weidenschilling 1978)

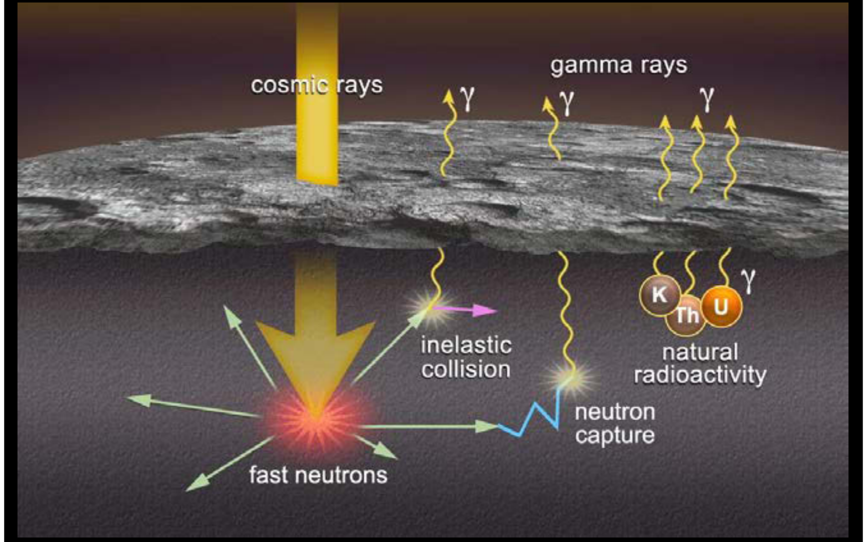


# Composition of Mercury

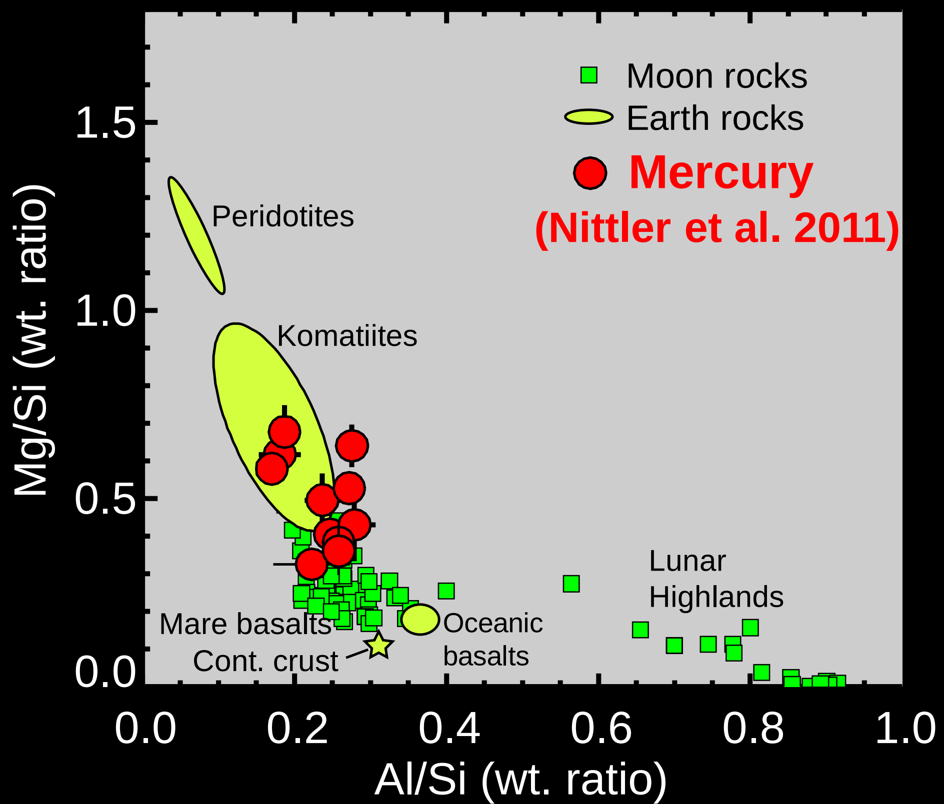


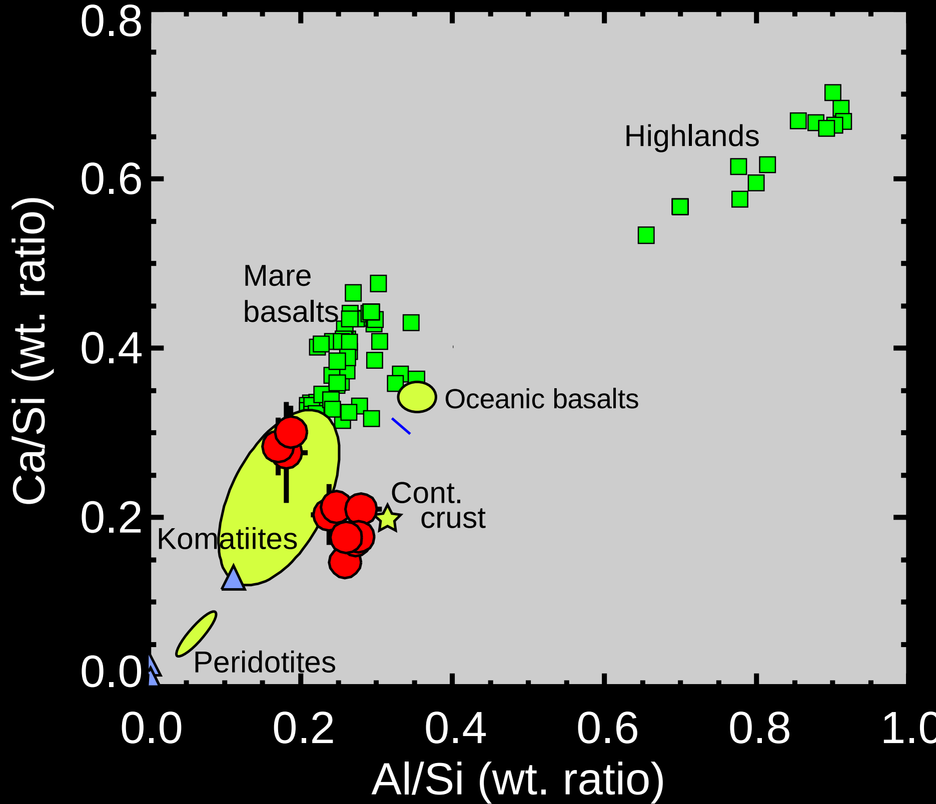

XRS measures surface composition by detecting solar-induced X-ray fluorescence

Gamma-ray/ Neutron Spectrometer (GRS/NS) measures surface composition by detecting cosmic-ray- and radioactivity-induced γ-rays and neutrons



# Major elements on Mercury




- XRS flare data indicate Mercury Mg-rich, Al-Ca-poor, relative to Earth and Moon surface

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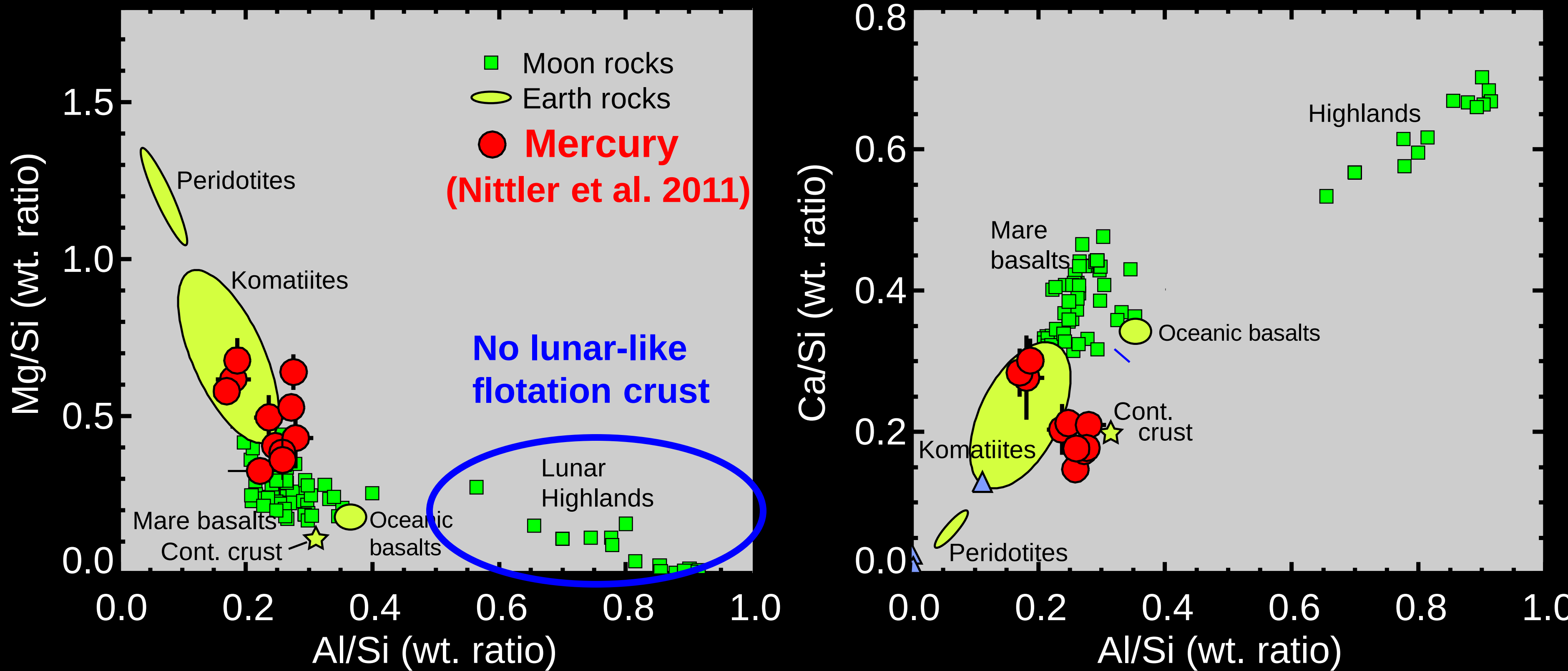


