University of Glasgow

Global to Local | Tectonics, Structural & Metamorphic Geology

LECT 3 | Planetary Formation

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WORLD CHANGING GLASGOW

Global2Local | Lesson Plan

Week	LECT | MON	LECT | TUE	LECT | WED	LECT | THU	LAB | M-T	LAB | W-F
INTRO 26/10/2020	–	–	**1 | Journey Across Scales**	2 | Firm Foundations	–	1 | Dimensional Analysis
UNIQUE EARTH 02/11/2020	3 | Planetary Formation	4 | Planetary Evolution	5 | Plate Boundaries	6 | Life Tectonics	2 | B-Y-O Planet	3 | Rock Deformation
DYNAMIC EARTH 09/11/2020	7 | Core Dynamics	8 | Mantle Dynamics	9 | Plate Dynamics	10 | Faulting & Folding	4 | Mantle Convection	5 | Faults & Folds
CONTINENTS 16/11/2020	11 | Collision & Orogeny	12 | Extension & Rifting	13 | Continental Metamorphism	14 | Topography & Erosion	6 | Metamorphic Rocks	7 | Structures & Textures
OCEANS 23/11/2020	15 | Formation	16 | Subduction	17 | Oceanic Metamorphism	18 | Hot Spots	8 | Metamorphic Rocks	9 | Tectonic Synthesis

Global2Local | Online Study Plan

Lecture Content

- *NO synchronous delivery*, work through in your own time (KEEP UP TO DATE!)
- Slides, video on **Moodle** one week before scheduled lecture
- Complete interactive tasks after each lecture (**Quiz**, **Padlet** link on Moodle)
- Ask and/or upvote questions online (**Slido** link on Moodle)

Lab Practicals

- Video, slides with instructions on Moodle on day of scheduled lab
- *Group-wise synchronous delivery* on **MS Teams** space as scheduled on timetable
- 15 min instructions on general channel at start (*not recorded!*)
- Work on Lab activities in existing Study Group channels (*not recorded!*)
- 15 min wrap-up at the end (*not recorded!*, video version available on Moodle after)
- Lab leader available throughout for questions, trouble shooting (*not recorded!*)

General Q&A

- drop-in session with GTA, Thursdays 9-10 am on Teams

Global2Local | Intended Learning Outcomes

UNIQUE EARTH | Planetary Formation

PART I – Dust to Planets

- Recent discoveries: images of protoplanetary disks, detection of exoplanets
- Planetary building blocks: gas, dust, ice; metals, silicates, volatiles
- Planetary accretion: from dust, to planetesimals, to planets

PART II – Solar System

- Terrestrial Planets: Mercury, Venus, Earth, Mars
- Gas & Ice Giants: Jupiter, Saturn, Uranus, Neptune
- Asteroid Belt, Kuiper Belt, Oordt Cloud: Pluto, Ceres, Vesta, asteroids, comets, etc.

Part I – Accretionary Disk

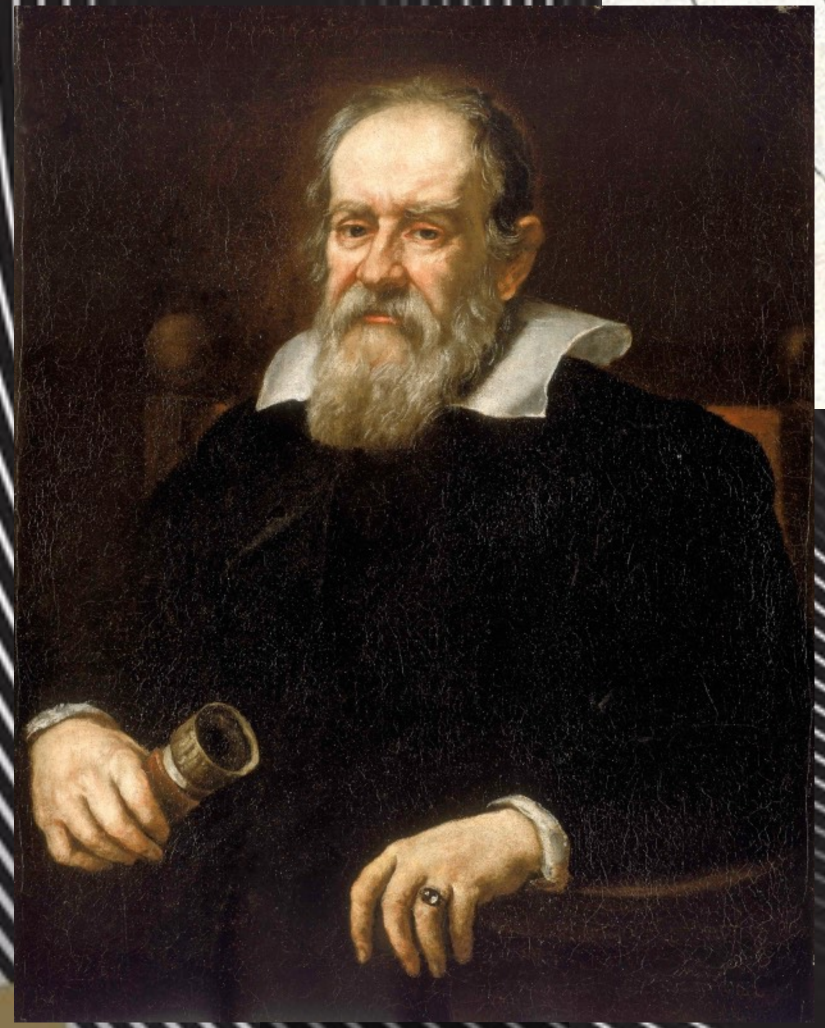
A Brief History

or why we're no longer at the centre of our worldview…

From Earth-centred to heliocentric

- for most of history, Earth thought stationary with sun, planets, stars rotation about it
- 16th century: ***Nicolaus Copernicus***, clergy man and astronomer, first presents heliocentric model of solar system
- 17th century: ***Galileo Galilei***, father of observational astronomy, studies details of sun, moon, planets by early telescope
- 17th century: ***Johannes Kepler***, mathe-matician and astronomer, formulates laws of planetary motion orbiting the sun

Copernicus



Galileo

Kepler

images: Wikipedia

The Solar System

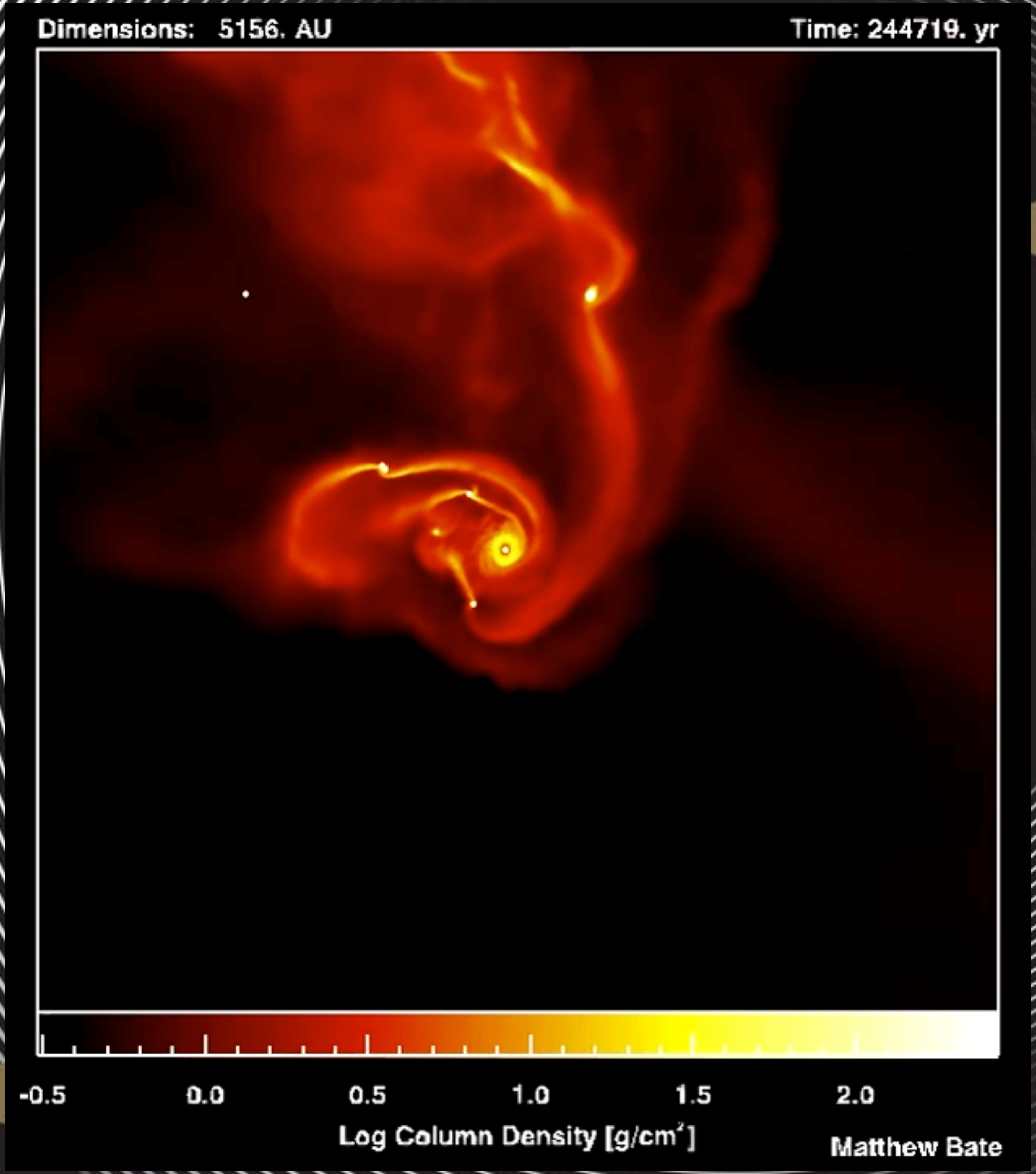
image: Wikipedia

We Are All Stardust

dust bunnies in a corner of the universe…

From cloud to disk

- H => He => light elements created by fusion in stars
- heavier elements created by supernova explosions
- new stars surrounded by proto-planetary disks form by gravitational collapse of molecular cloud



video: www.ukaff.ac.uk/starcluster/

Exiting Times

witness planetary formation *live!*

ALMA telescope images

- Atacama Large Millimetre Array
- images show gas/dust disks around young stars
- wide range of patterns
- rings and gaps visible

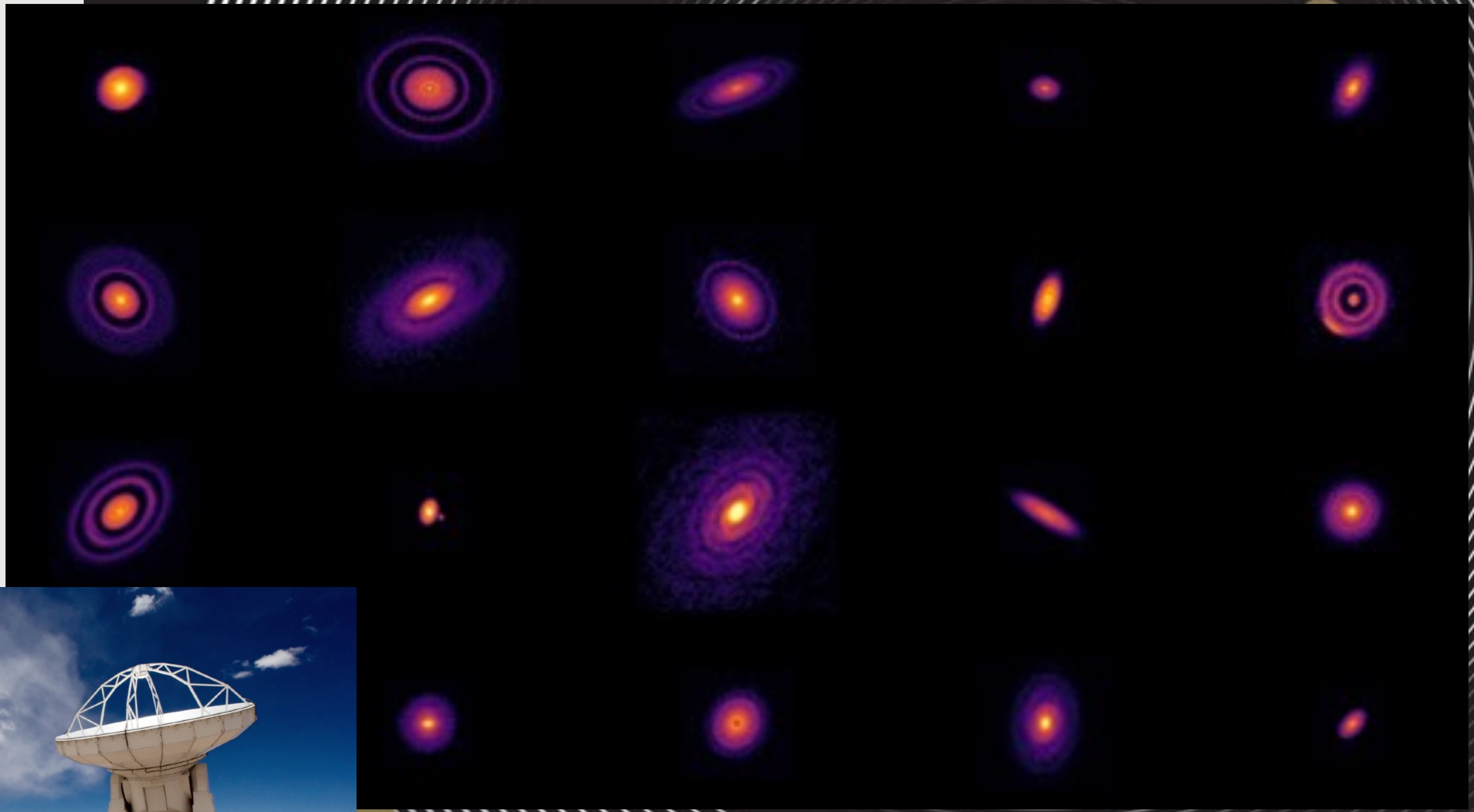


image: ALMA

Exoplanetary Zoo

Exoplanets *everywhere!*

Planets present around most stars

- >1000 of new worlds discovered
- mostly gas and ice giants so far
- large planets close to star easiest to detect
- some systems with >10 planets
- wide diversity of planetary systems

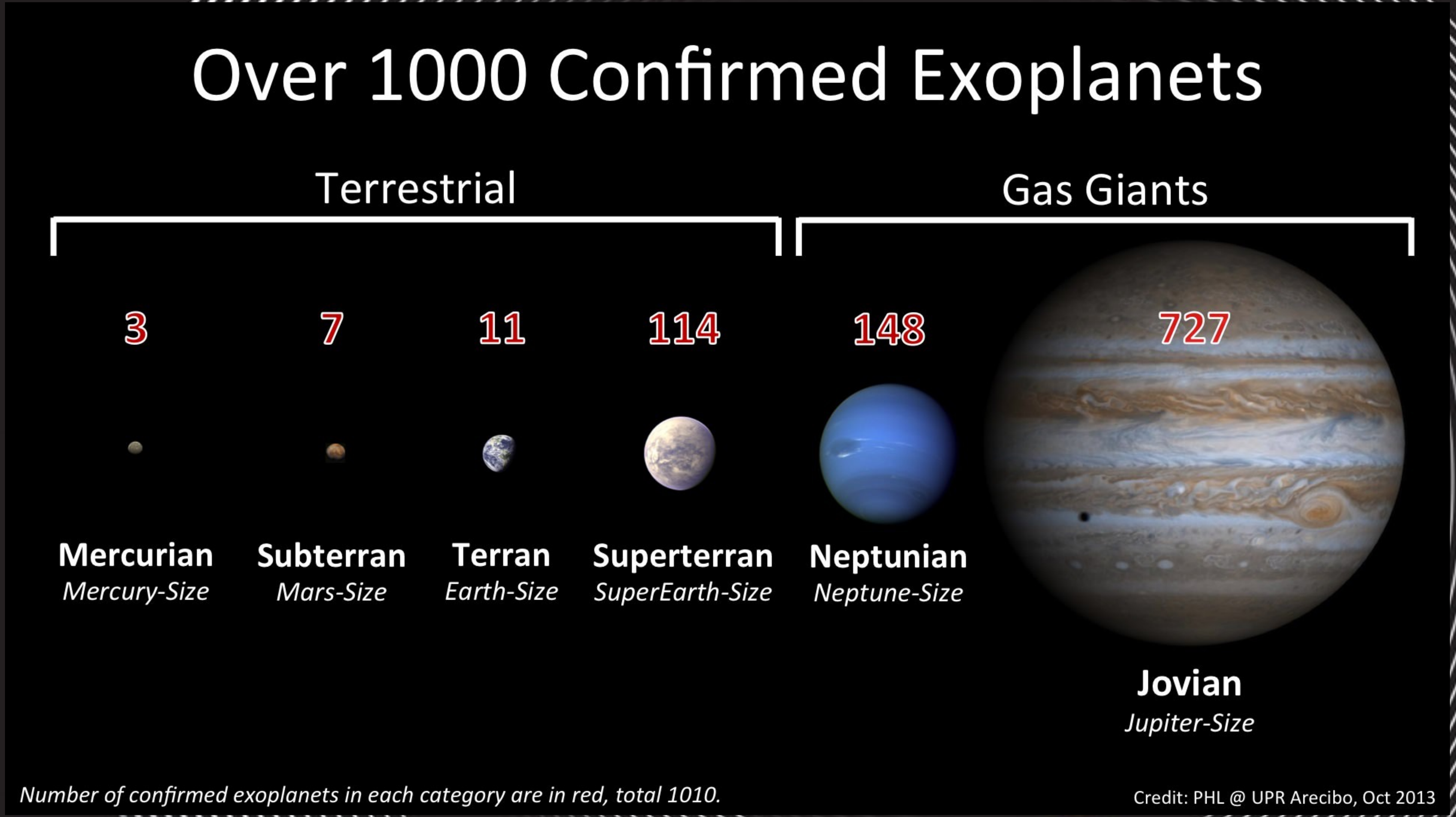


image: Planetary Habitability Laboratory, UPR Arecibo


video: California Academy of Sciences

Planetary Formation | Dust to Planets

Planetary Disk Condensation

- Disk made up of various materials
  - gas (H/He,~99%), ices (H2O, CH4, NH3, etc.), silicates (olivine, pyroxene, feldspar), metals (Fe,Ni), Ca-Al-rich minerals (CAIs)
- material condensation follows disk temperature
  - high-*T* condensation in inner disk
  - low-*T* condensation in outer disk
  - *snow-line* marks disk radius outside which ice grains condensate, increase in particle density

