Pic: Dana Berry

The origin of the Earth-Moon system

as revealed by the Moon

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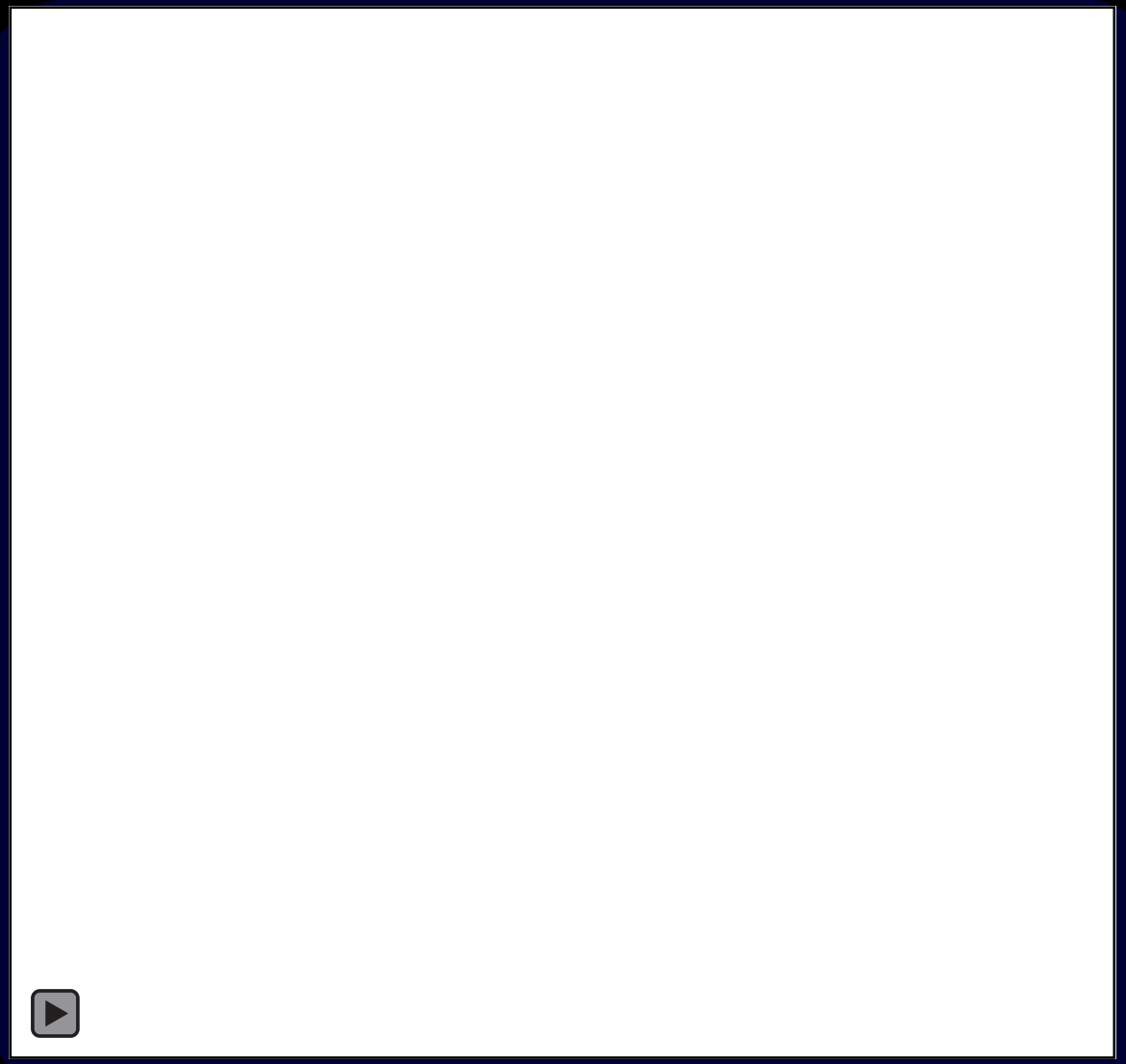
Canonical giant impact

Hartmann & Davis (1975); Cameron & Ward W.R. (1976)

