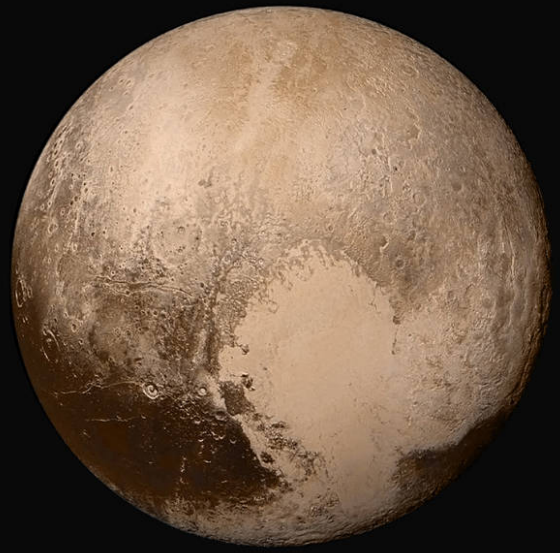
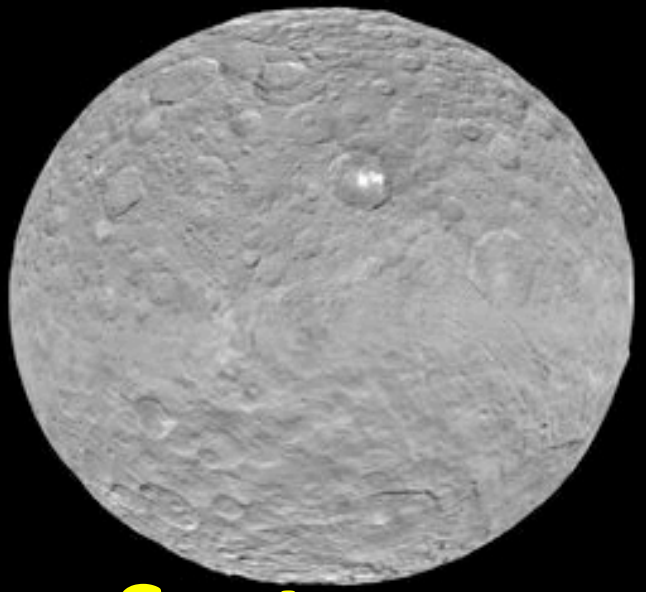
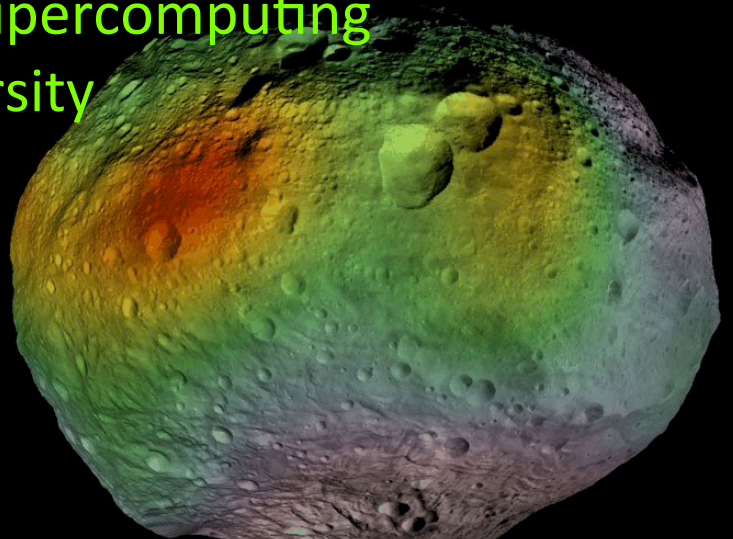




New View of the Solar System

Prof Sarah Maddison
Centre for Astrophysics & Supercomputing
Swinburne University



Part I:

The current Solar System revolution (¡viva!)

What is a planet?

Everyone knows what a planet is, right??

What is a planet?

Everyone knows what a planet is, right??

After all, we live on one….!

What is a planet?

Everyone knows what a planet is, right??

After all, we live on one….!

Pop quiz!

- Q: Can you name all the “naked-eye” planet of our Solar System?

What is a planet?

Everyone knows what a planet is, right??

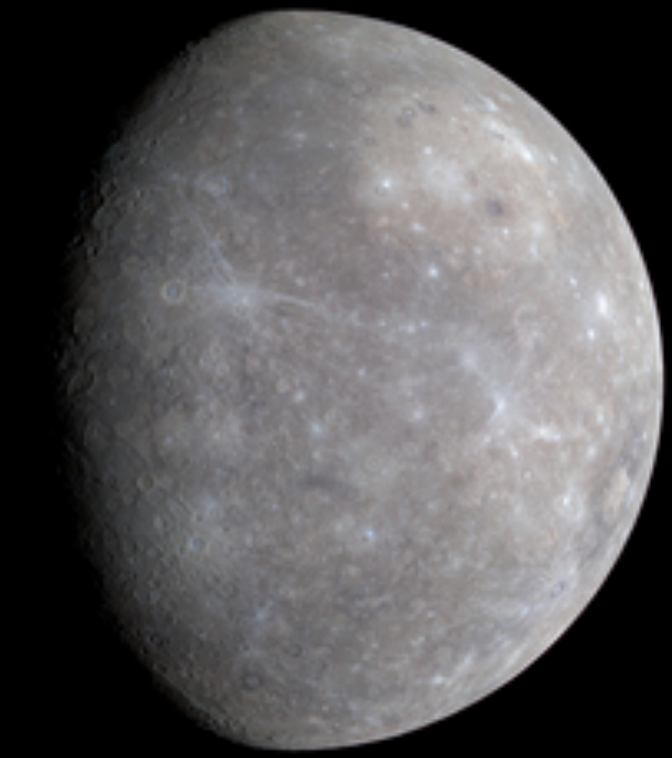
After all, we live on one….!

Pop quiz!

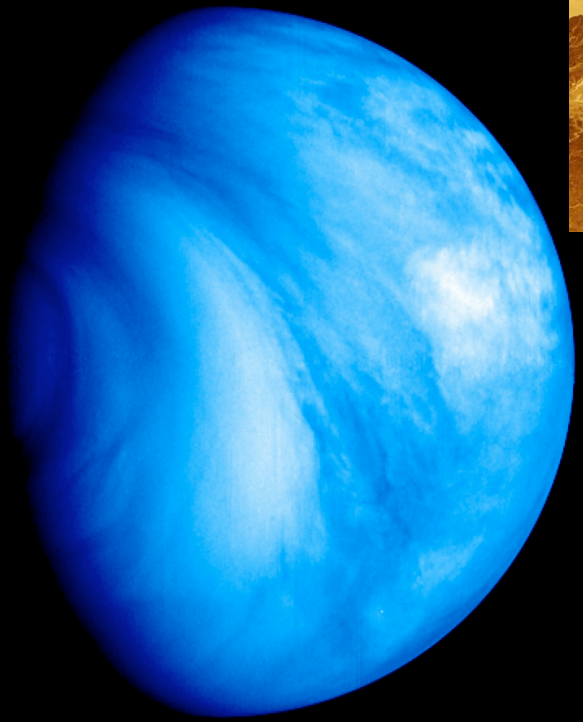
- Q: Can you name all the “naked-eye” planet of our Solar System?

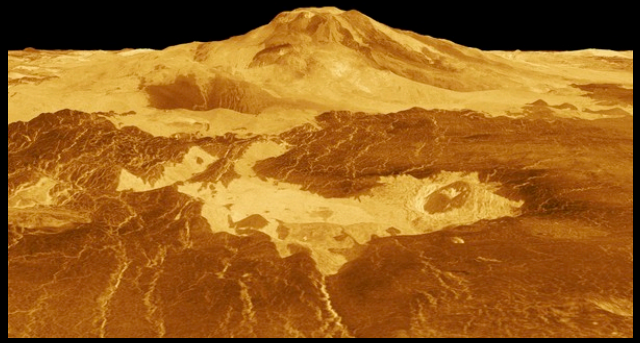
  Mercury, Venus, Mars, Jupiter & Saturn

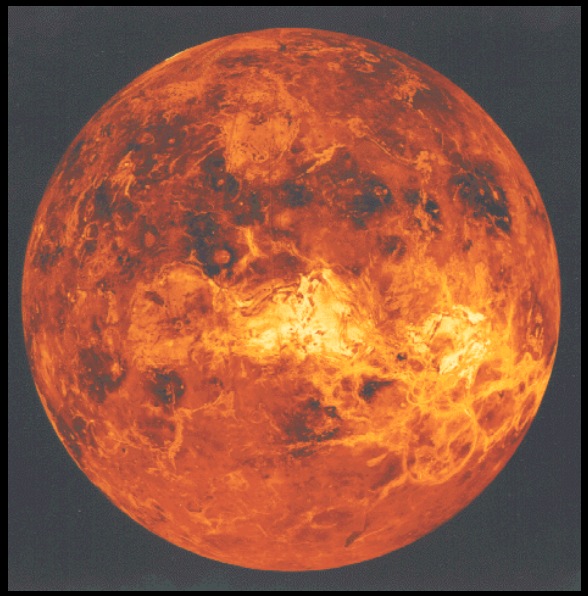
Mercury

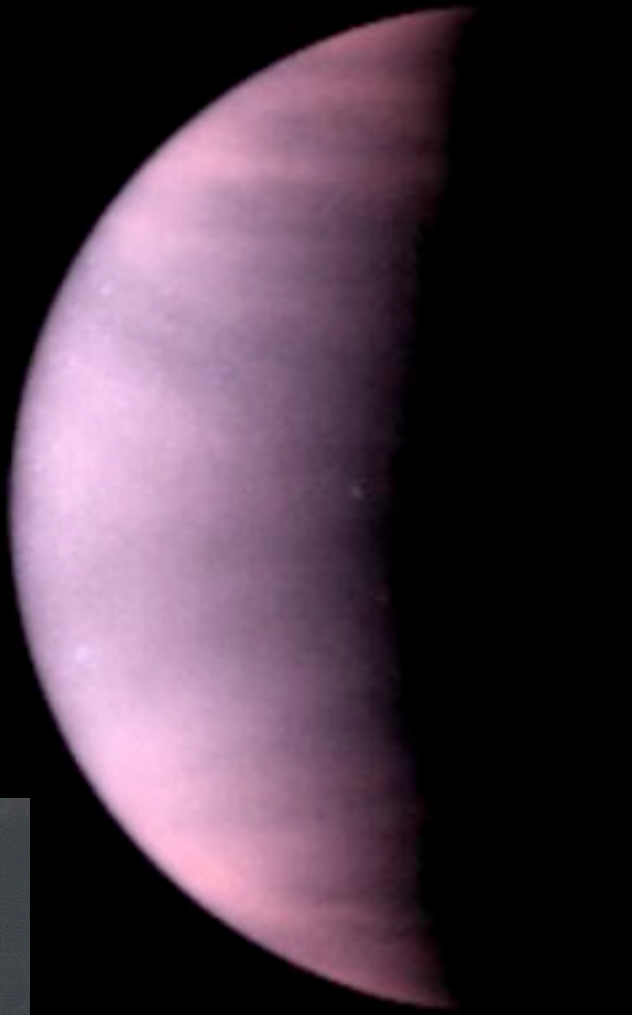


Venus

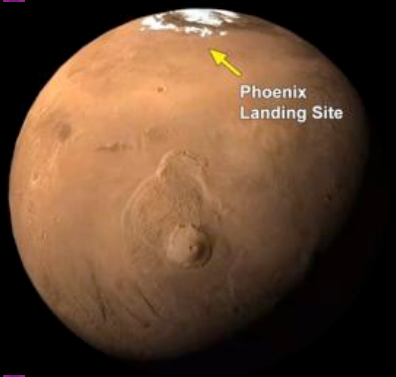


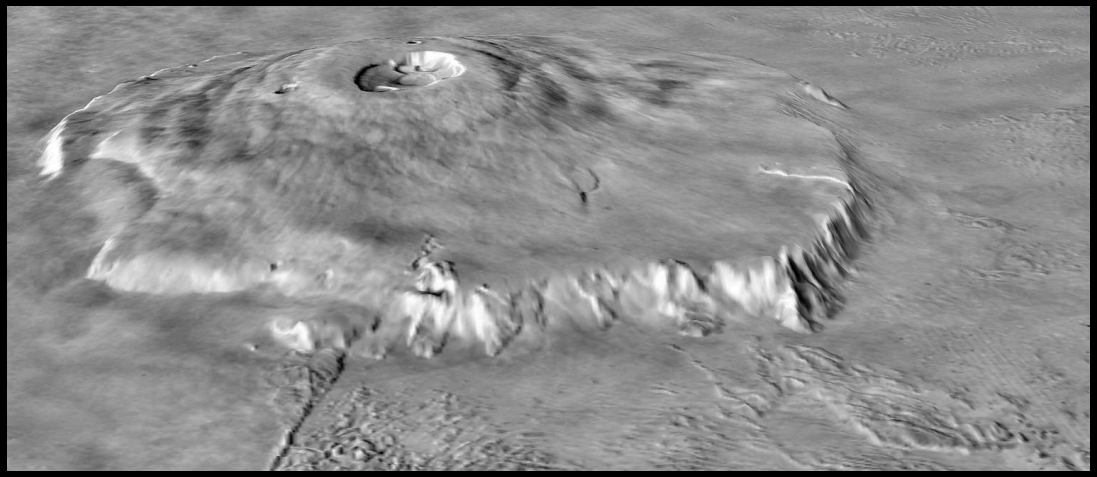






Mars





Jupiter

Saturn

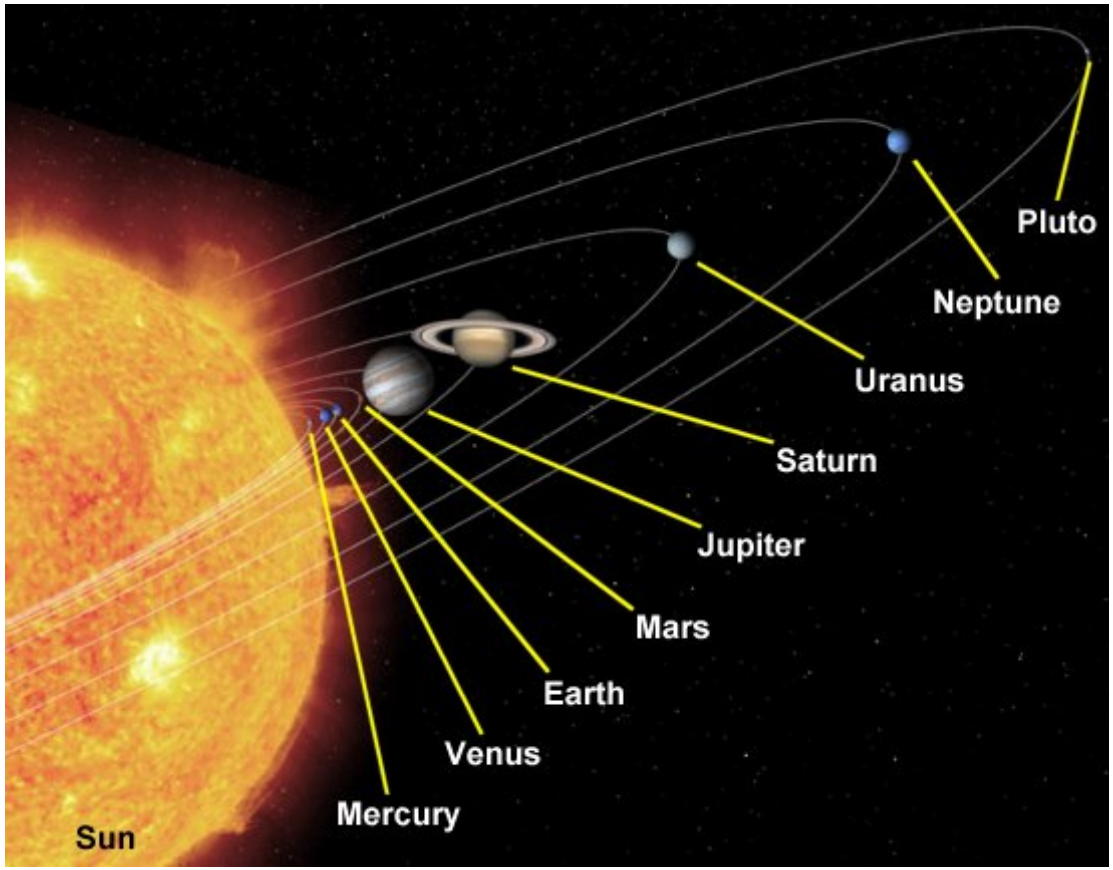
Janus and Pandora

More than 5 planets…

But what about the other planets?

Mercury, Venus, **Earth**, Mars,

Jupiter, Saturn, **Uranus**, **Neptune**? [and **Pluto**?]



NOT to scale!

More than 5 planets…

But what about the other planets?

Mercury, Venus, **Earth**, Mars,

Jupiter, Saturn, **Uranus**, **Neptune**? [and **Pluto**?]

Pop quiz!

Q: What is "special" about the Earth, Uranus, Neptune (and Pluto)?

More than 5 planets…

But what about the other planets?

Mercury, Venus, **Earth**, Mars,
Jupiter, Saturn, **Uranus**, **Neptune**? [and **Pluto**?]

Pop quiz!

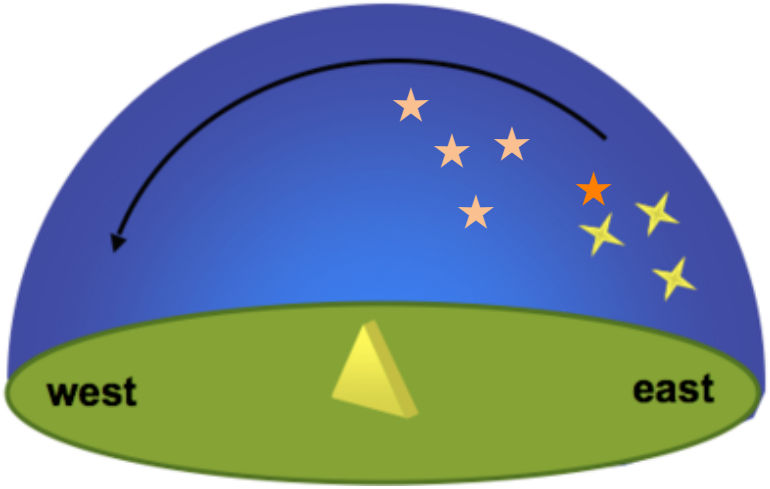
Q: What is "special" about the Earth, Uranus, Neptune (and Pluto)?

- The other planets were "discovered" once telescopes were invented and pointed towards the heavens in early 1600's

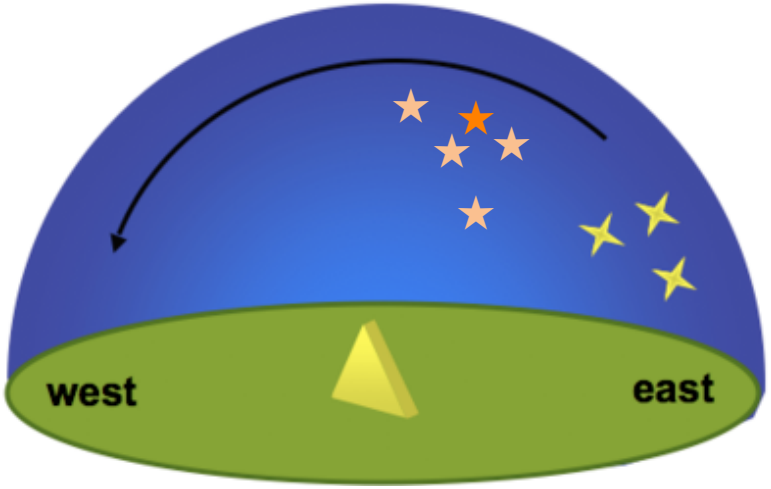
- Earth originally thought be centre of the universe!