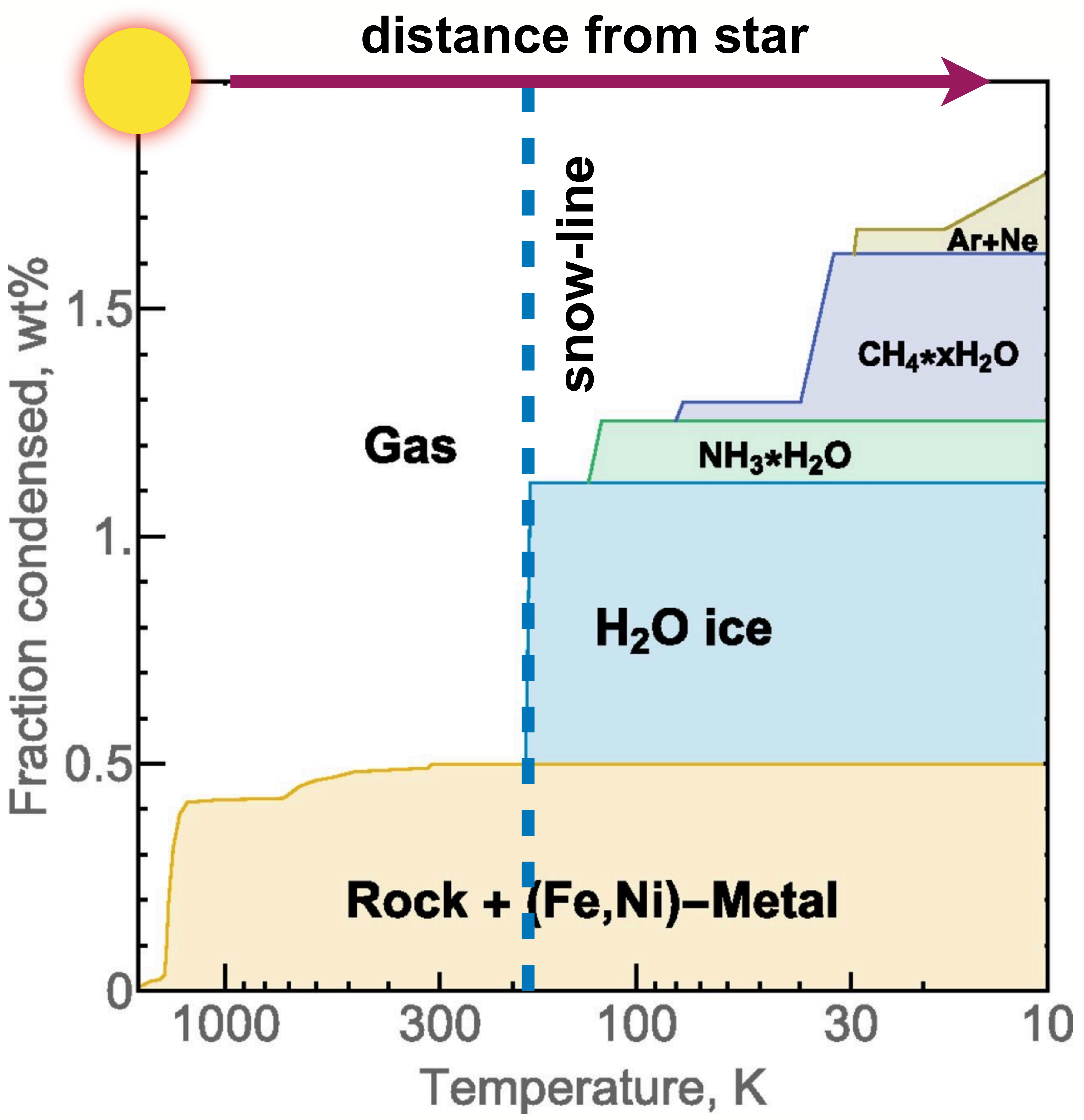


figure: Zeng et al., *PNAS*, 2019

Planetary Formation | Dust to Planets

Planetary Disk Condensation

- high-to-mid *T* condensation:
  - Ca-Al-rich minerals
  - metals, olivine
  - feldspar, pyroxene

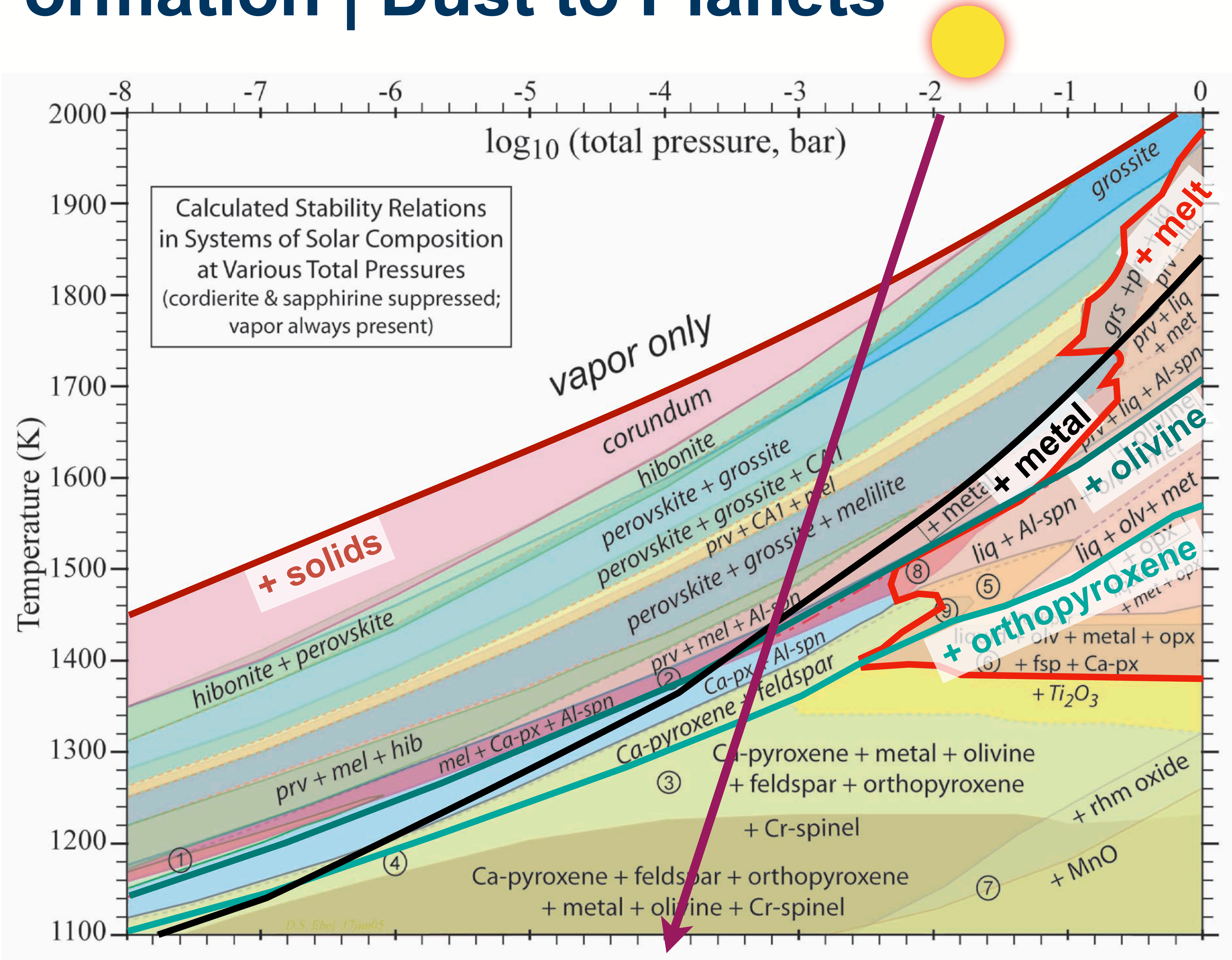


figure: Ebel, in Lauretta & McSween, 2006

Planetary Formation | Dust to Planets

Planetary Formation Mechanisms

Dust to Planetesimals

- Gravity: mass attracts more mass, but is weak for gas, small grains, to pebbles
- Turbulence: turbulent flow instabilities can lead to matter concentration in disk
- Adhesion: dust and ice grains loosely clump together by static adhesion
- Metre-sized barrier: cm- to m-size "pebbles" do not accrete well by collision!
- Jump straight from gas/dust/fluff/pebbles to ~100 km size planetesimals?

Law of Gravitation: $F = G\frac{M_1 M_2}{r^2}$

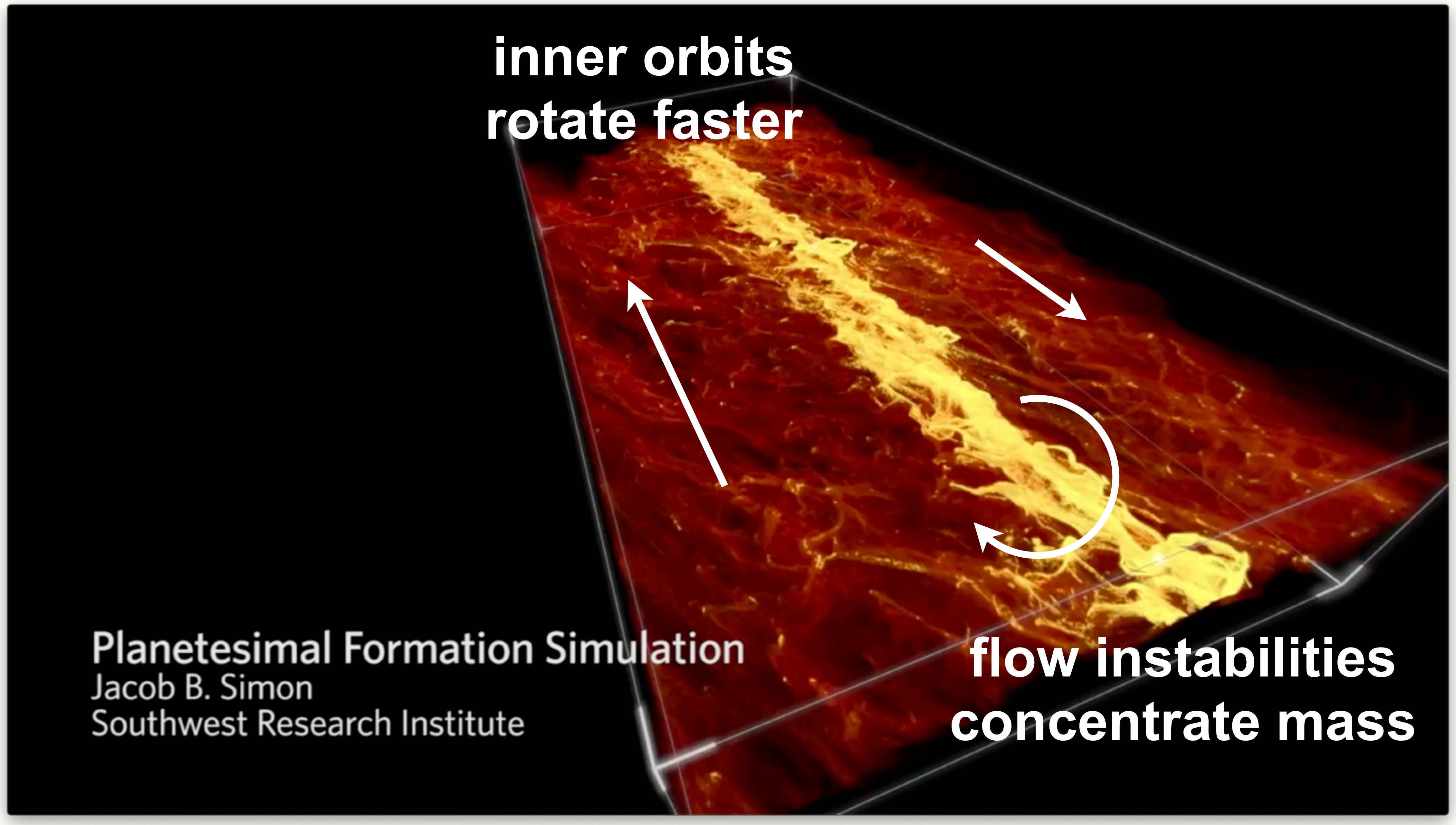
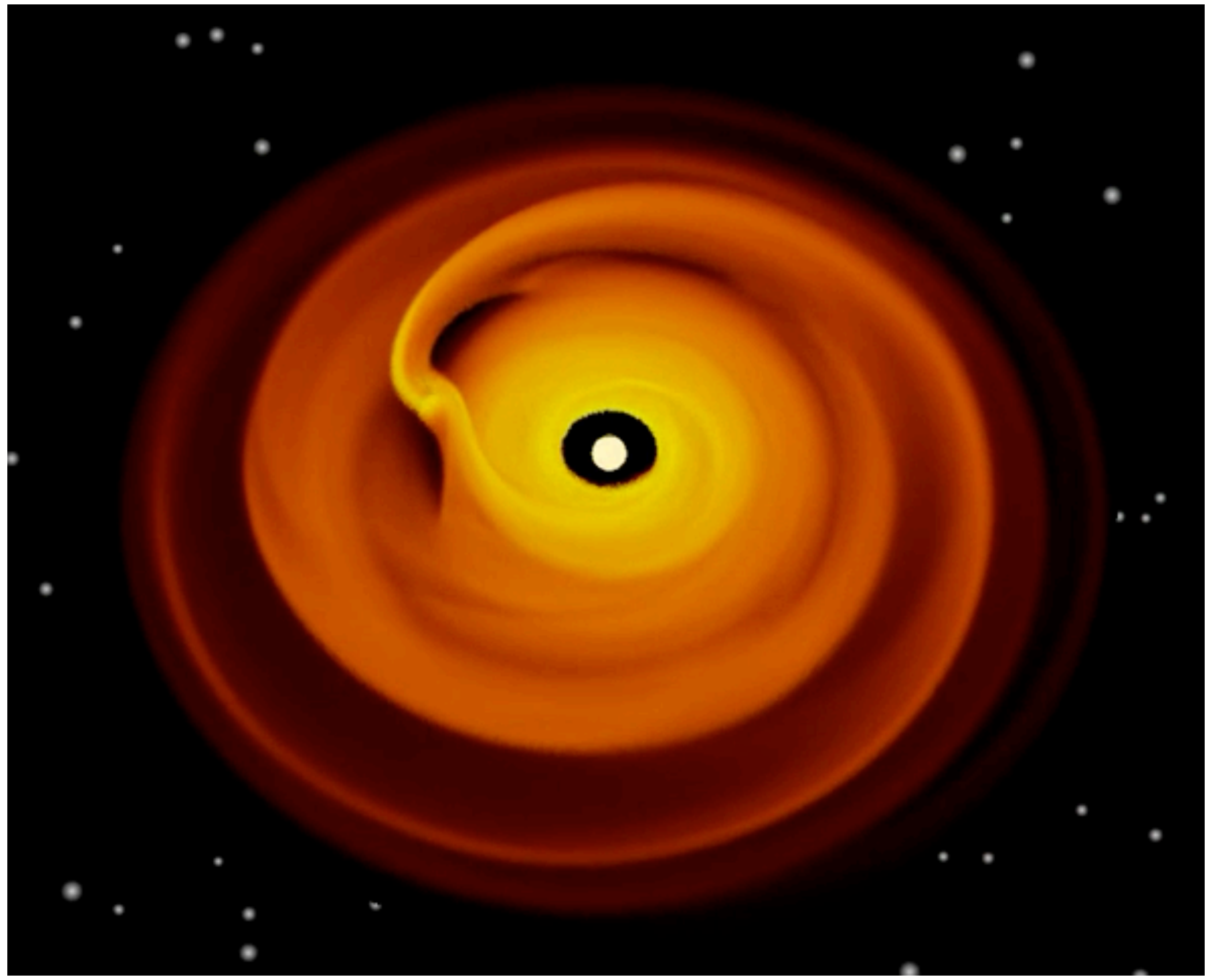


image: J. Simon, Southwest Research Institute

Planetary Formation | Dust to Planets

Planetary Formation Mechanisms



Gas giants

- *Composition*: comprise mostly H/He gas, perhaps around rocky, metallic core
- *Solar wind*: rapidly pushes gas, lighter elements to outer disk, inner disk rich in heavier elements
- *Core accretions*: large enough rocky protoplanets could hold on to gas envelope, but takes long to grow
- *Disk instability*: flow instabilities in early disk clump together gas, dust to quickly form gas giants
- *Pebble accretion:* pebbles slowed down by gas drag, accrete rapidly to form gas giants
- *Snow line*: inside snow line ices evaporate, insufficient material for gas giants

video: S. Perez, FARGO3D

Planetary Formation | Dust to Planets

Planetary Formation Mechanisms

Planetesimals to Planets

- *Collisions*: depending on speed, angle, collision *accretionary* or *disruptive*
- *Runaway growth:* rapid growth of protoplanets by accretion of planetesimals
- *Oligarchic growth*: larger protoplanets attract more collisions with other protoplanets, planetesimals
- *Orbital dynamics*: as larger embryos migrate and settle into stable orbits, smaller bodies gathered up or ejected