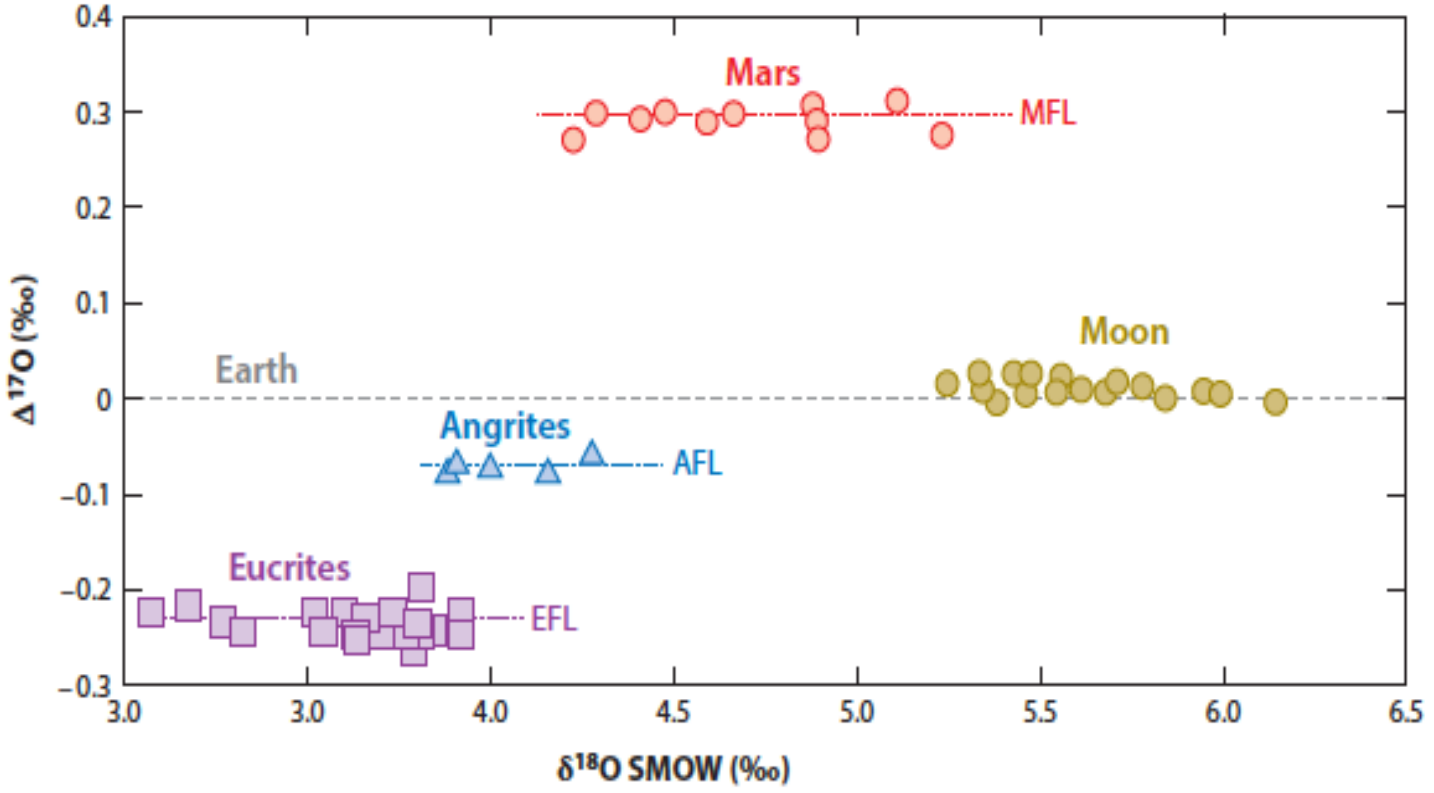
- Small core
- Low amount of volatiles
- Moon younger than Earth
- Initial lunar magma ocean

- Earth-Moon isotopic similarity



Isotopic crisis

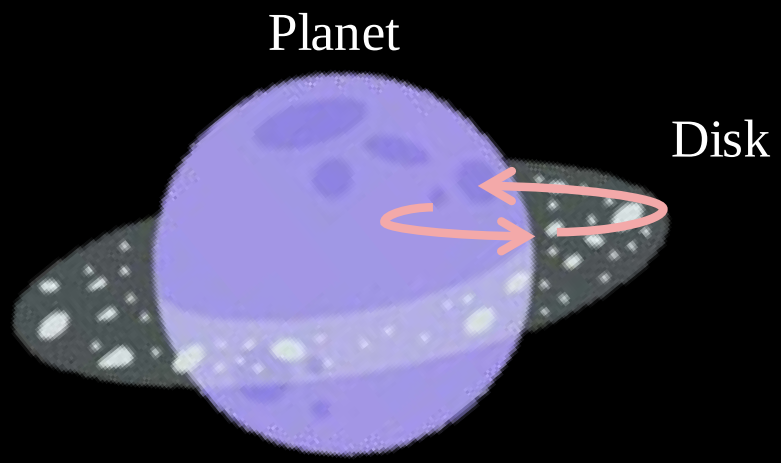
(Kevin Righter, NASA Johnson Space Center)



- The Moon is indistinguishable from Earth in oxygen (Herwart et al. 2014), titanium (Zhang et al. 2012), pre-late veneer tungsten (Kruijer et al. 2015) isotopes and more.