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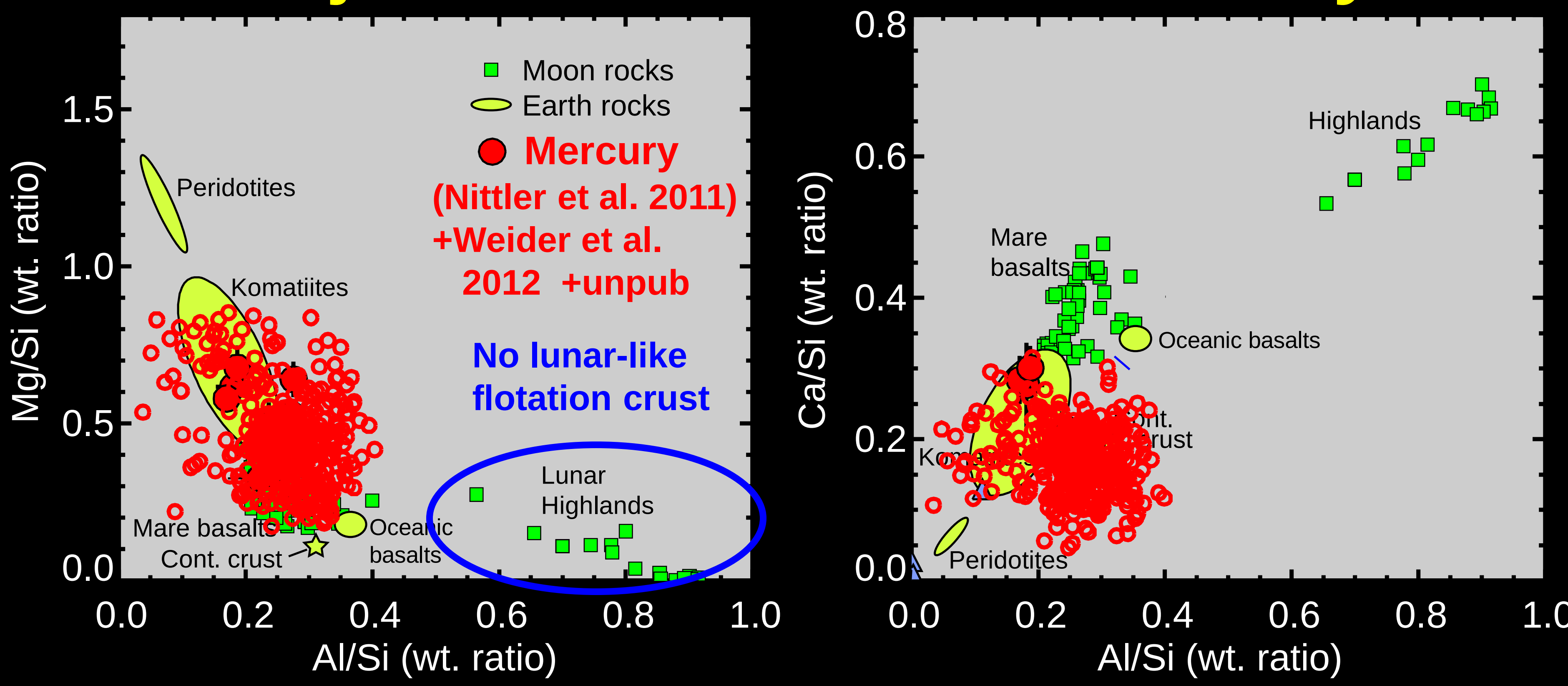


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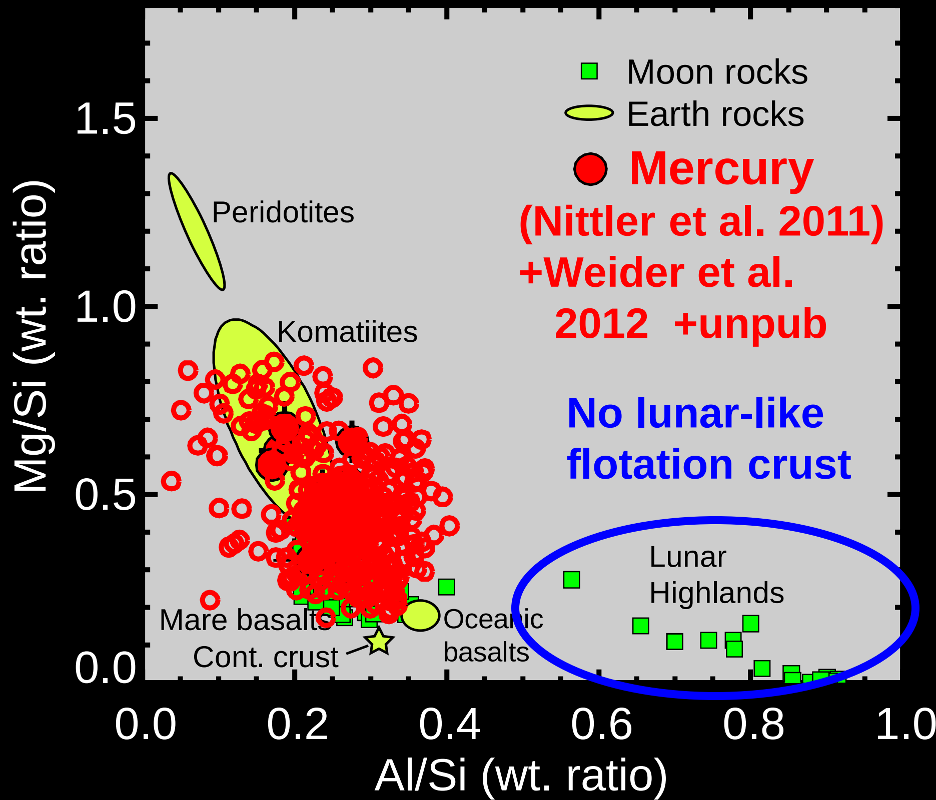
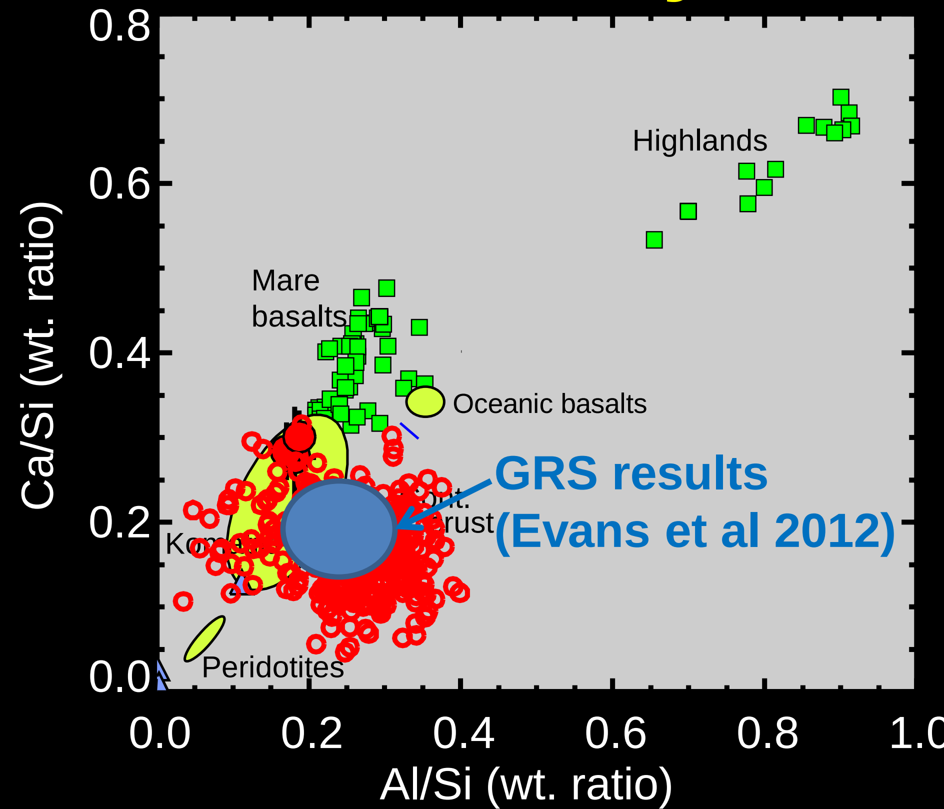
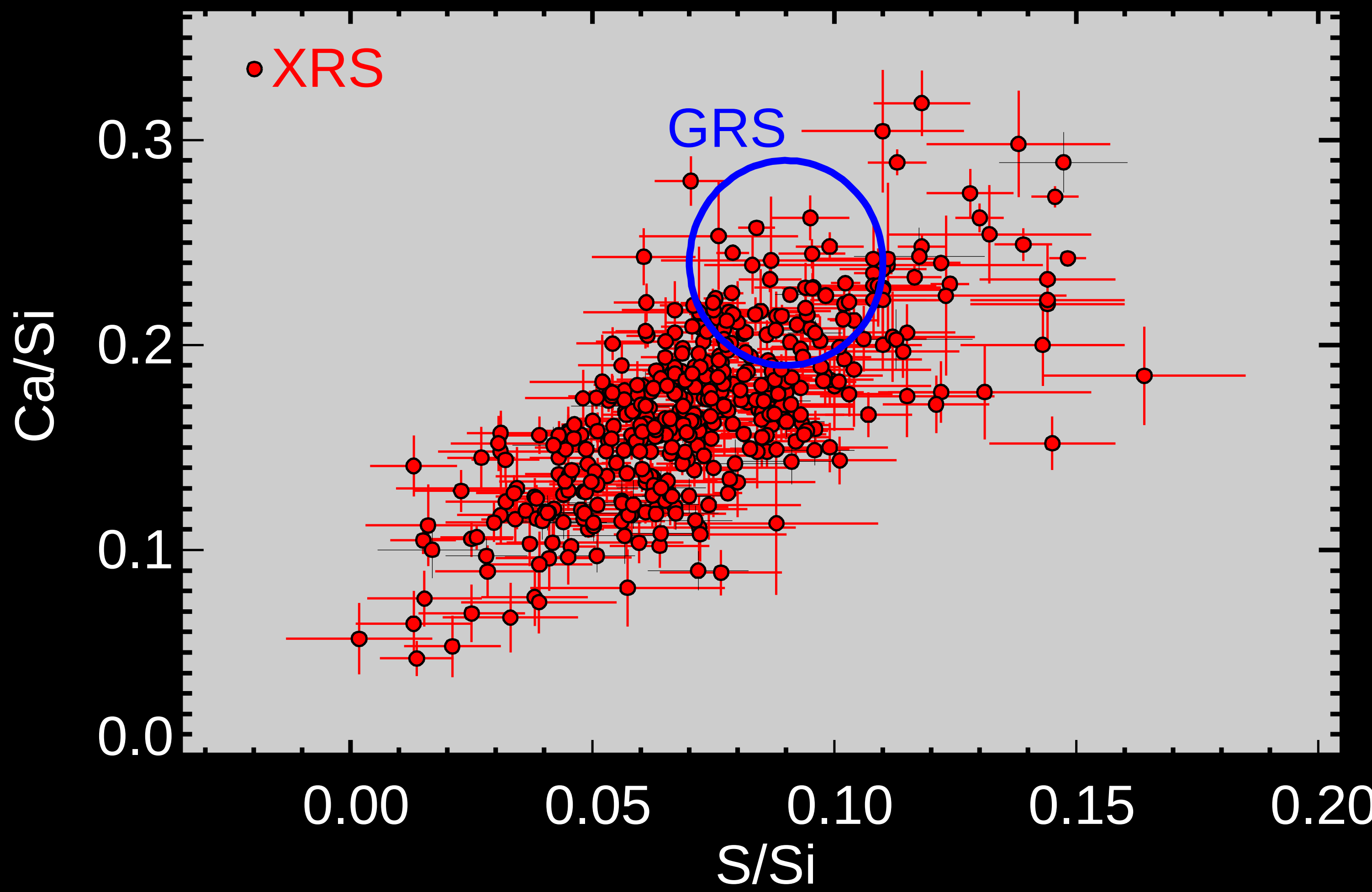