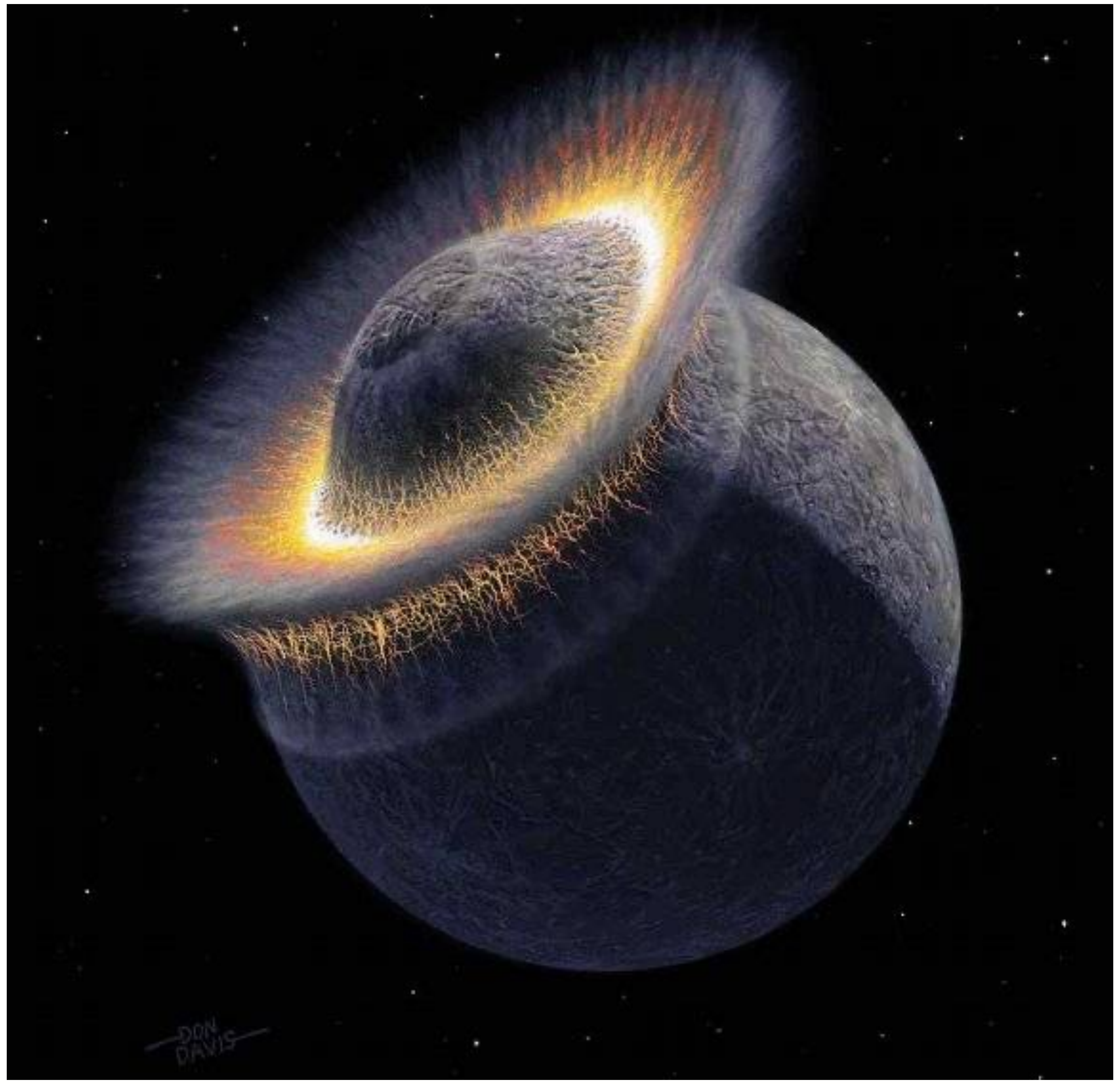
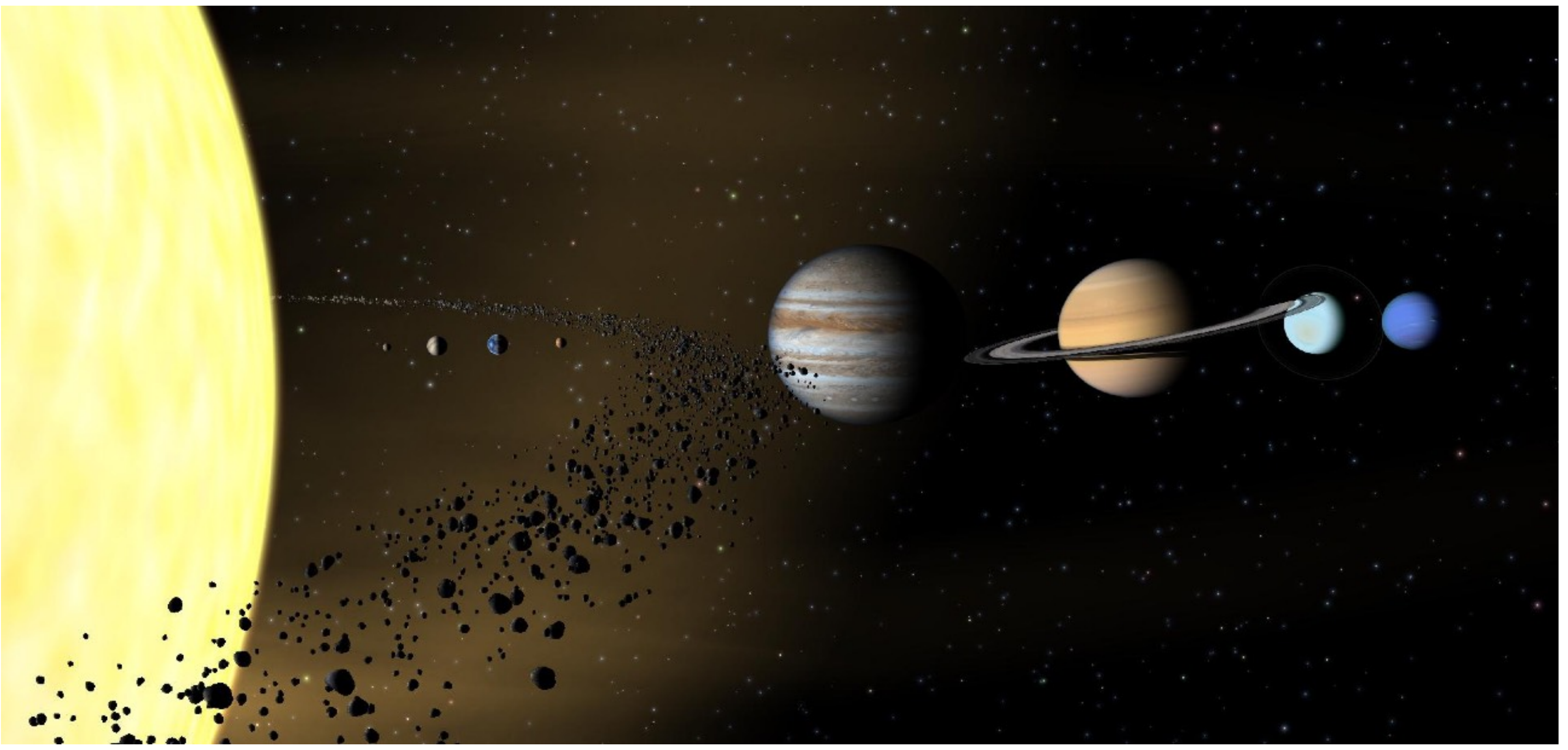


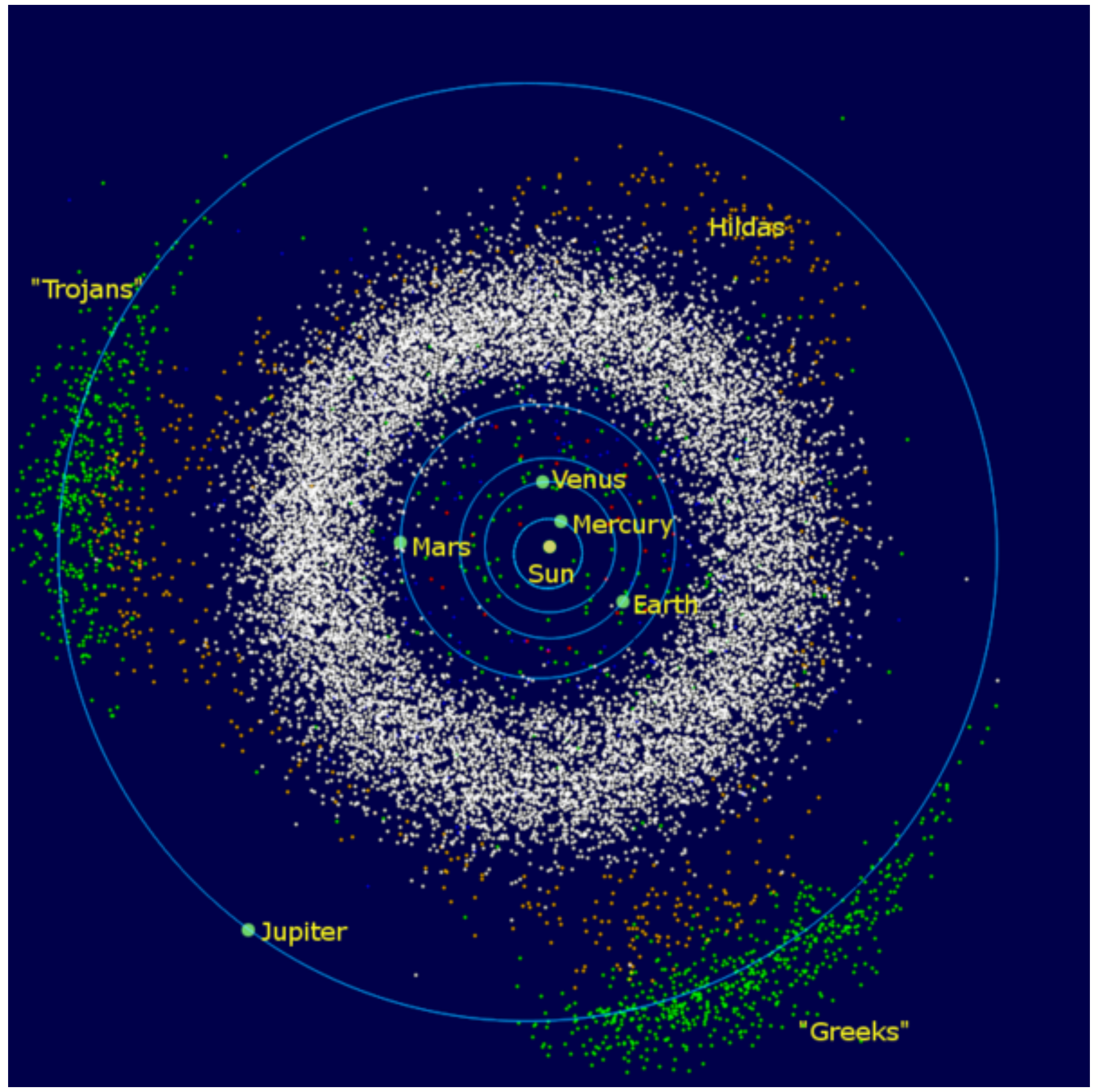
image: Don Davis

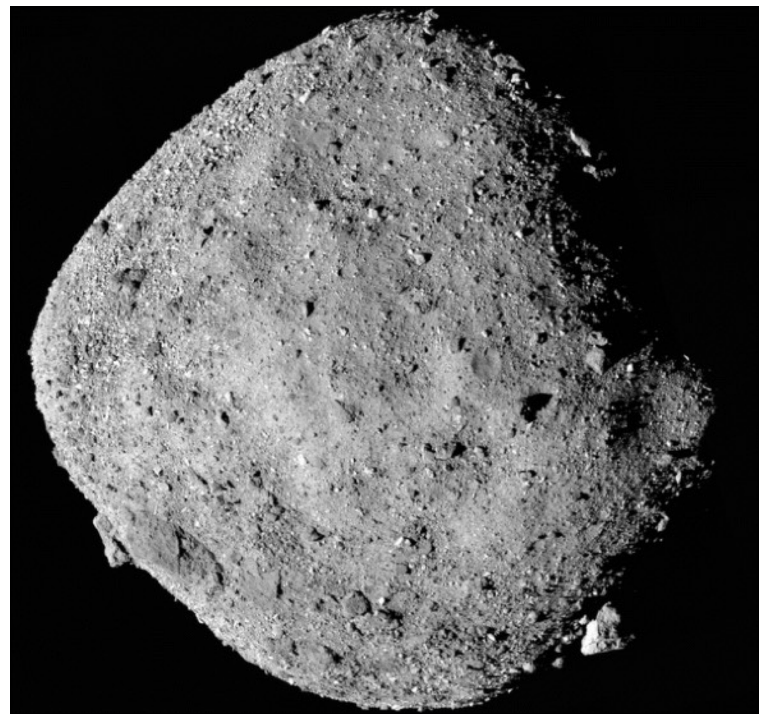
Planetary Formation | Dust to Planets

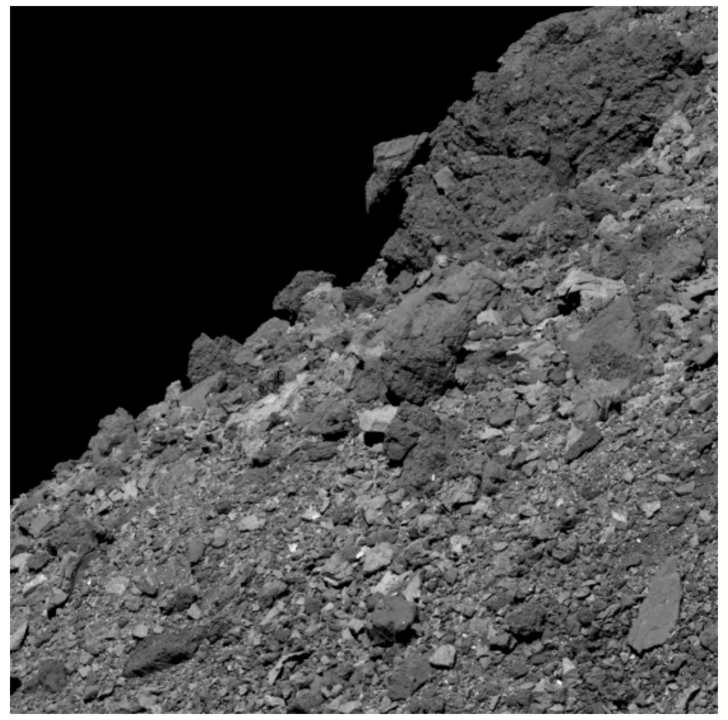
Asteroids

- left-over building blocks of planetary formation
- planetesimals and fragments
- concentrated in Main Belt, between Mars and Jupiter
- largest asteroids: Ceres (dwarf planet), 4 Vesta
- upcoming NASA mission to iron asteroid Psyche
- ongoing sample return missions to near-Earth asteroids
  - OSIRIS-Rex to Bennu
  - Hayabusa2 to Ryugu







