An introduction to

Solar System Origins

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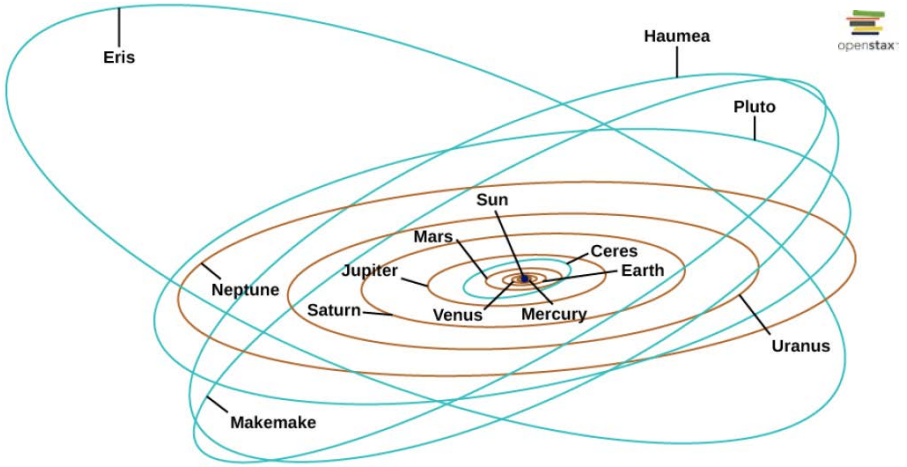
Clues to the origin and evolution of the solar system

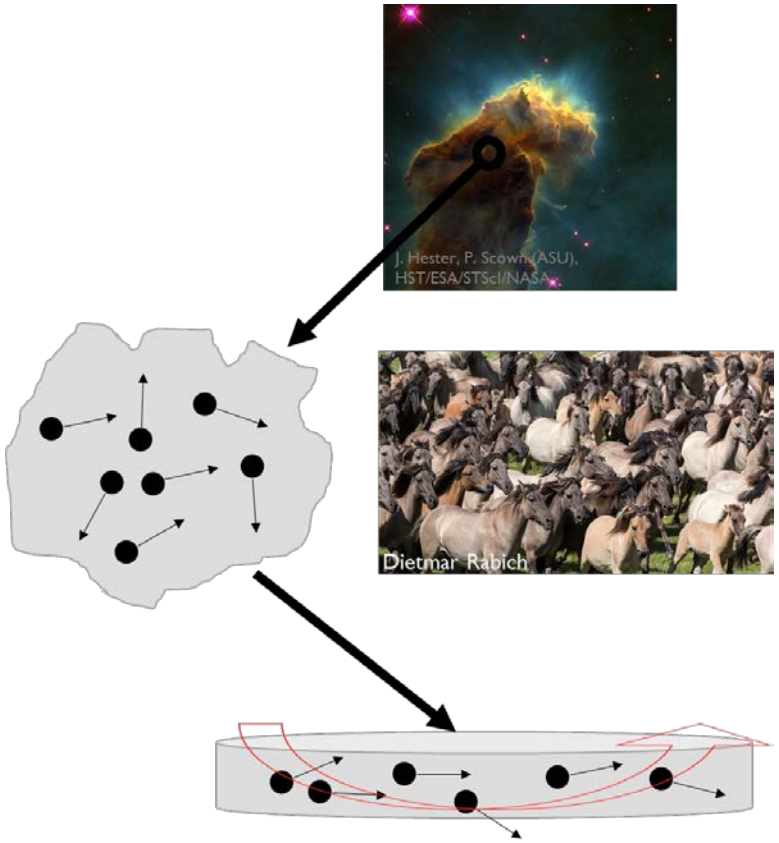
- Some* Patterns
  - Objects orbit in a near-circle within roughly the same plane in the same direction
  - Gas/ice giants are at large orbital radii and terrestrial planets are at smaller radii
- Some* Irregularities
  - Mercury is extremely dense
  - Venus has a retrograde spin
  - The Moon is huge compared to the Earth has a very similar composition
  - The asteroid belt is clumpy
  - Saturn has prominent rings and only one large moon
  - Uranus has a very high axial tilt
  - Neptune has few moons and one in retrograde orbit

*These are (very) non-exhaustive lists!