The wanderers

- Constellations rise in East and set in West each night
- Over several nights, some ‘stars’ wander from the constellations; ancient Greeks called them ***asteres planetai*** or “wandering stars”

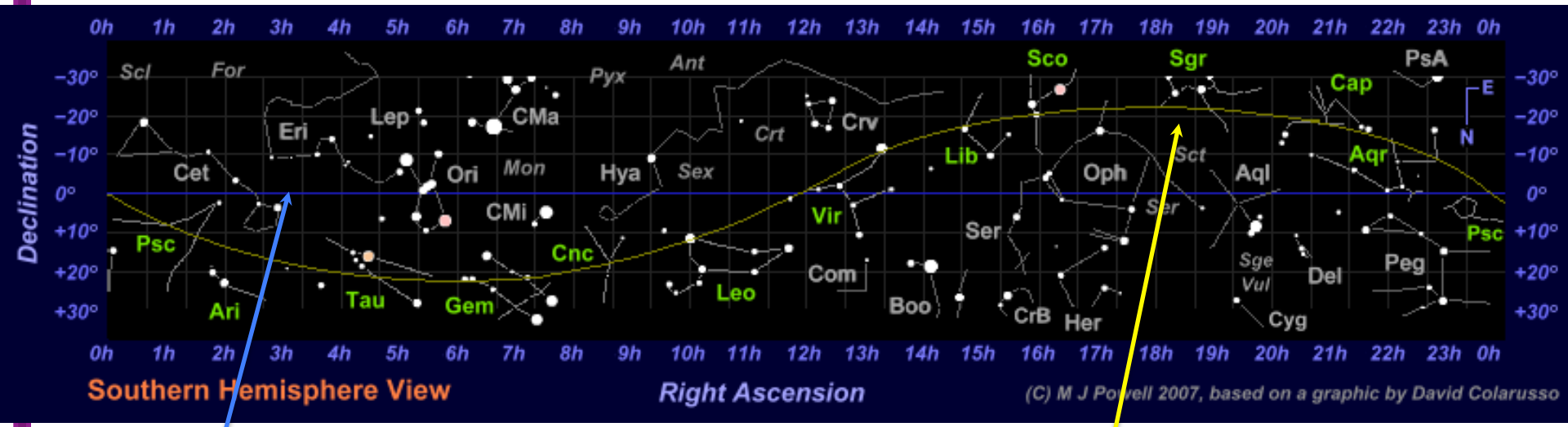


March



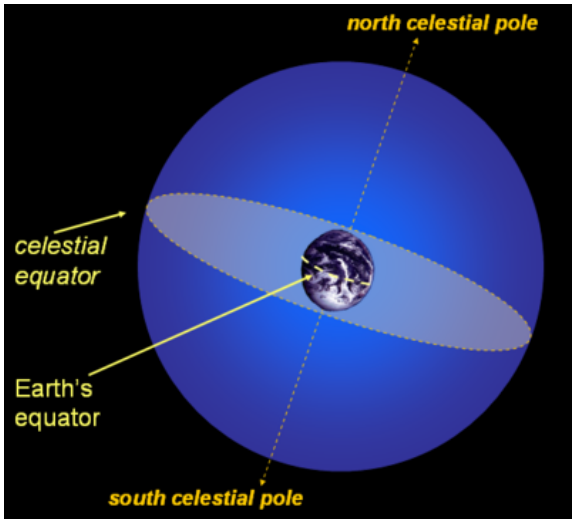
April

The wanderers

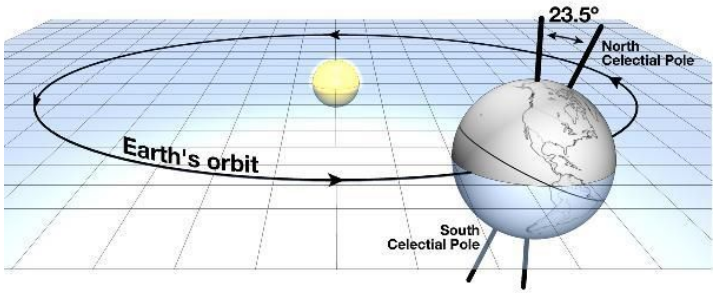


Equatorial sky map (coords RA & dec)

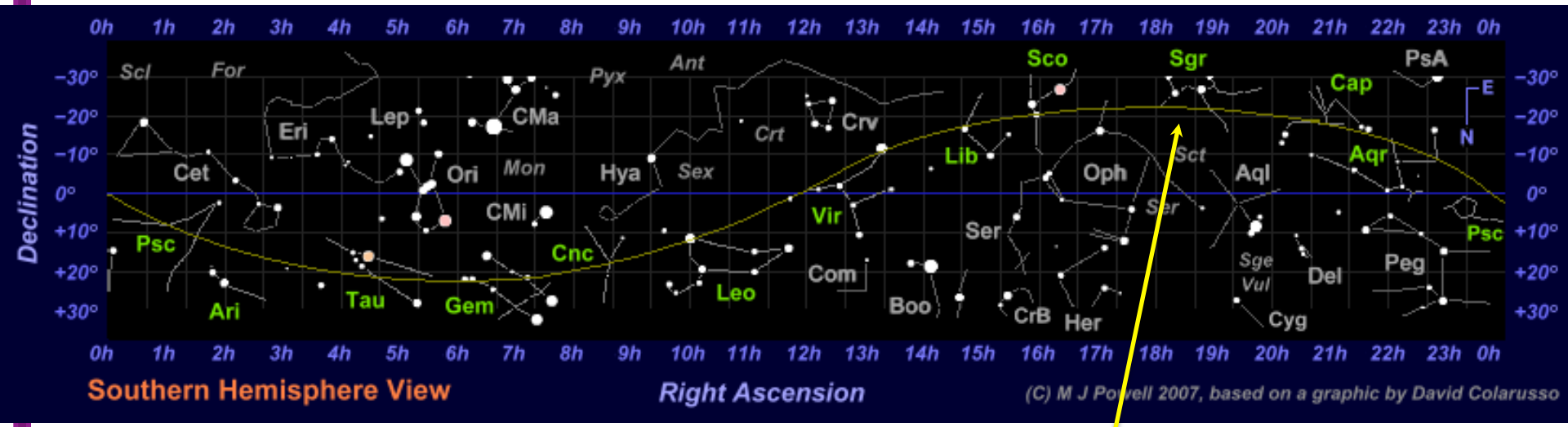
Celestial equator, extension of Earth's equator



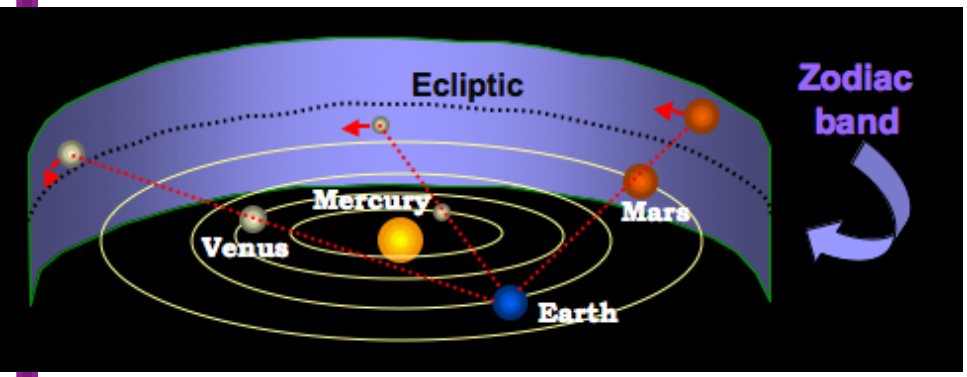
Ecliptic, path followed by the Sun



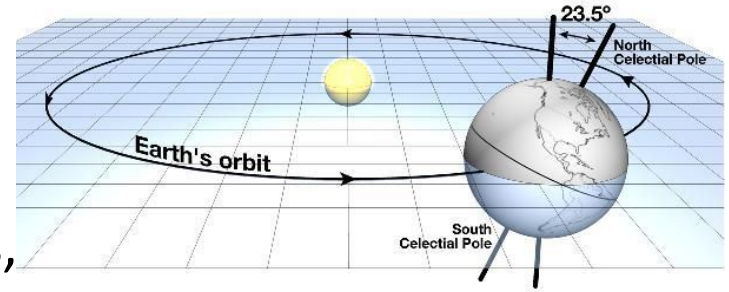
The wanderers



Equatorial sky map (coords RA & dec)



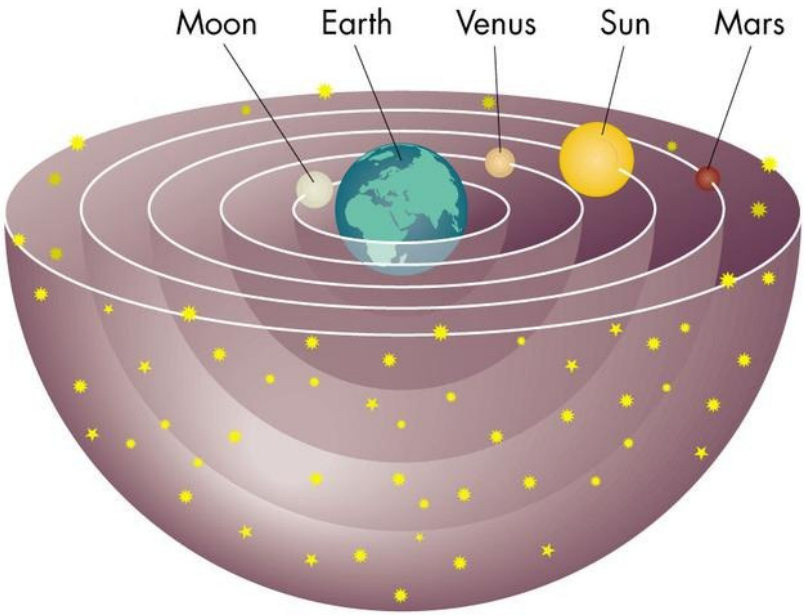
Ecliptic, path followed by the Sun



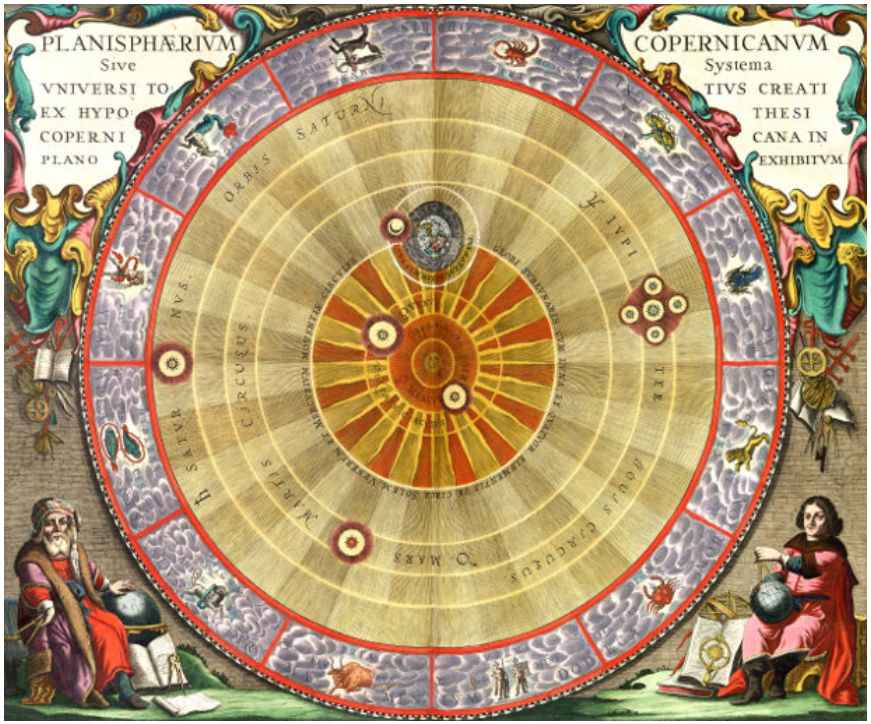
The 5 naked-eye planets (Mercury, Venus, Mars, Jupiter & Saturn) all move through the zodiac band around the ecliptic

The 1st solar system revolution

- Until the early 1500's, Earth was at the centre of the Universe!
- "Copernican revolution" put the Sun at centre → Earth another planet



Earth-centered



Sun-centered

Nicolai Copernicus overthrew Aristotle's earth-centre "common sense" model

The 1st solar system revolution

- Until the early 1500's, Earth was at the centre of the Universe!
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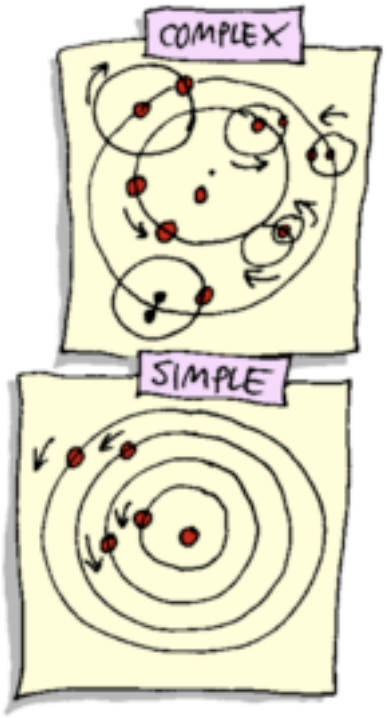
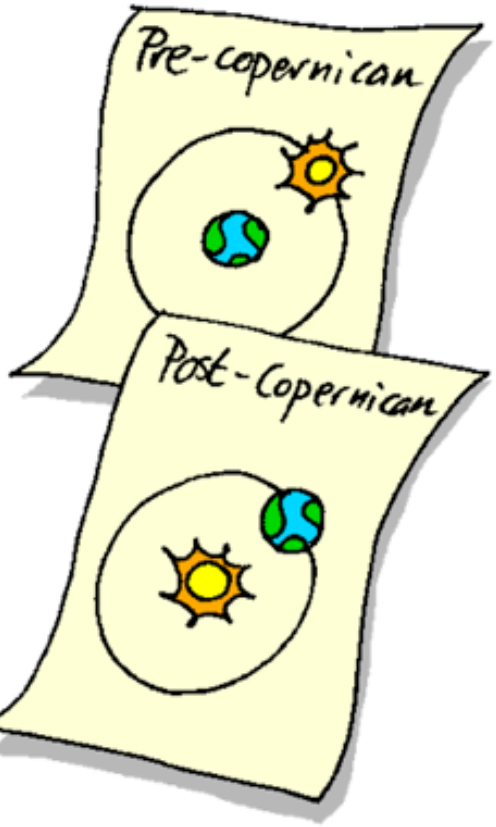
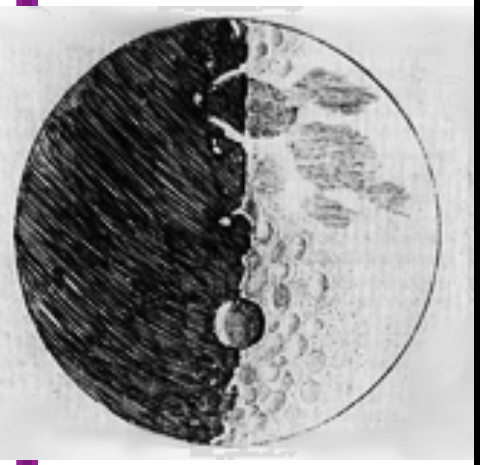




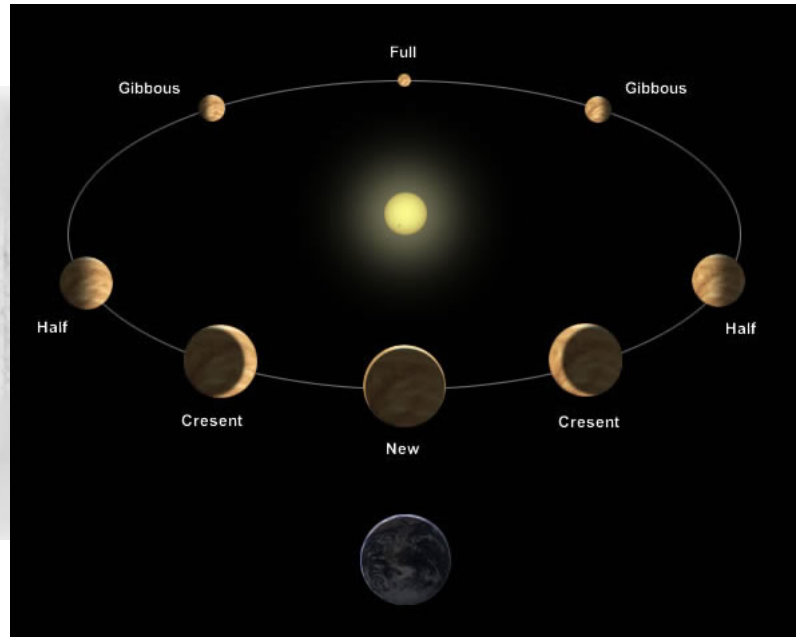
Nicolai Copernicus overthrew Aristotle's earth-centre "common sense" model

The 1st solar system revolution

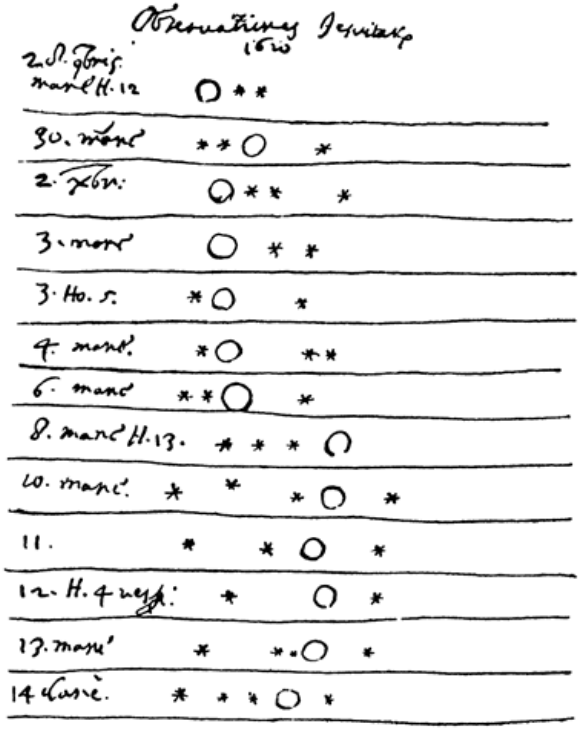
- Until the early 1500's, Earth was at the centre of the Universe!
- "Copernican revolution" put the Sun at centre → Earth another planet
- Telescopes in early 1600's showed the cratered surface of the moon, phases of Venus and moons orbiting Jupiter



surface of another world



proof that Venus orbits the Sun



Earth nor Sun only orbital centers

The 1st solar system revolution

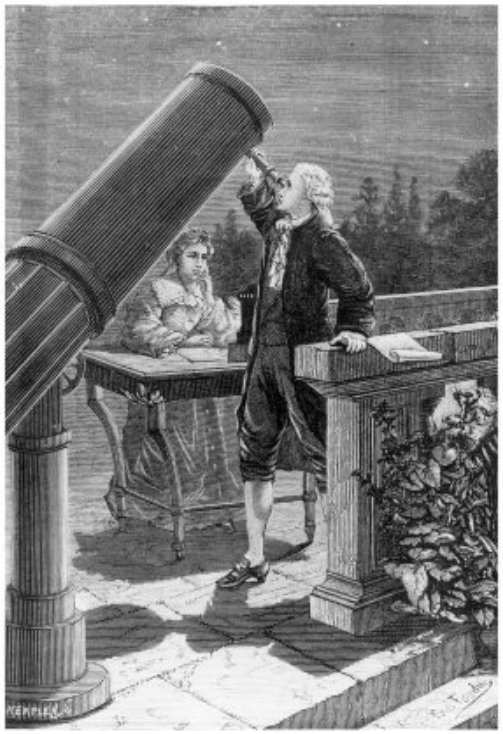
SWINBURNE CENTRE FOR ASTROPHYSICS AND SUPERCOMPUTING

Summary of the first solar system revolution:

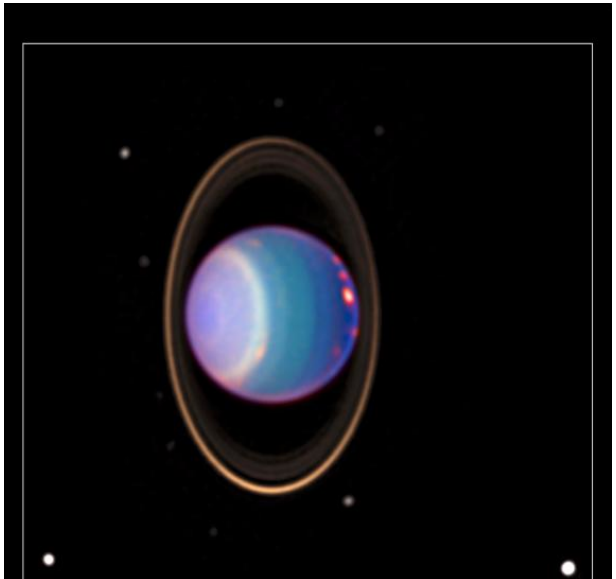
→ Earth is a planet, and all planets orbit the Sun!