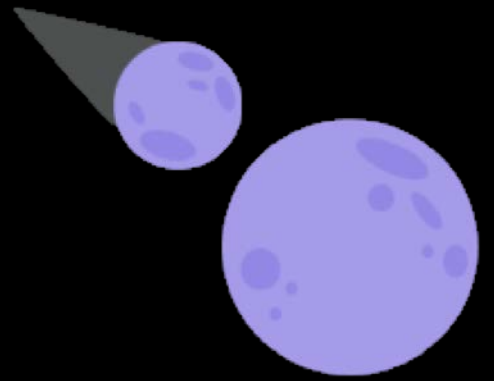
Alternatives

Post impact equilibration
(Pahlevan & Stevenson 2007)



- Material exchanges between Earth atmosphere and disk vapor phase might reduce isotopic differences
- Timescales and mixing efficiency of refractory elements is problematic

Earth-like impactor
(Mastrobuono-Battisti et al. 2015; Kaib et al. 2015)



- Impactor with Earth-like composition would produce Earth-like Moon
- Issues remain with some elements (e.g. tungsten)

Pic: Lucy Reading-Ikkanda /Quanta Magazine

Alternatives - High angular momentum impacts

Fast-rotating proto-Earth
Ćuk & Stewart (2012)

Similar-sized embryos
Canup (2012)

vaporization

co-rotating synestia
Lock et al. (2018)

Accreted moon is isotopically = Earth

- Post-impact Earth-Moon system has large excess of angular momentum
- Need to remove the excess angular momentum after lunar accretion

(Ćuk & Stewart 2012; Wisdom & Tian 2015; Ćuk et al. 2016; Tian & Wisdom 2020; Rufu & Canup 2020)

Alternatives

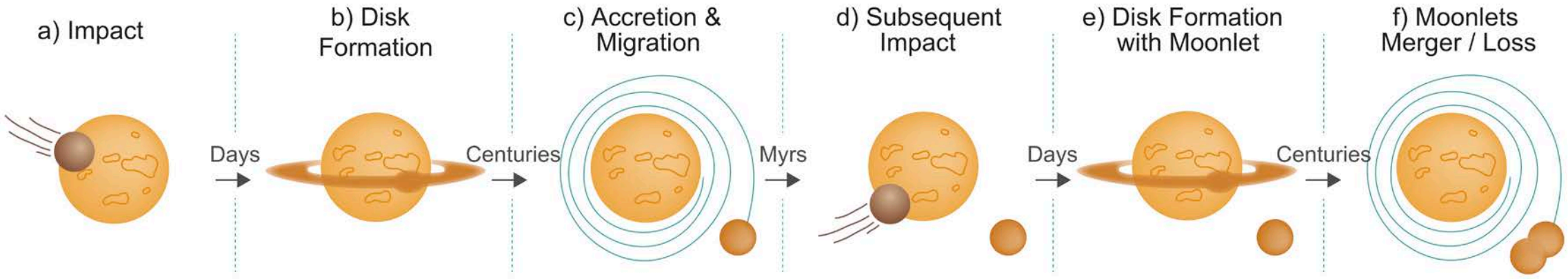
Hit and Run (Reufer et al. 2012)

Part of the impactor escapes;
Earth material in disk > 60%

Accreted moon is isotopically
~ Earth

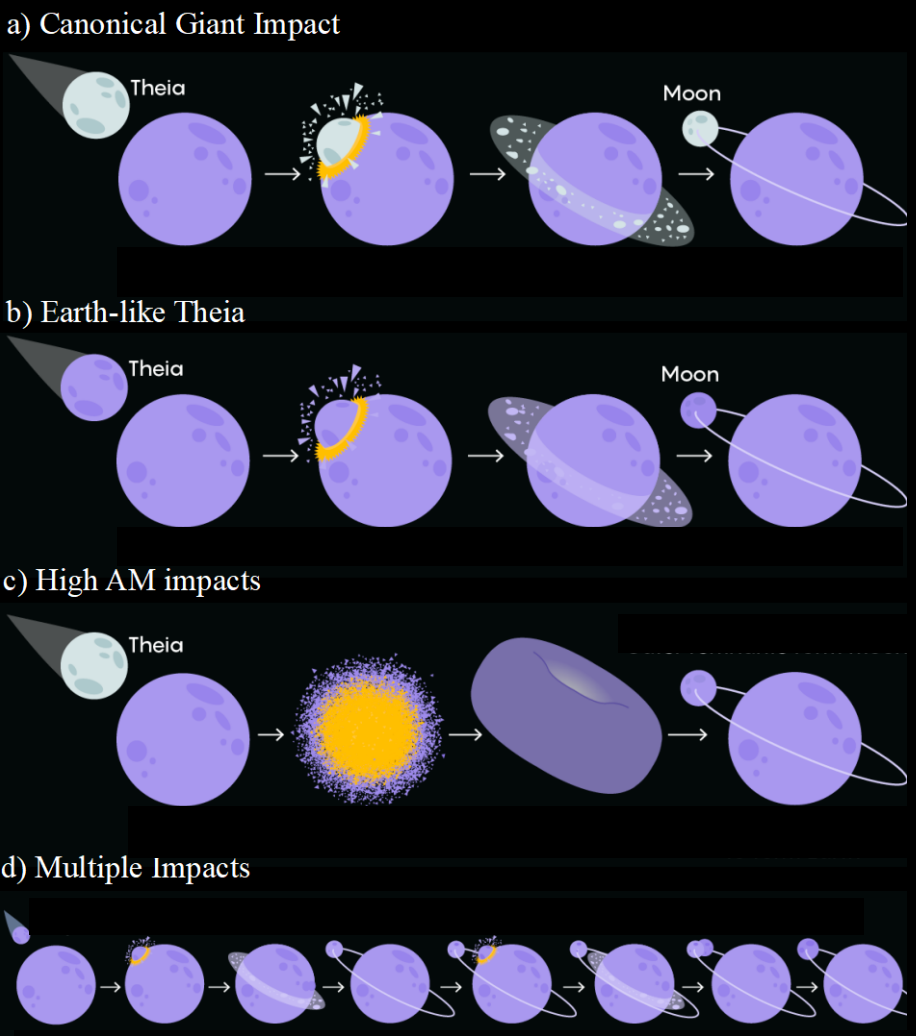
Impact generated disk has low mass that might not be enough to form a lunar-mass moon