What do these patterns tell us?

- Two prominent features of the solar system:
  - Objects orbit in a near-circle within roughly the same plane in the same direction
  - Gas/ice giants are at large orbital radii and terrestrial planets are at smaller radii
- Implications:
  - The nebular collapse hypothesis is largely accurate (see *Intro to Star Formation & Intro to Planet Formation*)
  - *This is a bit of a cheat, since the above data are the foundation of the nebular collapse hypothesis*

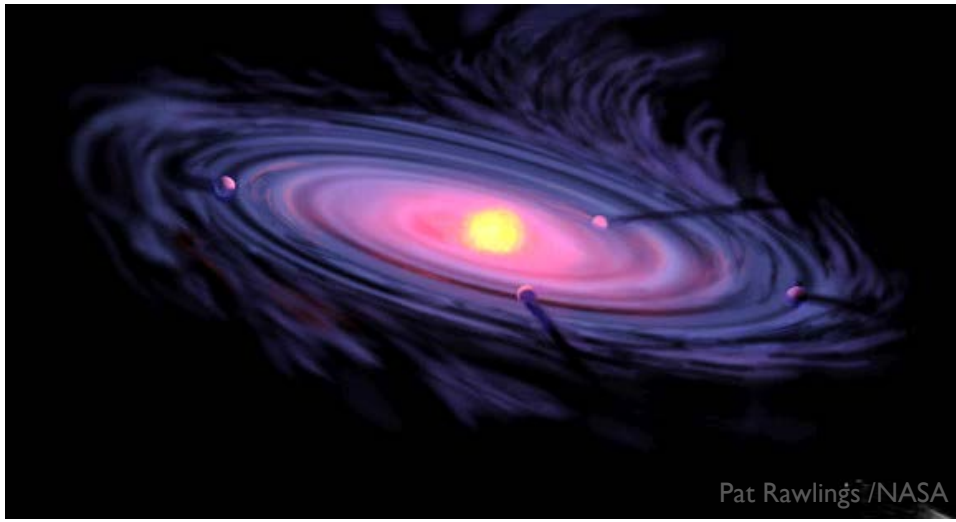




What about …Mercury's high density?

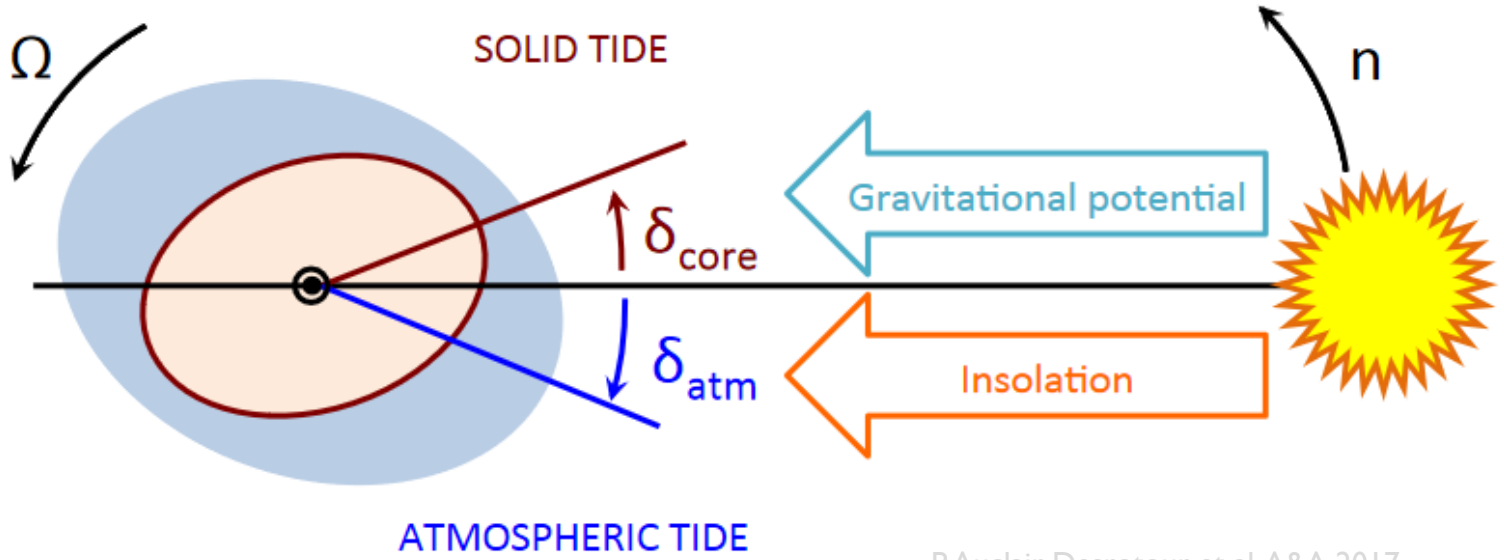
- Mercury has the largest uncompressed density of planets in the solar system
- The (high-density, iron) core is though to be ~1/2 of the volume.
  Compare to Earth, whose core is ~1/5 of the volume.
- It used to be thought a large impact must have stripped away Mercury's surface layer. However, the issue is that volatile (i.e. easy to evaporate) elements are abundant, indicating significant heating (from a large impact) hasn't occurred.
- This also disfavors the surface being vaporized off in a hot, young solar system
- Instead, it seems less dense planetesimals were more significantly impacted by drag from the solar nebula, leaving behind the more dense planetesimals to form a planet.
- *Lesson learned:* drag forces can be important in stellar system formation, especially for inner planets