The 2nd solar system revolution

- 1781: William Herschel discovered **Uranus** [7th planet in solar system]



- Herschel built reflecting telescope to study faint stars
- Found a large "non-stellar disk" (comet?); orbit was planetary, beyond Saturn
- Named planet *Georgium Sidus* (Georgian Planet) in honor of King George III of England. French did not like that!
- Astronomer Johann Bode suggested "Uranus" (ancient Greek god of the heavens) following classical mythology



(element ***uranium*** discovered in 1789 and named in honour of new planet!)

The 2nd solar system revolution

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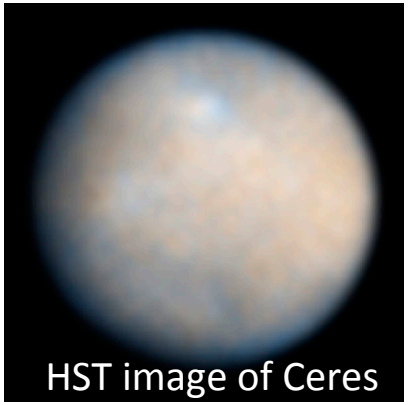
- 1801: Giuseppe Piazzi discovered **Ceres** [8th planet in solar system]

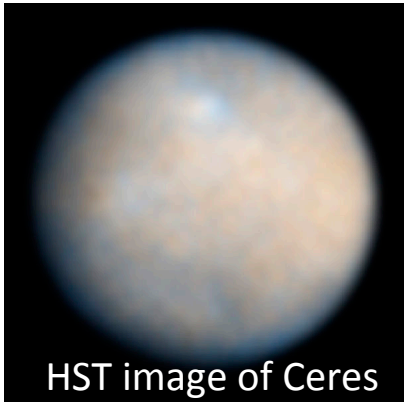

HST image of Ceres

- Piazzi also studying faint stars with telescope
- Discovered new planet between Mars & Jupiter

(element ***cerium*** discovered in 1803 and named in honour of Ceres)

The 2nd solar system revolution

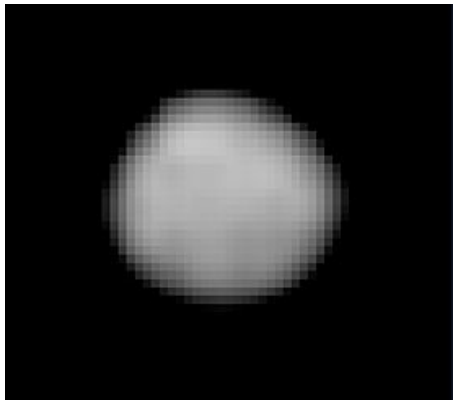
- 1801: Giuseppe Piazzi discovered **Ceres** [8th planet in solar system]



HST image of Ceres

- Piazzi also studying faint stars with telescope
- Discovered new planet between Mars & Jupiter

- 1802: Heinrich Olbers discovered **Pallas** [9th planet in solar system!]



- Olbers was studying Ceres when he discovered Pallas
- Also between Mars & Jupiter….

(element ***cerium*** discovered in 1803 and named in honour of Ceres;
element ***palladium*** discovered in 1802, named in honour of Pallas)

The 2nd solar system revolution

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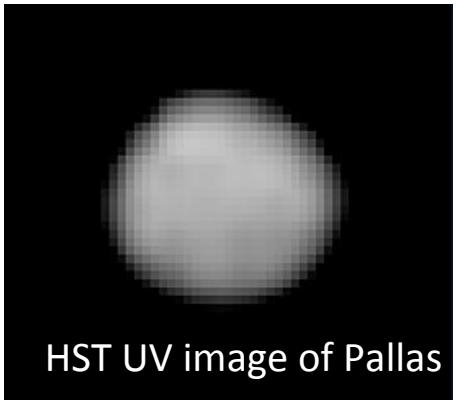
- Two new planets in “same place” ?? Is that possible?

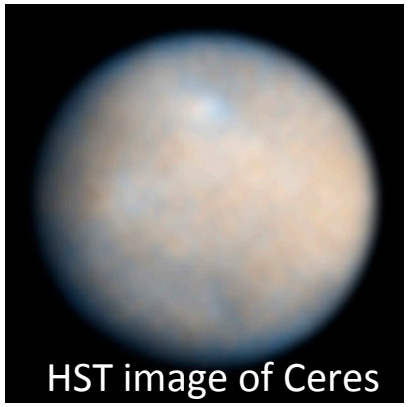
The 2nd solar system revolution

- Two new planets in “same place” ?? Is that possible?
- And both must be very small…

  • Need telescope to see distant Uranus, but see it as a disk with telescope
  • Ceres & Pallas much closer, but still need telescope & only see point of light
  • Herschel called them asteroids (‘aster’ = star + ‘oid’ = like)



HST UV image of Pallas



HST image of Ceres

Pallas ~ 550 km is size
~ 7% mass of asteroid belt

Ceres ~ 950 km is size
~ 35% mass of asteroid belt

The 2nd solar system revolution

- Two new planets in “same place” ?? Is that possible?
- And both must be very small…

  • Need telescope to see distant Uranus, but see it as a disk with telescope
  • Ceres & Pallas much closer, but still need telescope & only see point of light
  • Herschel called them asteroids (‘aster’ = star + ‘oid’ = like)

- Quickly more wanders were found…
- 1804: Karl Harding discovered **Juno** [10th planet in solar system]
- 1807: Heinrich Olbers discovered **Vesta** [11th planet…]

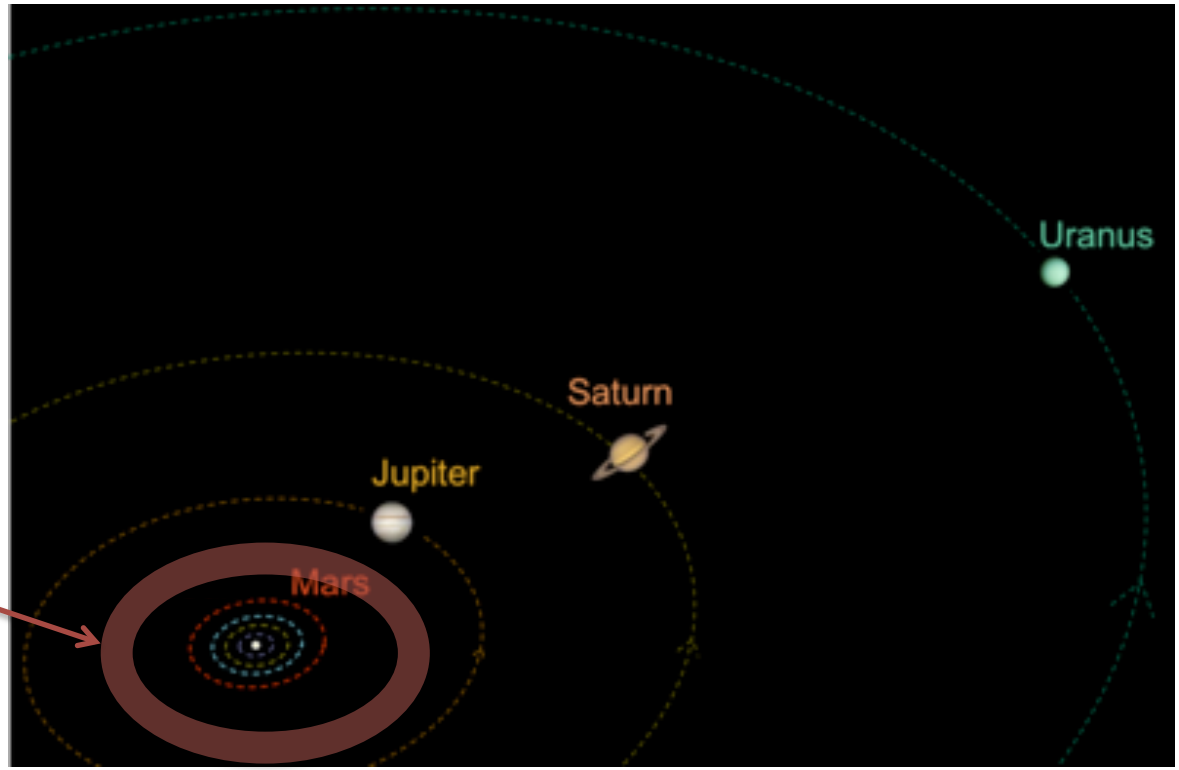
…. All getting is a bit crazy….

(no elements were named after Juno or Vesta…)

The 2nd solar system revolution

- Then nothing much happened for 40 years…
  (besides another dozen or so asteroids found)

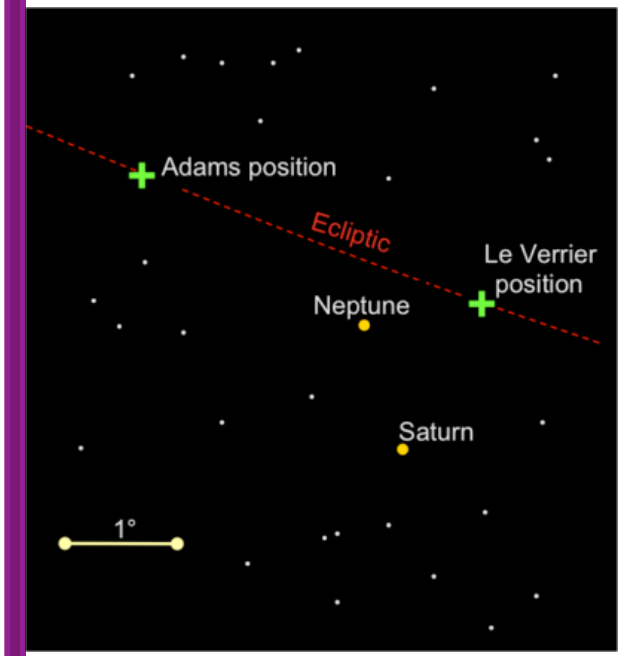
Swarm of **asteroids**
between Mars & Jupiter



The 2nd solar system revolution

- Then nothing much happened for 40 years…
  (besides another dozen or so asteroids found)

- 1846: **Neptune** discovered [12th planet?? Or 8th planet??]
  - had been observed by many times over the years
  - history: 'co-discovered' by John Adams and Urbain Le Verrier



Neptune's moon Triton discovered a few weeks later; could determine mass of Neptune

The 2nd solar system revolution

Summary of the second solar system revolution:

→ Solar system contains more than just the naked-eye planets

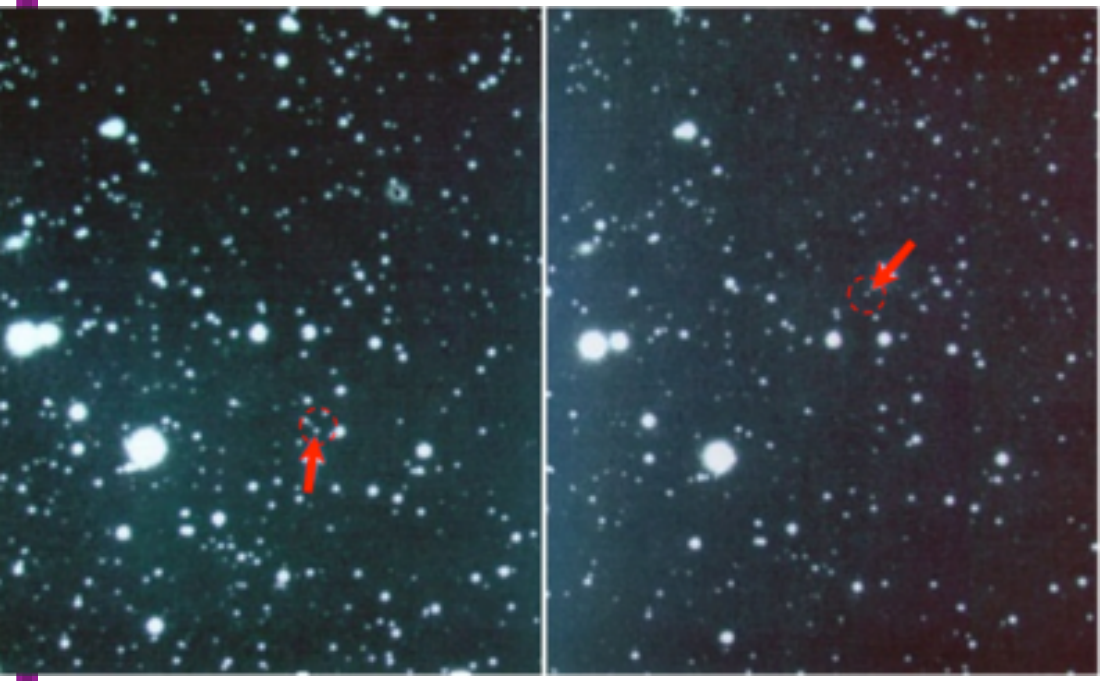
→ By early 1900s, our Solar System had **8 planets**
plus **asteroid belt** between Mars & Jupiter

The 2nd solar system revolution

BUT WAIT!! One more planet discovered in outer Solar System…

The 2nd solar system revolution

- 1930: Clyde Tombaugh discovered **Pluto** [9th planet in Solar System]



Lowell Observatory discovery plates

But Pluto was a bit strange…
-Tiny dot of light: planet or asteroid?
-Orbit not a circle (like the planets)
-Orbit tilted to ecliptic (unlike planets)

(element ***plutonian*** discovered in 1940 and named in honour of Pluto)

The 2nd solar system revolution

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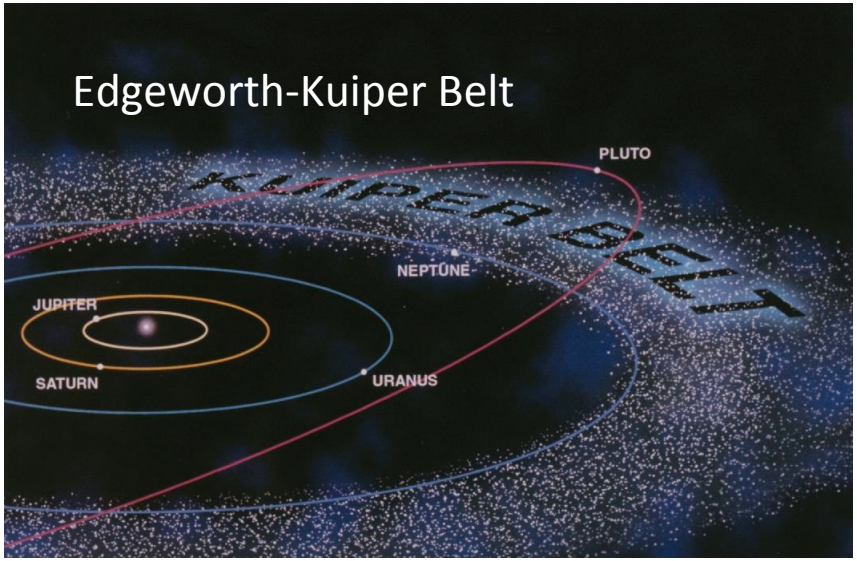
(2nd) summary of the second solar system revolution:

→ By 1940s, our Solar System had **9 planets**, a swarm of **asteroids** between Mars & Jupiter (plus icy **comets** in outer Solar System)

(What is a planet? A large body that orbits the Sun?
Asteroids different: they travel in swarms)

The 3rd solar system revolution

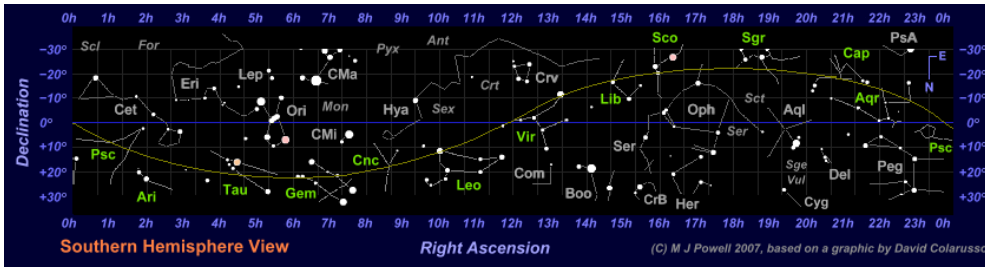
- But planet searches did not stop…
- Theorised that an outer belt of asteroids should also exist



Edgeworth-Kuiper belt: predicted in the late 1940s-early 1950s, a belt of icy bodies beyond Neptune left over from formation of Solar System

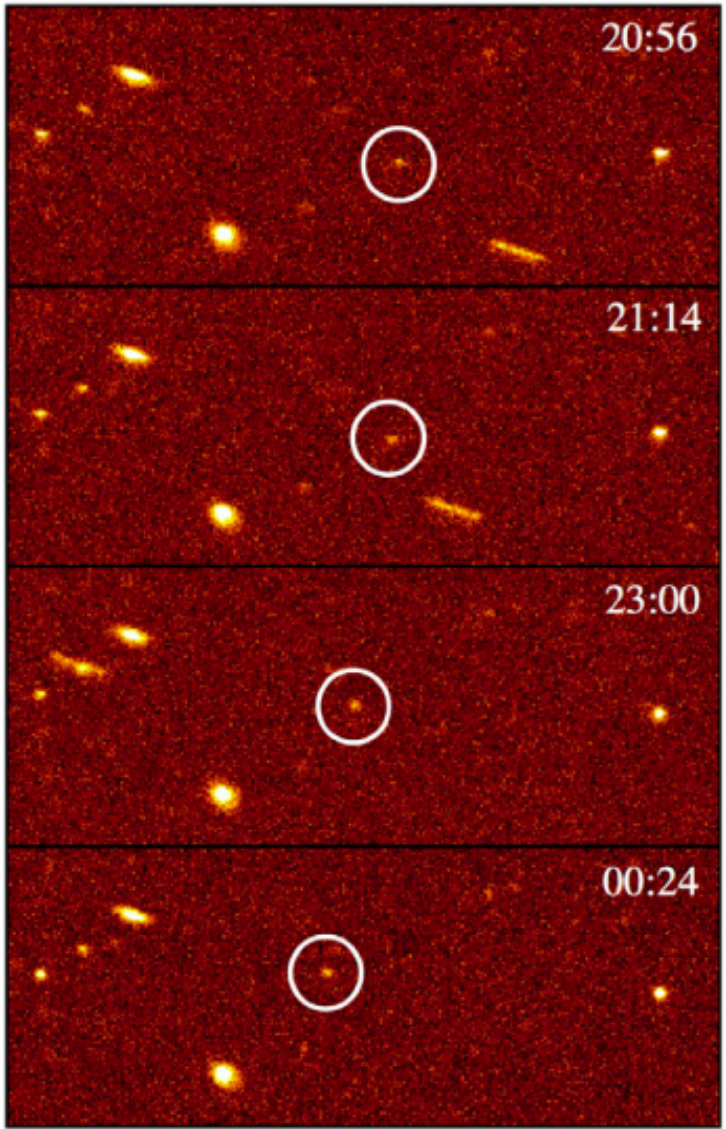
In 1980 suggested to be source of short period comets, so the hunt was on!