Multiple Impacts (Rufu et al. 2017)



Forming a lunar-mass moon requires many consecutive moonlet mergers whose likelihood is unclear

Moon-forming scenarios

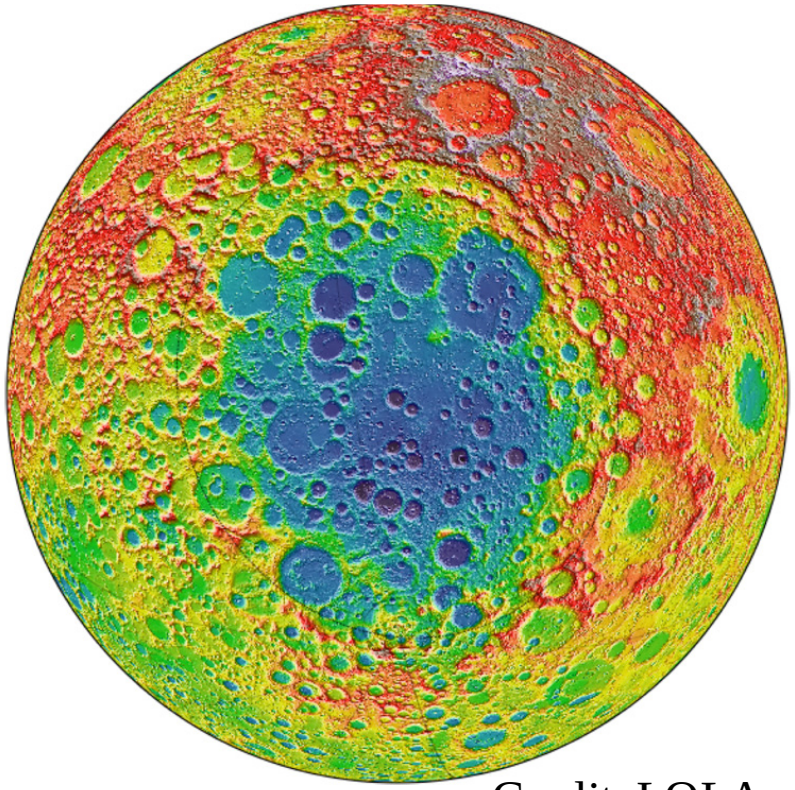


Credit: Lucy Reading-Ikkanda /Quanta Magazine

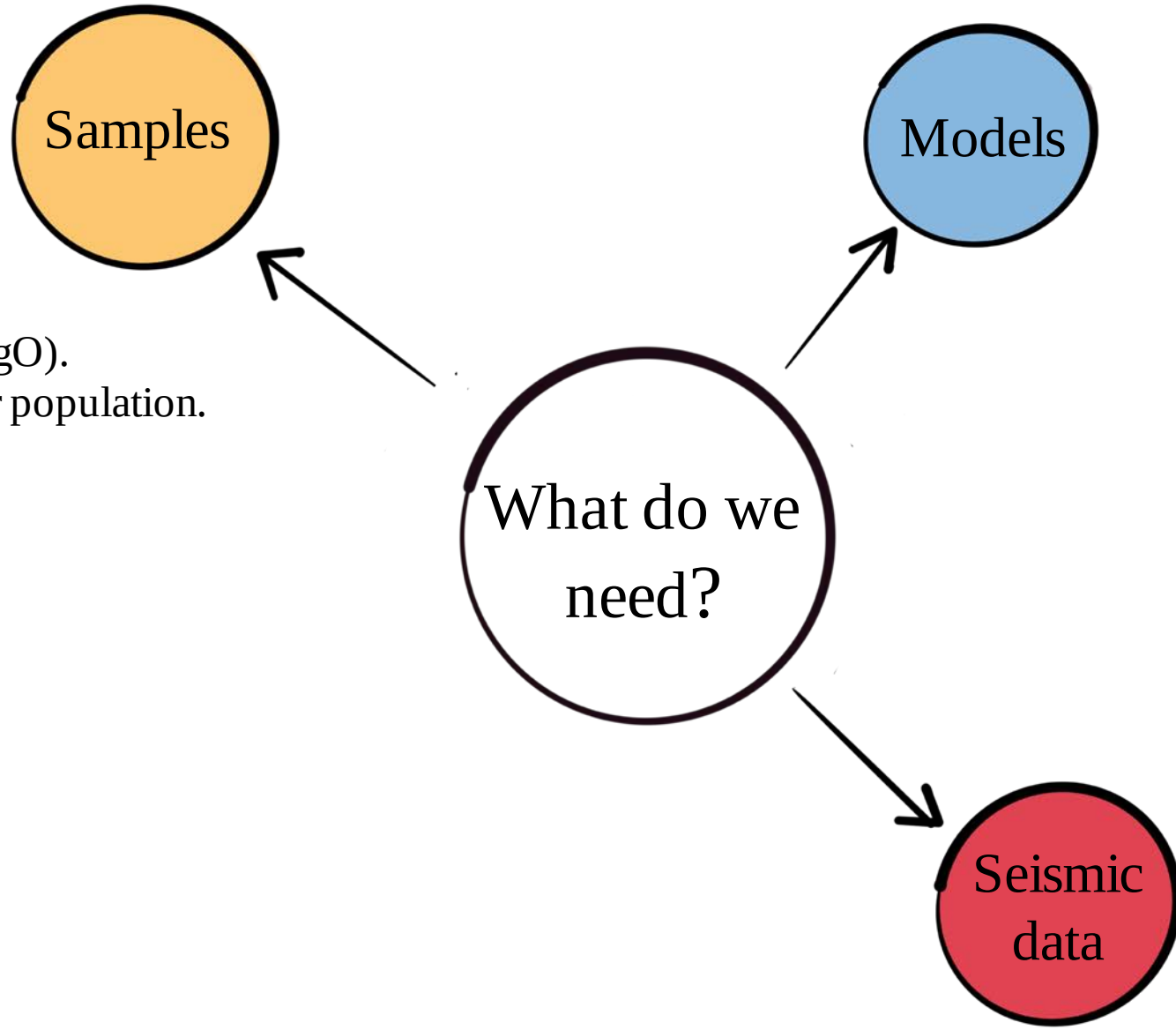
Scenario	Impactor mass [$M_{\oplus}$]	Impact Velocity [V_{esc}]
Canonical impact	0.13 - 0.2	1-1.2
High angular momentum: Fast spinning Earth	0.03 - 0.1	1.5-3
High angular momentum: half-Earth impact	0.4 - 0.5	1-1.5
Hit-and-run	0.2 - 0.3	1.2-1.4
Multiple impact	0.01 - 0.1	1-3

- Scenarios span a wide range of impactor masses and velocities.
  - Implications for the final major impact event on Earth vary widely: spin rate, thermal state, composition, lunar accretion timescales…
- More data and physical constraints are needed to
  - Assess the likelihood of a given scenario
  - Assess the ability of a given scenario to produce the current Earth-Moon

- Samples from diverse depths (e.g., South Pole Aitken)
  - Determine the bulk lunar composition (e.g., FeO/MgO).
  - Dating of largest lunar basins to determine impactor population.