Object	Density ($g \cdot cm^{-3}$)	
	Mean	Uncompressed
Mercury	5.4	5.3
Venus	5.2	4.4
Earth	5.5	4.4
Mars	3.9	3.8



What about …Venus's retrograde spin?

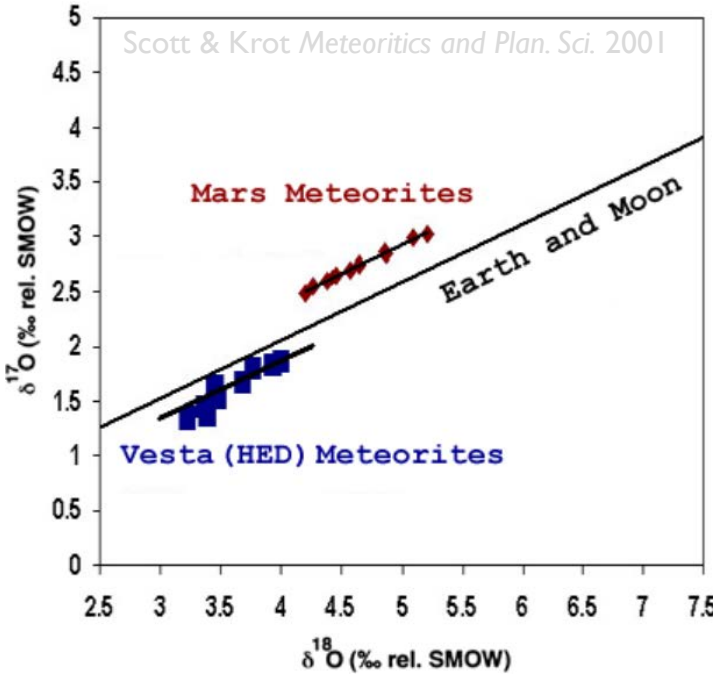
- On Venus the sun (slowly) rises in the West and sets in the East
- This retrograde orbit is unusual and was once thought to be due to an early planetary collision…but this requires a bit of fine-tuning: probably two collisions and any resultant moon(s) ejected into the sun
- Instead, a more natural (and forgiving) explanation comes from sophisticated models taking into account torques on the planet and atmosphere
- *Lesson learned:* planetary rotation is complicated and firm conclusions require considering lots of details