- But where to hunt?? In the ecliptic, but space in big… Need to do surveys of big patches of the sky…

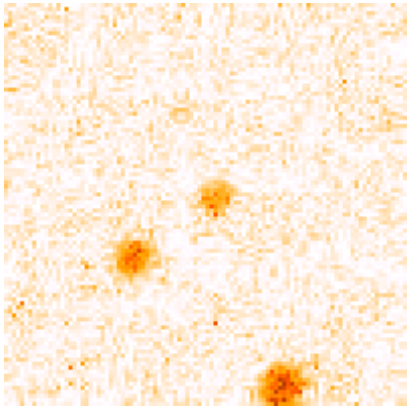


The 3rd solar system revolution

- First Kuiper belt object (KBO) discovered 1992 by Dave Jewitt & Jan Luu



- Searches intensities, and by 1999 over 200 KBOs discovered; over 1000 today
- HUGE revolution in the solar system!
- Overnight we have an entirely new class of objects…

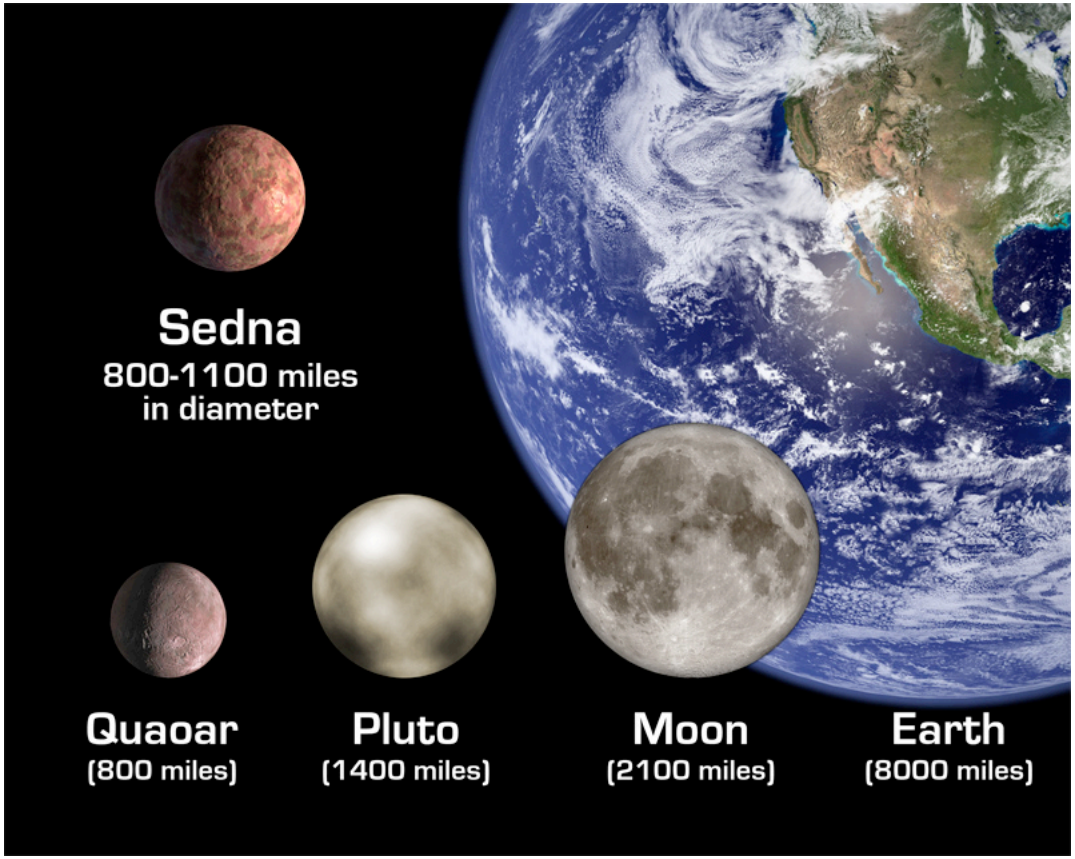


1995 WY2 discovery images from Keck taken 18 mins apart

1992 QB1 (aka “cubewano”) discovery images from the University of Hawaii’s 2.2-m telescope

The 3rd solar system revolution

- Planet hunter Mike Brown has discovered many KBOs
- Use old Palomar Sky Survey plates that covered large chunks of sky
- June 1992 discovered big **Quaoar** (‘Kwa-o-ar’) 1,200 (60% of Pluto)….
  → Maybe objects BIGGER than Pluto out there??



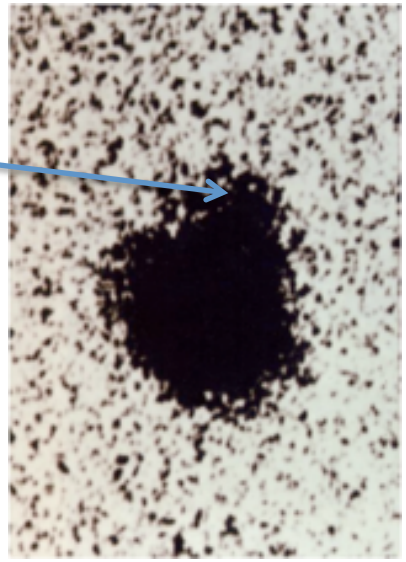
Examining a Palomar Sky Survey plate

The 3rd solar system revolution

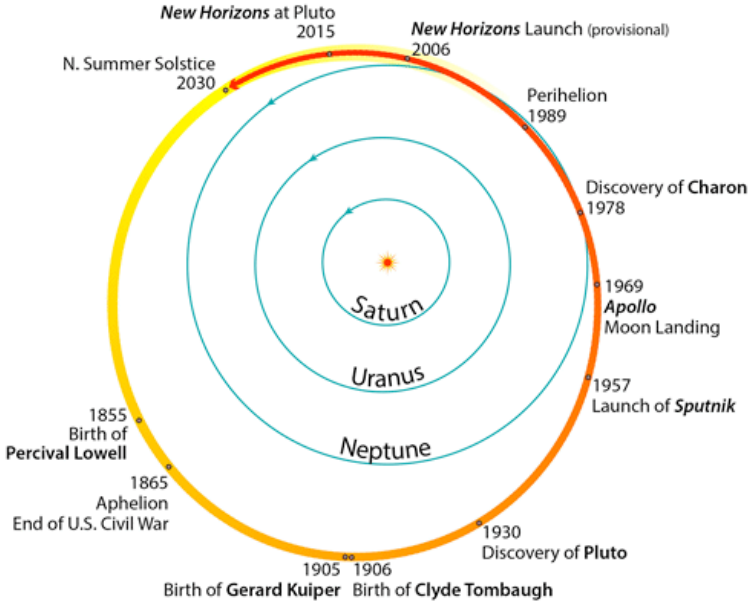
SWINBURNE CENTRE FOR ASTROPHYSICS AND SUPERCOMPUTING

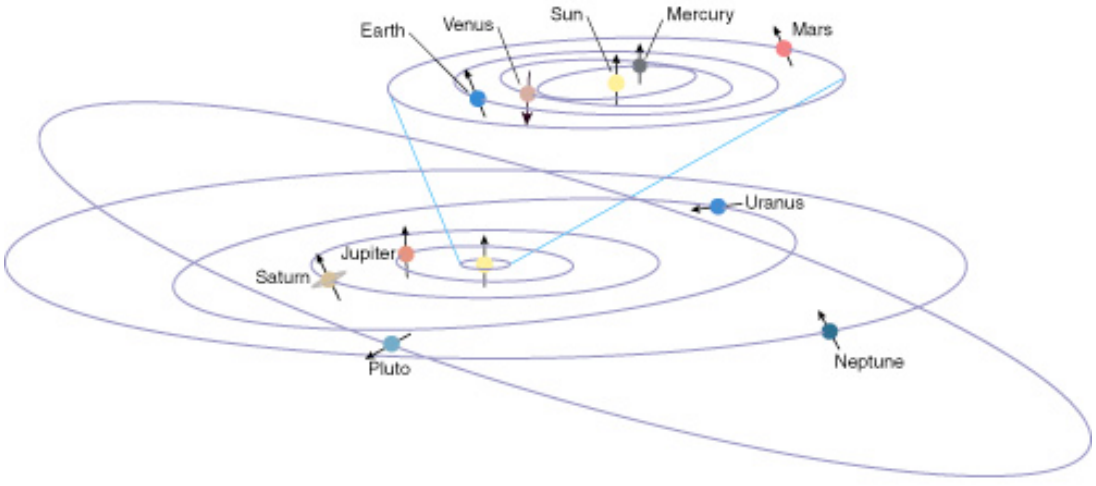
Interlude: a bit more about Pluto

- Pluto's moon Charon discovered in 1978
  can determined mass (0.2% of Earth!!)
  and it's small (65% of Moon!)
- Unlike the rocky planets or the giants, it's a mix of ice (30%) and rock (70%)
- Has a thin atmosphere of N_2, CO and NH_3
- It's orbit is weird



e=0.25
i=17°

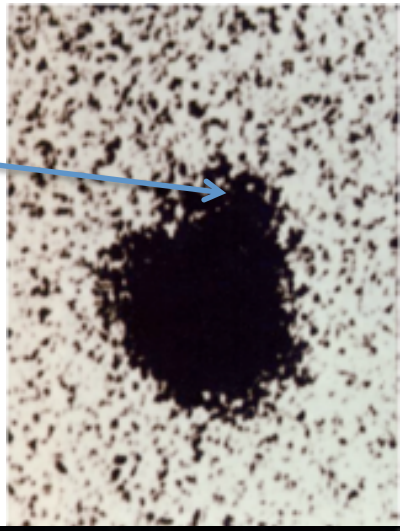


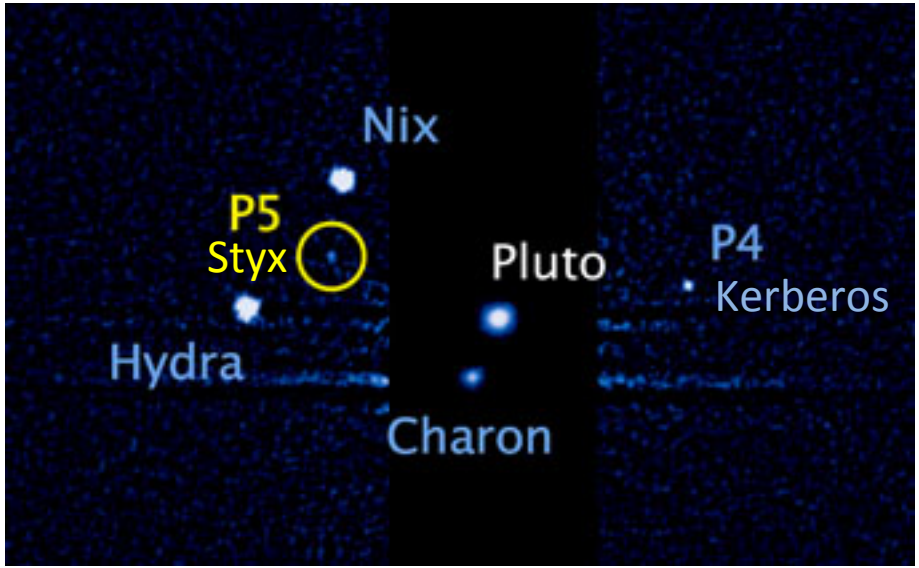


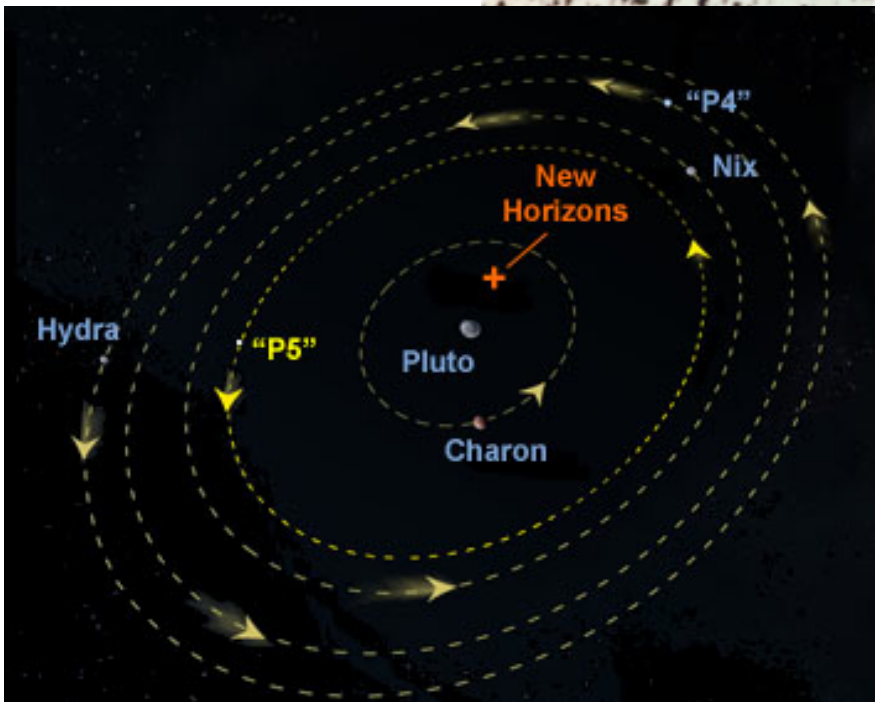
The 3rd solar system revolution

Interlude: a bit more about Pluto

- Pluto's moon Charon discovered in 1978
  can determined mass (0.2% of Earth!!)
  and it's small (65% of Moon!)
- Unlike the rocky planets or the giants, it's a mix of ice (30%) and rock (70%)
- Has a thin atmosphere of N_2, CO and NH_3
- It's orbit is weird
- And it has heaps of companions!

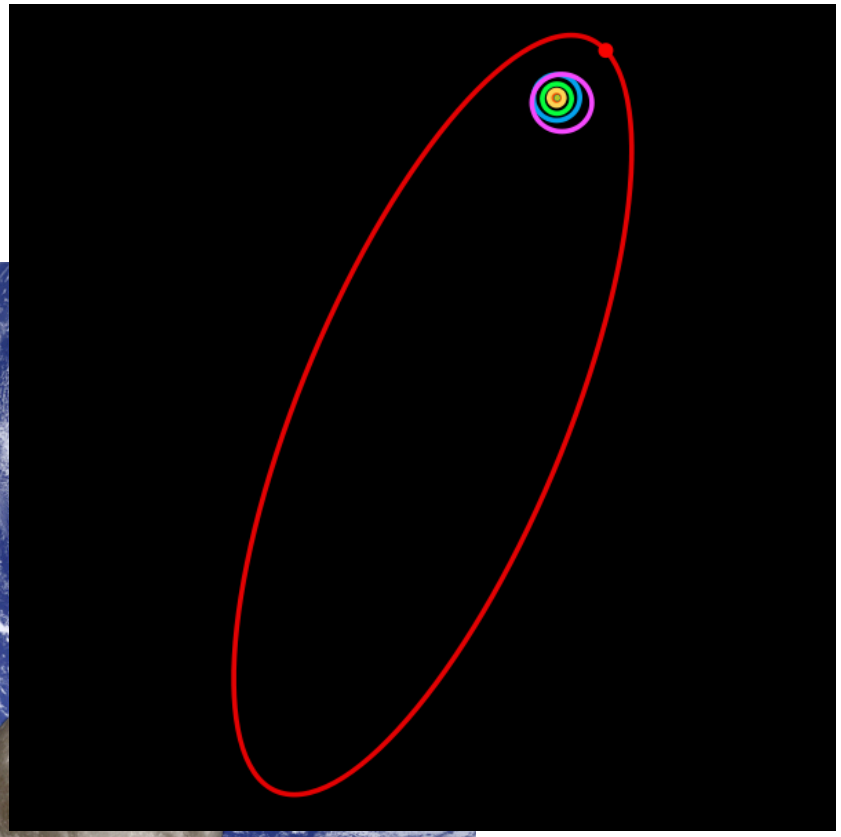




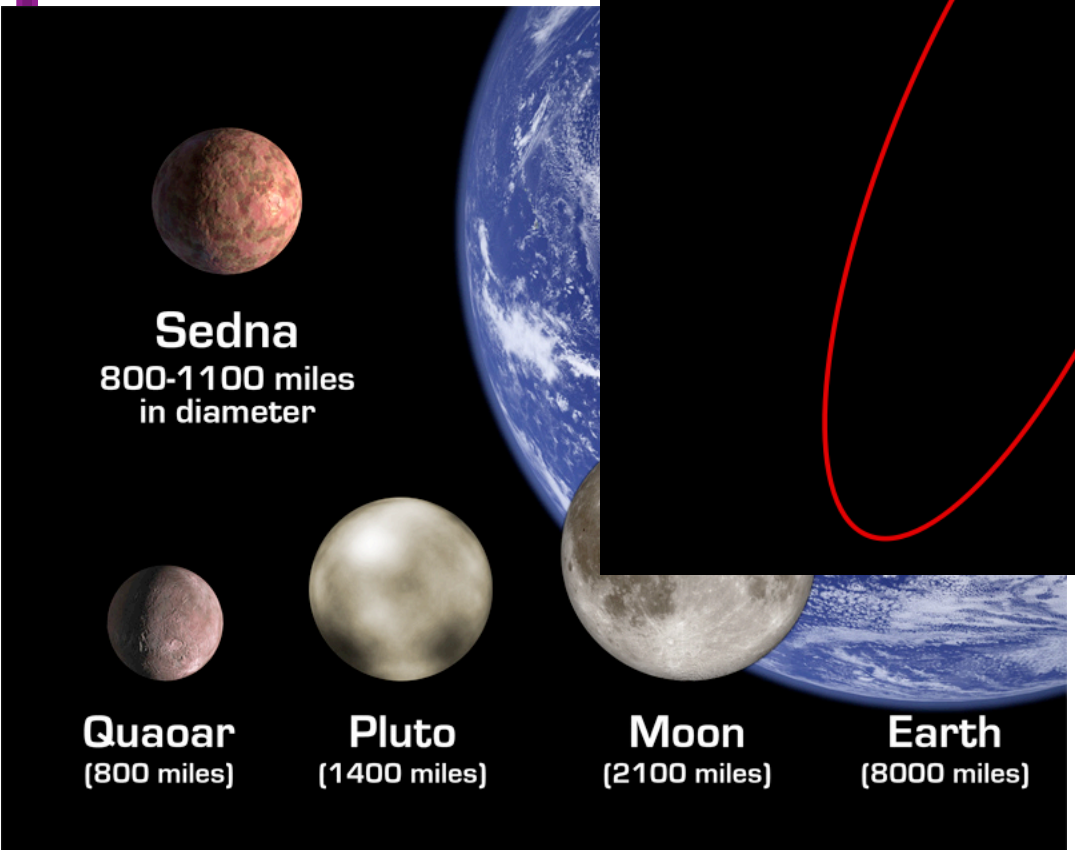


The 3rd solar system revolution

- Nov 2003, Mike Brown discovered **Sedna**
- Totally crazy orbit…

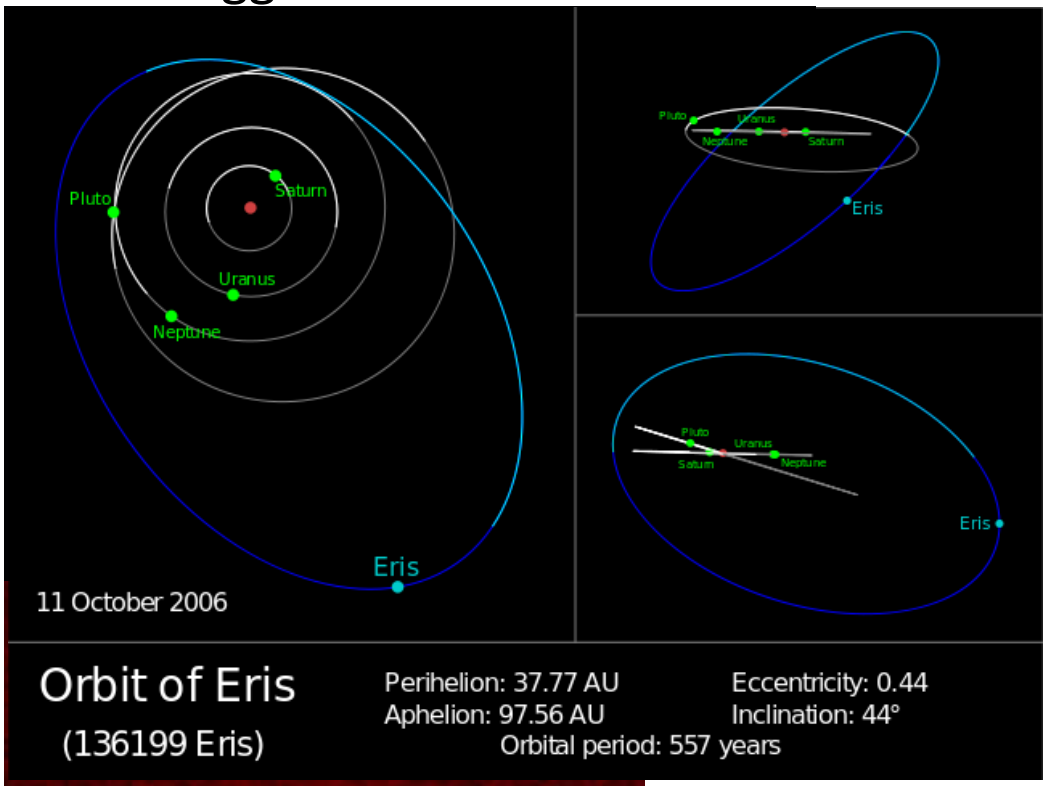


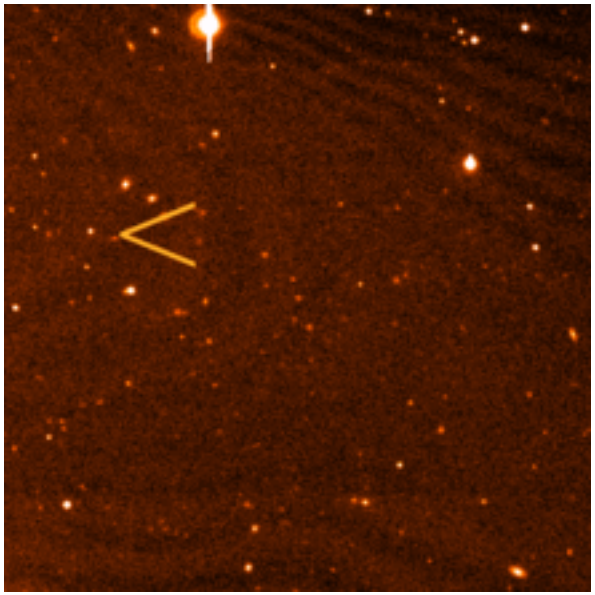
Sedna	(Pluto)
e = 0.85	(cf. e=0.2)
a =520 AU	(cf. 40 AU)
a_{min} = 76 AU	(cf. 30 AU)
a_{max} = 940 AU	(cf. 49 AU)