Credit: LOLA



- Samples from diverse depths (e.g., South Pole Aitken)
  - Determine the bulk lunar composition (e.g., FeO/MgO).
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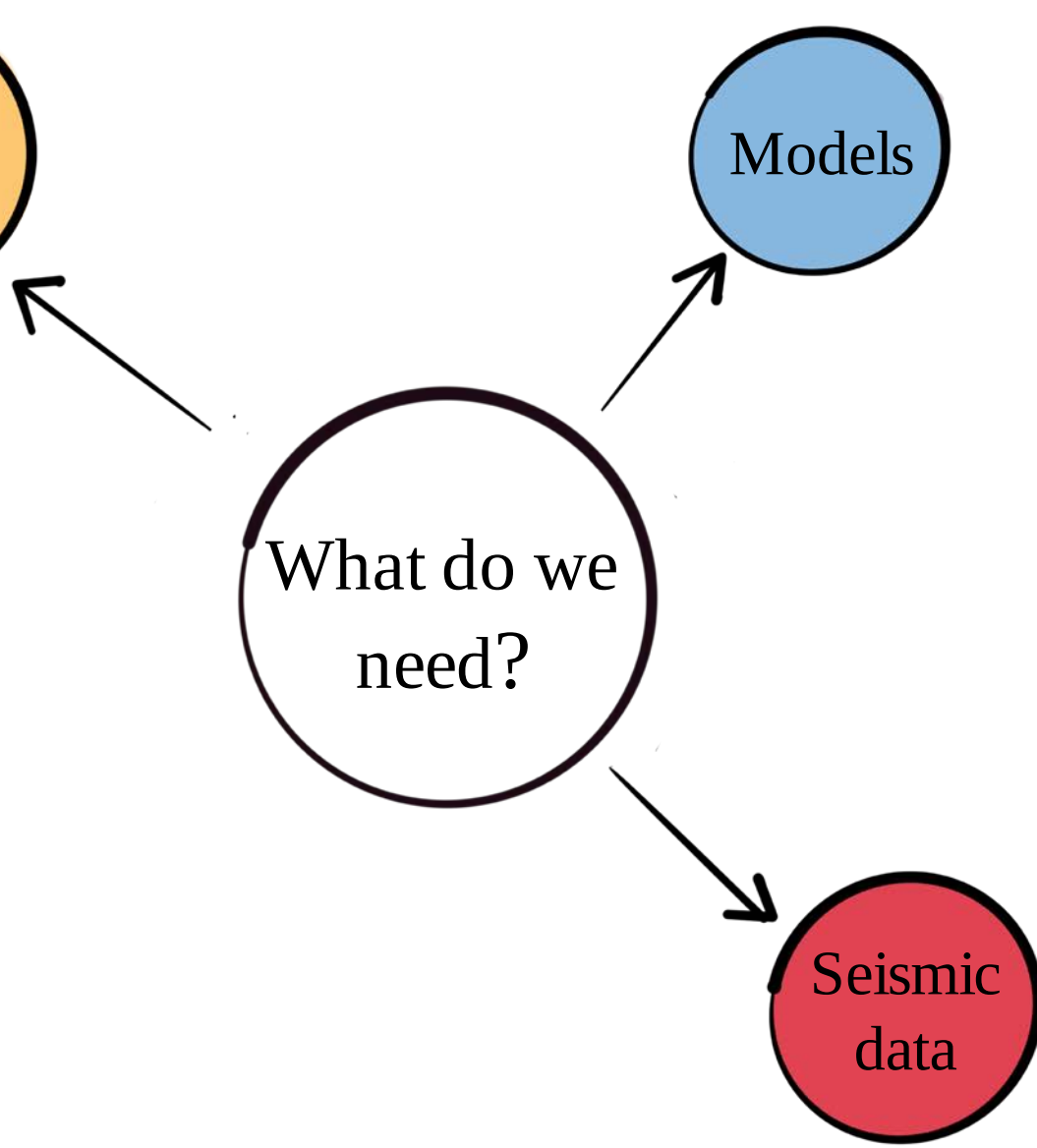
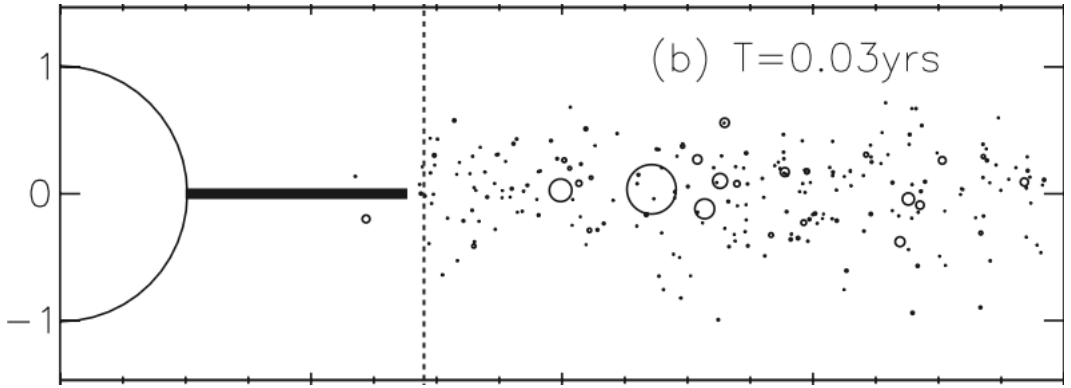
- Sample from diverse locations on the surface
  - Volatile abundances
  - Isotopic composition of refractory elements