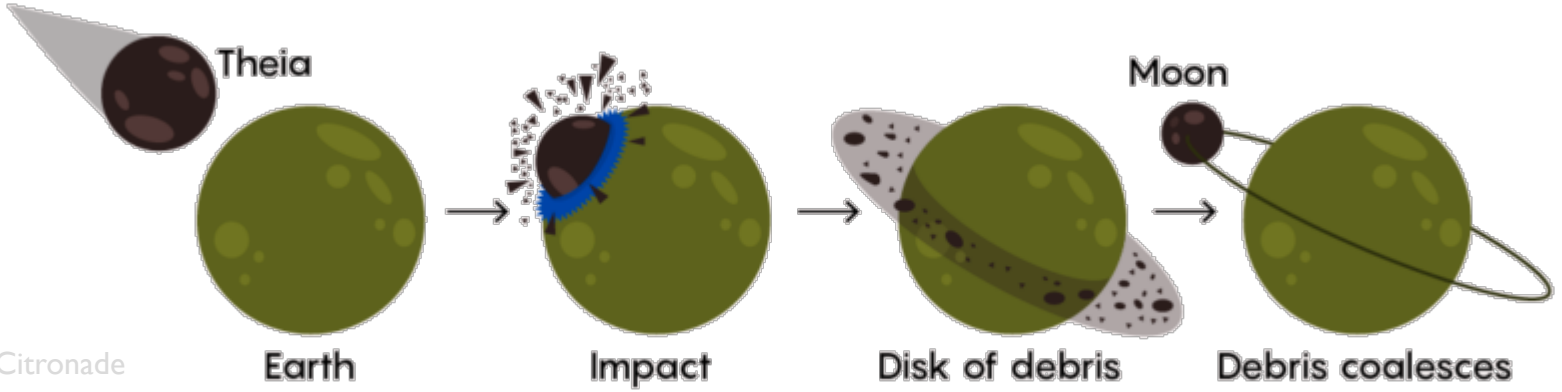


P. Auclair-Desrotour et al. A&A 2017

What about …the Moon's size and composition?