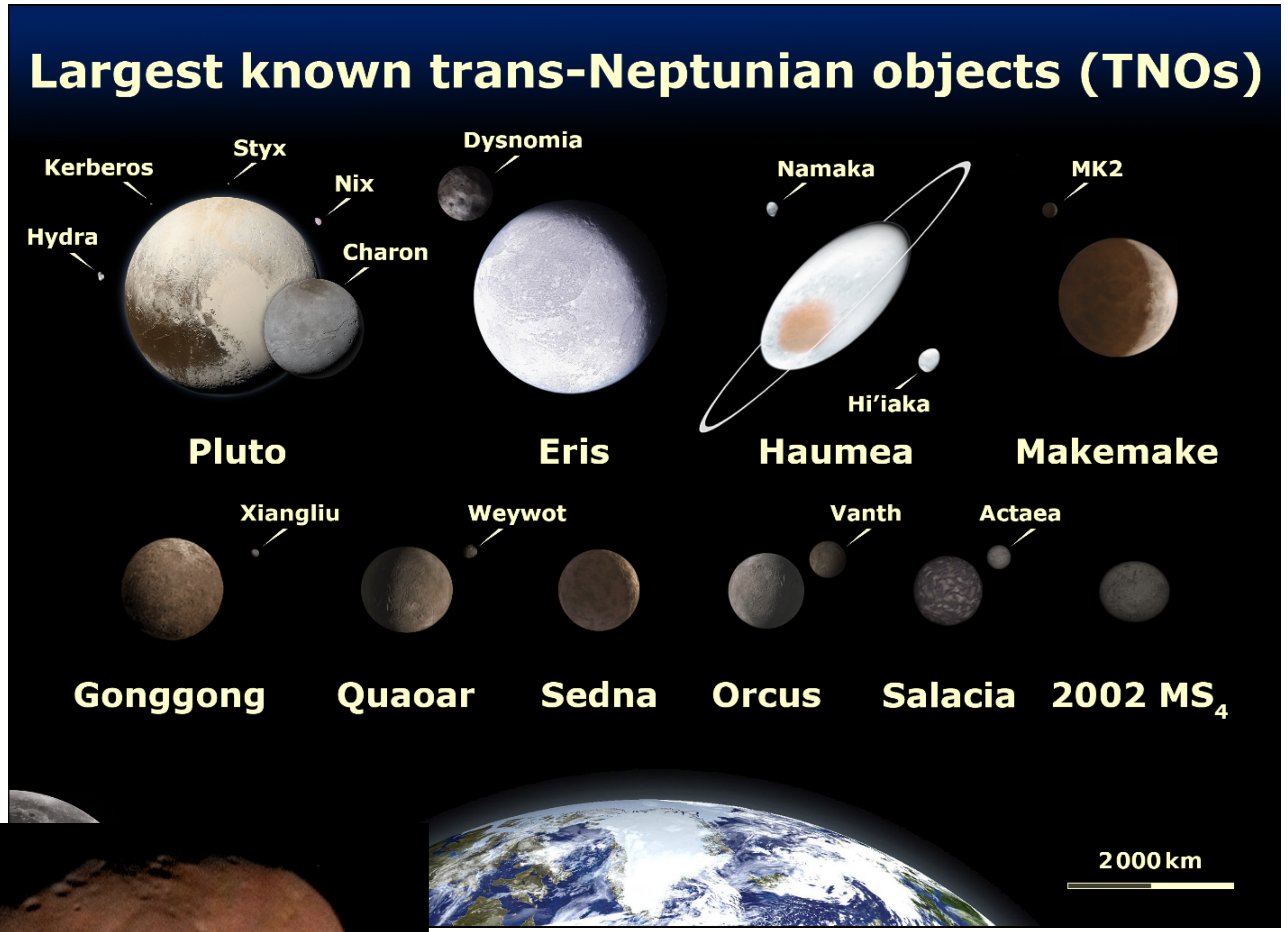


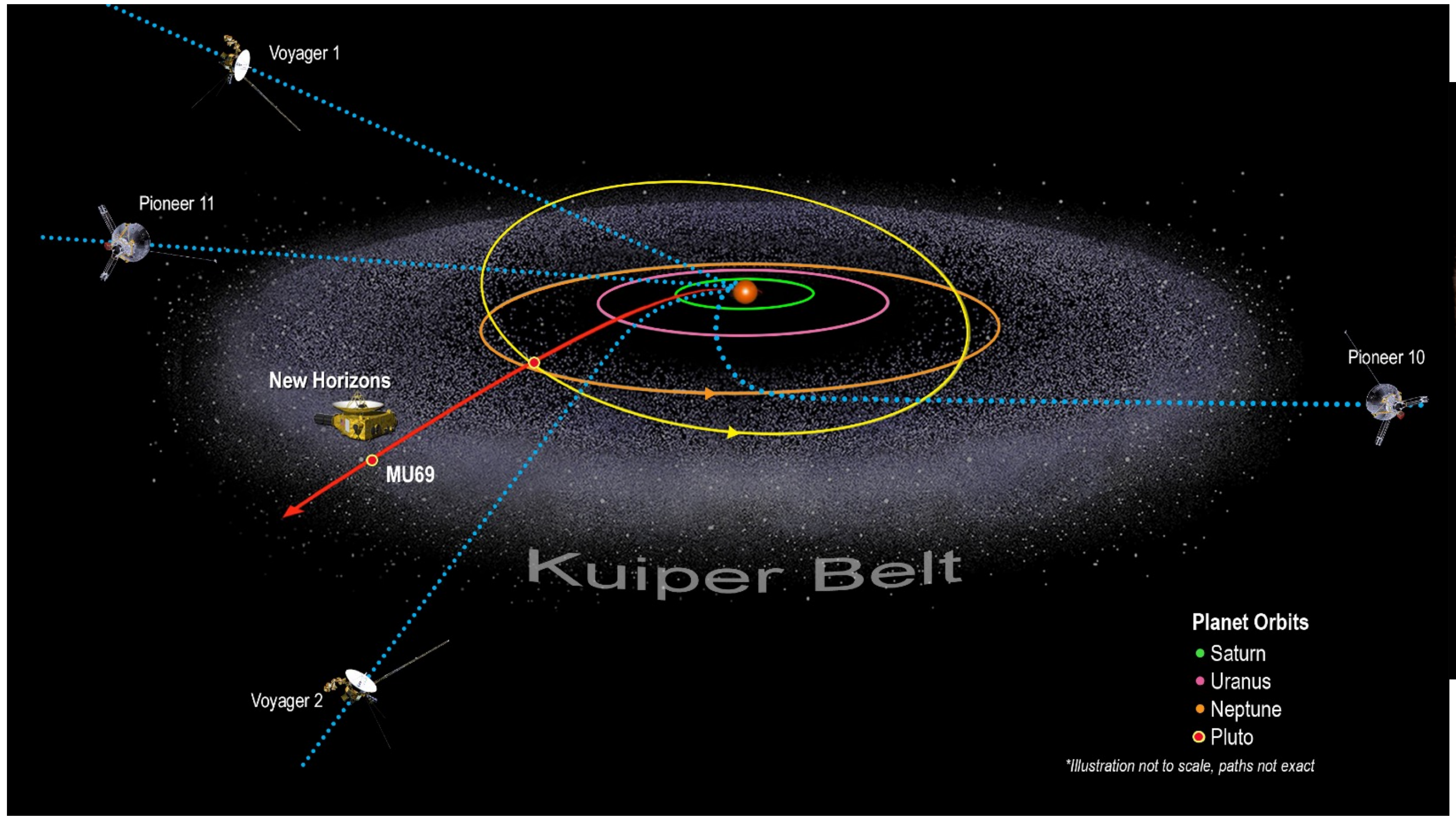
images: NASA, Wikipedia

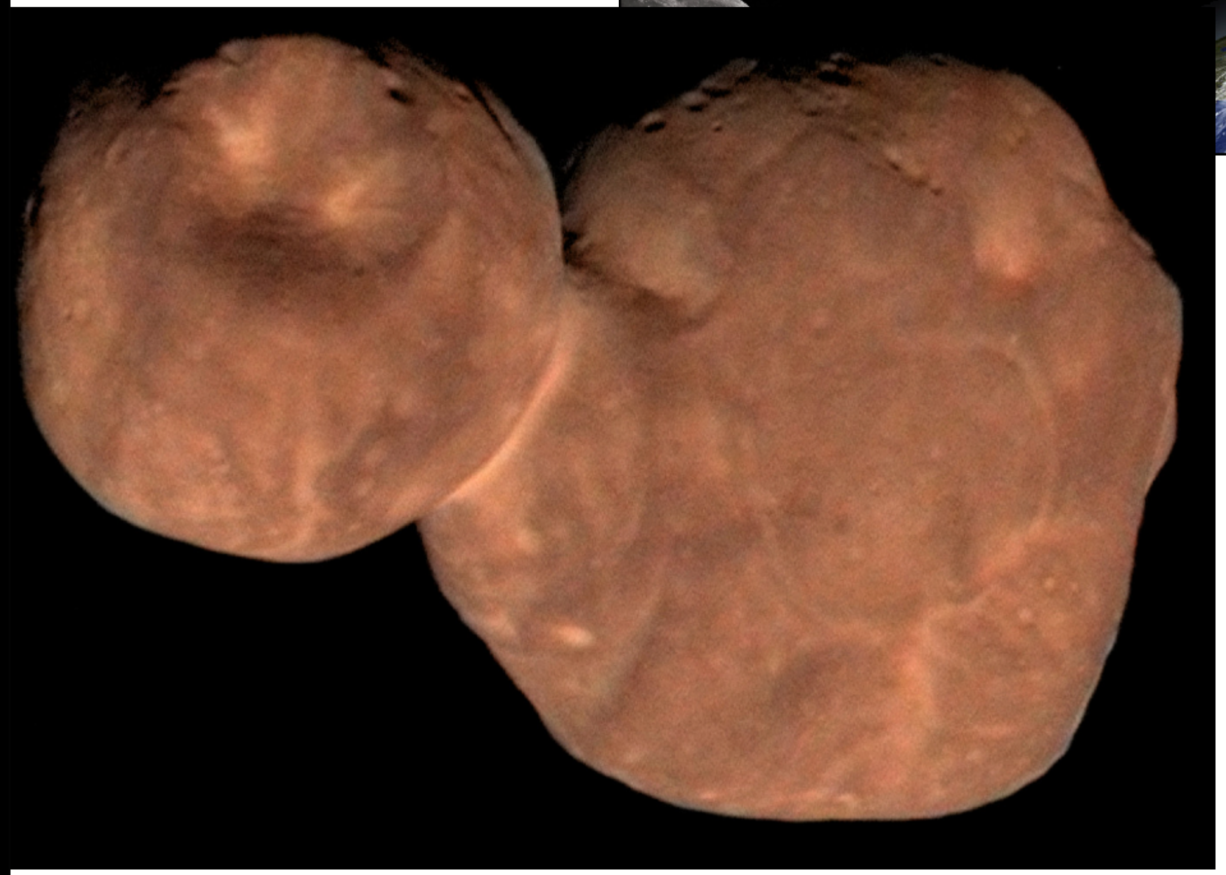
Planetary Formation | Dust to Planets

Kuiper Belt

- scattered building blocks of planetary formation
- dwarf planets, planetesimals, fragments
- outside Neptun’s orbit (trans-Neptunian objects)
- New Horizons probe returned first clear images







images: NASA, Wikipedia

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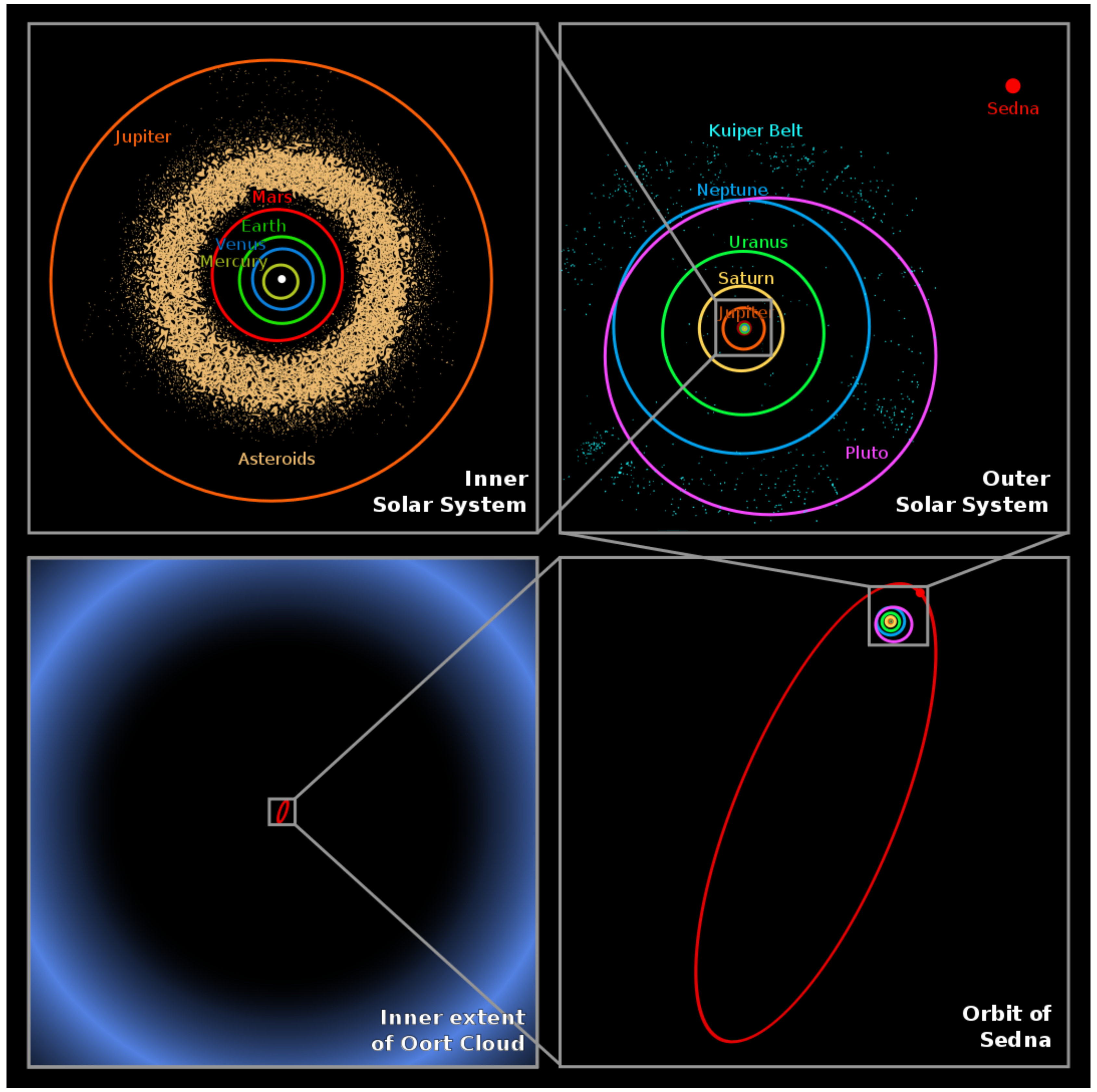
Planetary Formation | Dust to Planets

Oordt Cloud

- scattered icy building blocks of planetary formation
- ~2000–5000 AU wide region
- possibly millions of objects out there
- highly eccentric elliptical orbits
- source of comets visiting inner system
- Voyager-1 probe will reach Oordt cloud in ~300 years!



images: NASA, Wikipedia

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Planetary Formation | Dust to Planets

Meteorites

- fragments of solar system bodies
- range of compositions, rocky to iron
  (icy fragments burn up in atmosphere)
- important witnesses of planetary formation!

image: The Meteorite Exchange Inc.

Planetary Formation | Dust to Planets

Meteorites: chondrites

- *chondrites*: most primitive composition, same as sun (other than H/He)
- *chondrules*: rounded inclusions, texture and chemistry consistent w/ melt droplets in space!
- *Calcium-Aluminium-rich Inclusions (CAI)*: probably oldest solar system solids, condensed at high *T*
- thought to derive from undifferentiated bodies, represent initial disk composition, earliest planetary building blocks

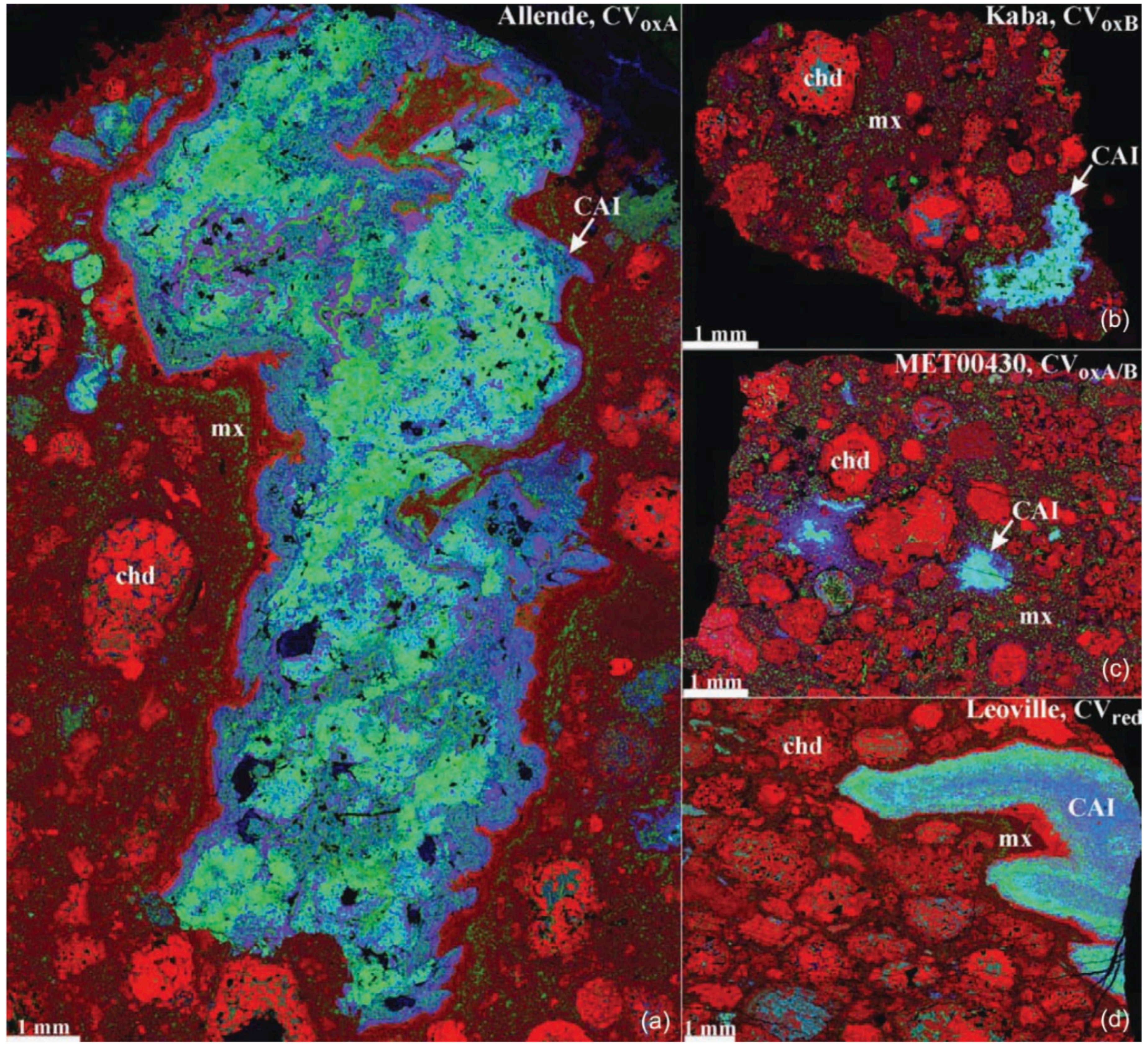


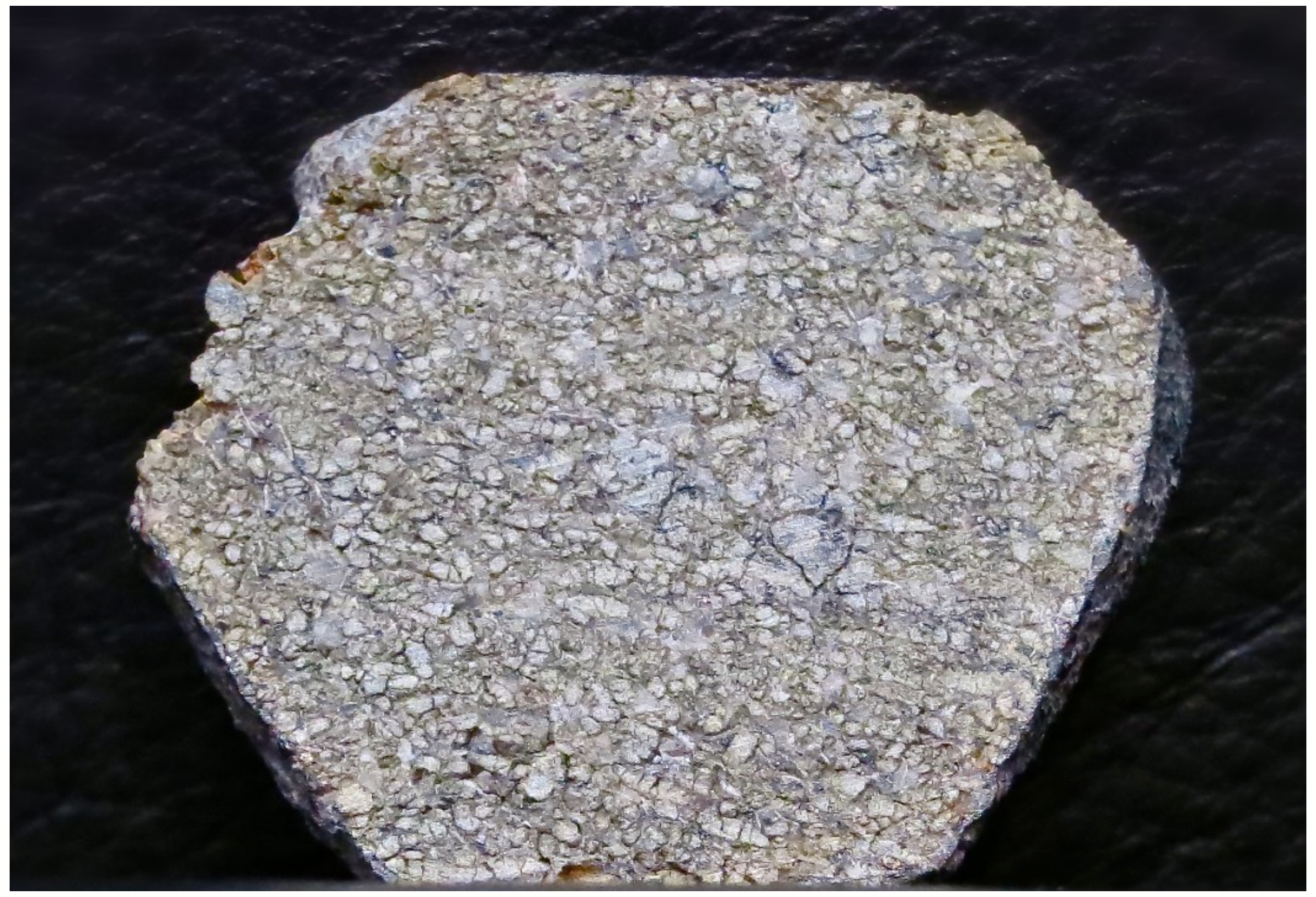
image: Weisberg et al., in Lauretta & McSween, 2006

Planetary Formation | Dust to Planets

Meteorites: achondrites

- *primitive achondrites*: low-degree melting, of chondrite, partly differentiated parent bodies
- *achondrites*: high-degree melting of chondrite further differentiated parent bodies
- *asteroidal:* fragments of asteroids, e.g., 4 Vesta
- *planetary*: fragments from Moon, Mars

eucrite (Vesta)



shergottite (Mars)

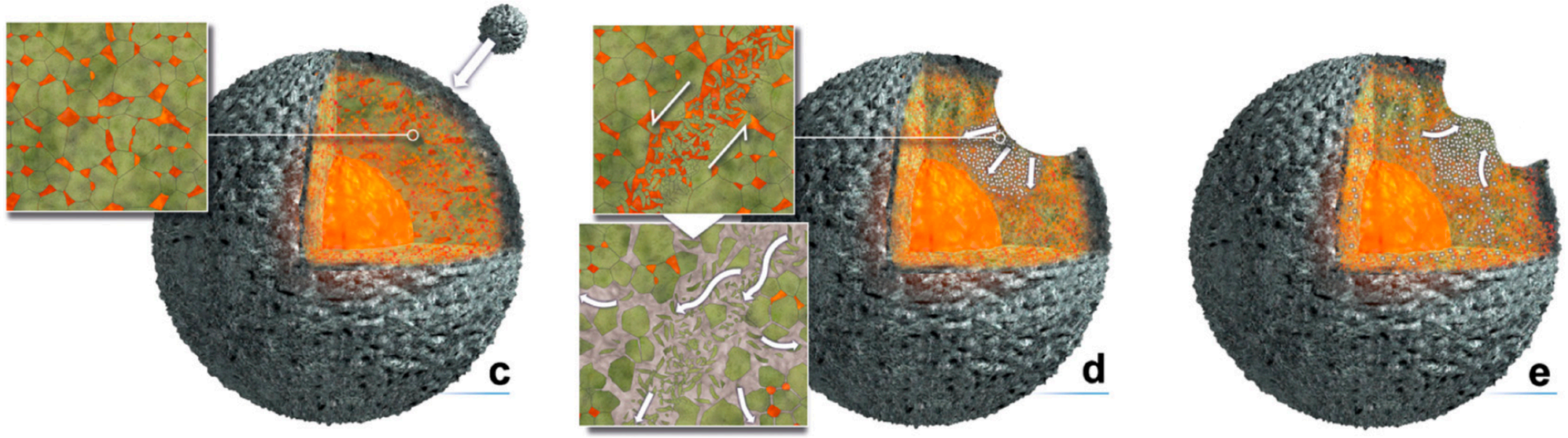
nakhlite (Mars)

images: Wikipedia

Planetary Formation | Dust to Planets

Meteorites: irons, pallasites

- *irons*: Fe-Ni metal, characteristic *Widmanstätten* pattern of Fe-Ni crystals
- thought to sample differentiated planetesimal core
- *pallasites*: Fe-Ni metal and olivine,
- formation is hotly debated
  - partly differentiated planetesimal mantle?
  - impactor core melt invading planetesimal mantle?