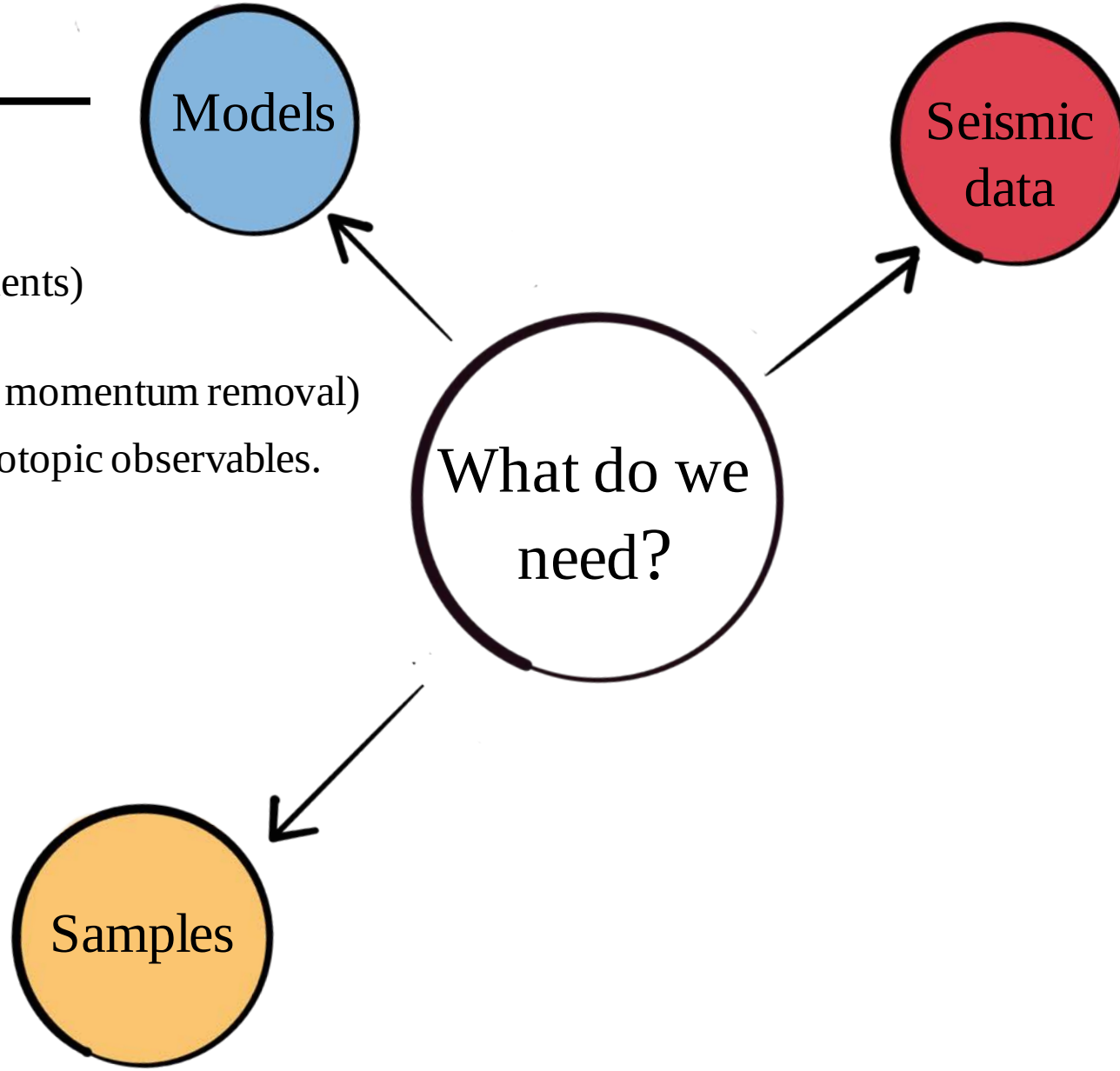
- Venus
  - Determine the mixing in the inner solar system



- Equations of state (e.g., shock compression experiments)
- Realistic post-accretion lunar dynamical models
  (e.g., timing of magma ocean solidification, angular momentum removal)
- Models that link the disk evolution with chemical/isotopic observables.



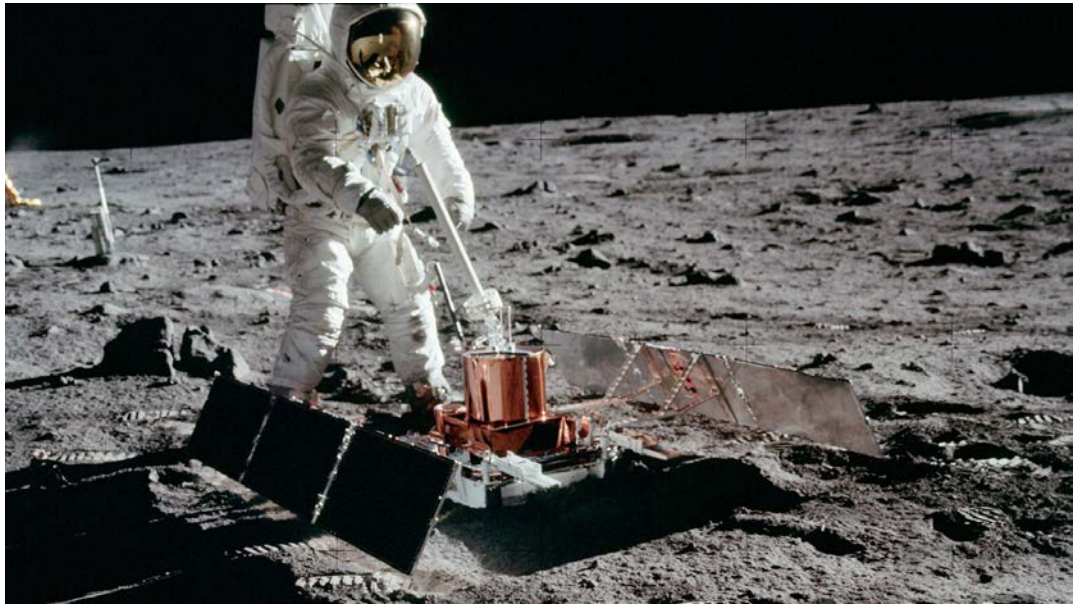
Salmon & Canup (2012)