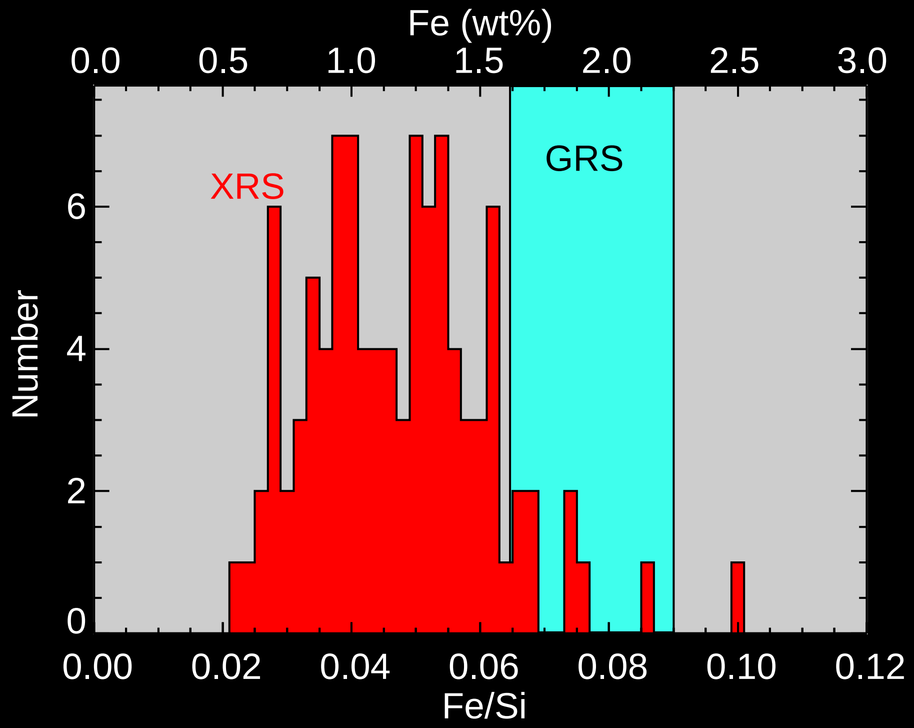

- XRS flare data indicate Mercury Mg-rich, Al-Ca-poor, relative to Earth and Moon surface
- GRS data consistent

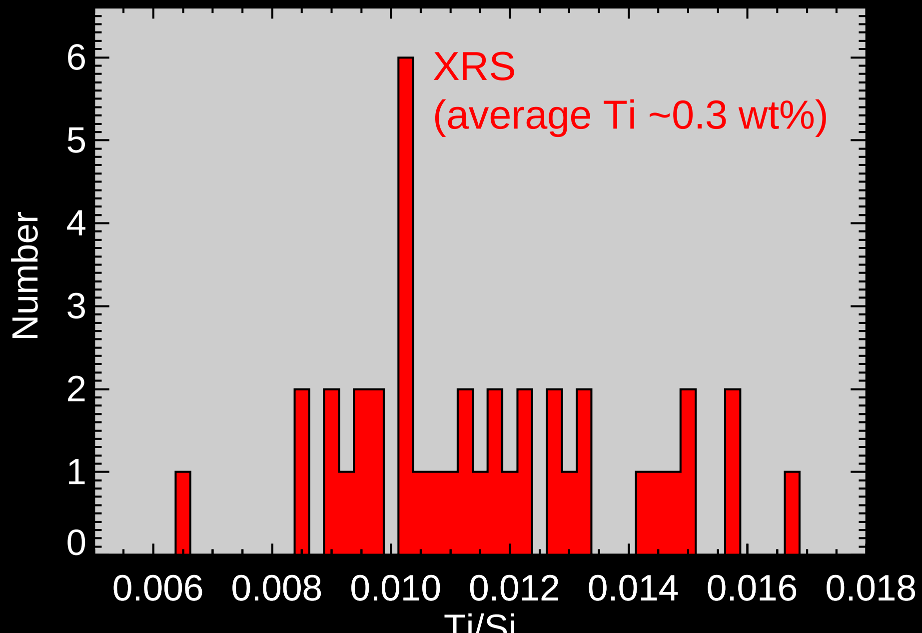
# High Sulfur




- S ~1-4 wt% (10x other terrestrial planet crusts)
- S strongly correlated with Ca
  - Presence of CaS?

# Iron & Titanium

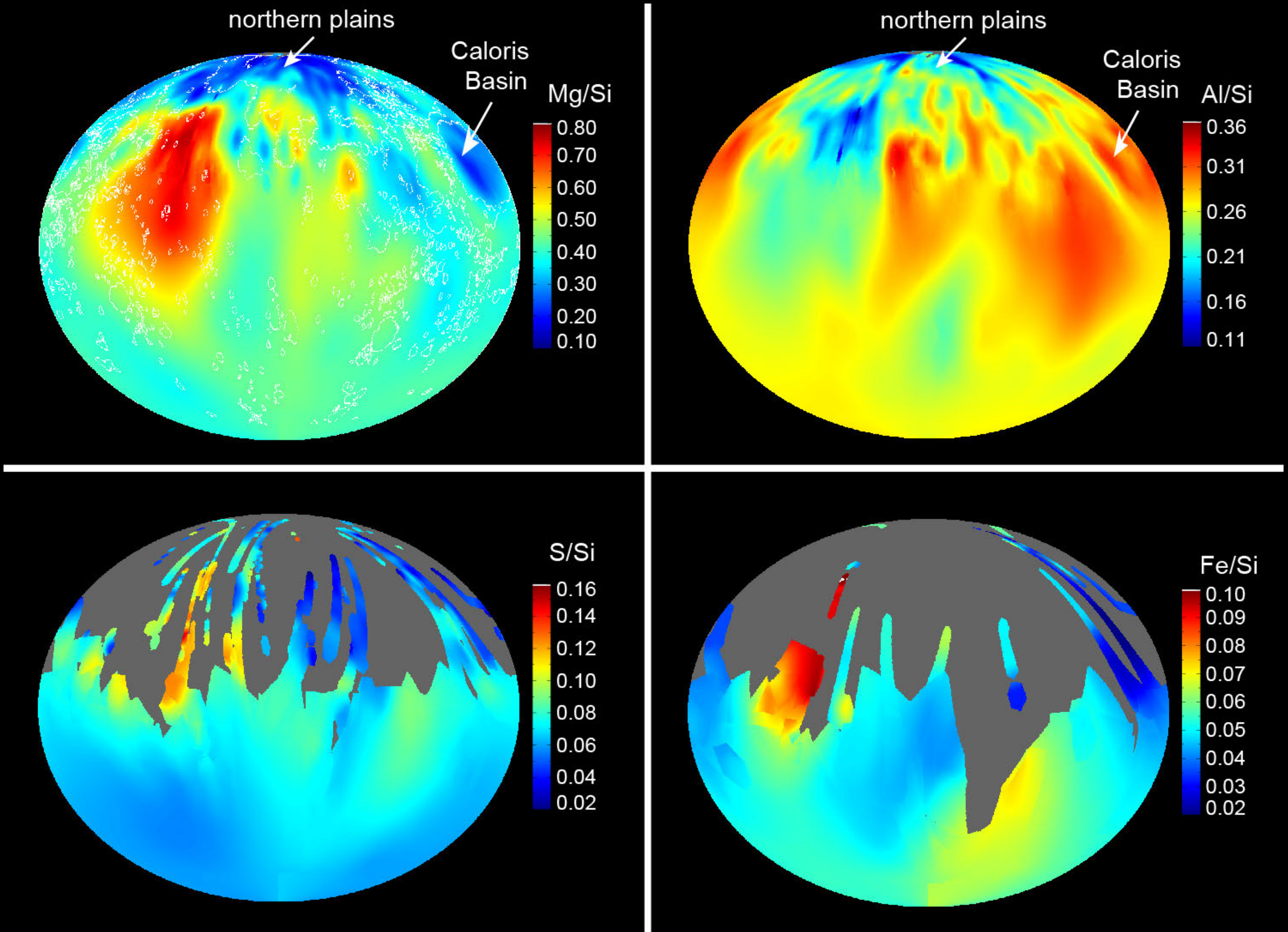



- Total Fe is low (<2 wt%)

- Ti low (<0.4 wt%)