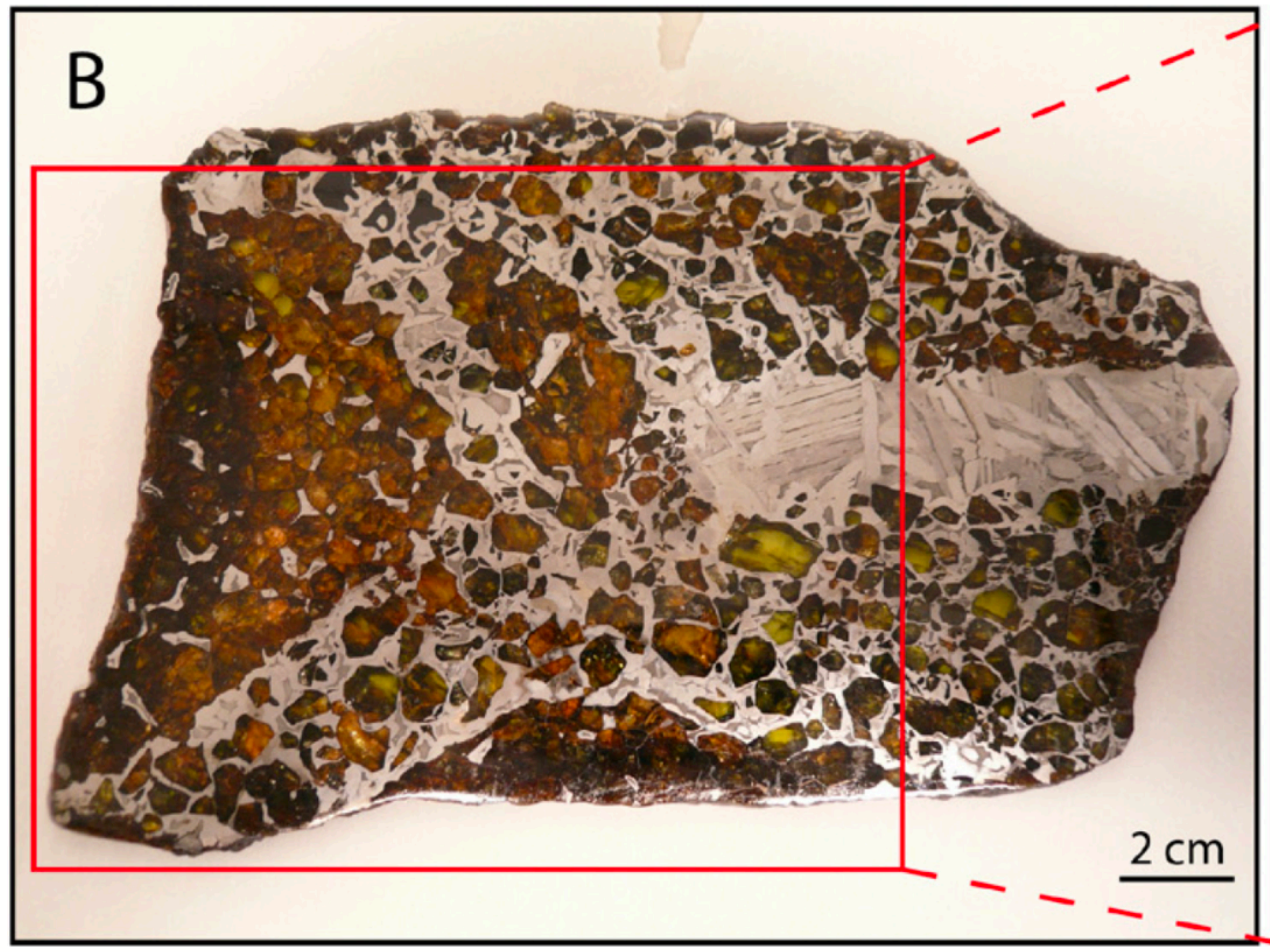


image: Wikipedia; figures: Walte et al., *EPSL*, 2020

Part II – Solar System

Solar System

a family portrait

Planets, the *Wanderers* in the sky

- some stars in the night sky wander
- discovery of solar system structure, great shift in human perspective
- exciting time for planetary research,
  - robotic missions to planets now
  - sample return missions soon
  - human exploration on horizon

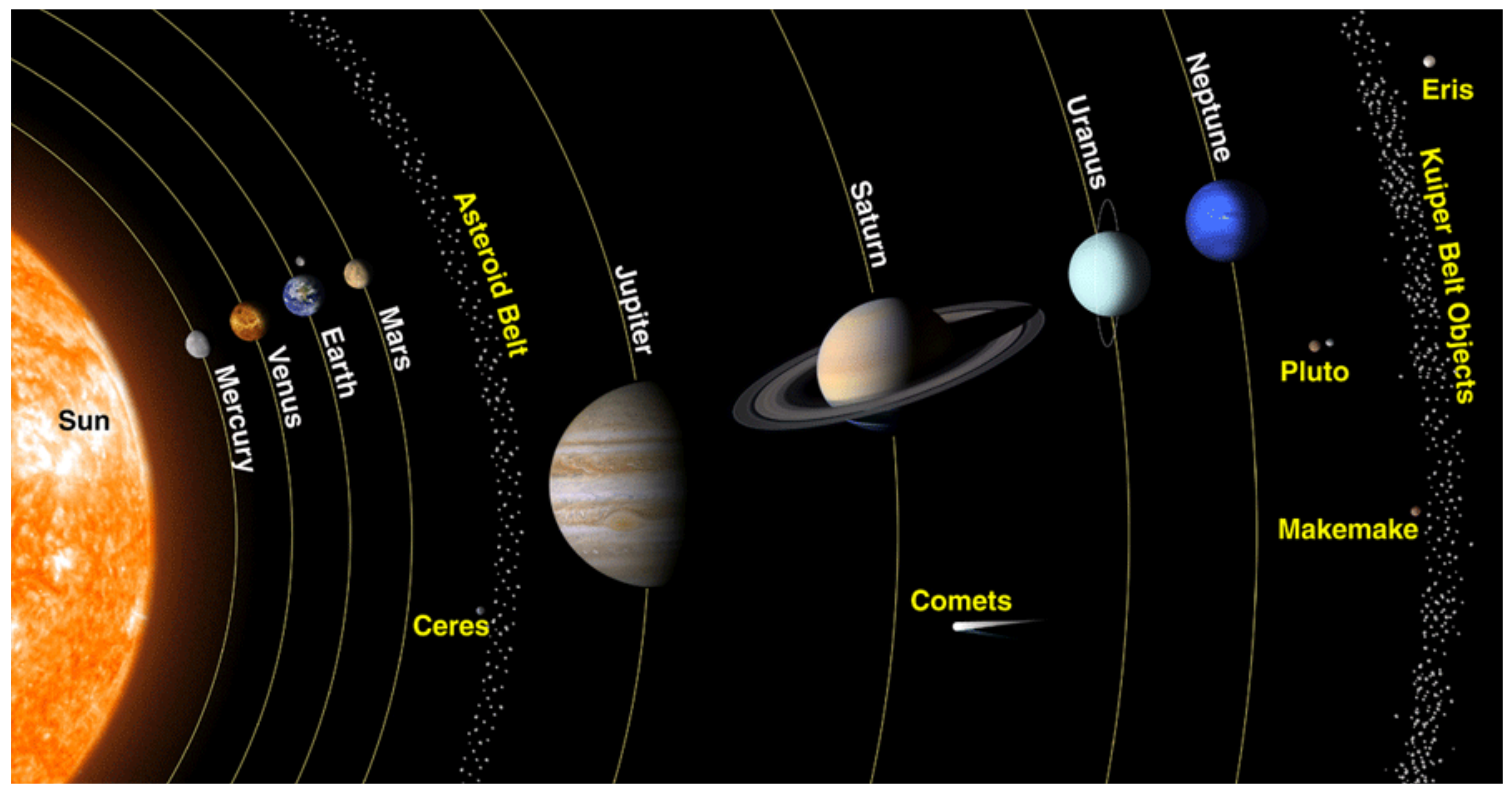


image: Wikipedia

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What is a Planet?

… poor Pluto …

Definition of what a Planet is

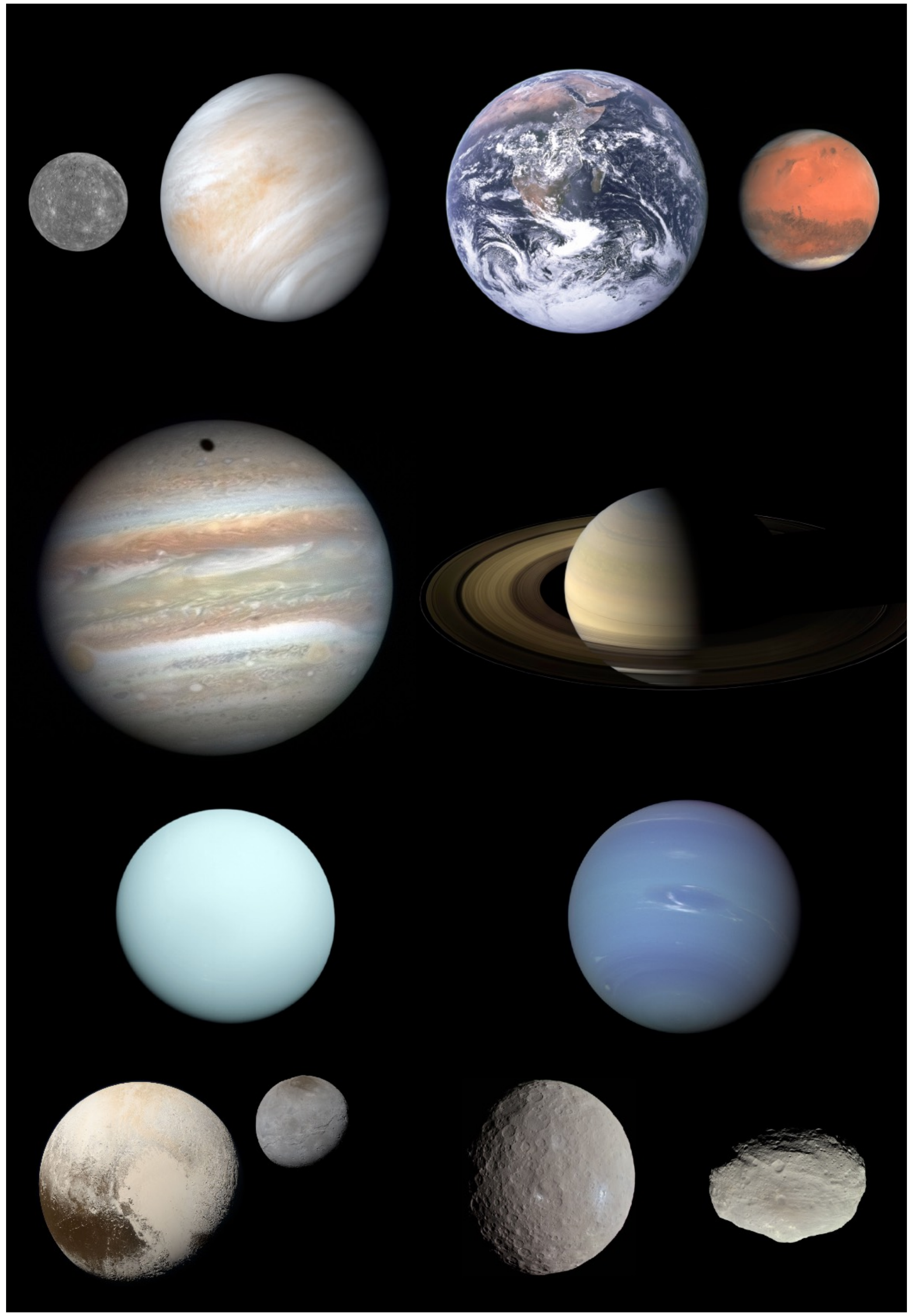
- how to classify planetary bodies?
- Pluto demoted to Dwarf Planet…
- planets? dwarf planets? asteroids? comets? Kuiper Belt objects?
- currently inconclusive debate
- how would you define *planets*?
  - share on Padlet!

image: M. Pedersen

Planetary Formation | Solar System

Planets of the Solar System

- Terrestrial planets: rocky mantle, metallic core
  - Mercury, Venus, Earth, Mars
- Gas giants: large mass, mostly H/He gas
  - Jupiter, Saturn
- Ice giants: mostly volatiles heavier than H/He
  - Uranus, Neptun
- Smaller bodies: mostly icy, rocky
  - Pluto & Charon, Ceres, Vesta, Eris, Makemake
- Moons: mostly icy, rocky, ocean worlds
  - Luna, Io, Europa, Ganymede, Callisto, Titan, Enceladus, Mimas, etc.

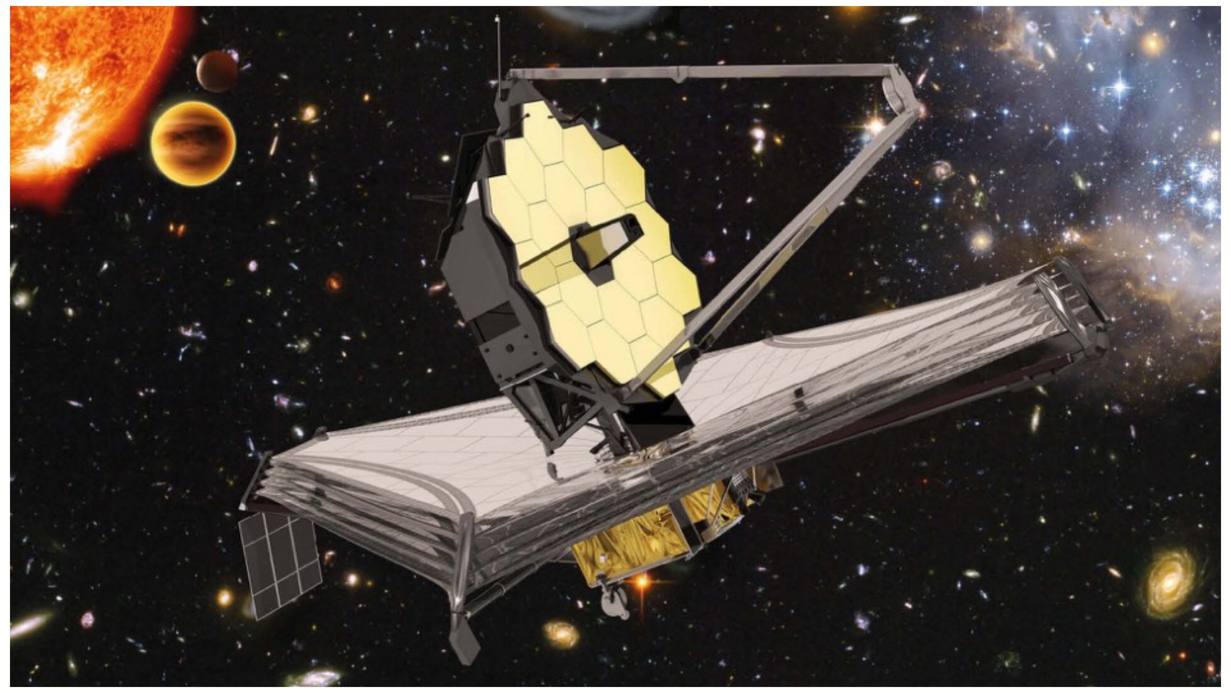


images: NASA

Planetary Formation | Terrestrial Planets

Comparison with Exoplanets

- *hot Jupiters* abound
- *Super Earths* are a thing
- *Water worlds* also common
- more Earth-like planets bound to be discovered as interments improve
- stay tuned for James Webb space telescope in 2021