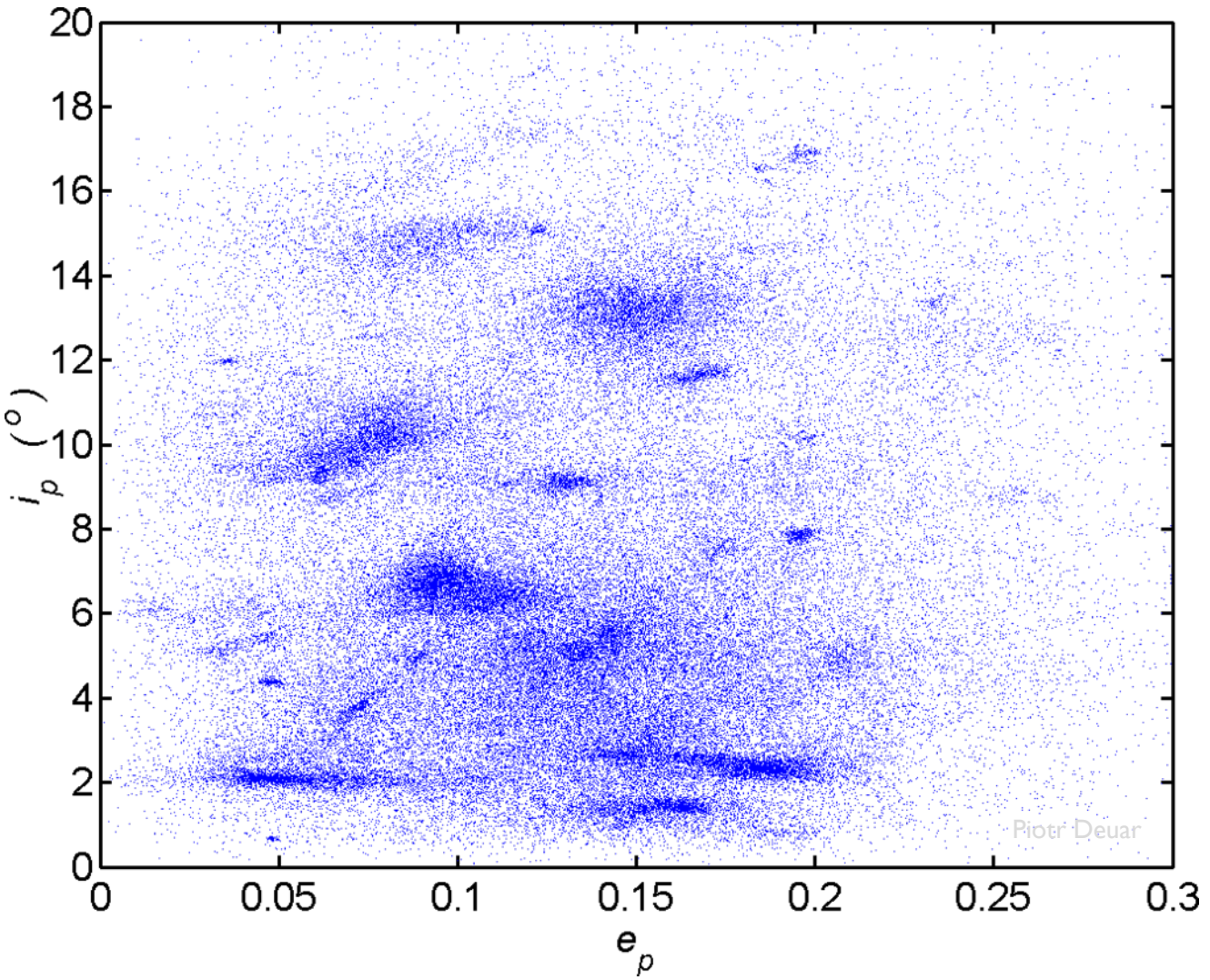
- Relative to its host planet, the Moon is pretty large and it's isotopic ratios are generally similar to the Earth, though the body is lower density
- Other moons in the solar system are typically much smaller relative to the host planet and a different composition
- A favored explanation is the Giant Impact Hypothesis
- *Lesson learned:* the Solar System likely started with more planets than we ended up with





What about …the clumpy structure of the asteroid belt?