# XRS element maps

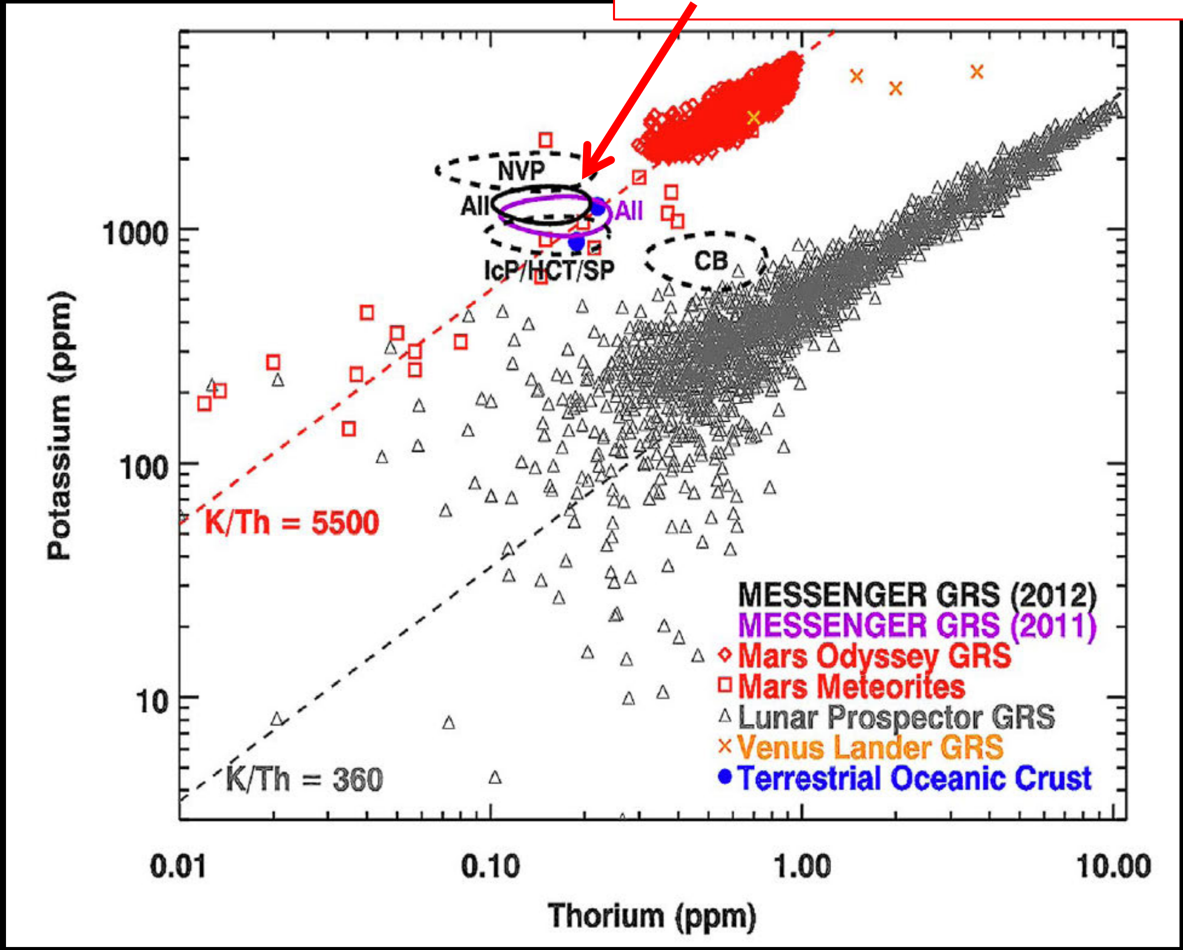



Weider et al. submitted

# K, Th on Mercury

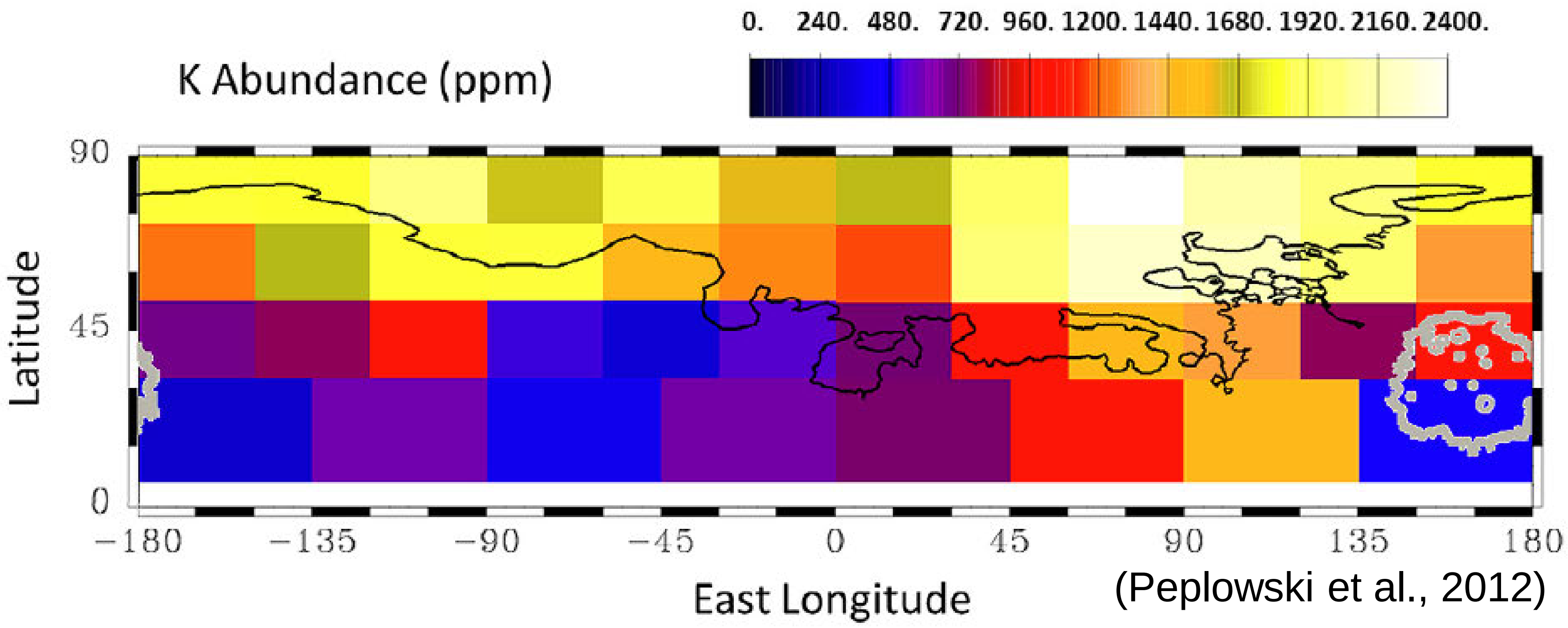
- GRS detects direct radioactive decay
- K~1000 ppm
- Th ~ 100 ppb
- K/Th~8000±3000
  - No sign of volatile depletion as seen in Moon

Mercury similar to Mars, Earth




(Peplowski et al., 2011,2012)

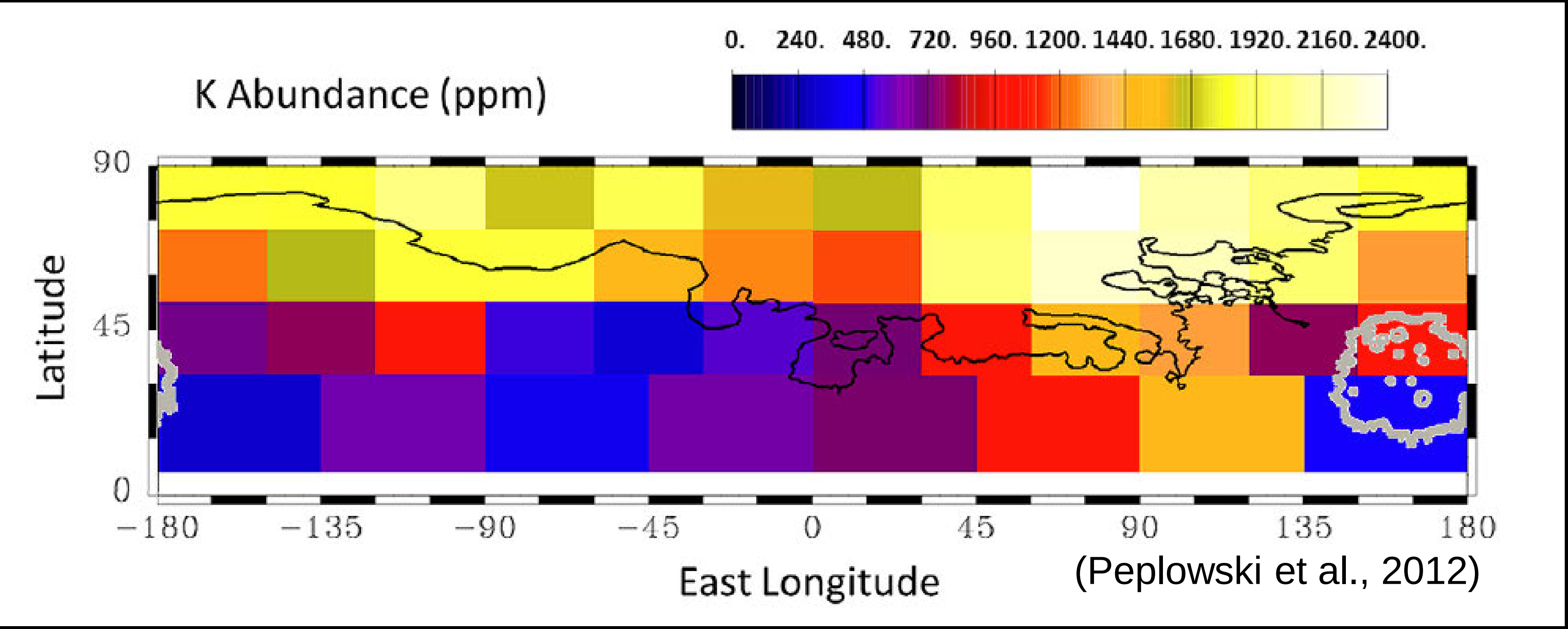
# K heterogeneity



(Peplowski et al., 2012)

- K abundance varies by factor of ~10
- Highest in North polar region (volcanic plains)
- Lowest where surface T highest
  - Thermal redistribution?

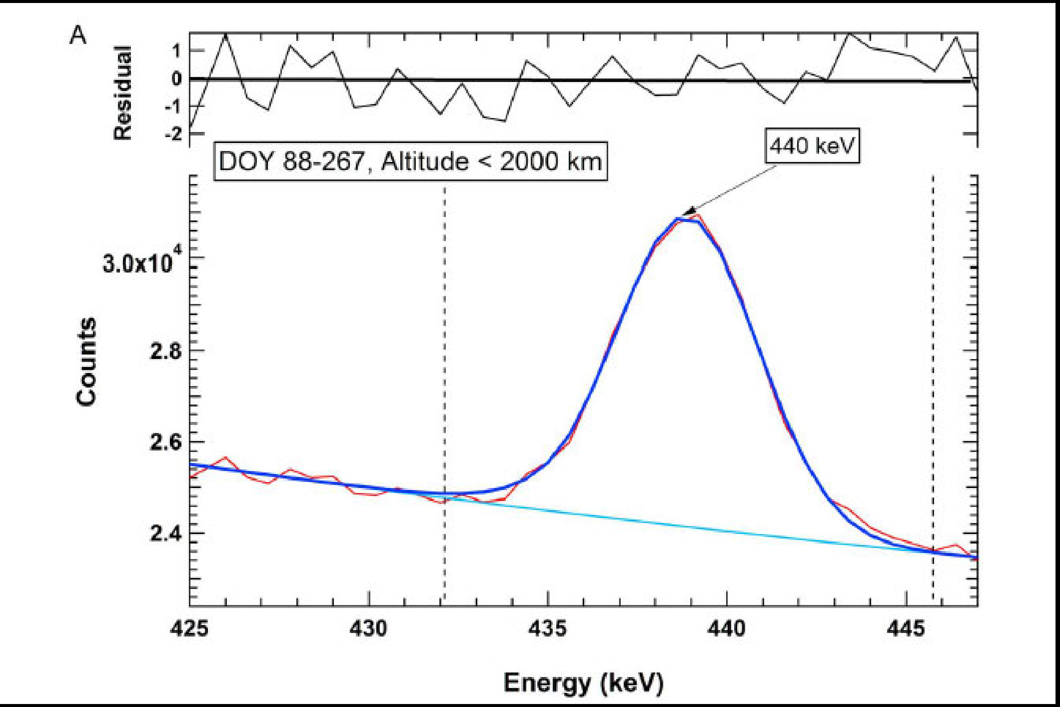
# K heterogeneity




- K abundance varies by factor of ~10
- Highest in North polar region (volcanic plains)
- Lowest where surface T highest
  - ~~Thermal redistribution?~~ Mineralogy