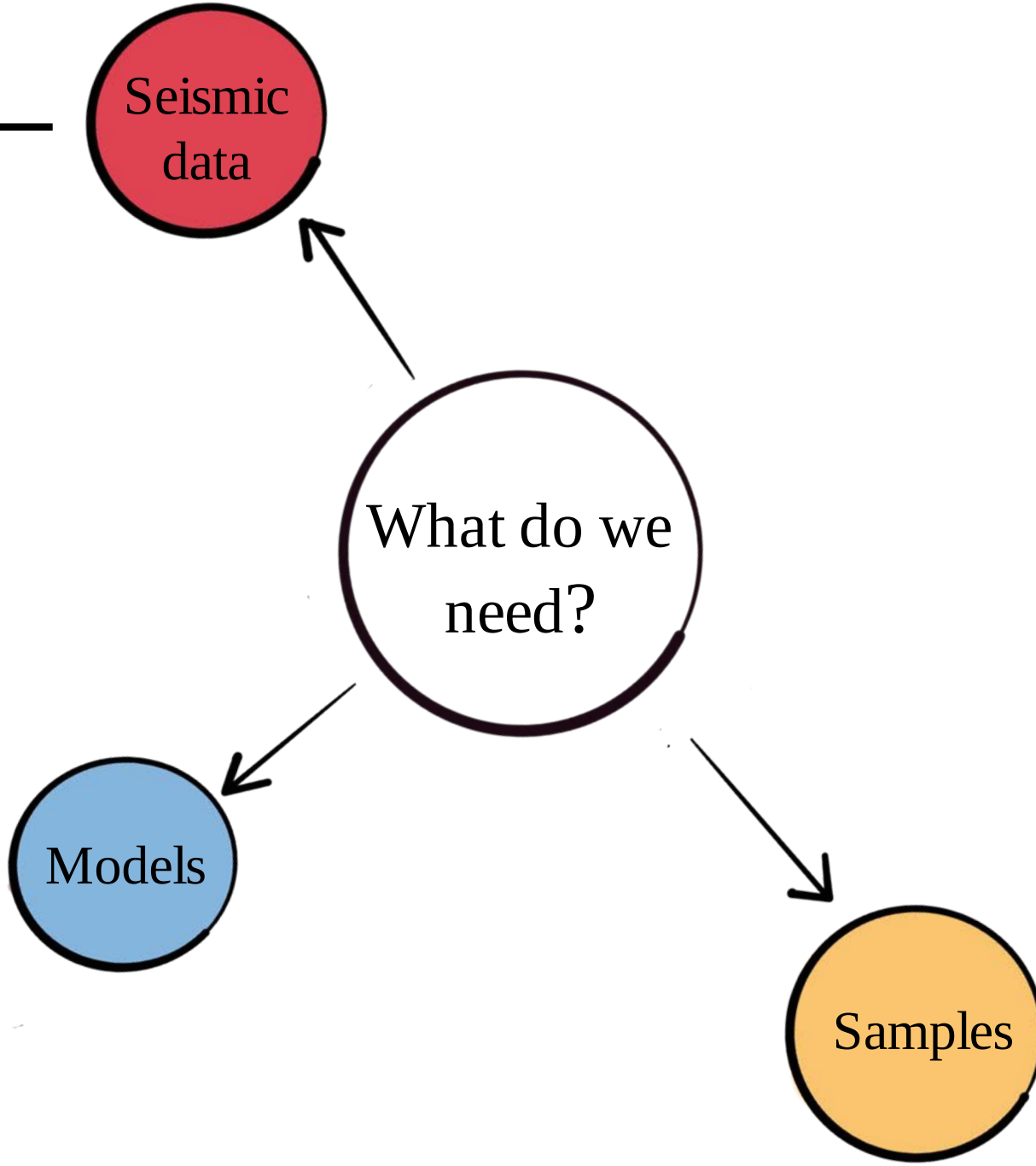
Long-term seismic array on the Moon

- Constrain the lunar crust depth

  (e.g. depth of the initial lunar magma ocean)
- Constraint the size and composition of the core.



Credit: NASA



Key outstanding questions on lunar origin

- Moon's initial thermal state: How do the various accretion scenarios relate to the geophysical evidence that the Moon had a partially melted mantle?
- Earth-Moon isotopic similarities: Are there any – albeit small – differences for more refractory elements? How do these relate to possible limited equilibration in the protolunar disk?
- Moon's bulk composition: Are there any differences regarding isotopic signatures between crust and mantle samples?
- Largest lunar basins: When did they occur?
- Lunar magma ocean: What was the depth and longevity of the magma ocean? How does this affect the evolution of the lunar orbit and the angular momentum of the Earth-Moon system?
- Lunar interior: What is the composition and size of the lunar core?
- Modeling: How are impact simulations affected by more advanced material equation of states? How are the dynamics and timescales of lunar accretion affected by more accurate modeling of the post-impact disk/synestia?