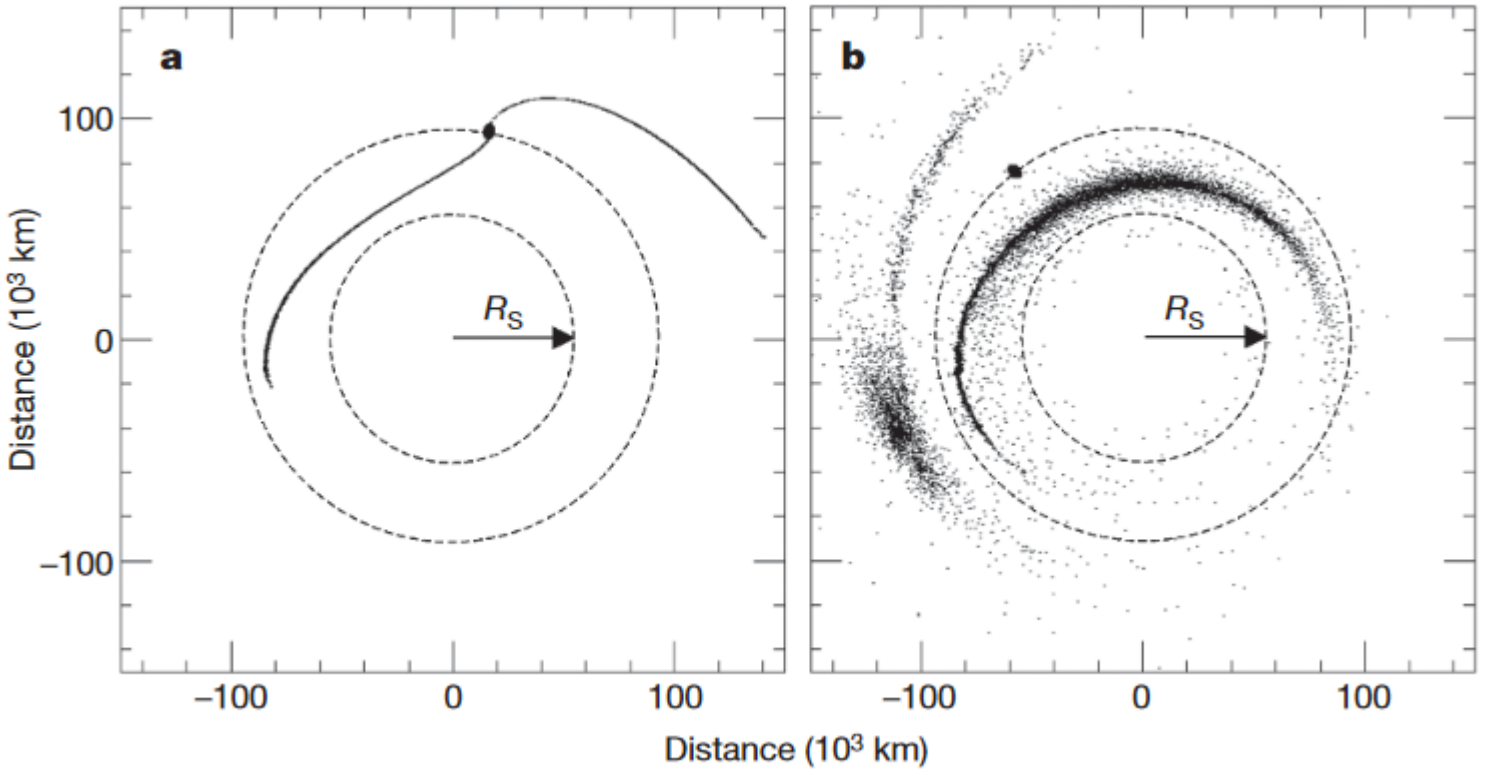
- The nebular collapse model results in a relatively uniform disk of stuff that collides and combines to make progressively larger objects
- But the asteroid belt didn't get beyond the planetesimal phase (except Ceres)
- Also, it has clumps: populations with similar orbits & composition
- But, there isn't that much mass in the asteroid belt $3 \times 10^{-4}\ M_{\oplus}$
- This suggests that gravitational interactions (primarily from Jupiter) disrupted planet formation in the asteroid belt region of the solar system
- *Lesson learned:* the influence of Jupiter is important in solar system evolution



What about …Saturn's rings and only one large moon?

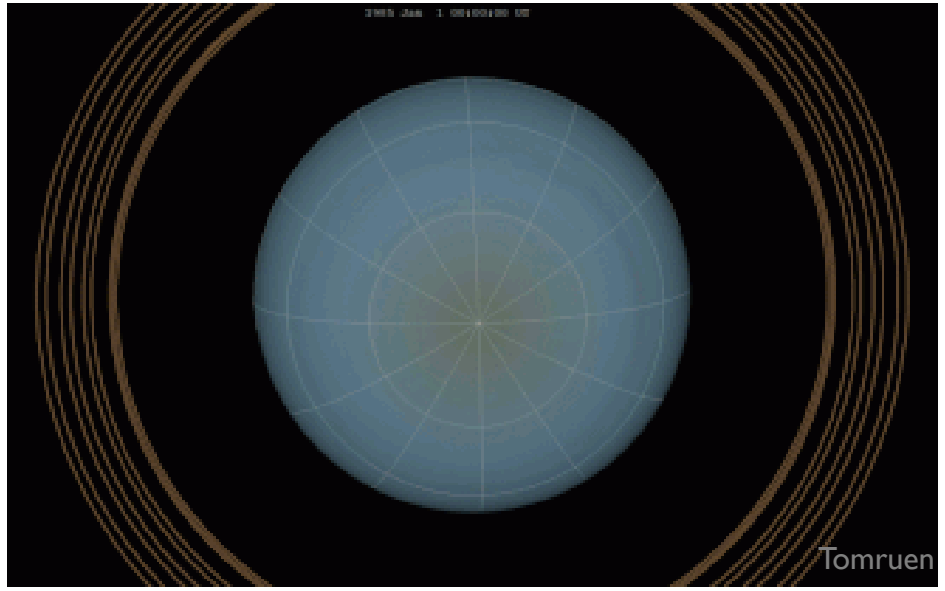
- Jupiter has 4 large moons, to Saturn's 1 and a relatively minor ring system to Saturn's magnificent ring system
- Saturn's rings are >90% water ice, even though they are constantly polluted by rocky meteoroids
- Several small ice moons are embedded within the icy rings
- This suggests that ~10-100 Myr ago a large ~Titan-sized moon spiraled into Saturn due to gravitational interactions and that the icy-envelope was stripped from the moon before the rocky core crashed into Saturn.
- *Lesson learned:* the solar system is not stable and is constantly evolving