# Na on Mercury

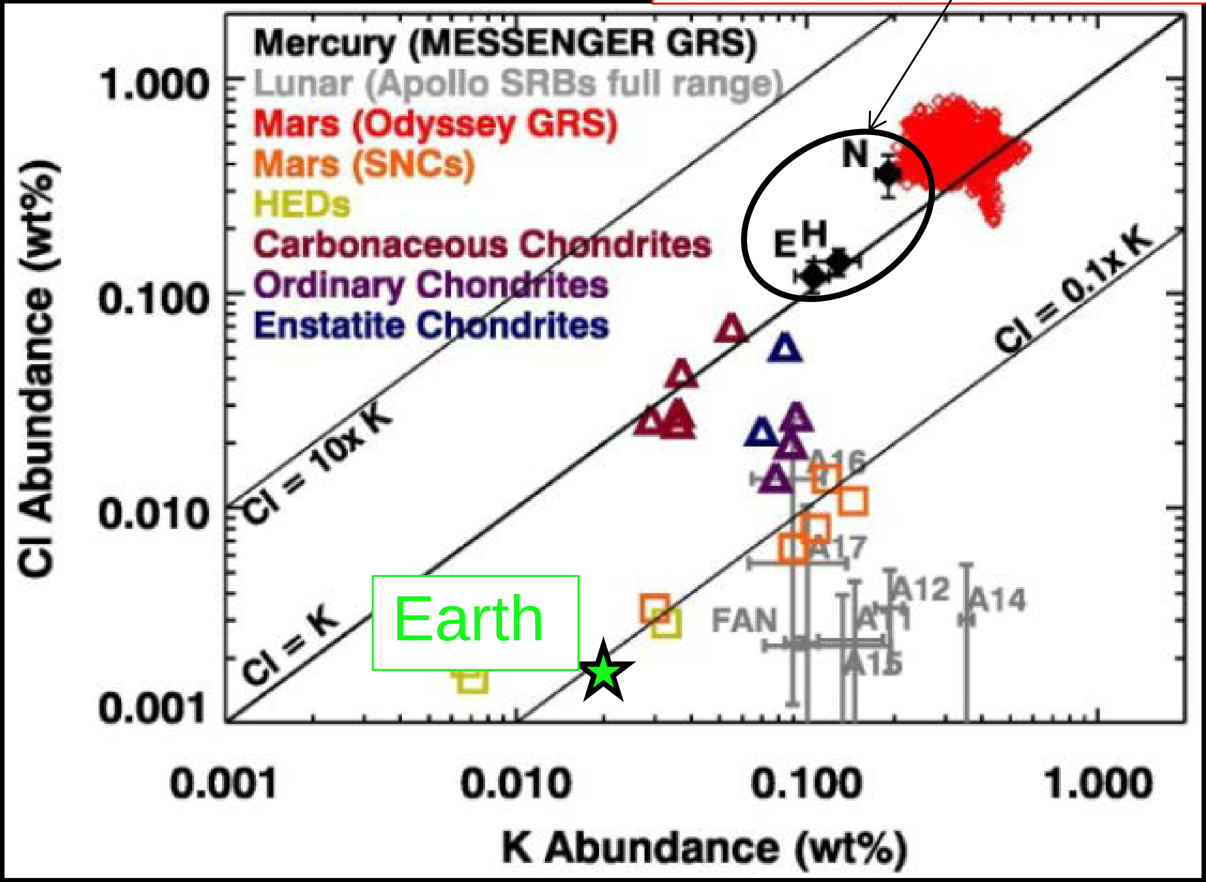
- Known to be present on surface from exosphere measurements
- GRS data reveals high abundance:
  - ~2.5 wt% at equator; 5% at north pole. (Evans et al. 2012, Peplowski et al 2013)



# Cl on Mercury

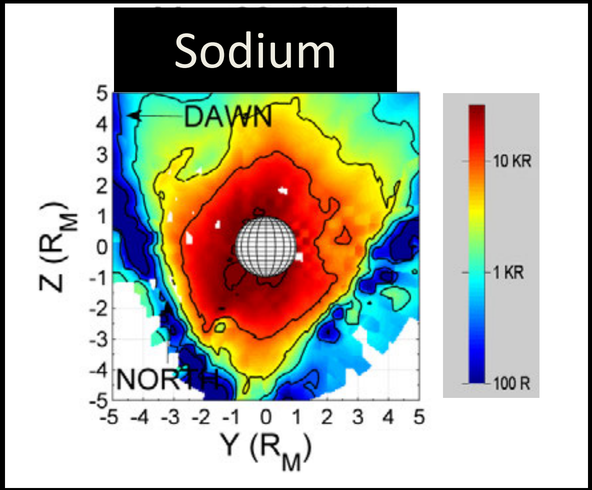
Mercury similar to Mars, Sun

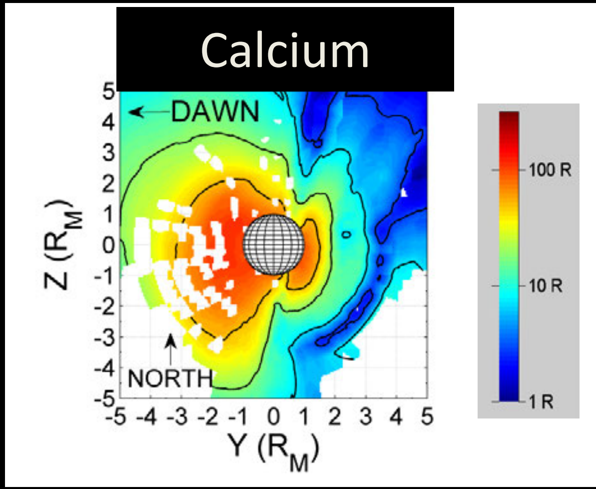
- Cl ~0.14 wt% on average (Evans et al. 2014)
  - 0.12 -0.35%
- High Cl/K may argue against giant impact



# Mercury's Exosphere

- Na, Ca, Mg most abundant species (H, O also seen)
- Asymmetries in distributions: different source mechanisms
  - Na uniformly distributed
  - Ca shows Dawn enhancement
  - Both show seasonal variability



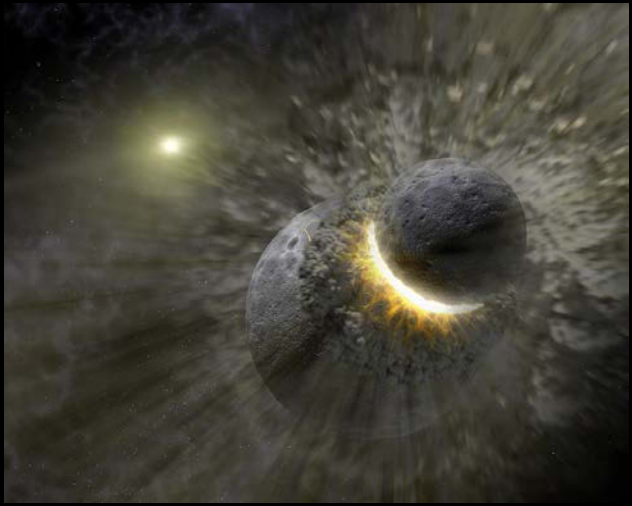




Vervack et al., 2011, Killen et al., 2012, Burger et al., 2012, 2014; Merkel et al., 2012

# (pre-MESSENGER) Mercury Formation Models

- Accretion at high-T? (Lewis 1973)
- Evaporation by hot Sun? (Cameron 1985)

- Giant impact stripping? (Wetherill, Benz 1988)



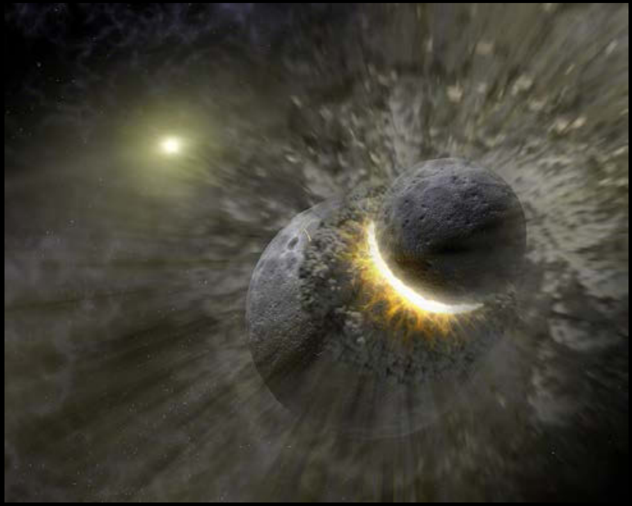
# (pre-MESSENGER) Mercury Formation Models