The 3rd solar system revolution

- Jan 2005, Mike Brown & coworkers found **Eris** (2003 UB 313), which was even bigger than Pluto… Mike called it *Xena* - planet X - the 10th planet

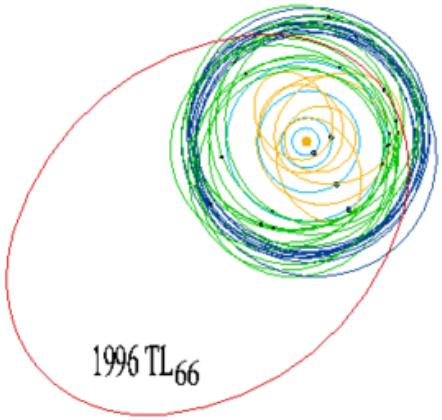




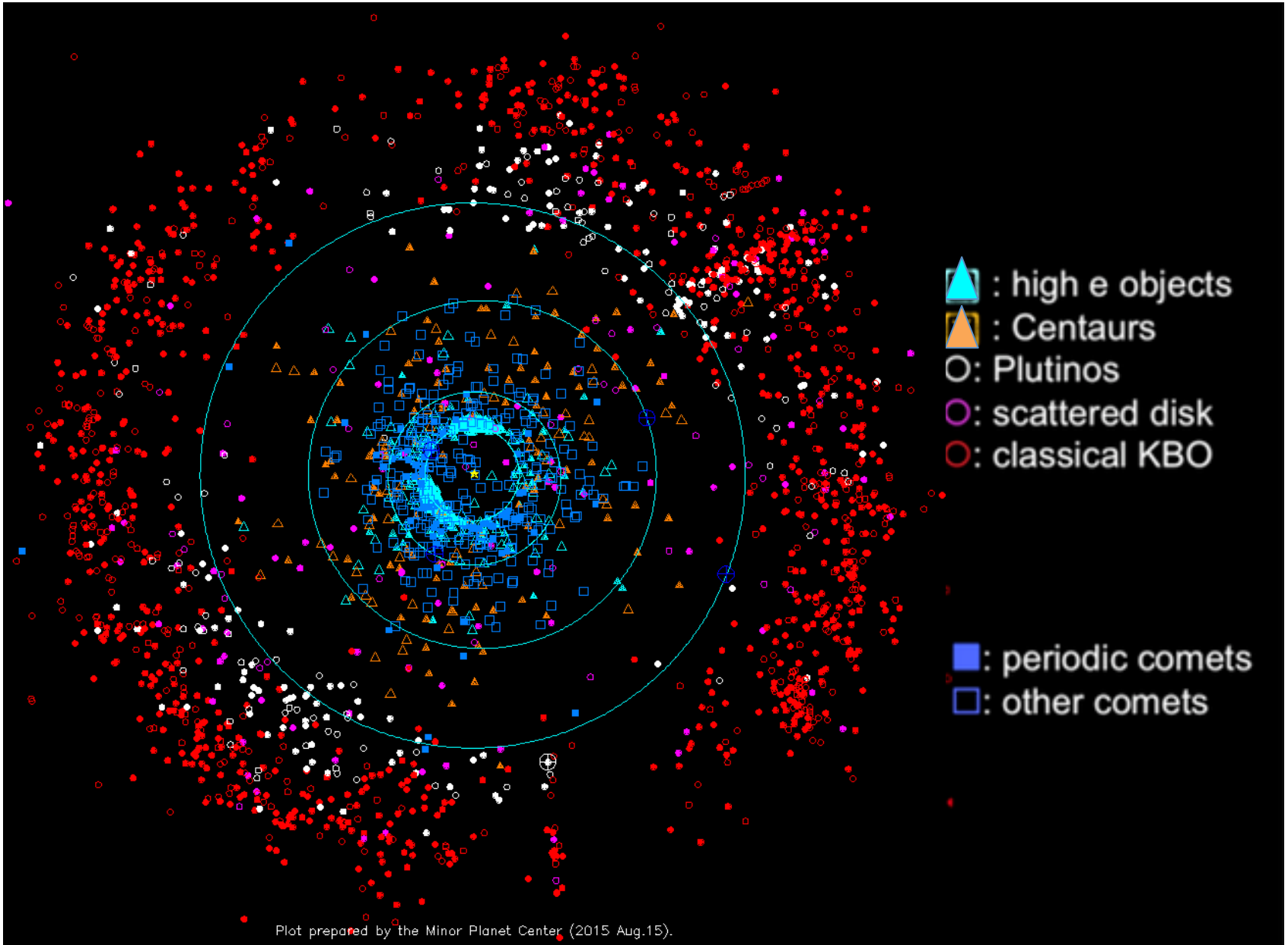
- Eris, like Pluto, also has a satellite called Dysnomia
- Many KBOs have satellites
- So….. Is it a planet or a KBO??

The 3rd solar system revolution

- It was time to decide what was a planet and what was not!
- Huge range of objects in our solar system:
  - **asteroids**
    near earth asteroids (with Earth near 1AU)
    main belt asteroids (between 2-3 AU)
    Trojans (with Jupiter near 5.2 AU)
    Centaurs (between Jupiter and Neptune 5-30 AU)
  - **KBOs** (or TNOs, Trans-Neptunian Objects)
    classical KBOs (between 42-50 AU, low ecc and low inc)
    resonant KBOs (like Pluto, on 3:2 resonance with Neptune)
    scattered KBOs (high ecc and high inc bodies)
- So is Pluto a planet? Is Eris a planet?



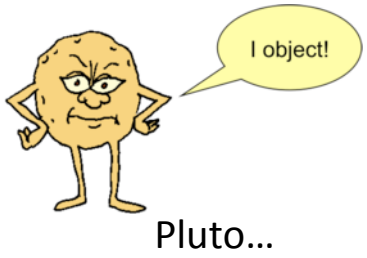
The 3rd solar system revolution



The 3rd solar system revolution

- International Astronomical Union (IAU) voted on the definition of a planet at the 2006 IAU General Assembly in Prague

- *A 'planet' is a celestial body that (a) is in orbit around the Sun, (b) has enough mass to be nearly round in shape, and (c) has cleared the neighbourhood around its orbit.*
- *A 'dwarf planet' is a celestial body that (a) is in orbit around the Sun, (b) has enough mass to be nearly round in shape, (c) has NOT cleared the neighbourhood around its orbit, and (d) is not a satellite.*



The 3rd solar system revolution

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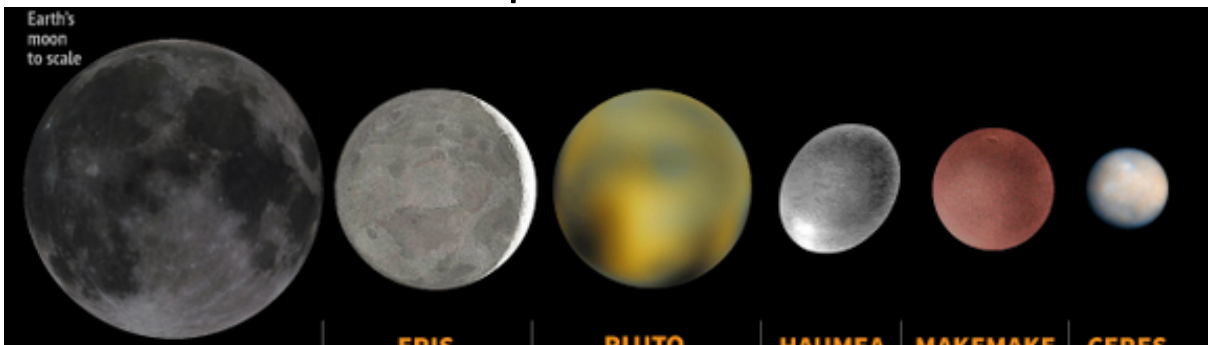
Summary of the third solar system revolution:

→ Outer solar system contains a swarm of icy bodies in the Kuiper belt
→ Pluto is a ***large*** member of the Kuiper belt
→ New IAU classification of 'dwarf planet'



	ERIS	PLUTO	HAUMEA	MAKEMAKE	CERES
Year of discovery	2003	1930	2003	2005	1801
Diameter (mean)	1,445 miles 2,326 km	1,430 miles 2,302 km	892.3 miles 1,436 km	882 miles 1,420 km	591.8 miles 952.4 km
Orbital period (Earth years)	561.4	247.9	281.9	305.34	4.6
Distance from sun (times Earth's distance)	68	39.5	43.1	45.3	2.8
Orbital inclination (degrees)	46.9	17.14	28.2	29	10.59
Rotation period	25.9 hours	6.39 Earth days	3.9 hours	22.5 hours	9.1 hours
Moons	1	5	2	0	0

Summary: Part I

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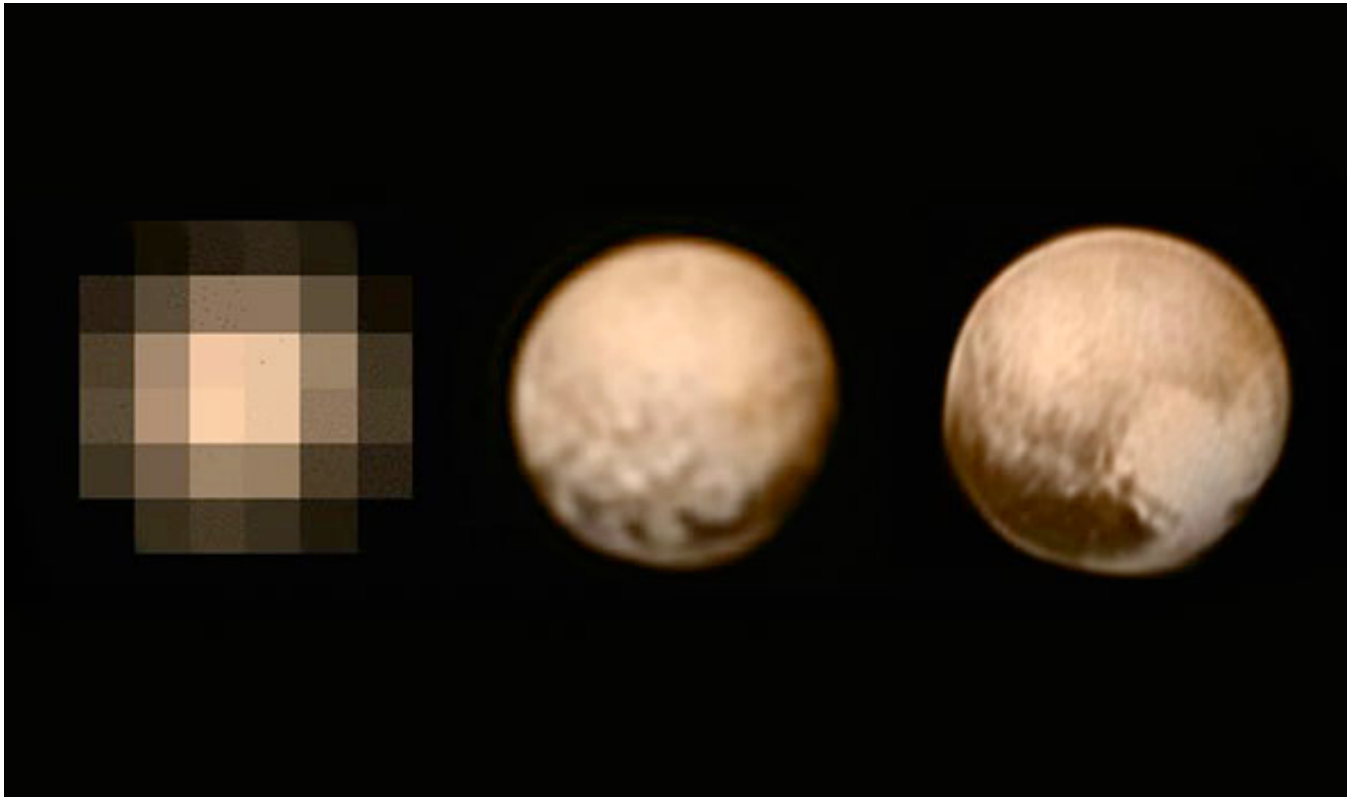
- Our view of the Solar System is currently undergoing its 3rd revolution
  - 1st revolution: by 1600s, we planets orbited the Sun and the Earth was a planet
  - 2nd revolution: discovery on (non-naked-eye) planets, and asteroids, during the 1800s
  - 3rd revolution: discovery of the Kuiper belt objects in the Outer Solar system from the 1990s
- All of these discoveries tell us about the formation & history of our Solar System…

Part II:

New views of our Solar System



Recent satellite missions

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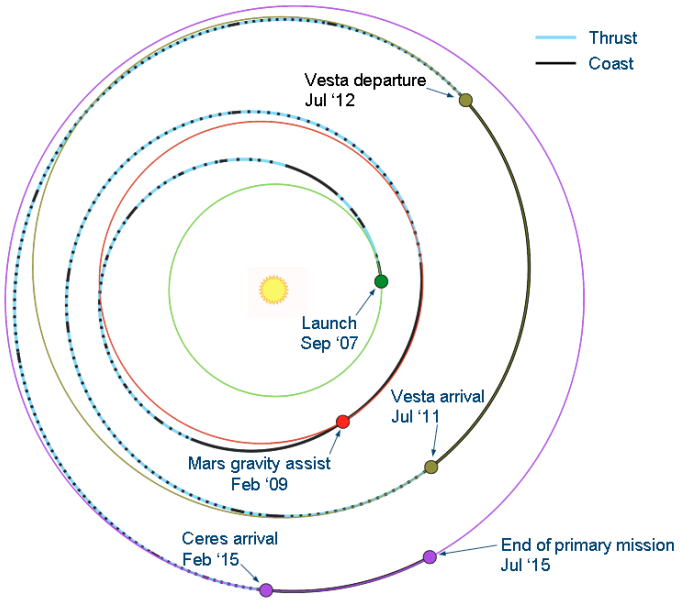
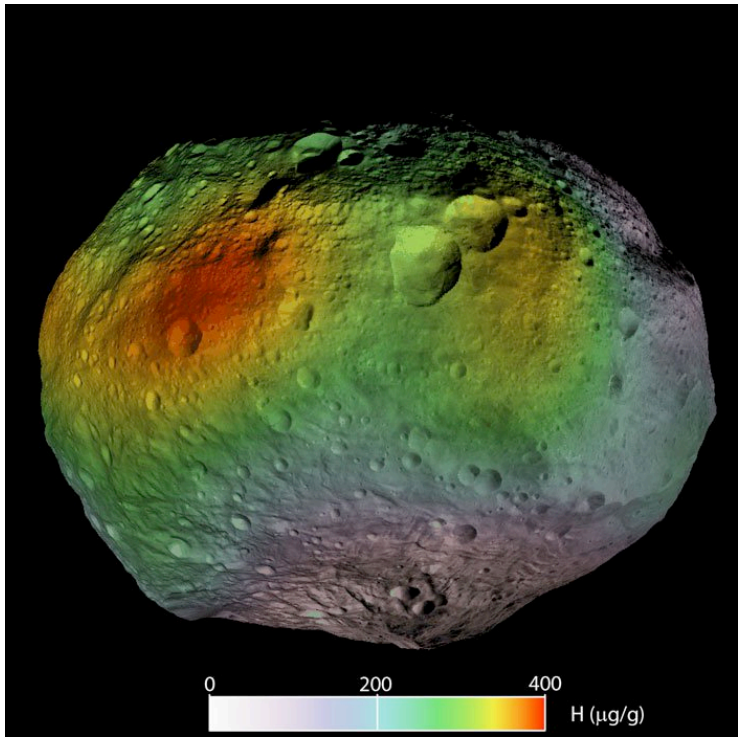
- Dawn: mission to the asteroid belt (orbit both Vesta & Ceres)
- Rosetta: mission to land on a comet (67P/Churyumov-Gerasimenko)
- New Horizons: fly-by Pluto and beyond to the Kuiper Belt

Dawn

- Aim: study two protoplanets in the asteroid belt Vesta & Ceres
- Launched Sept 2007; arrived at Vesta July 2011 (14 months in orbit); arrived at Ceres March 2015
- why these objects:
  … Vesta **dry & rocky** vs Ceres **wet & icy**
  … while neighbours, (a_{vesta}=2.36 AU, e=0.09; a_{ceres}=2.77 AU, e=0.07) must have different formation locations
  … Vesta: evolved; Ceres: primitive
  Q. Location of birth? Water content?

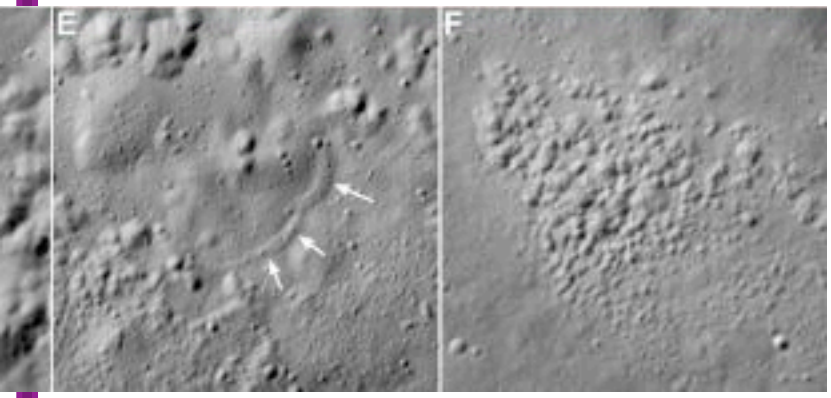


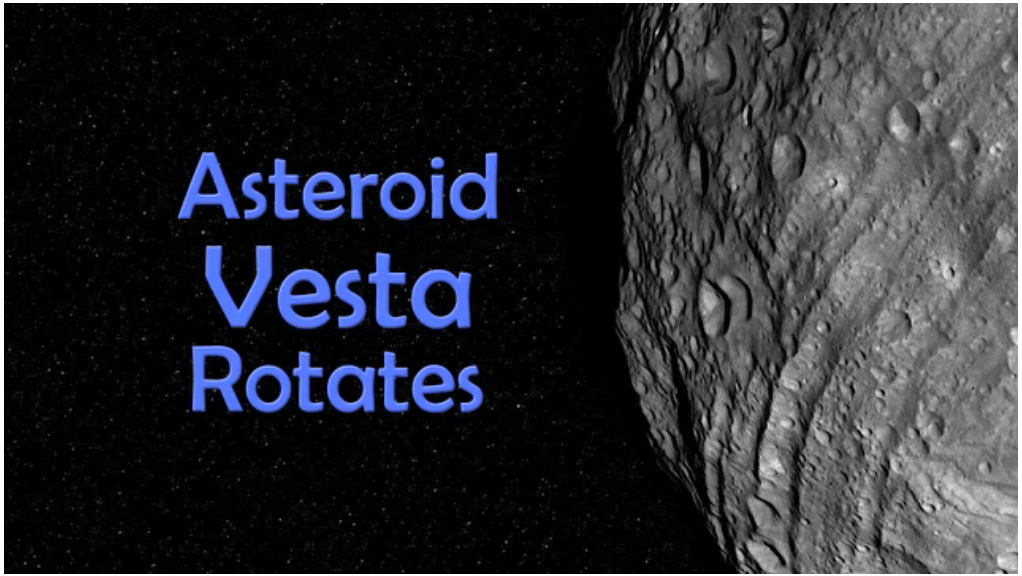
Dawn



Findings for Vesta:

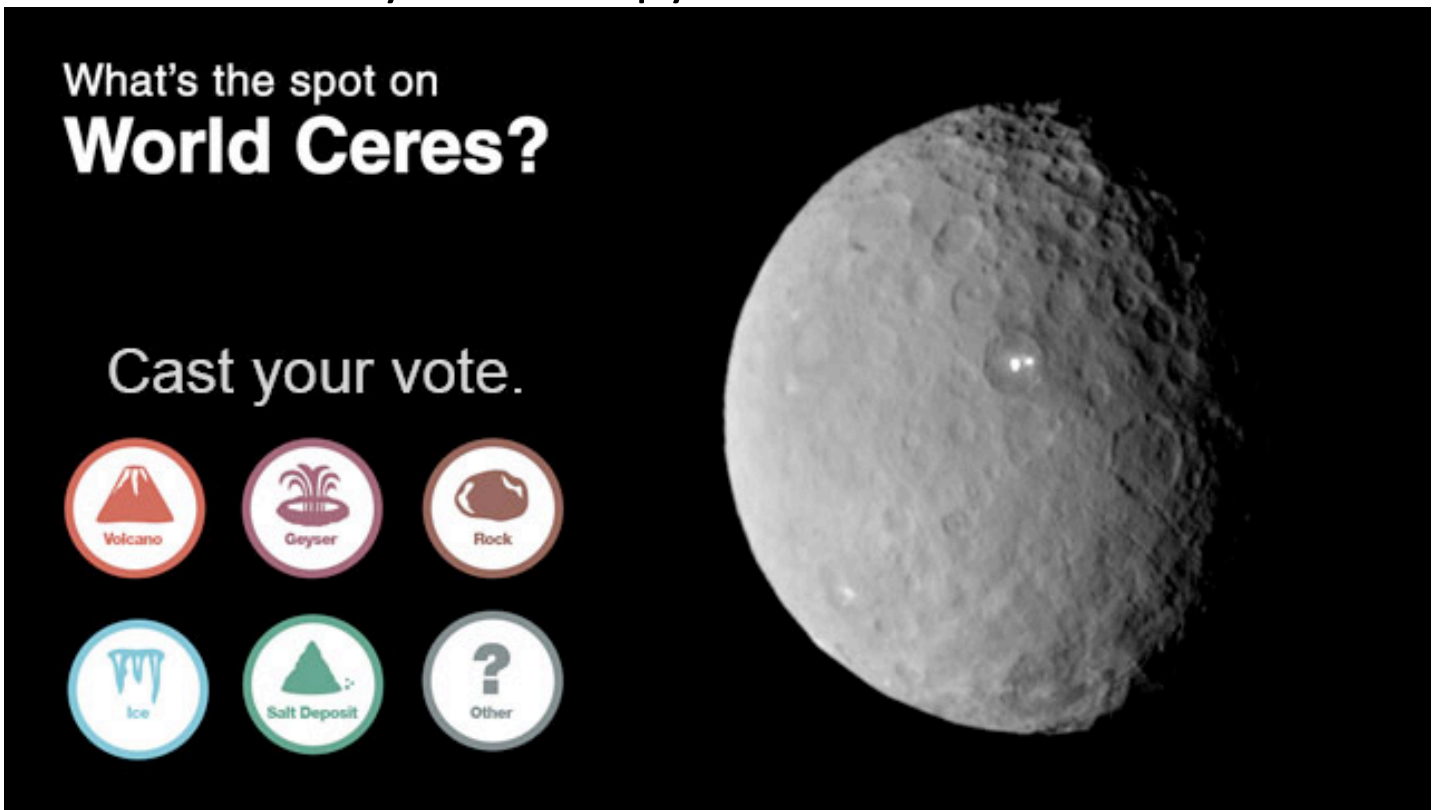
- confirmed differentiated protoplanet;
- 'Vestoid' asteroids & HEDs from material ejected from large impact at south pole;
- sufficient core to melt and segregate iron
- H from hydroxyl & water bound to equatorial surface minerals; must be exogenous – pitted terrain supports accretion of volatile-rich impactors





Dawn

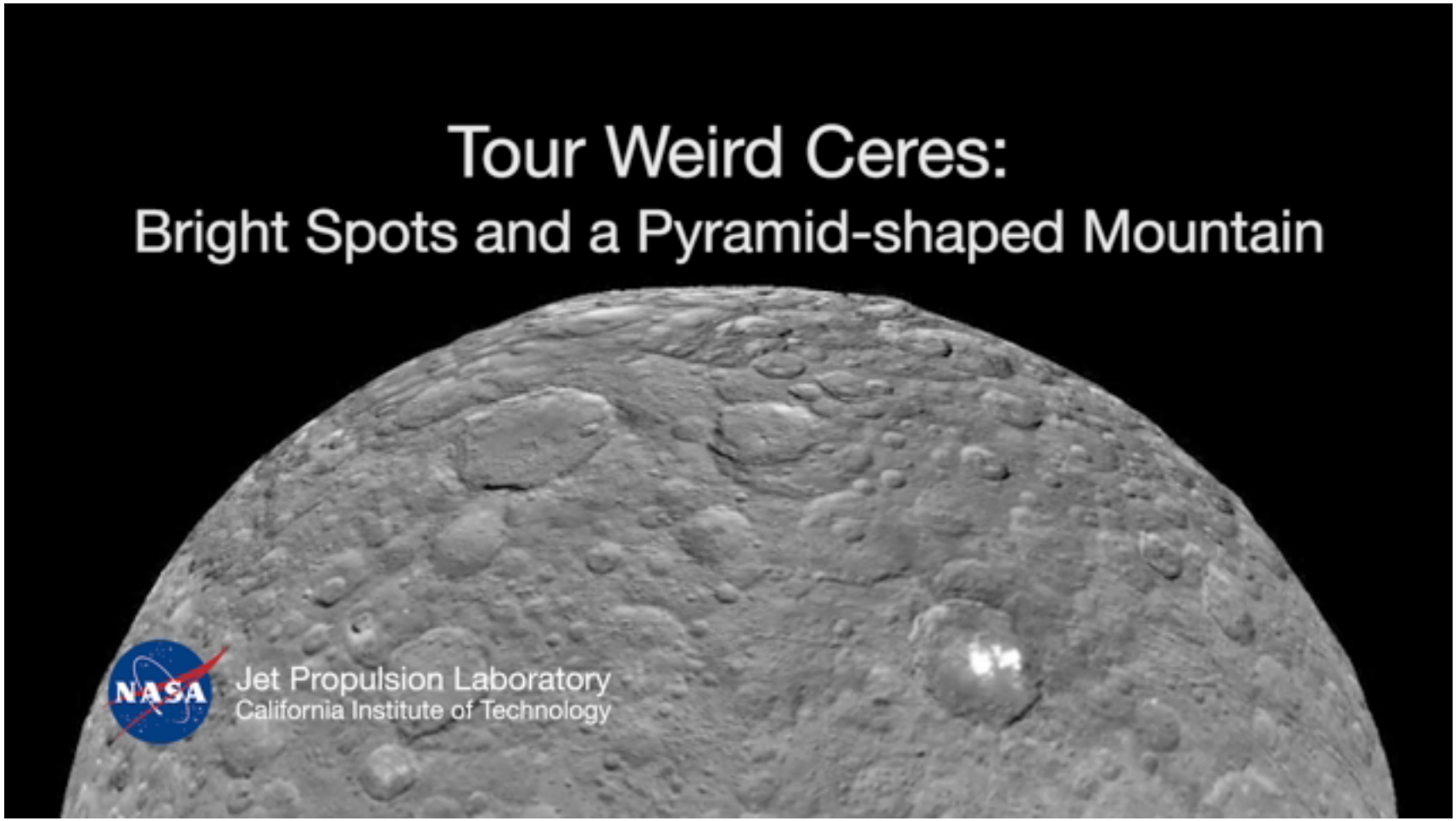
Findings for Ceres (so far!):
- Likely a differentiated rocky core & icy mantle
- Possible tenuous water vapour atmosphere from ice sublimation (from icy surface or cometary impacts?)
- Mysterious bright spots on Occator crater floor – Ice? Salt? …
- And even more mysterious “pyramid”…



Dawn

Findings for Ceres (so far!):

-
-
-
-



Rosetta

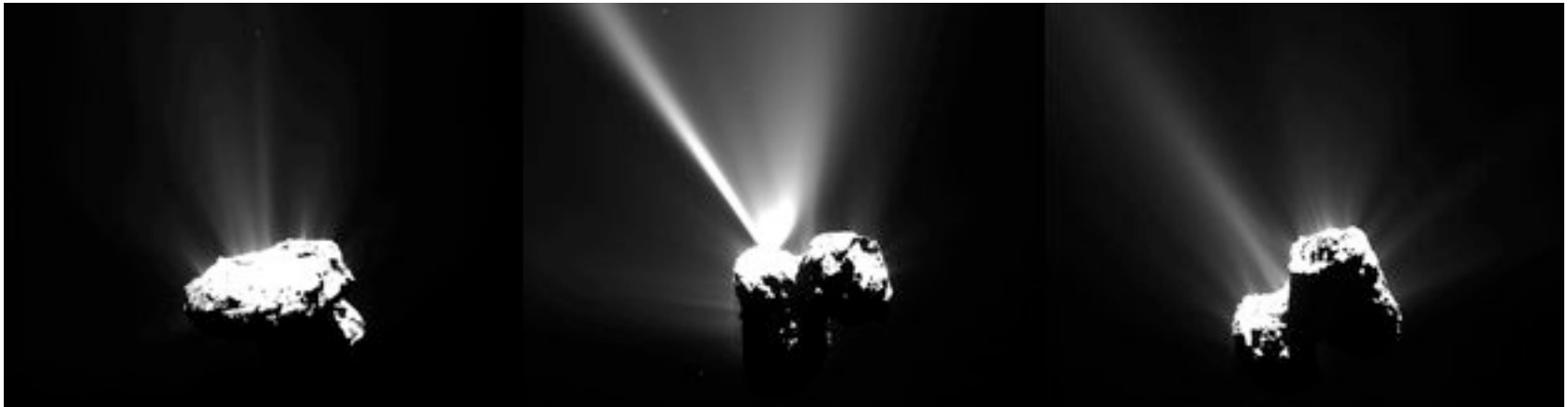
- Aim: land on a comet (67P/Churyumov-Gerasimenko)
- Launched March 2004; arrived Aug 2014; Philea lander 12 Nov 2014

Findings:

- isotopic water different: (D/H) ~ 3 $(D/H)_{earth}$
  → earth water not from comets like 67P
- organics, including radiation-induced formaldehyde (prebiotic chem?)
- electrons near surface likely photoionosation of surface water

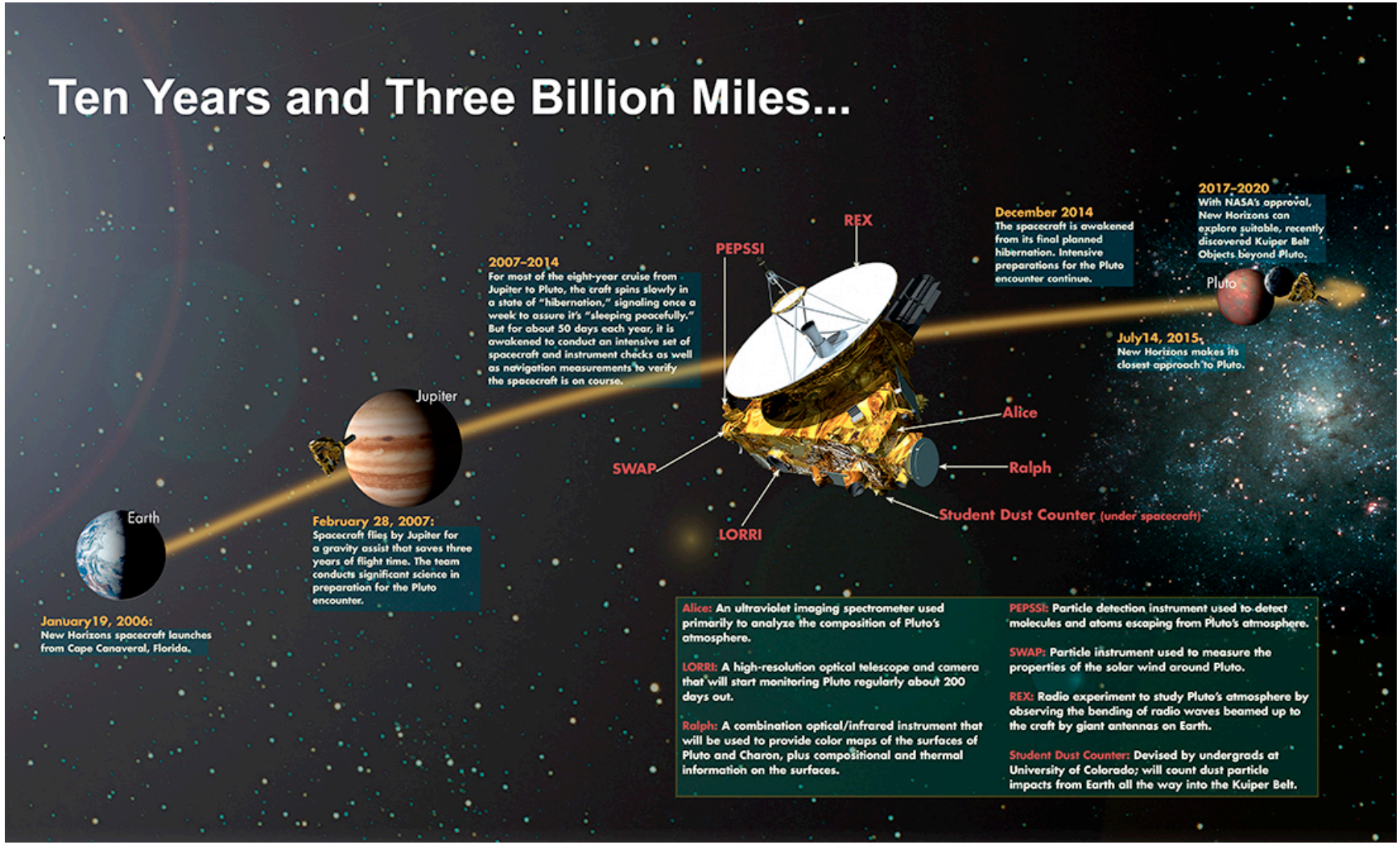
→ formation of cometary coma

- 13 August 2015: perihelion!

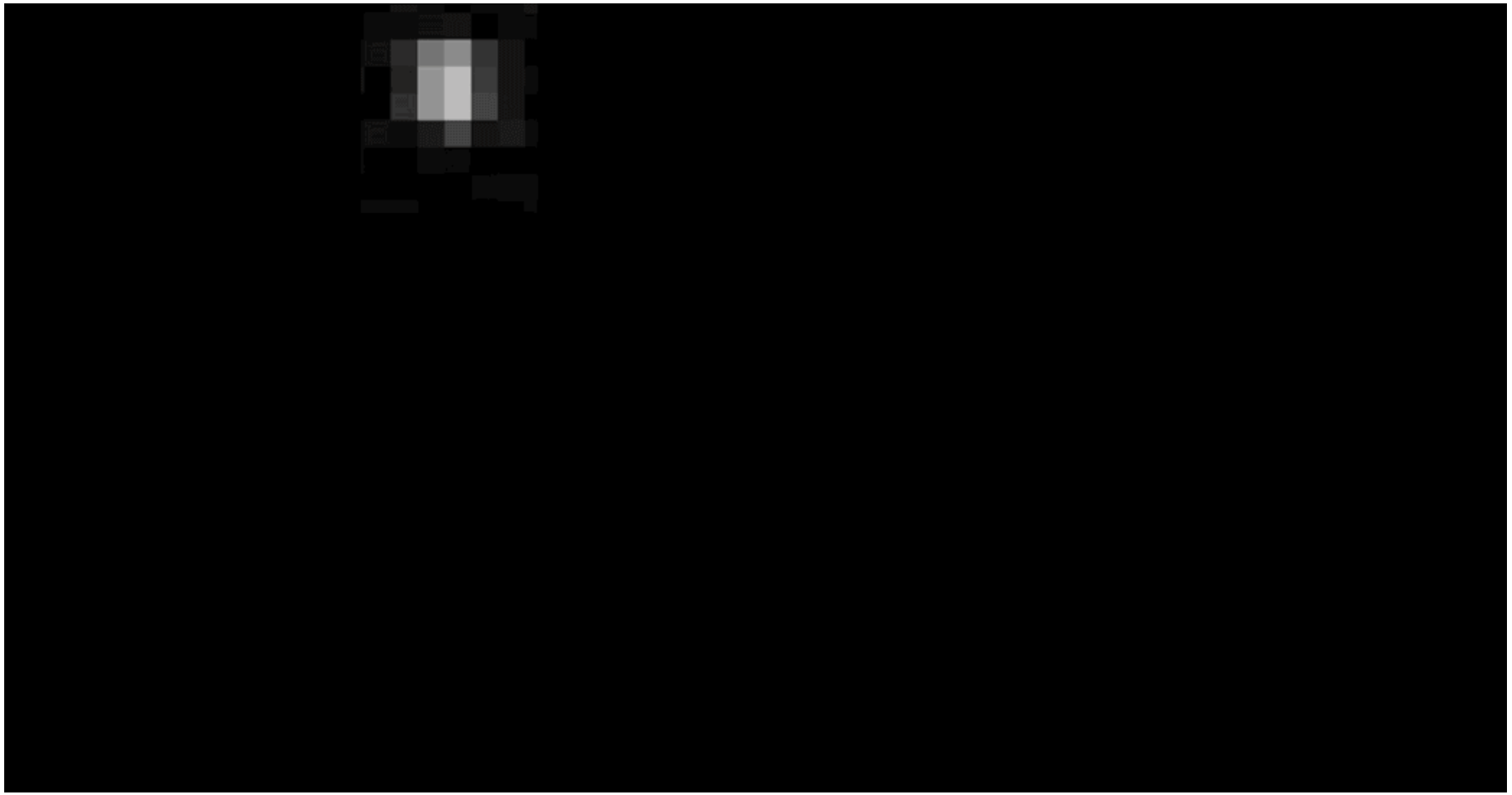


New Horizons

- Aim: study Pluto and its moons in a fly-by, plus one or more KBOs
- Launched Jan 2006; Pluto flyby 14 July 2015