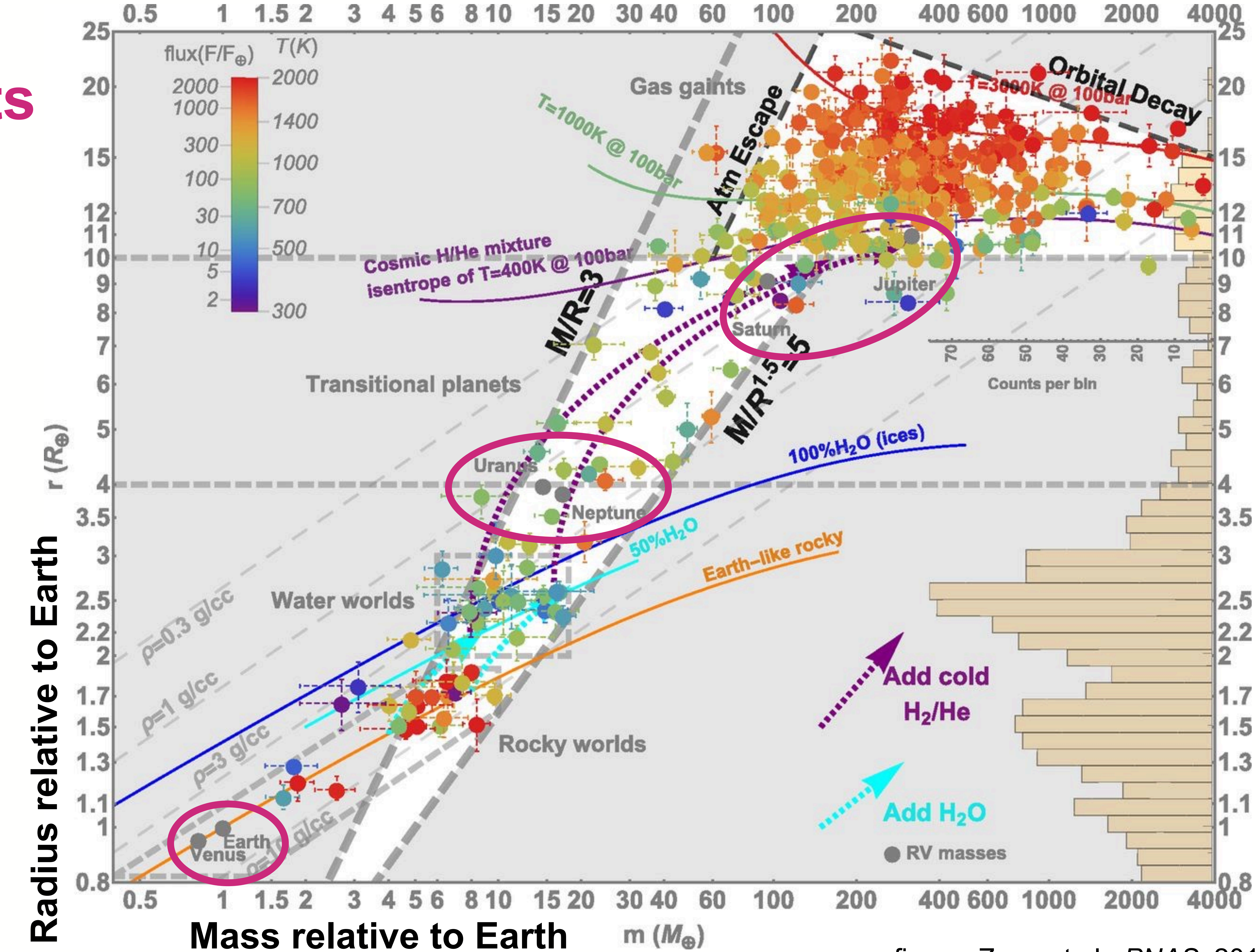
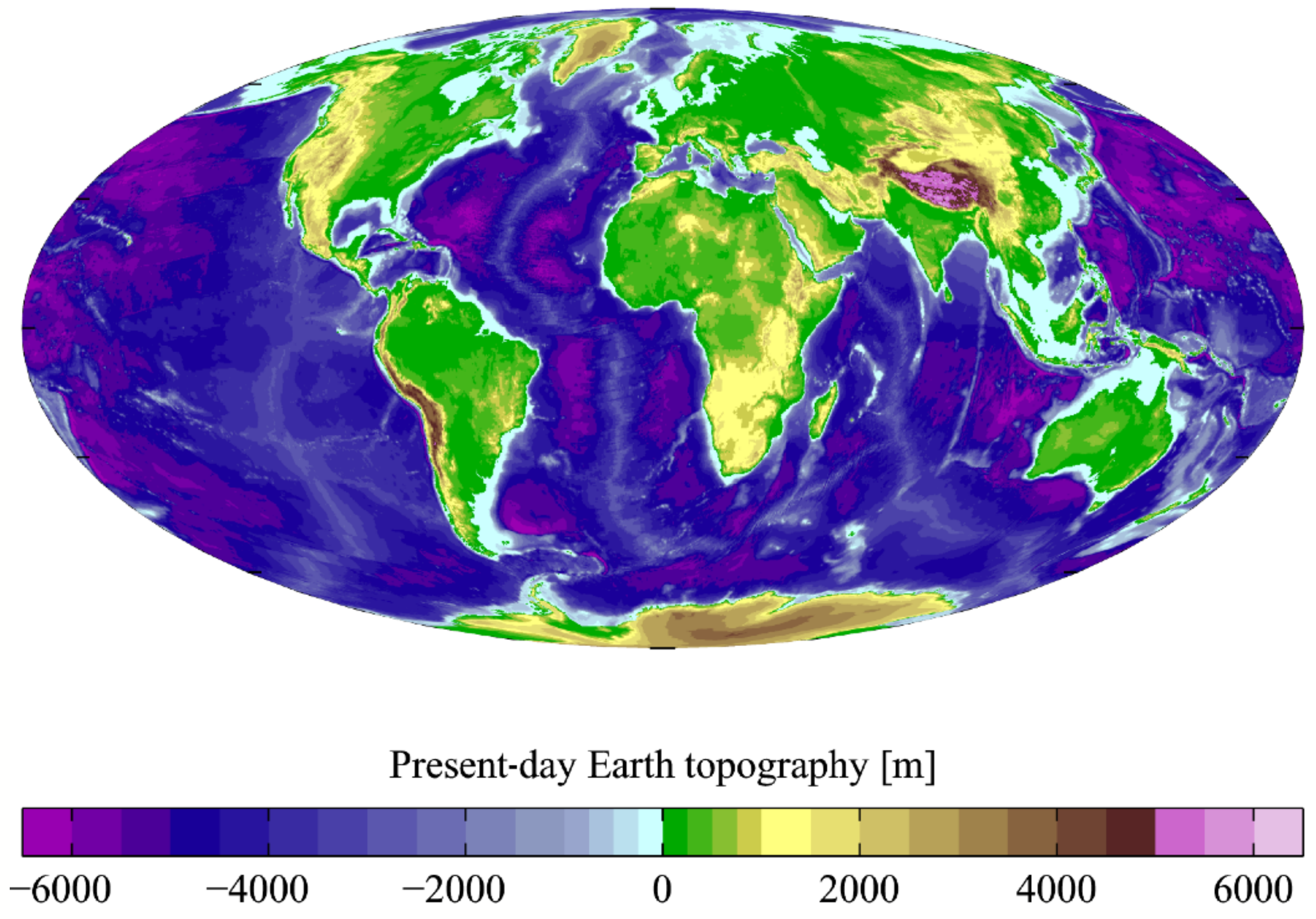


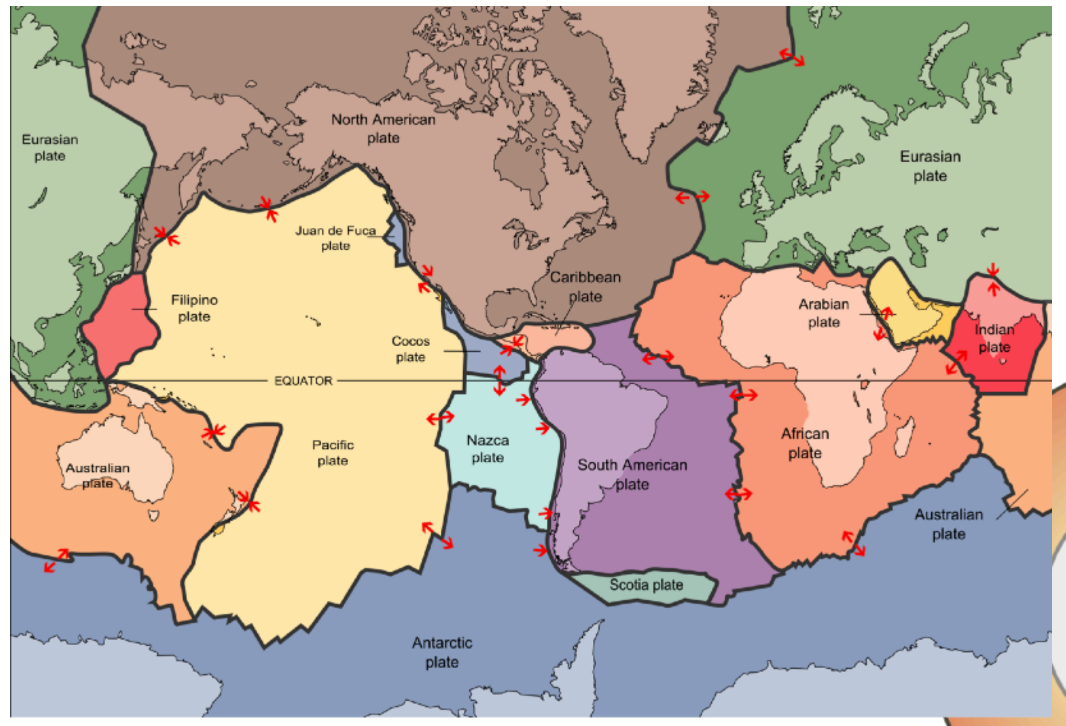
figure: Zeng et al., *PNAS*, 2019

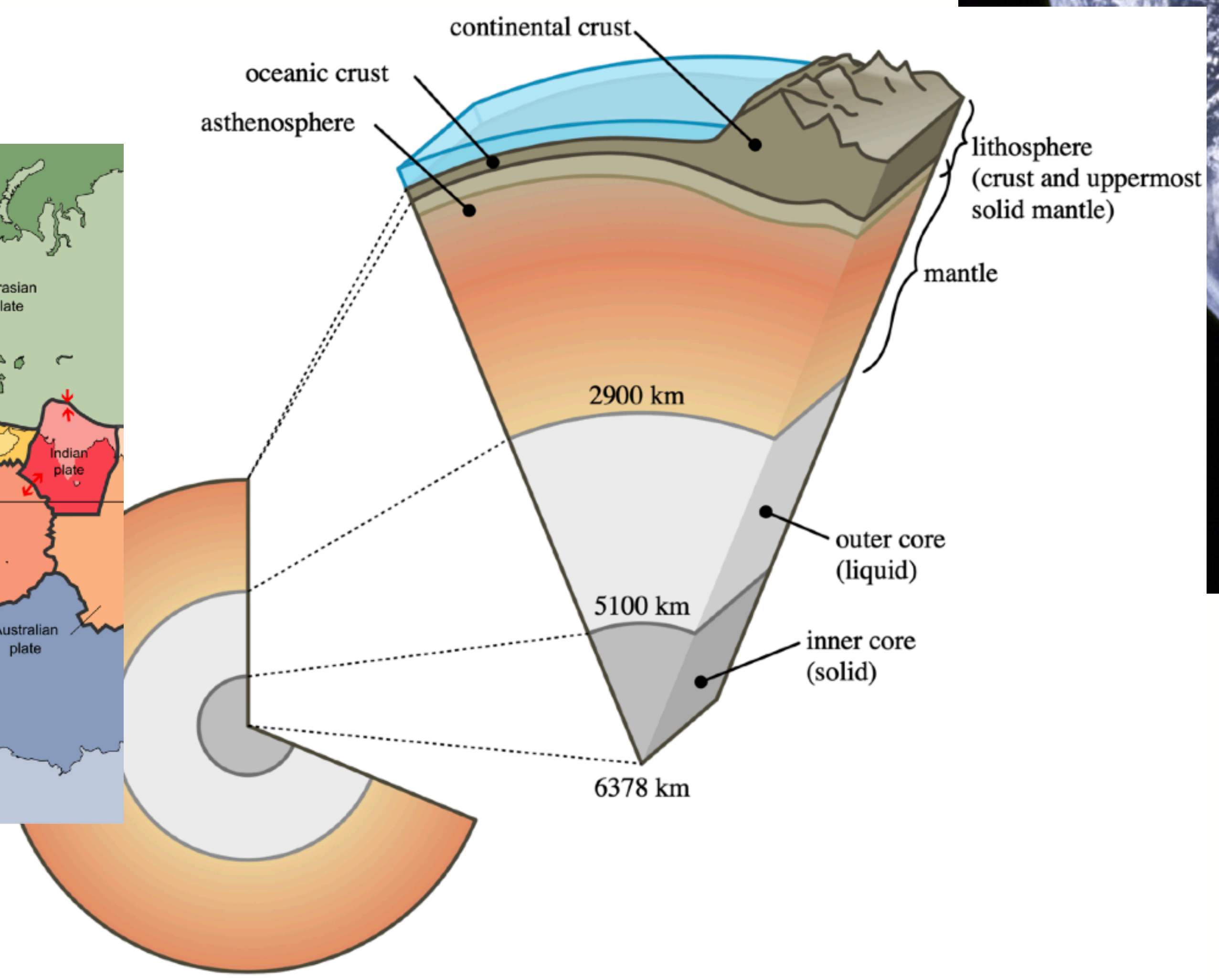
Planetary Formation | Terrestrial Planets

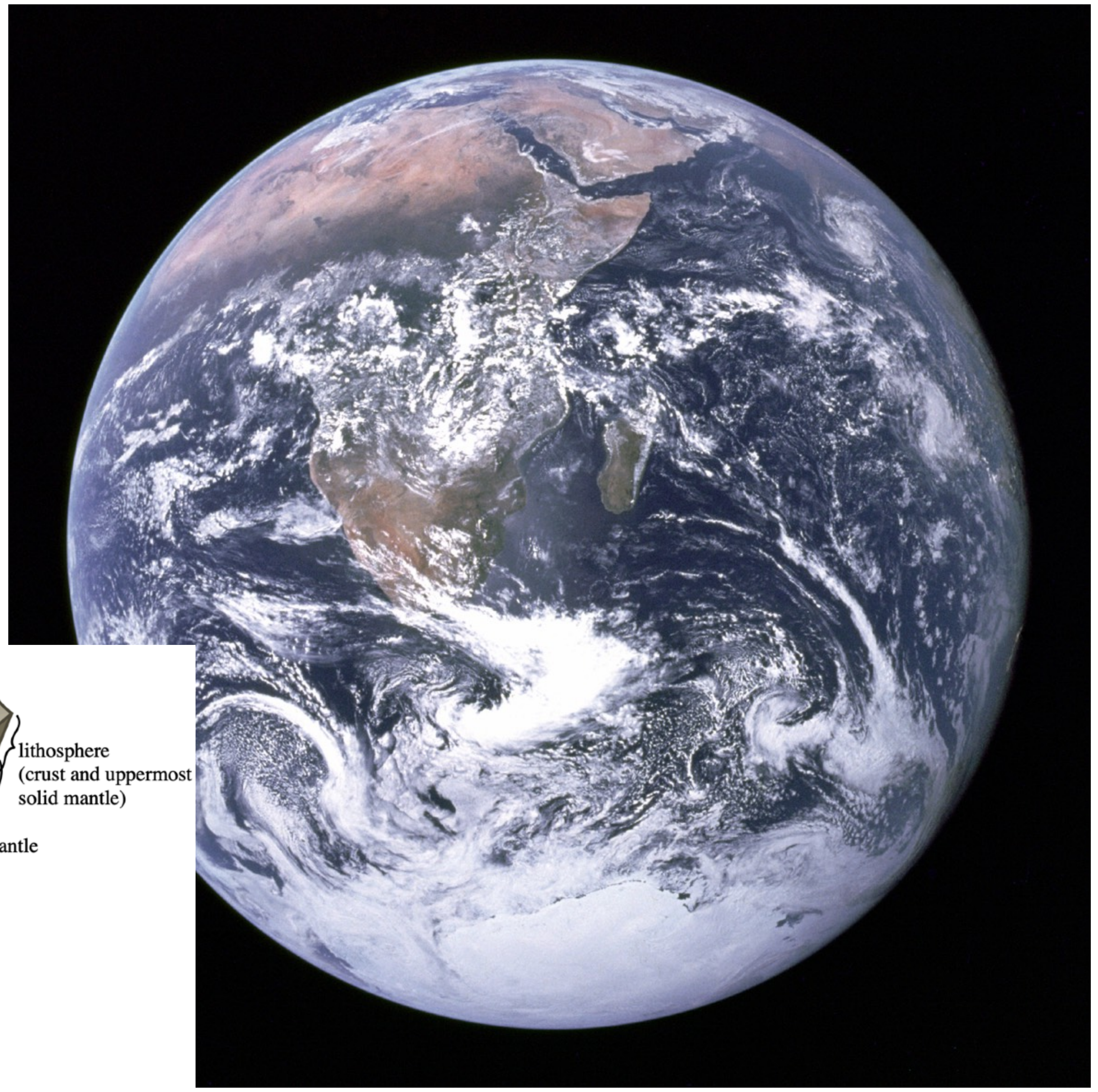
Earth

- OD 1 AU = 149,600 km; M 1 EM = 6x10^{24} kg; R 6371 km
- plate tectonics, oceans, continents, liquid water, *life!*
- atmosphere of N_2, O_2, ~15°C surface *T*
- ~2900 km iron core, ~3400 km silicate mantle, crust
- strong magnetic field