- Accretion at high-T? (Le
- Evaporation by hot Sun (

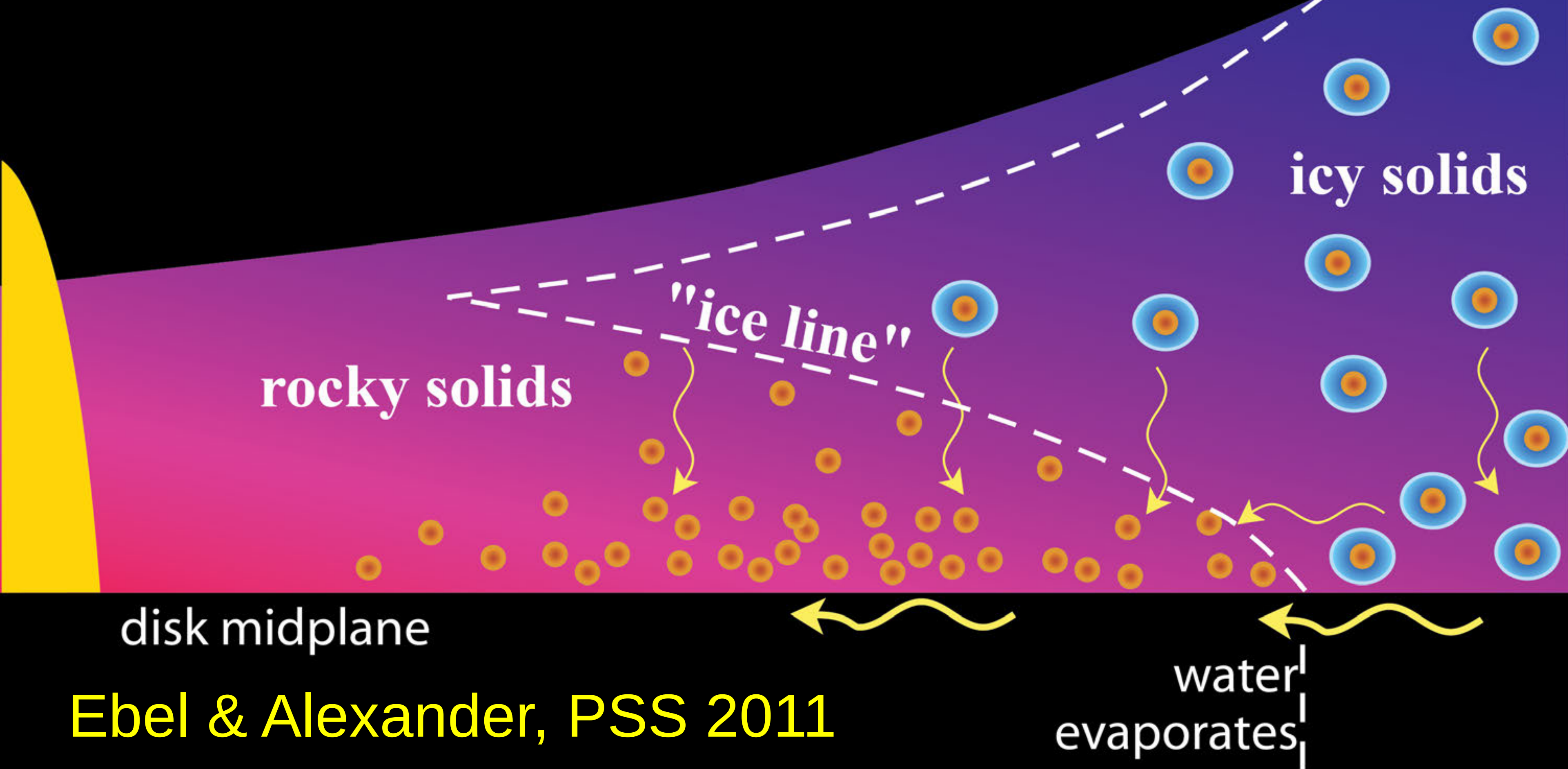
Predict very high Al, low K, S, Na

?

- Giant impact stripping? (Wetherill, Benz 1988)

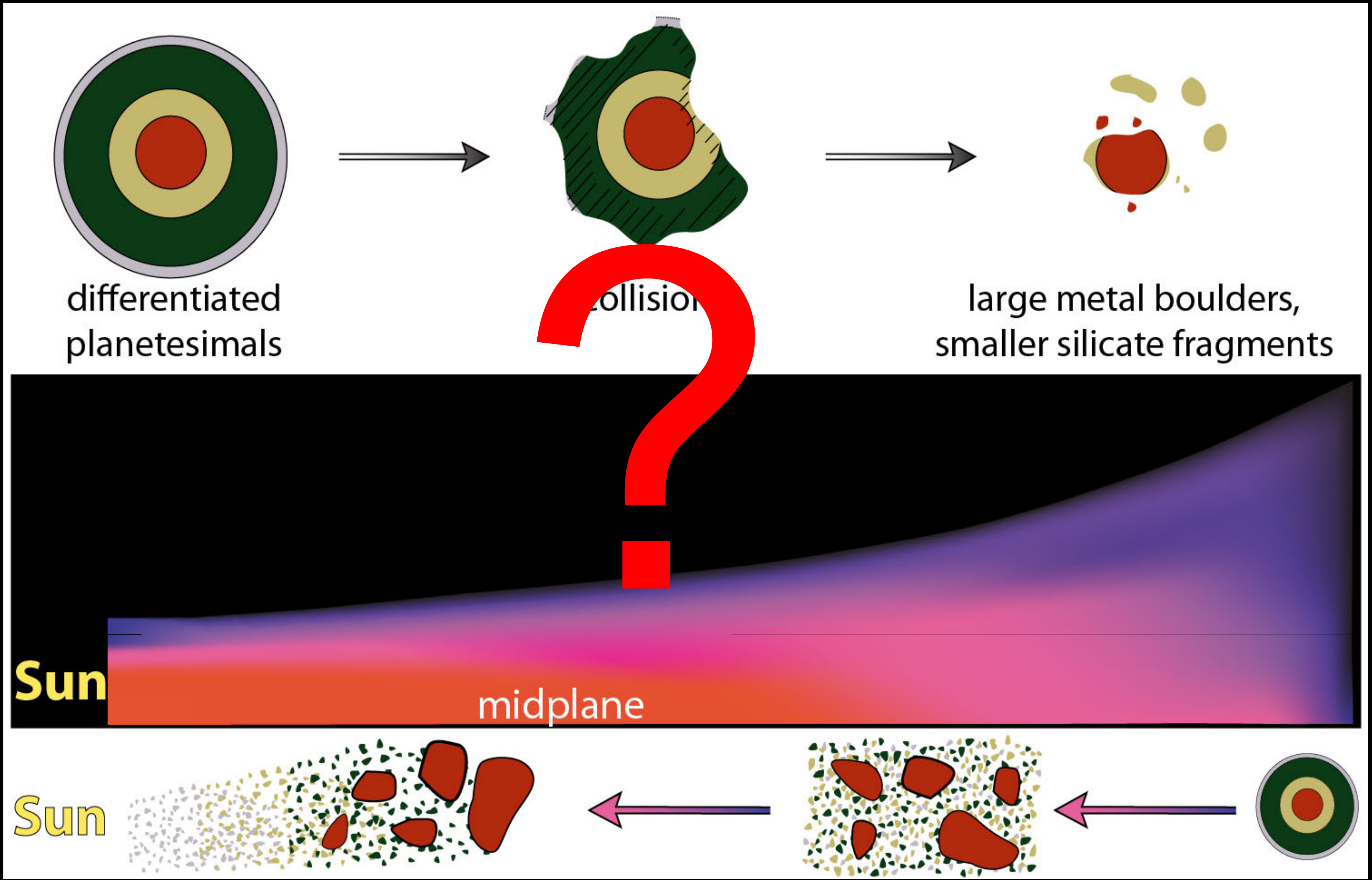


- High S, low Fe -> less O in starting materials compared to other planets
- Role of ice?