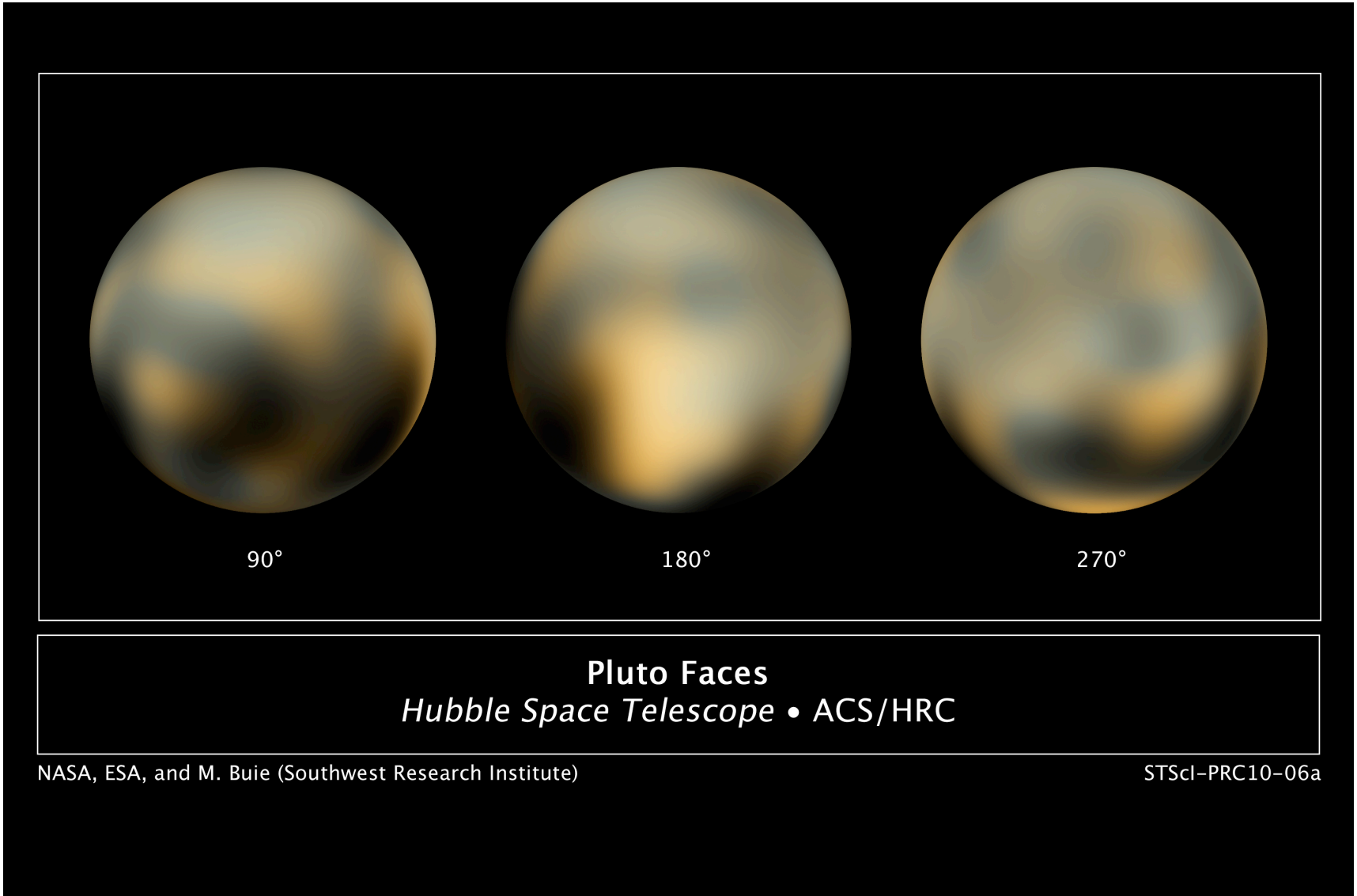


New Horizons

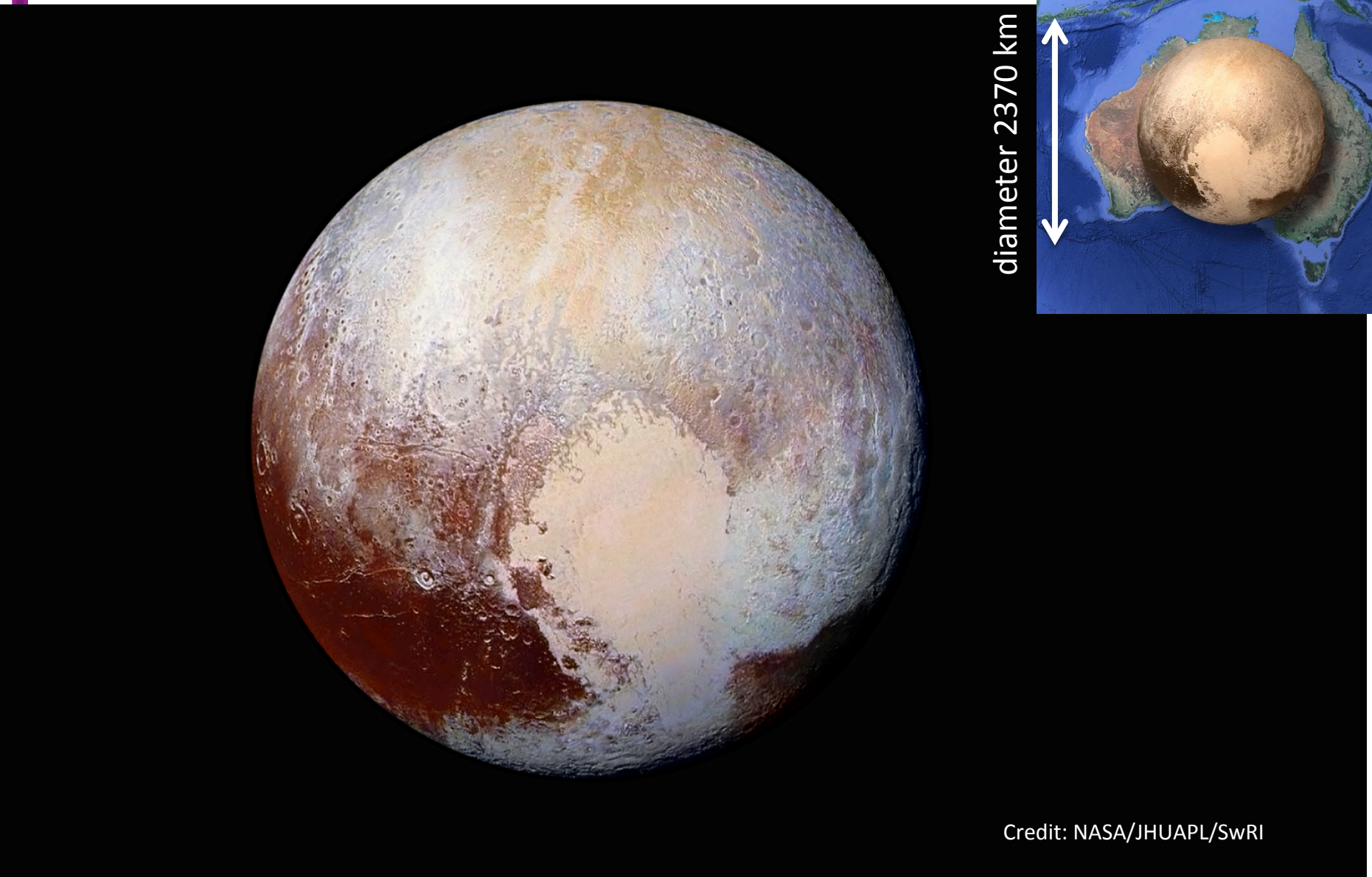


Pluto through the years (credit: Lowell Observatory/Hubble Space Telescope/New Horizons)

New Horizons



New Horizons



diameter 2370 km

Credit: NASA/JHUAPL/SwRI

New Horizons

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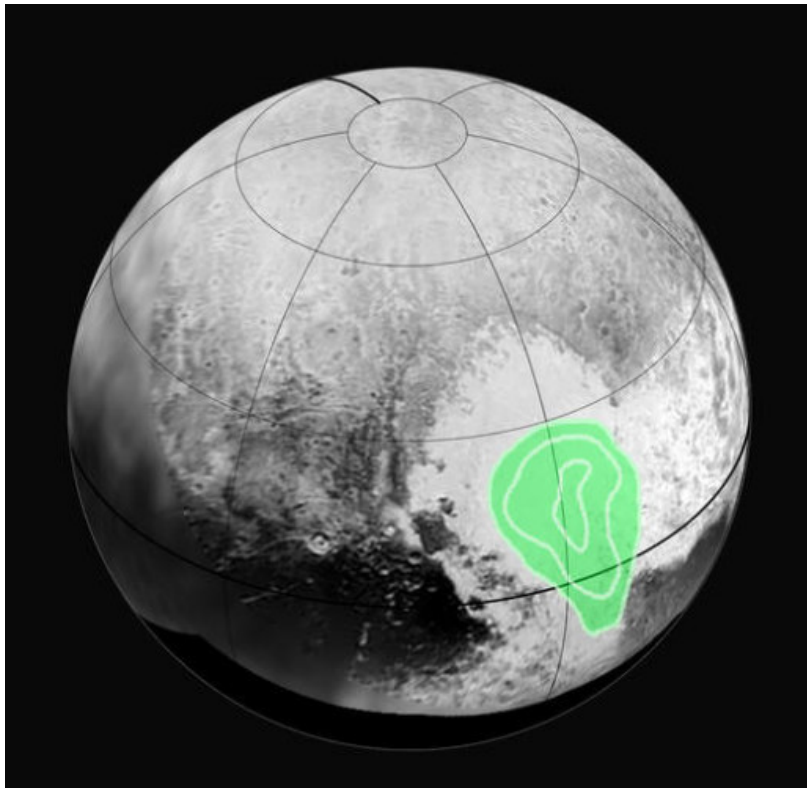
What has New Horizons revealed about Pluto (so far)?

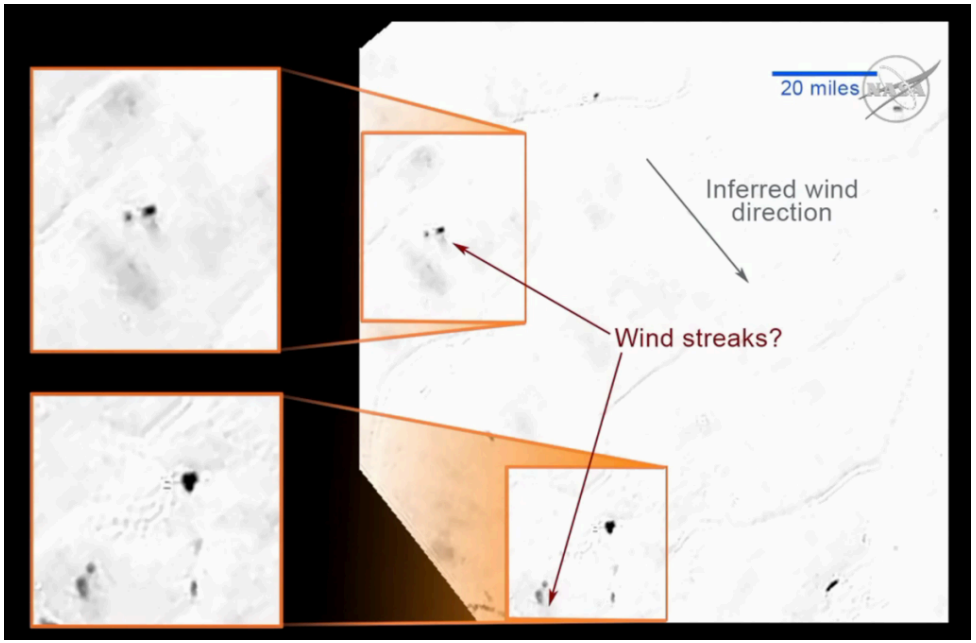
- flowing ices
- exotic surface chemistry
- mountain ranges
- a vast hazy atmosphere

And,

- Pluto's plasma tail – induced by the solar wind
- Pluto's moon Charon also has a young surface

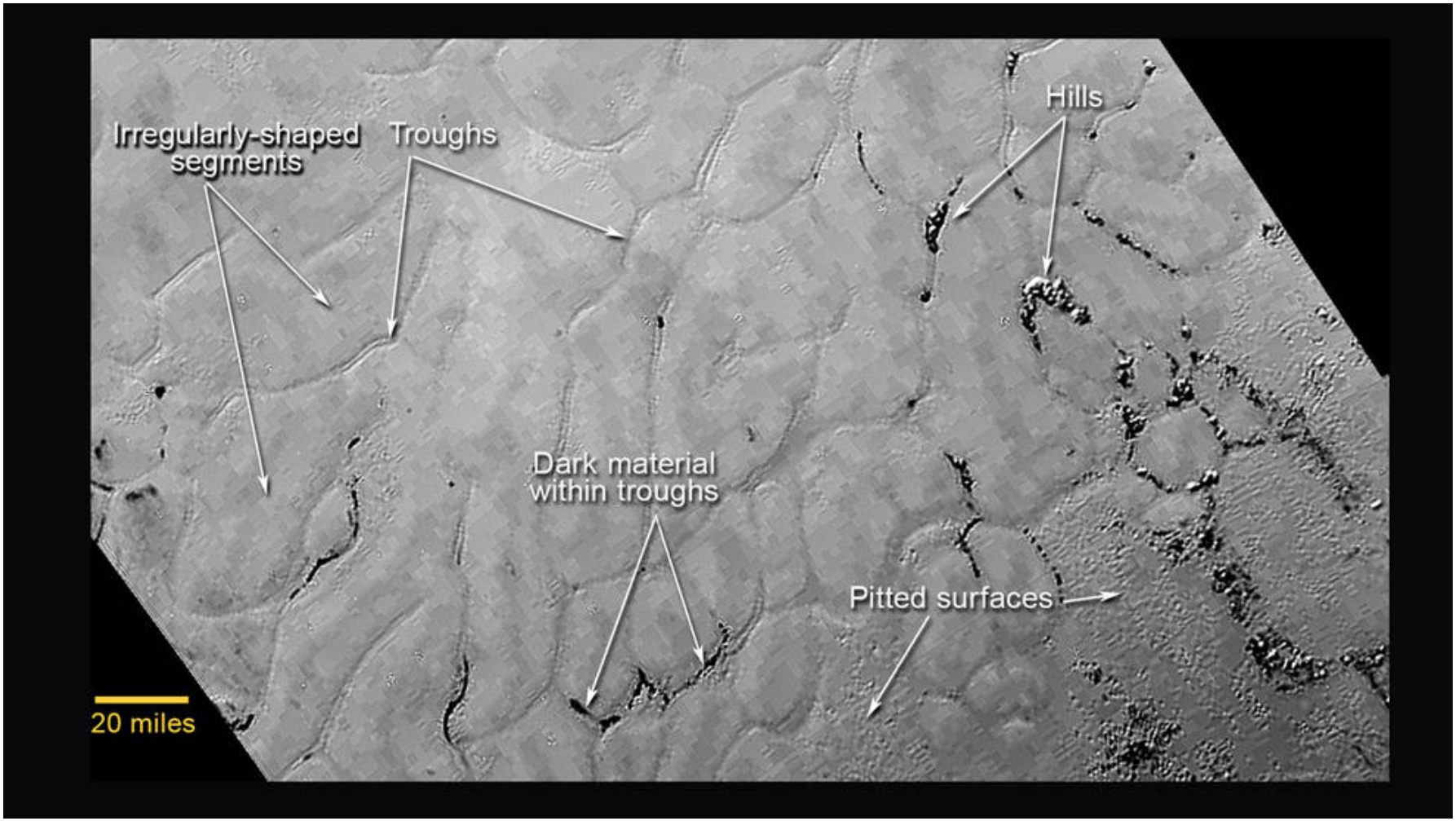
New Horizons





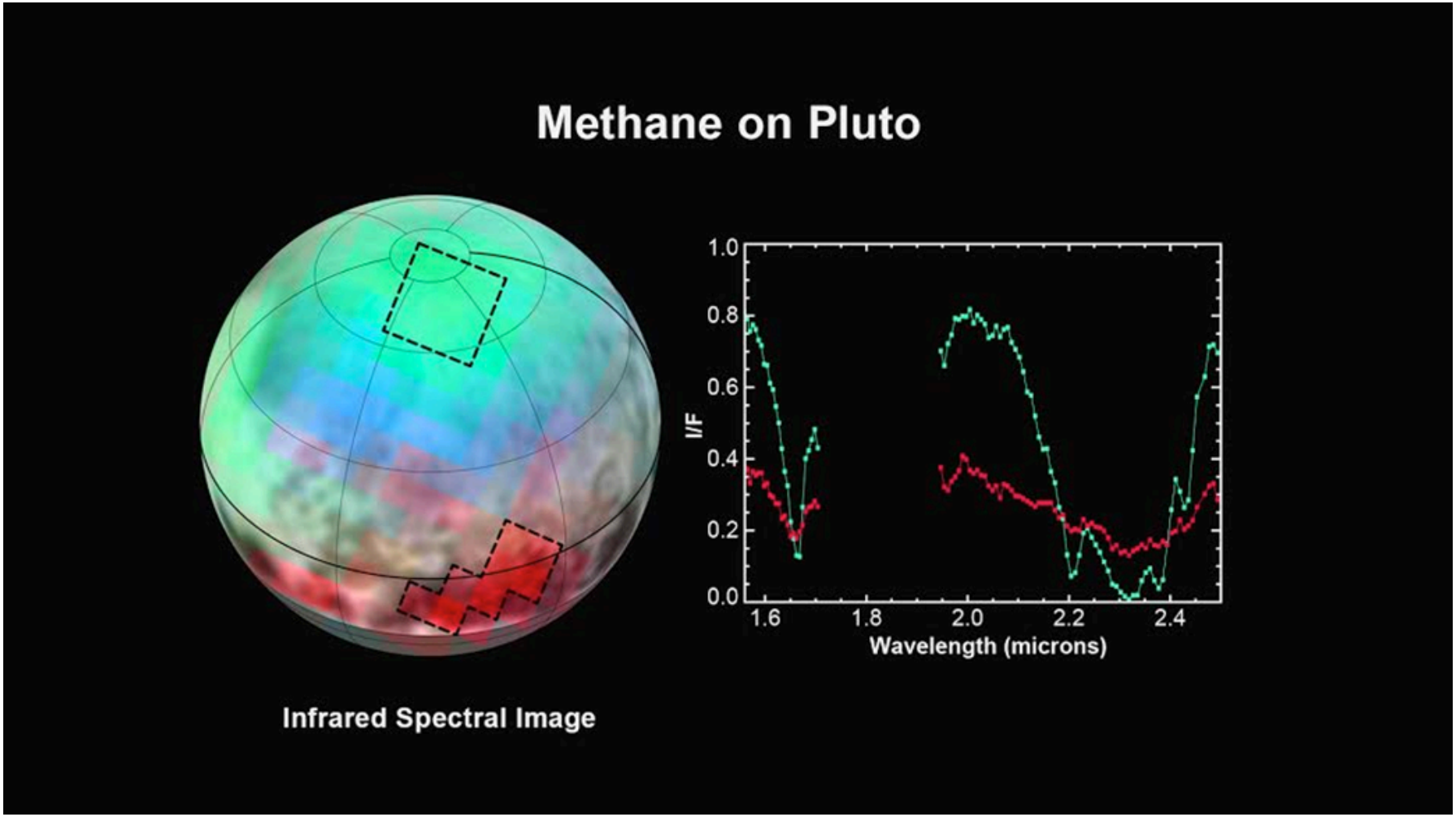
- Sputnik Planum is rich in nitrogen, carbon monoxide, and methane ices.
- At Pluto's temperatures of -230 degrees Celsius, these ices can flow like a glacier.
- Such surfaces have only been seen before on geologically active worlds like Earth and Mars.

New Horizons

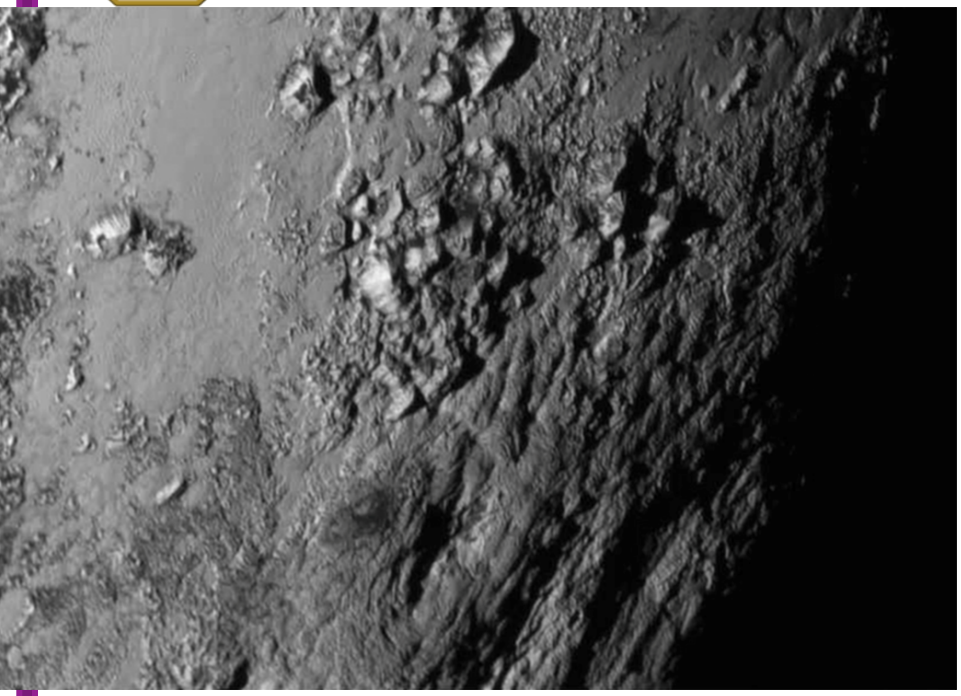


Frozen plains in Pluto's "heart", Tombaugh Regio

New Horizons

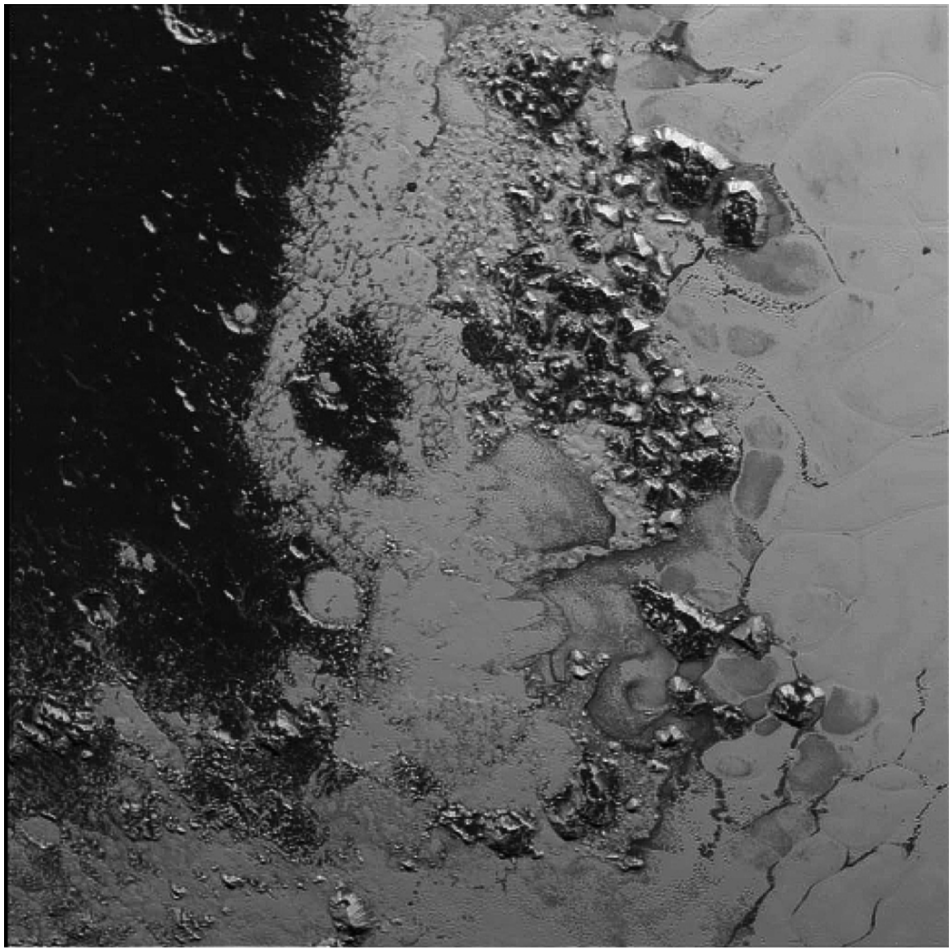


New Horizons



Youthful (100 million year old) mountains of water-ice rock rise as high as 3.5 km above the surface of Pluto.