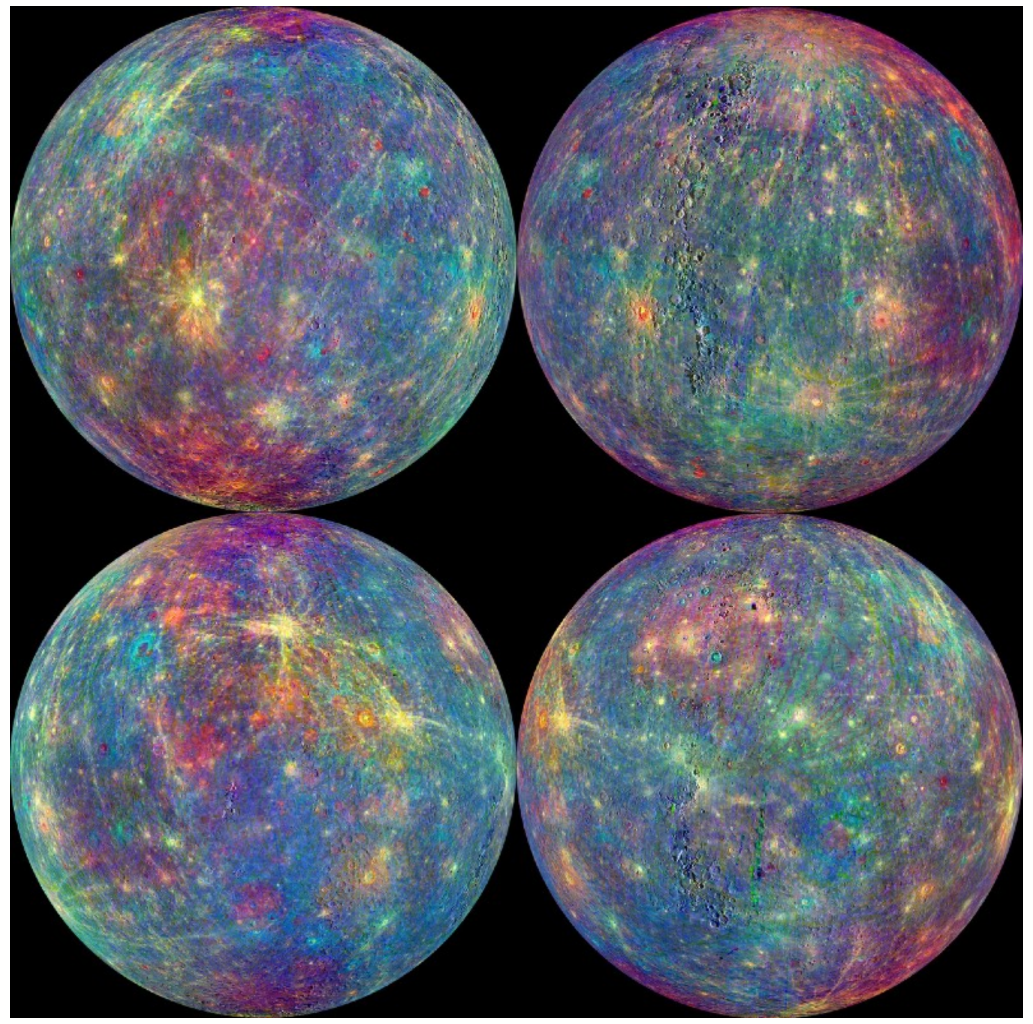


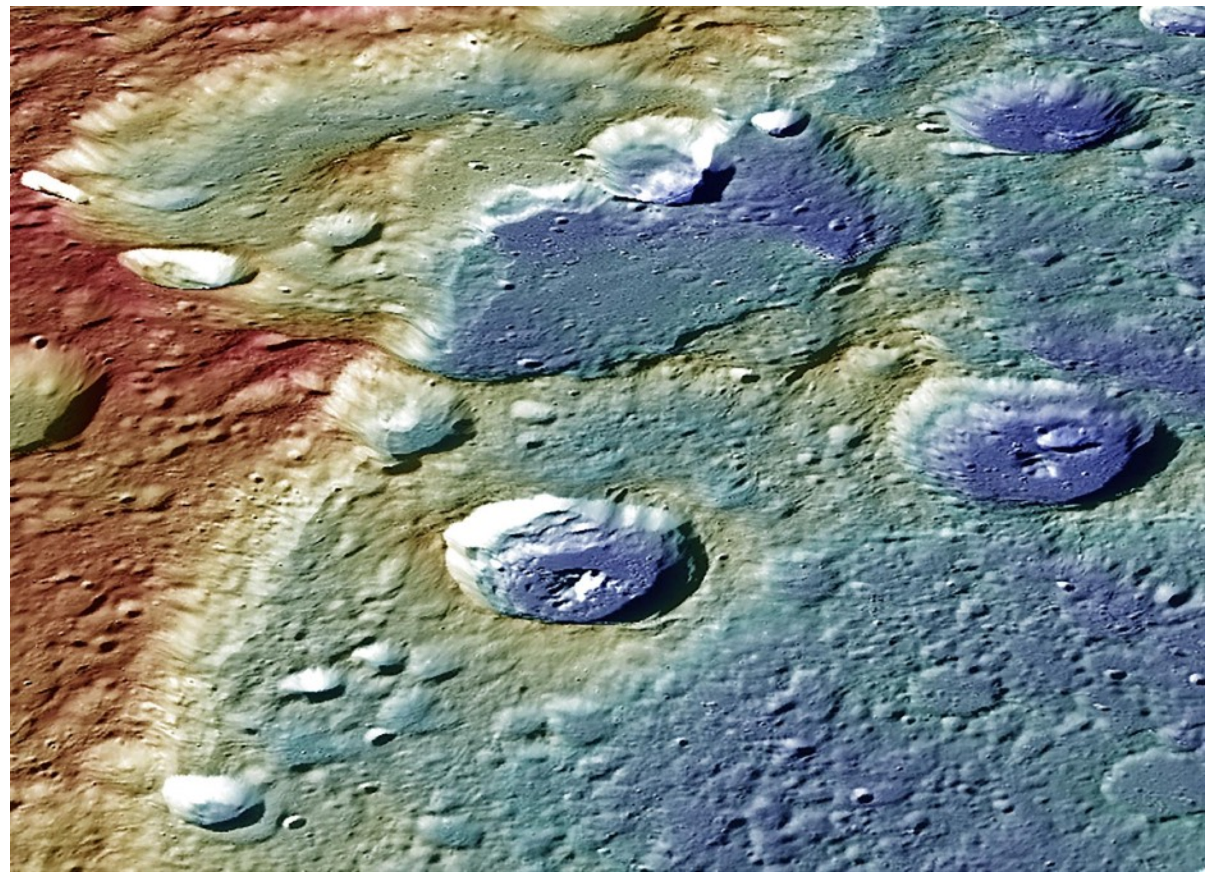
images: NASA, Wikipedia

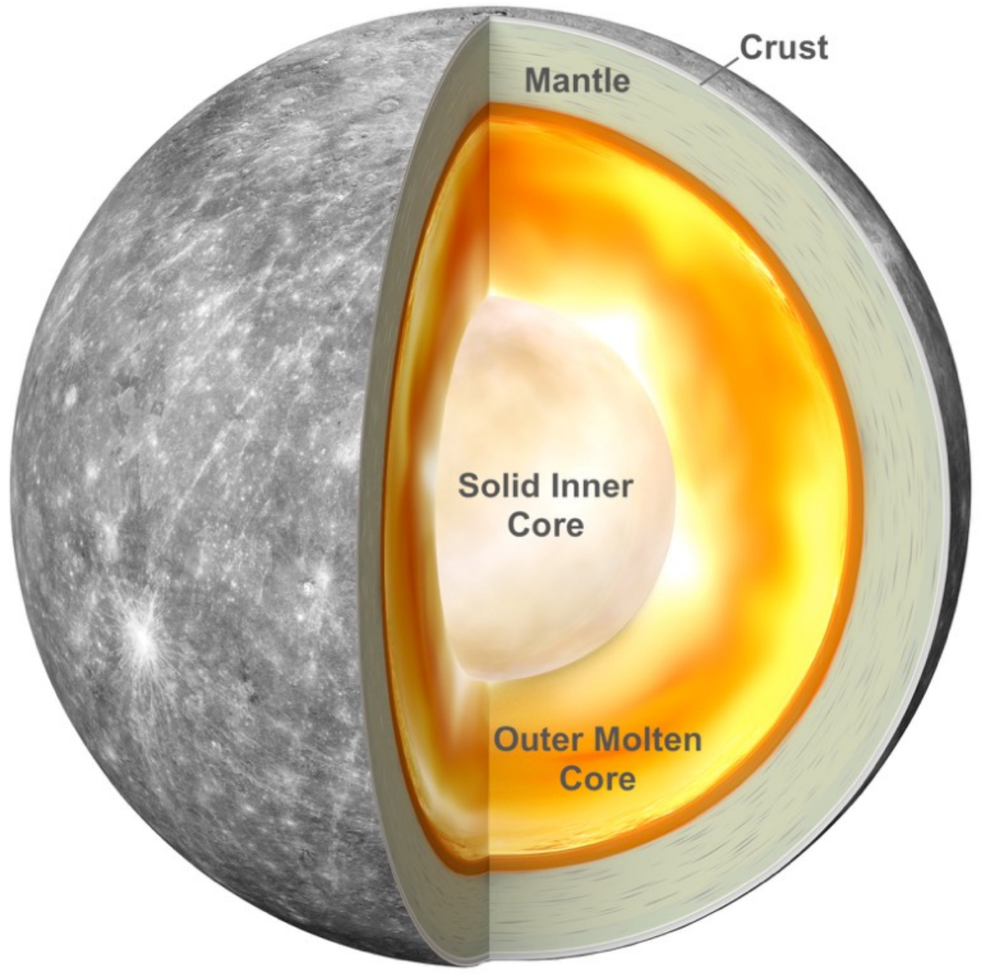
Planetary Formation | Terrestrial Planets

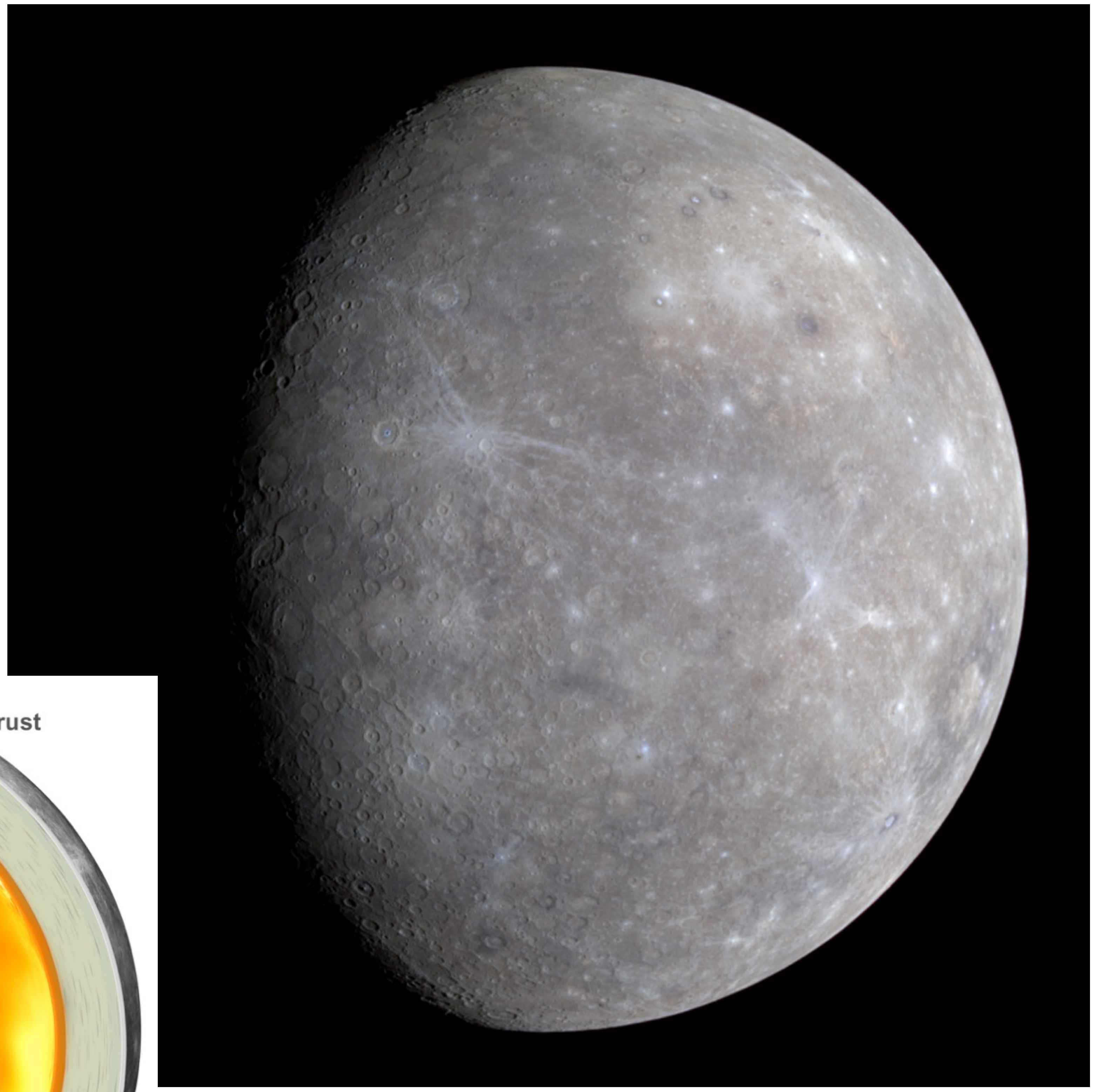
Mercury

- OD 0.39 AU; M 0.055 EM; R 2440 km
- heavily cratered surface
- long scarps indicating contraction
- large iron core, thin silicate mantle, crust
- has active magnetic field







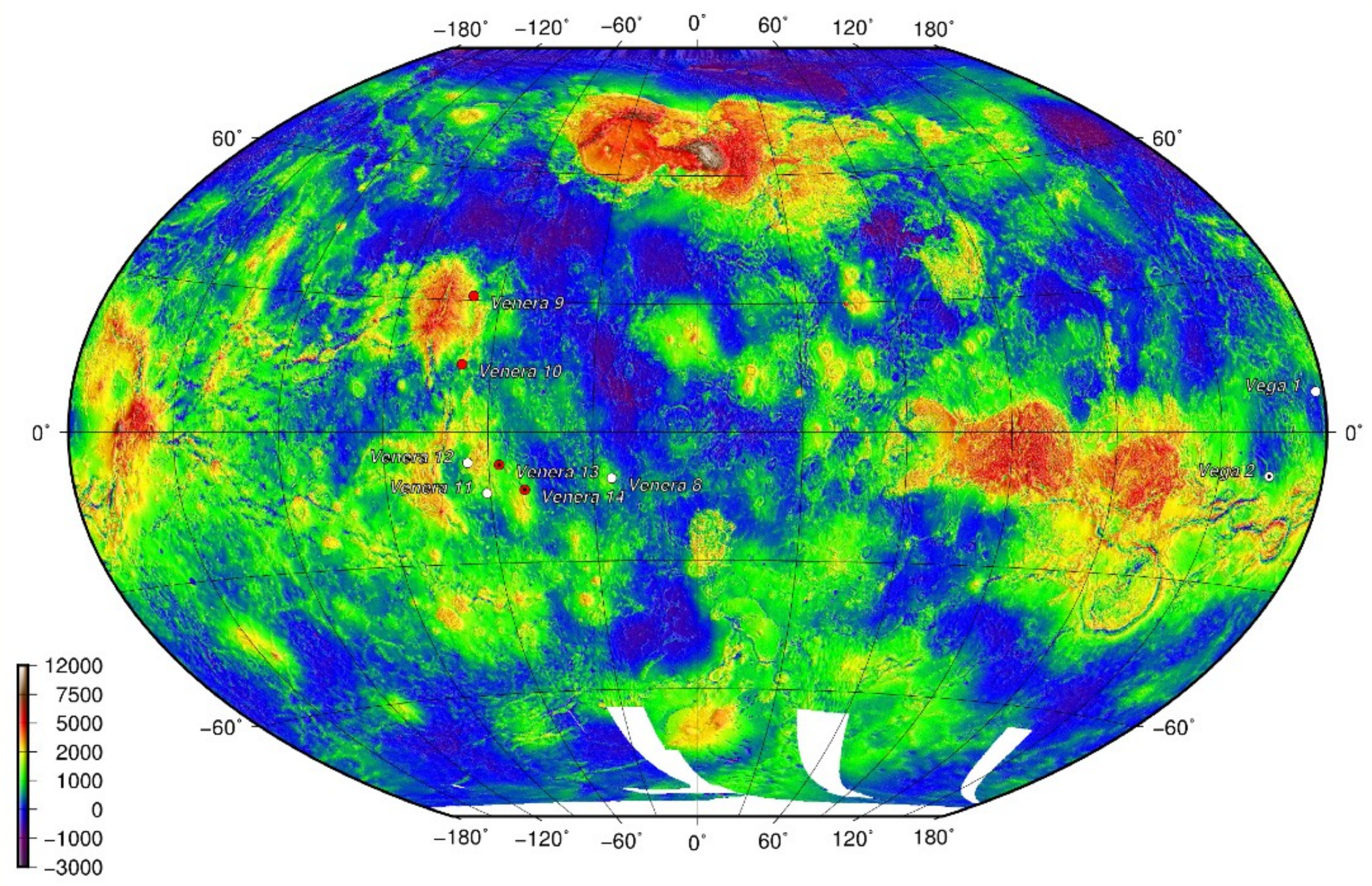


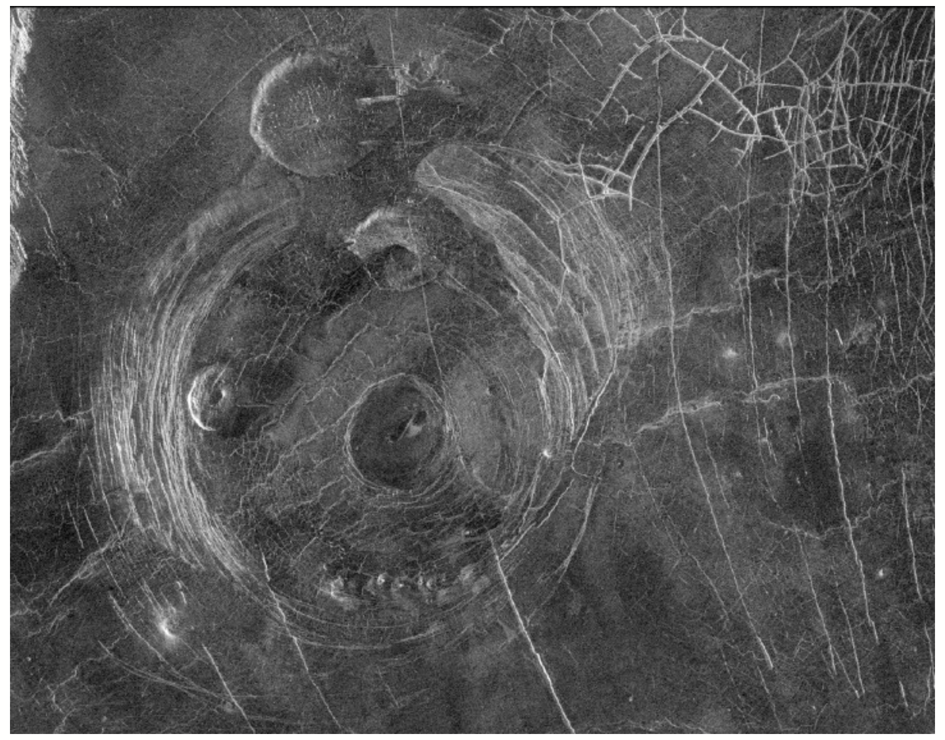
images: NASA

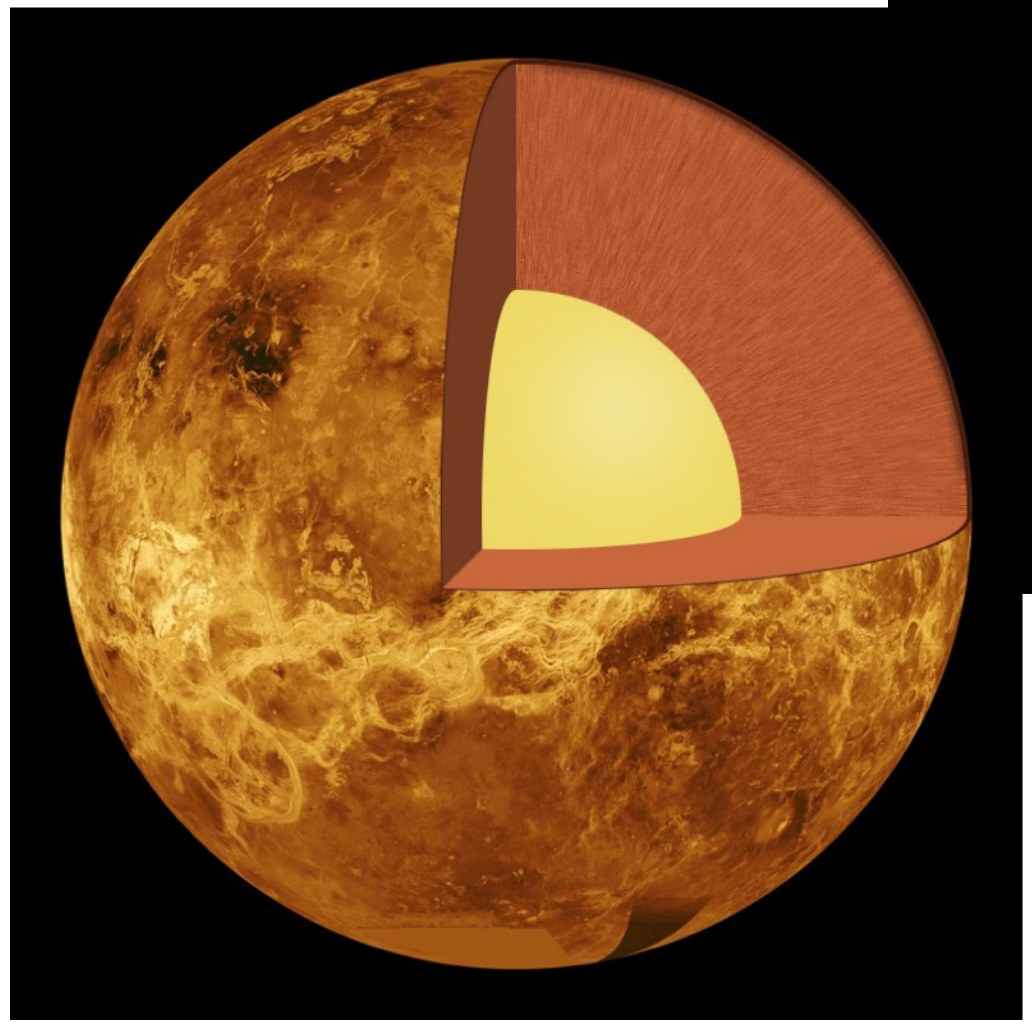
Planetary Formation | Terrestrial Planets