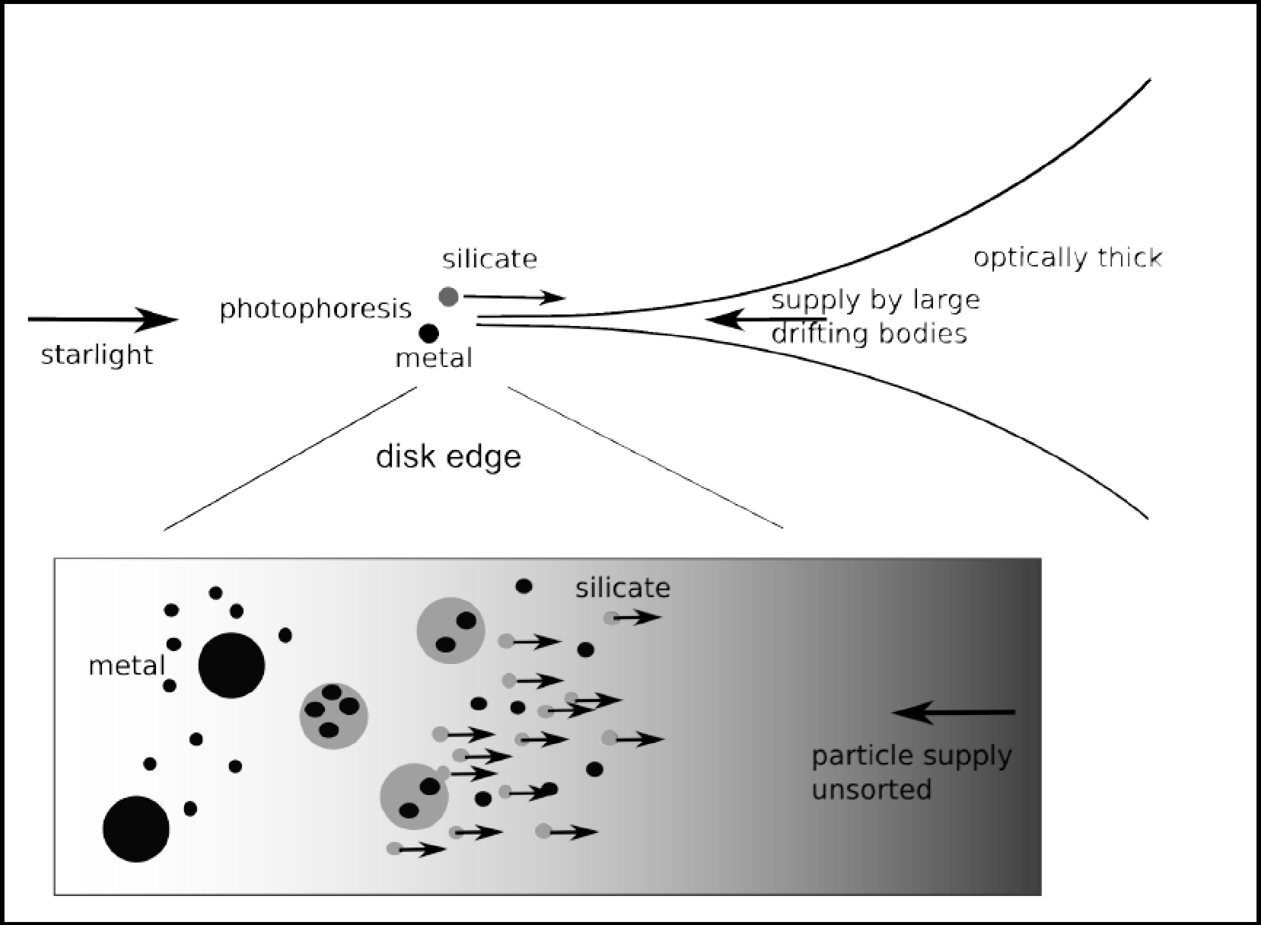



Ebel & Alexander, PSS 2011

# Aerodynamic sorting (Weidenschilling 1978)



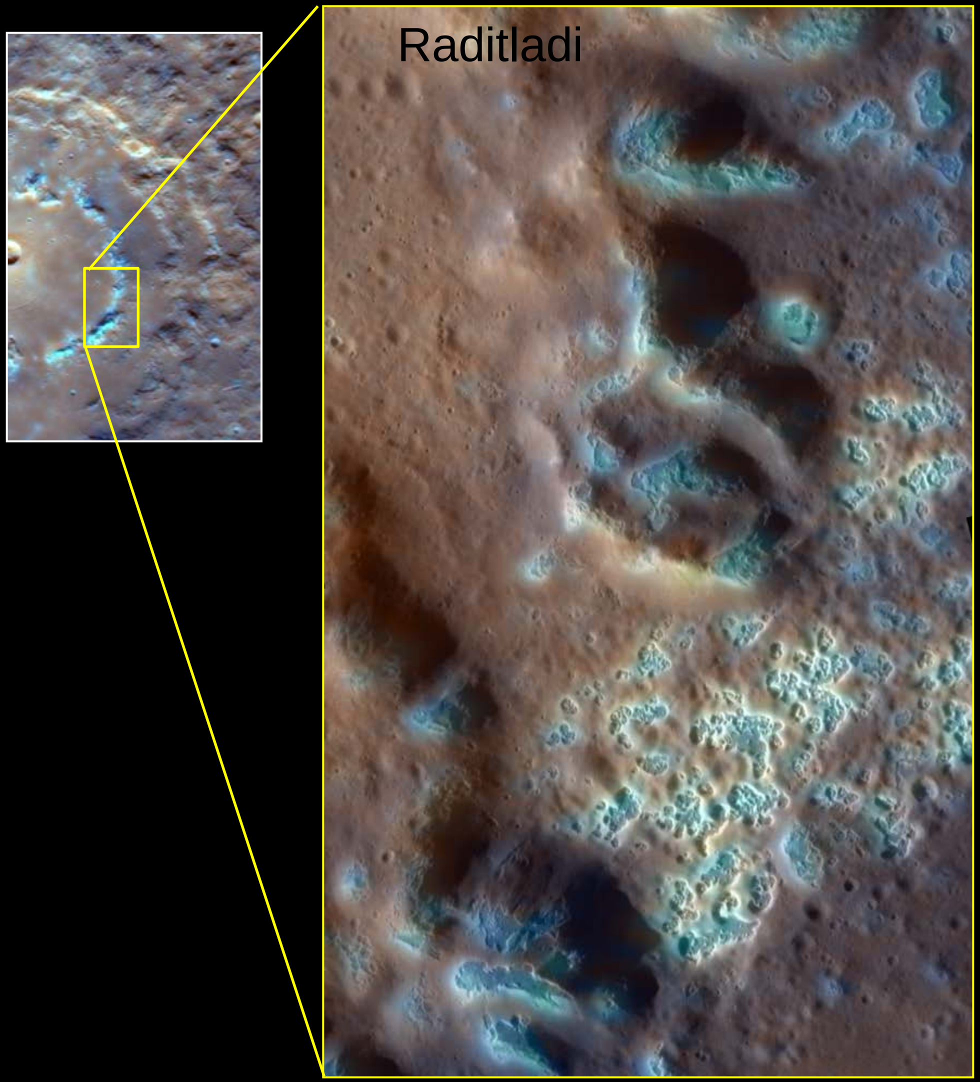
# Photophoresis?




*Wurm et al*. [ 2013]

# Volatiles: "Hollows"

- Bright deposits within impact craters show fresh-appearing, rimless depressions, commonly with halos.
- Formation from recent volatile loss?

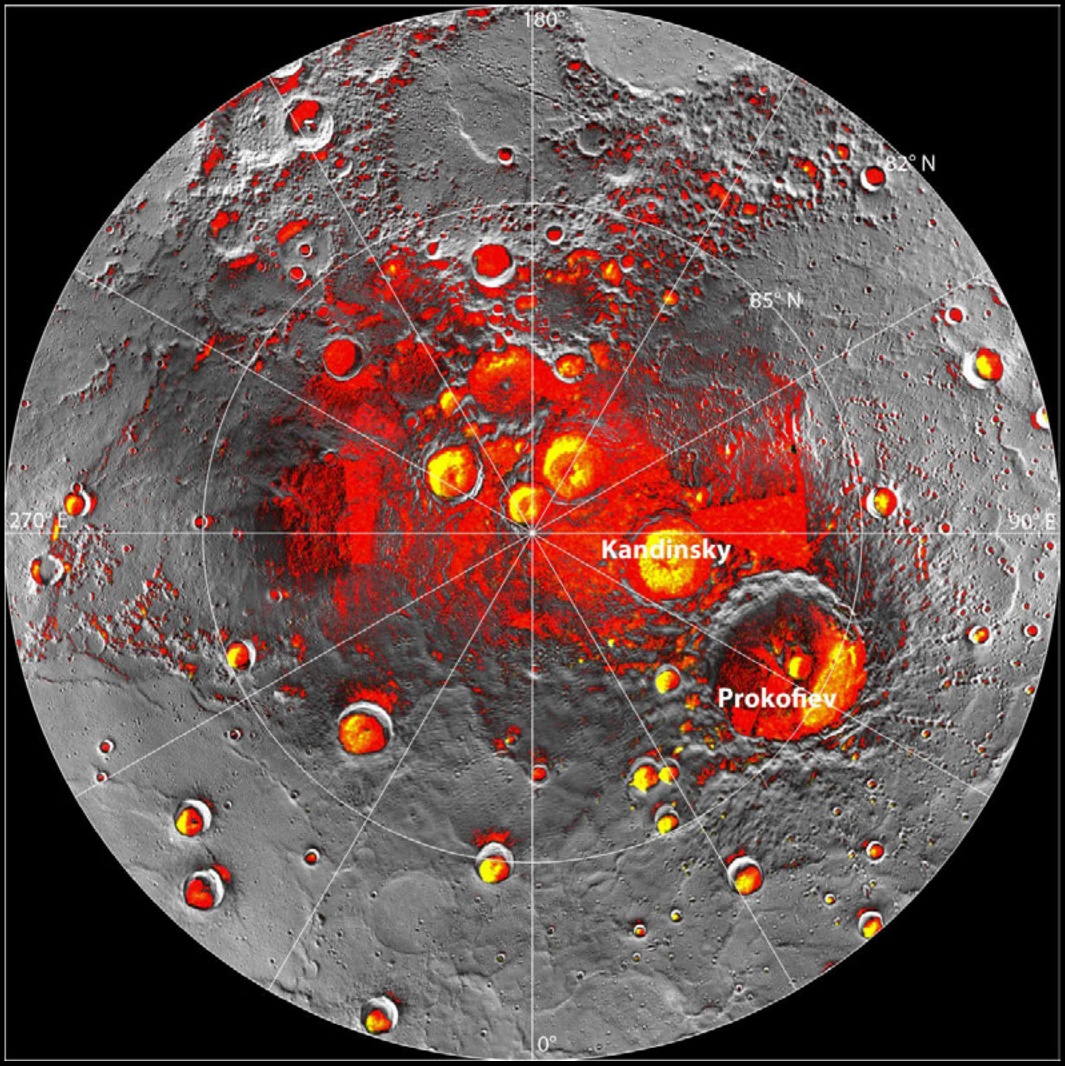



[Blewett et al., 2011]

# What are the unusual materials at the poles?


*Earth-based Radar map*
*(Harmon 1999)*

# What are the unusual materials at the poles?

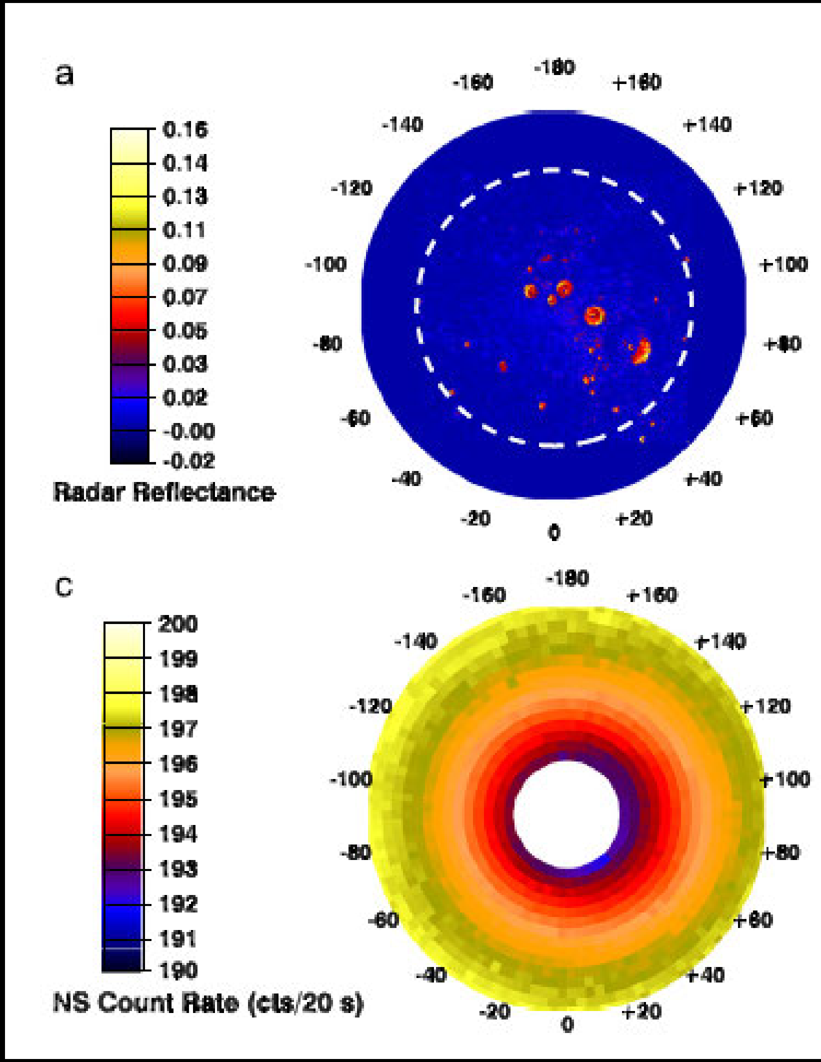



Polar deposits (yellow) and areas of persistent shadow (red) in Mercury's north polar region.