Pluto cannot be heated by gravitational interactions with a much larger planetary body - some other process must be generating the mountainous landscape.



Dark crated region (left) billions of years old starting to fill with bright sediment material

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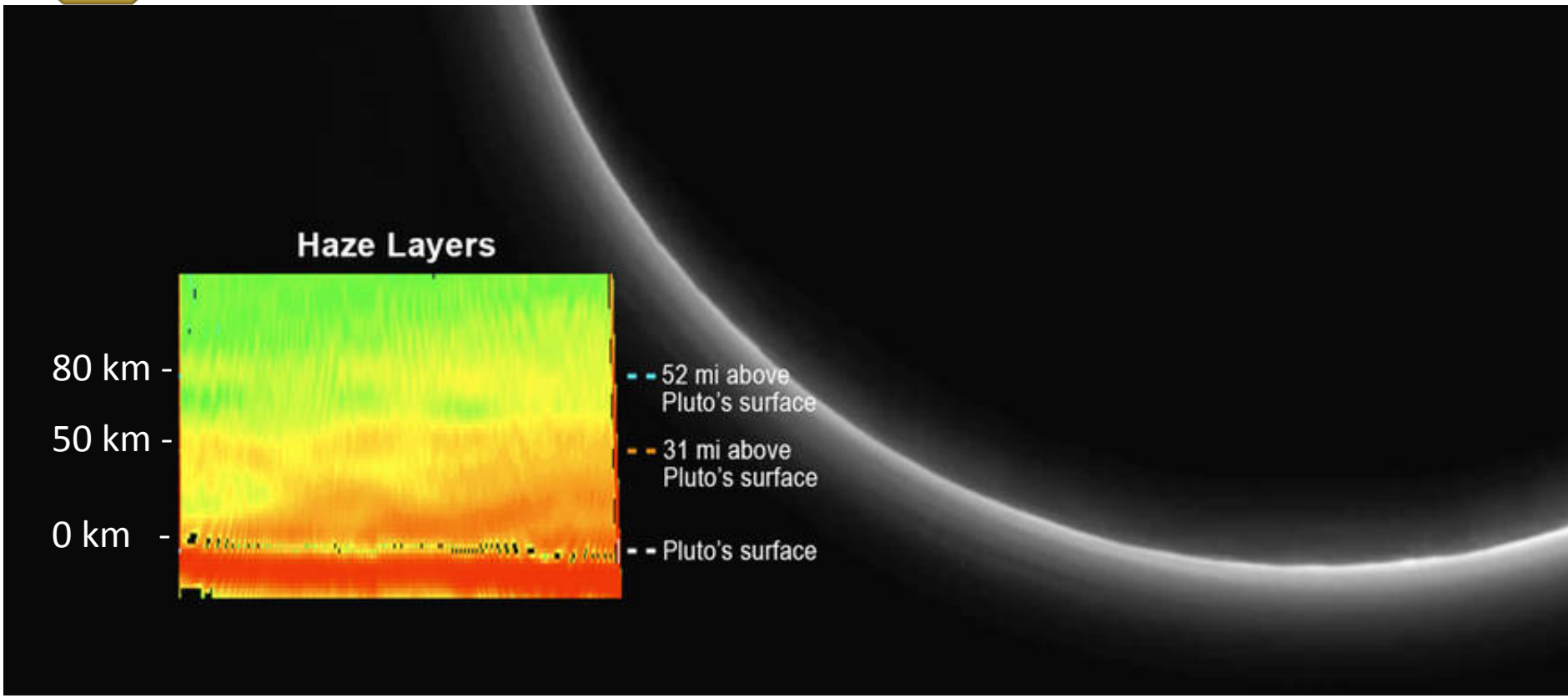
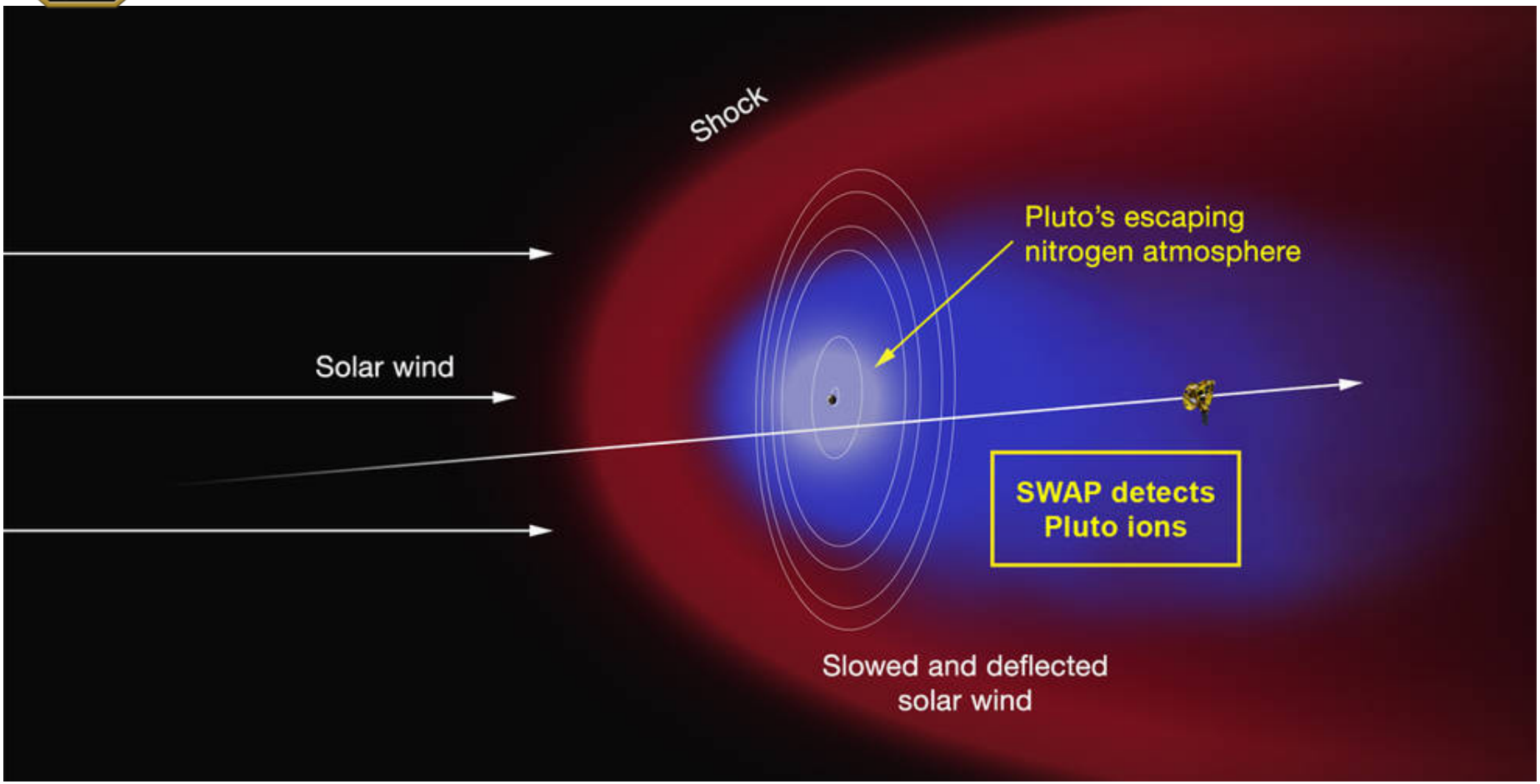
New Horizons



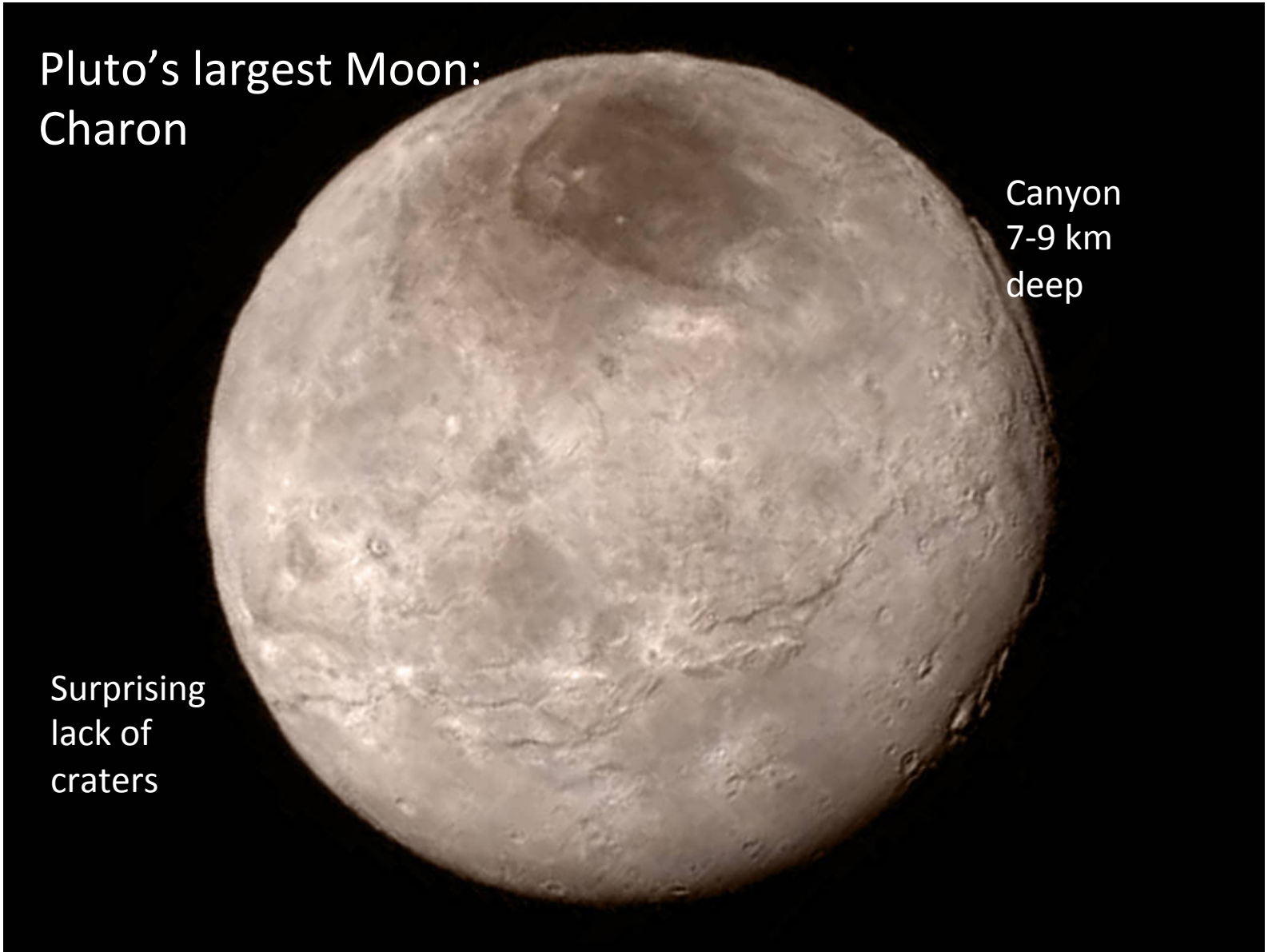
- Haze forms from UV sunlight breaking apart methane gas.
- Breakdown of methane triggers buildup of complex hydrocarbons that fall to lower, colder atmosphere and condense as ice particles, forming the haze.
- Complex hydrocarbons rain down on the planet's surface and give Pluto its reddish hue.
- Scientists previously calculated that temperatures would be too warm to form hazes above 30 km. These calculation will now need to be revised!

New Horizons



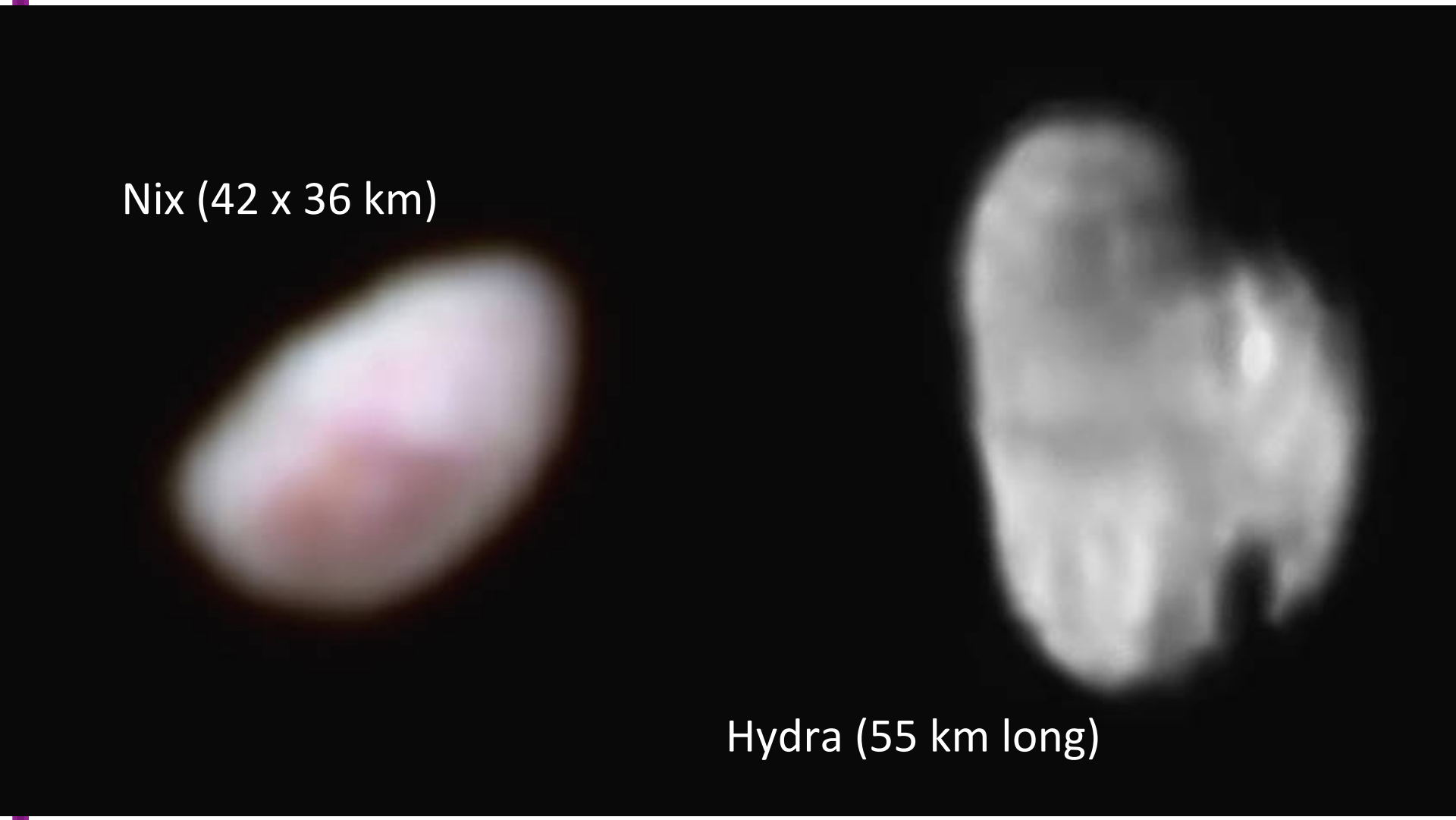
- The solar wind is a supersonic outflow of electrically charged particles
- Nitrogen molecules that escape Pluto's gravity field and are pick-up by the wind and form a plasma tail around Pluto (blue region)
- The solar wind forms a shock wave and is slowed and diverted around Pluto (red region)

New Horizons

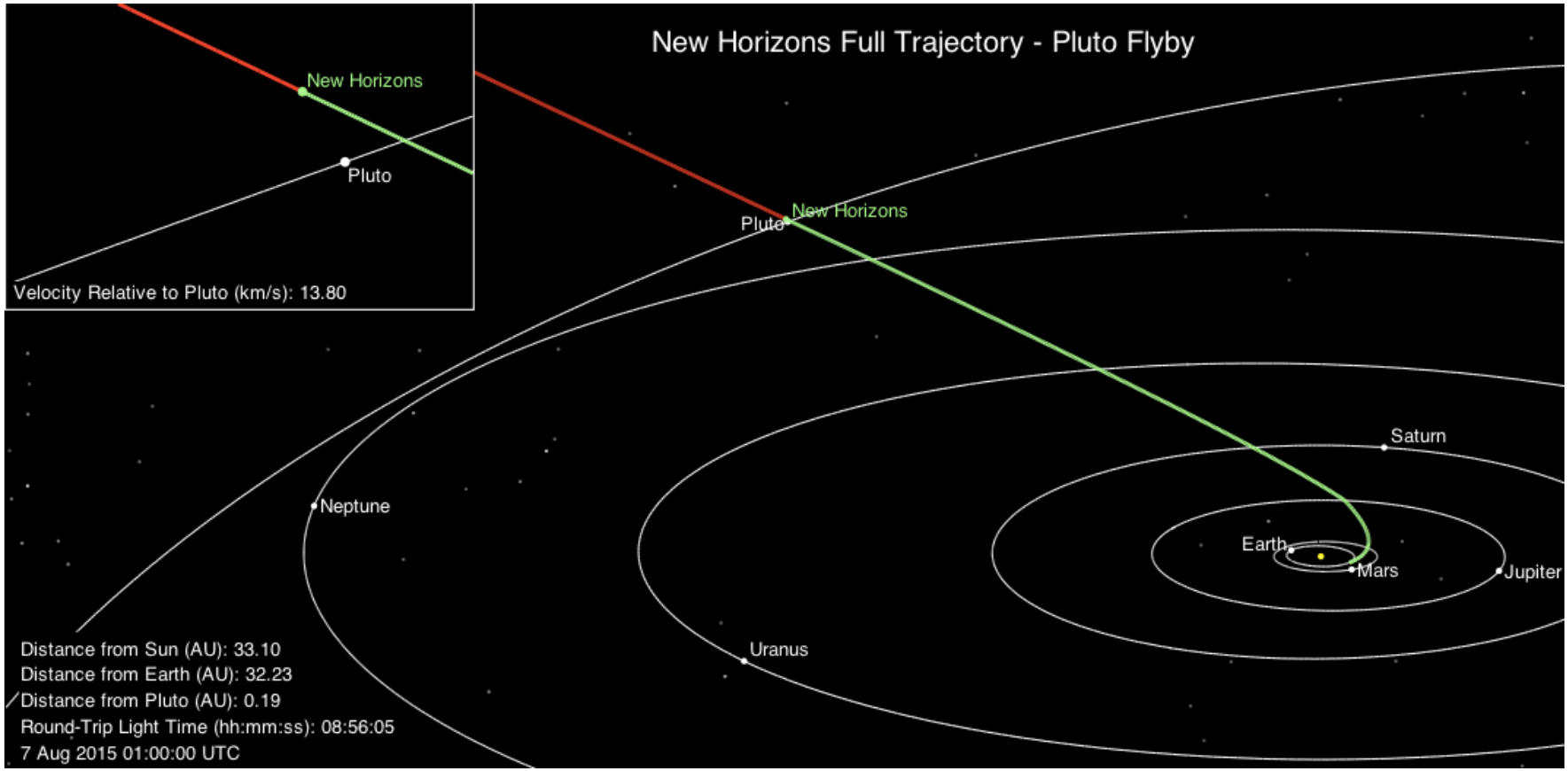


New Horizons

Discovered in 2005 by HST



New Horizons



New Horizons will continue to send data stored onboard back to Earth until late 2016. The Spacecraft is currently healthy and flying deeper into the Kuiper Belt.

New Horizons

Thank you!

Questions?