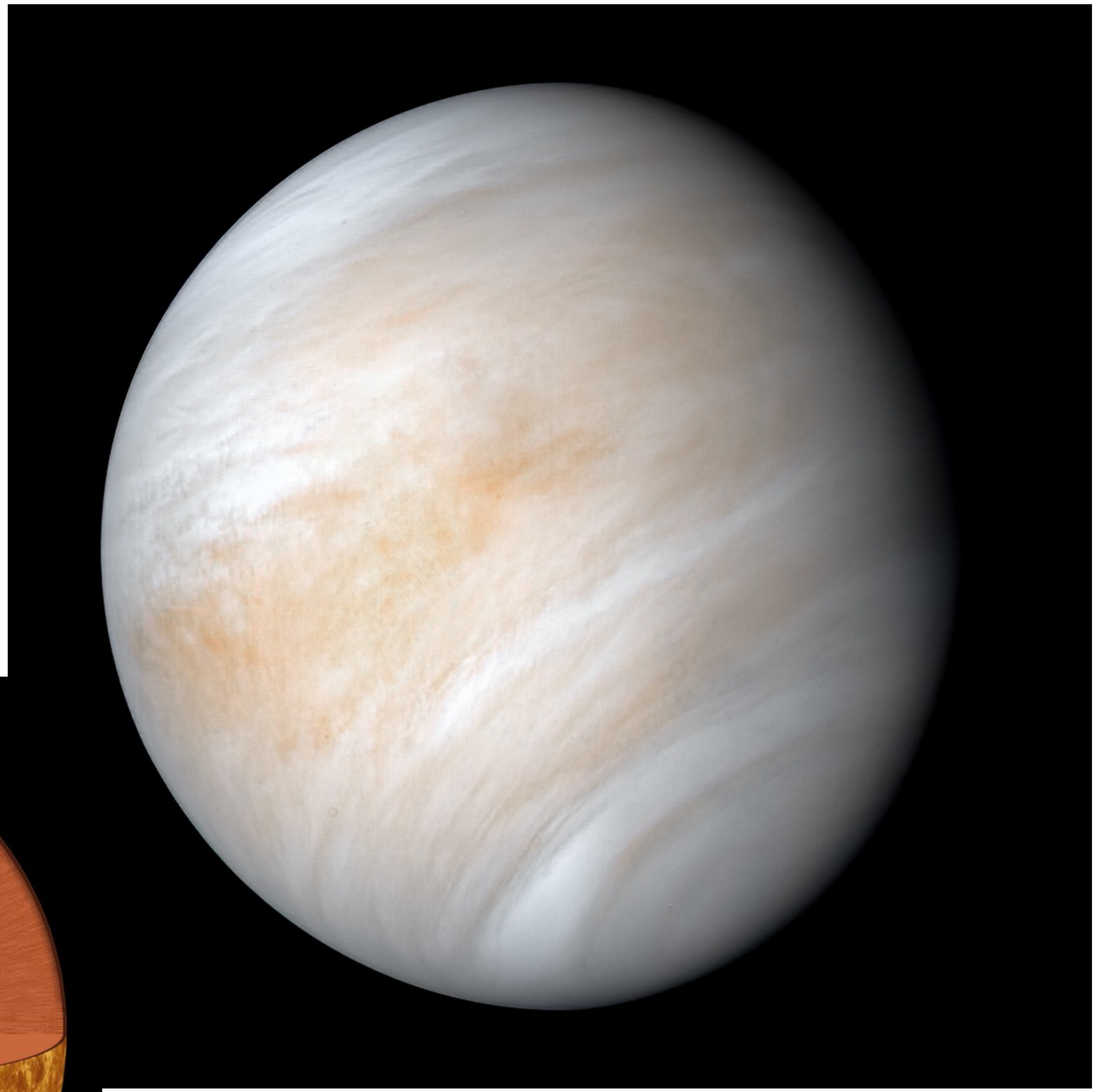
Venus

- OD 0.72 AU; M 0.815 EM; R 6052 km
- young surface, few highlands, volcanic features, coronae
- dense atmosphere of CO_2, ~470°C surface *T*
- ~3200 km iron core, ~2800 km silicate mantle, crust
- *weak* magnetic field







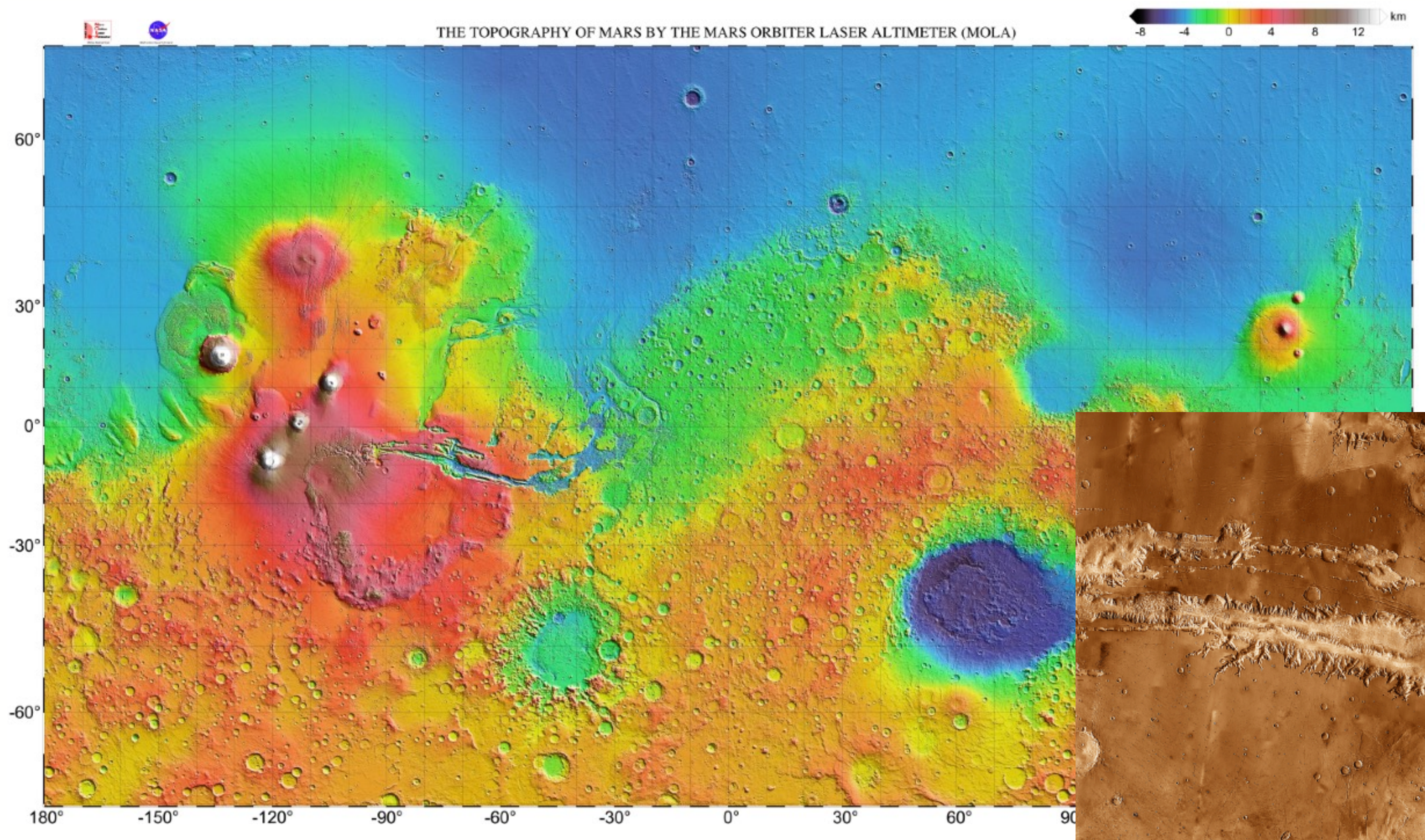


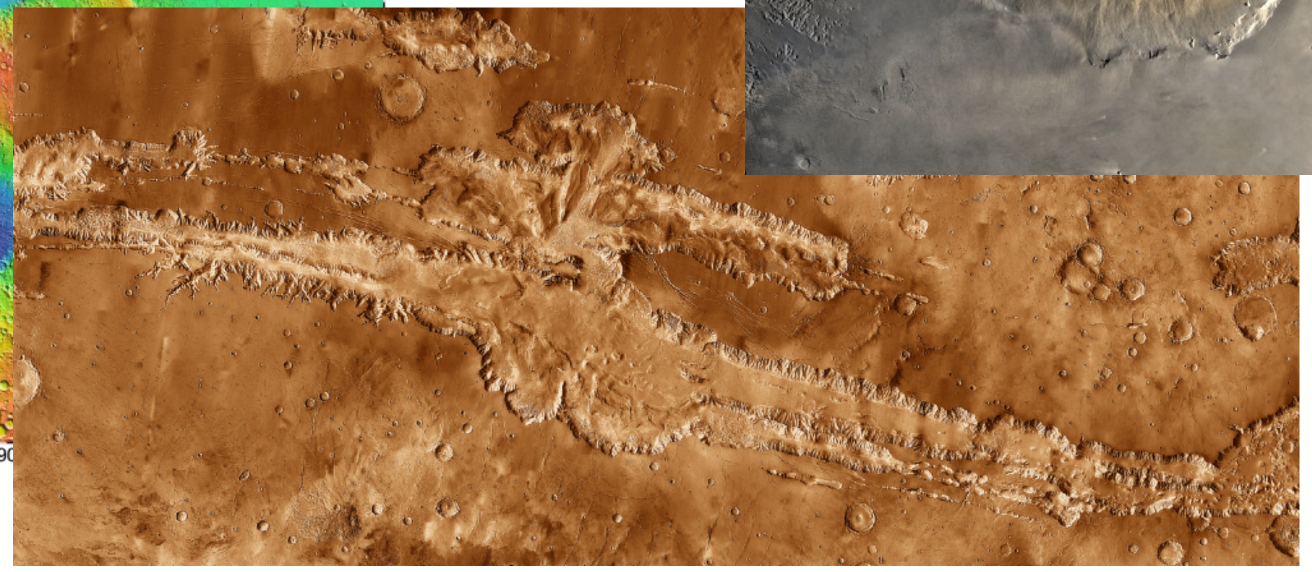
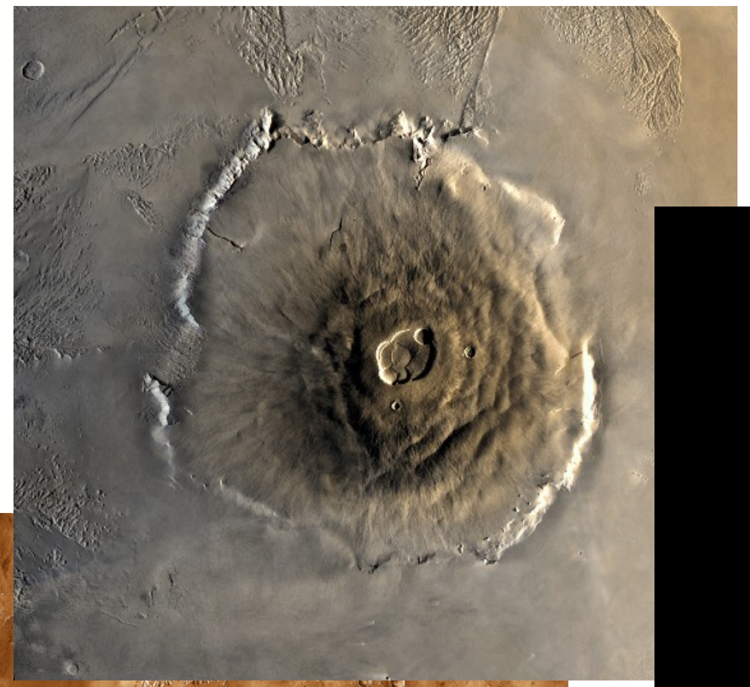
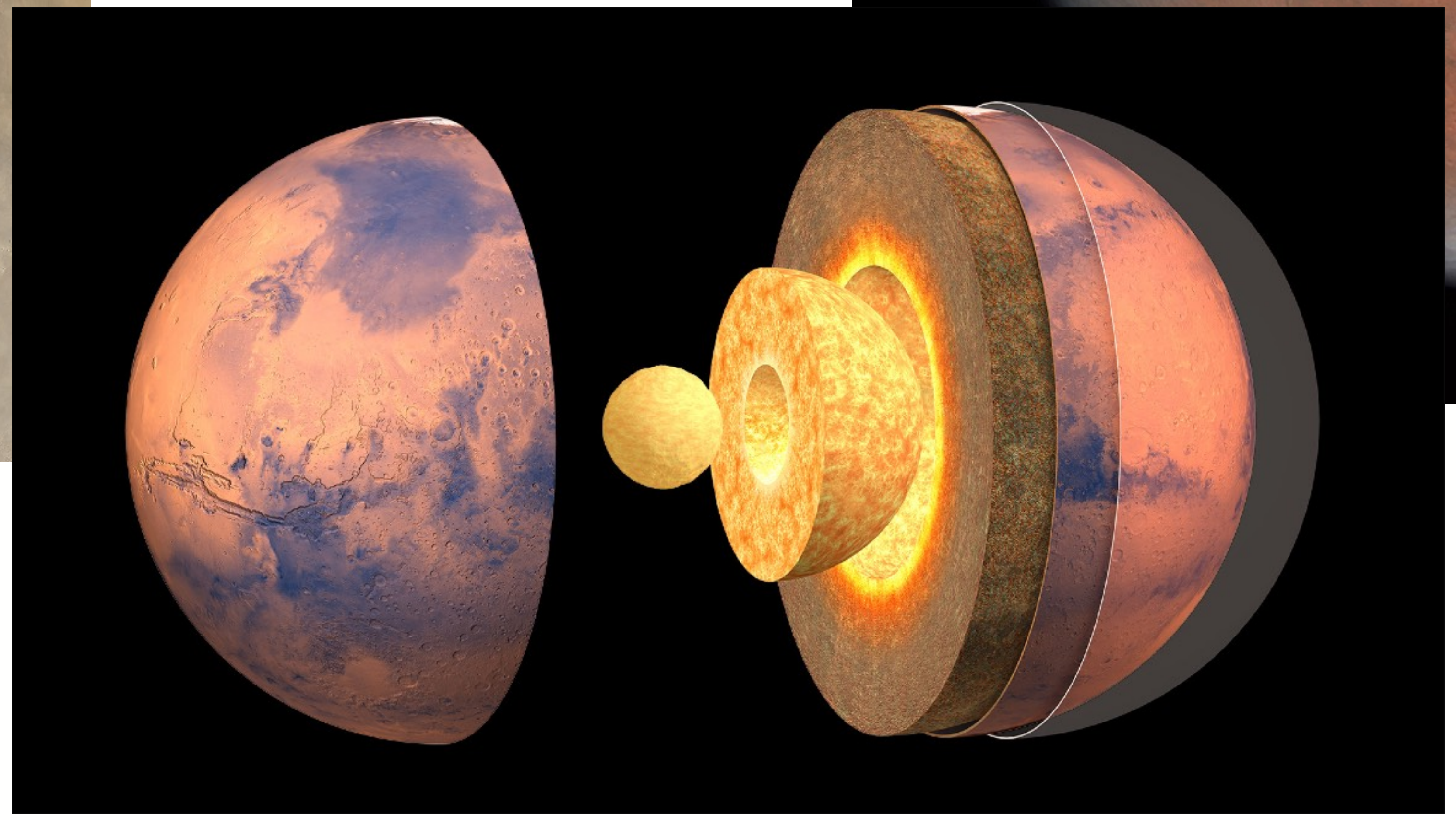
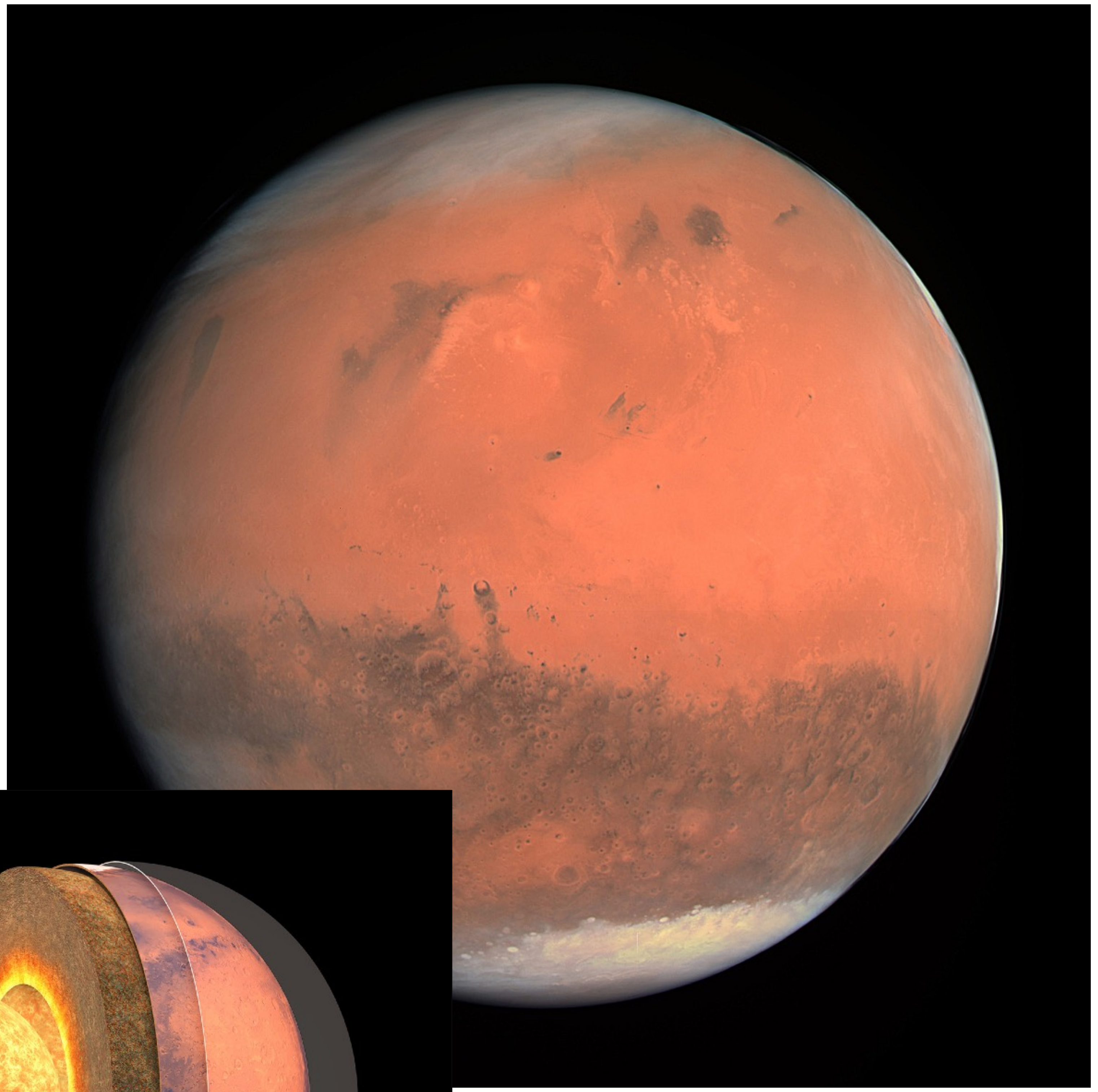
images: NASA

Planetary Formation | Terrestrial Planets

Mars

- OD 1.52 AU; M 0.1 EM; R 3390 km
- crustal dichotomy, Tharsis, Olympos Mons, Valles Marineris
- thin atmosphere of CO_2, ~ –60°C surface *T*
- ~1800 km iron core, ~1600 km silicate mantle, crust
- *no* active magnetic field



images: NASA

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UNIQUE EARTH | Planetary Formation

Summary

- Planets form by accretion from protoplanetary disk rotating around young Sun
- Accretion by dust adhesion, disk instabilities, pebble accretion, collisions
- Wide diversity of exoplanets discovered around many stars, currently biased to larger worlds
- Solar system comprises 4 terrestrial planets, 2 gas giants, 2 ice giants, numerous smaller bodies

Interactive Task on Padlet

- head over to Padlet (add Padlet link) and share your thoughts on…
- How would you define a planet (as opposed to stars, moons, asteroids, etc.)?

Any Questions?

- ask your questions or upvote existing ones on Slido (add Slido link)
- FAQs will be answered during Online Live Labs, GTA drop-in sessions on MS Teams