*MESSENGER data*

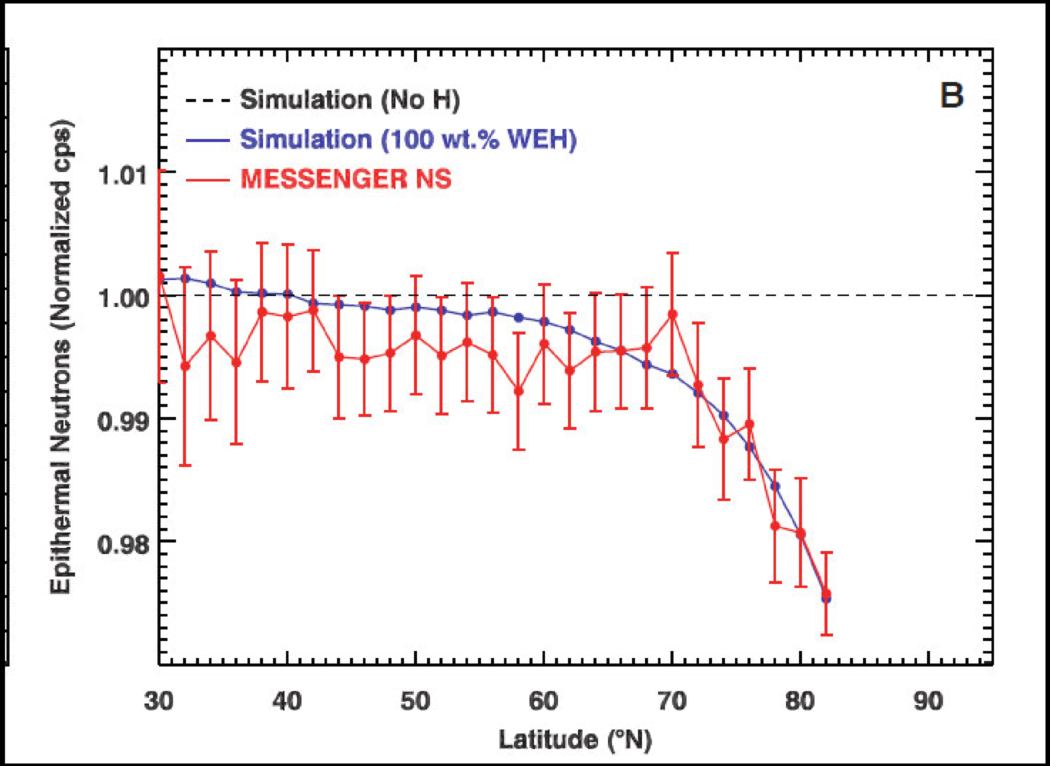
# What are the unusual materials at the poles?

- Neutrons highly sensitive to H
- Pre-orbit modeling indicated detectable dropoff in neutron signal in polar region if radar-bright regions are $H_2O$ ice




Lawrence et al., 2011

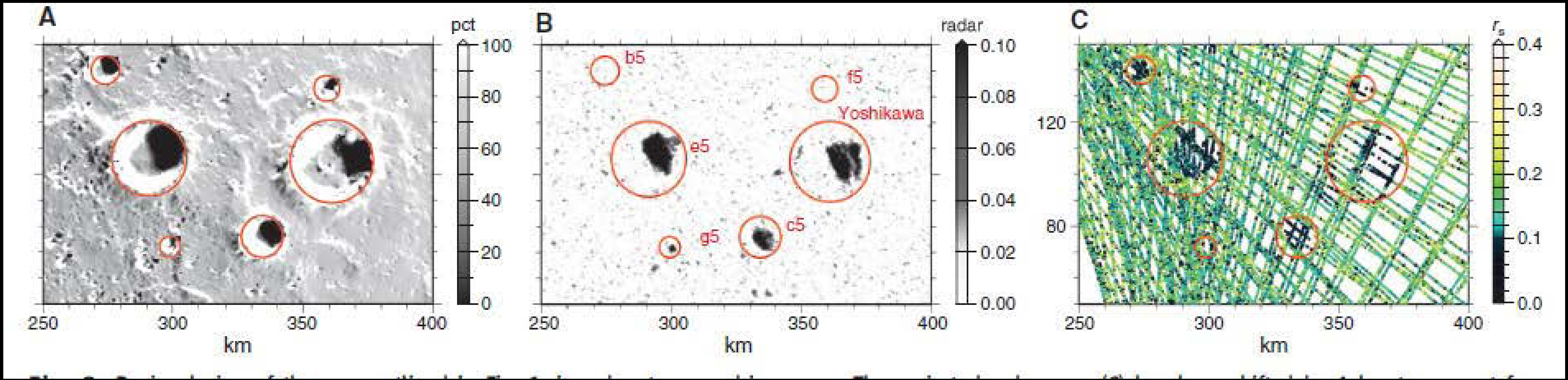
# What are the unusual materials at the poles?




- Neutrons indeed show predicted signal!
- Measurements of thermal (<0.5eV) and epithermal (<0.5MeV) indicate >tens of cm thick pure ice covered with layer of less-pure ice

*Lawrence et al.Science* [2013]

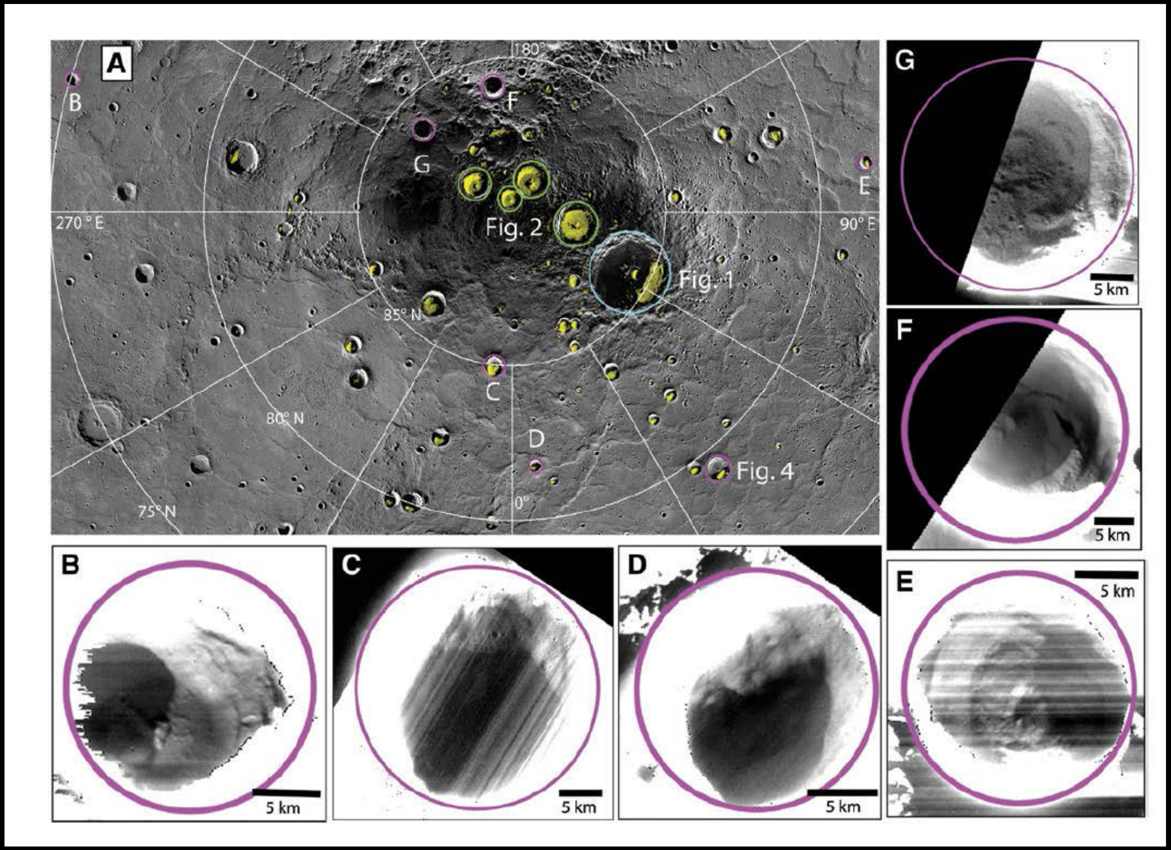
# What are the unusual materials at the poles?




- Reflectance from laser altimeter indicates some deposits dark at surface
- Points to presence of hydrocarbon layers on top of ice.
- Consistent with neutrons and thermal modeling

*Lawrence et al., Neumann et al., Paige et al. Science* [2013]

# What are the unusual materials at the poles?




- Deep imaging with main MESSENGER camera also reveals brightness variations in deposits (Chabot et al , 2014)

# What are the unusual materials at the poles?

- Neutrons, thermal modeling and MLA reflectance all point to radar bright materials being water ice + some organics
- Delivery by comets?

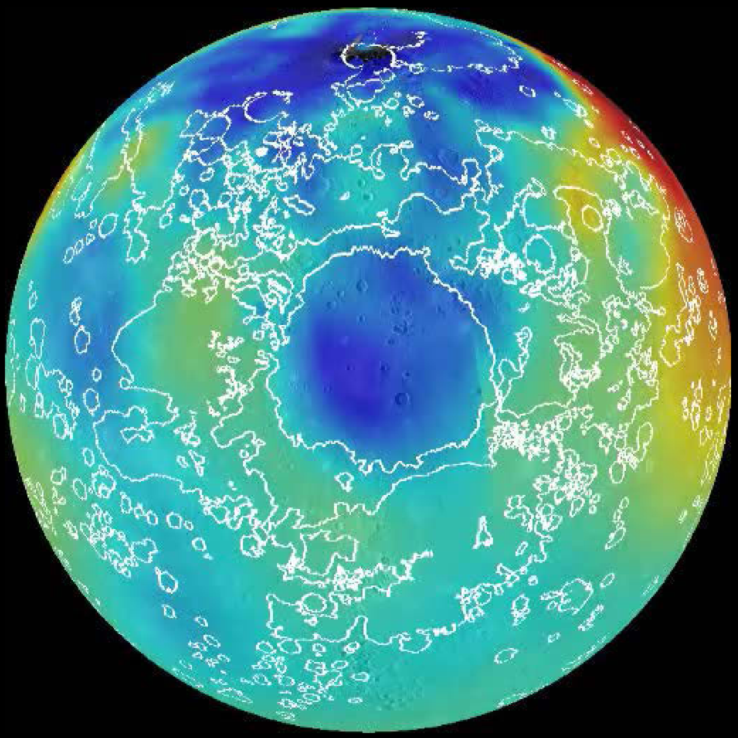
Ice and organics can be found everywhere throughout solar system

*Lawrence et al., Neumann et al., Paige et al. Science* [2013]

# The future?

- MESSENGER has enough fuel to last another 5 months
  - Achieving lower altitudes and unprecedented resolutions than before (and eventual impact in April 2015)
    - High resolution images, chemistry, (NS measurements of individual polar deposits, magnetic measurements (e.g., crustal anomalies)
  - Spacecraft is healthy and continuing to return great data

# MESSENGER at Mercury



Mg/Si on Mercury
Weider et al., submitted

- MESSENGER is an extraordinarily successful mission
- Despite its small size, Mercury is a weird and wonderful world.
  - Different in fundamental ways from other terrestrial planets
- Remarkably volatile-rich planet