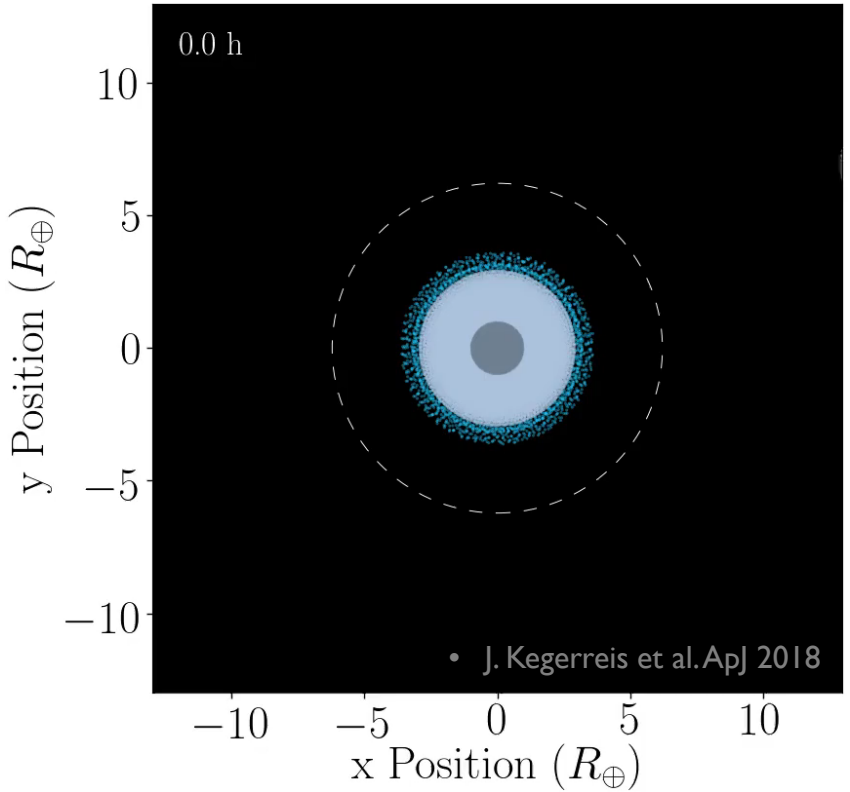
R. Canup *Nature* 2010



What about …Uranus's tilt?

- Uranus is titled on its side relative to its orbital direction
- The magnetic field and thermal structure are also very different from the other giant planets in the solar system
- The best explanation is a giant impact of a roughly earth-sized object in the first ~Gyr of the solar system
- *Lesson learned:* considering this and the origin of the Moon, giant impacts are a significant feature of stellar system formation and evolution





What about …Neptune's moons?

- Neptune has relatively few moons relative to the other giant planets (~1/2 as many as Uranus and ~1/5 as many as Jupiter and Saturn)
- The Neptunian moon Nereid has a highly eccentric orbit
- Triton, Neptune's largest moon by far, has a retrograde orbit
- Triton is thought to be a captured object, initially originating in a binary system in the Kuiper belt (like Pluto & Charon)
- *Lessons learned:* Neptune has had a significant impact on the evolution of the Kuiper belt