The Onset of the Cataclysm: In situ dating of a nearside basin impact-melt sheet

or, there and not back again

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A Lunar Cataclysm…?

- Impact-melt samples from Apollo & Luna are 3.85-4.1 Ga, tied to Imbrium, Serenitatis, Crisium, Nectaris, plus other craters?
- May have been caused by destabilization of material in early solar system by dynamic forces such as gas drag and gravitational interactions
- Coincident with the oldest rocks on the Earth and *later* than the earliest isotopic signs of life on Earth – Earth was already a planet with oceans, plate tectonics, and single celled life
- **What was happening on the Moon before 3.9 Ga affected the course of life on Earth, the structure of our Solar System, and the dynamics of extrasolar planetary systems**

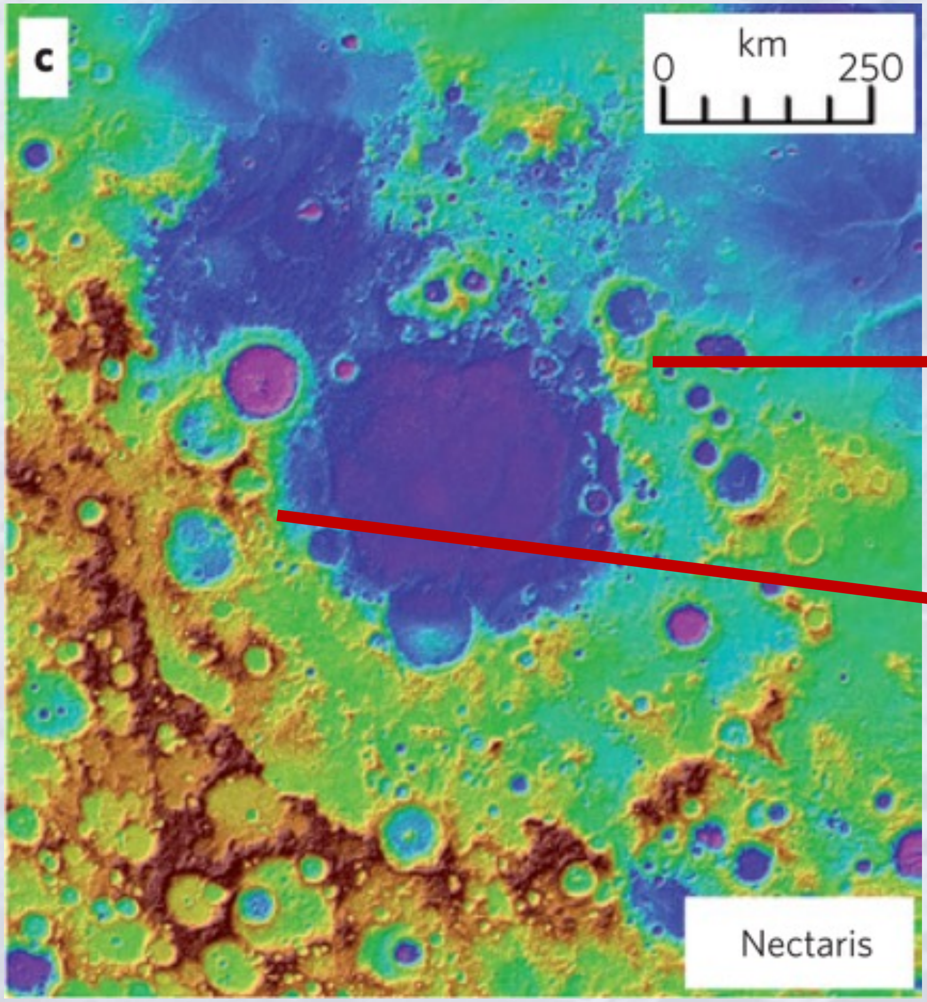
But wait. What if there was no cataclysm?

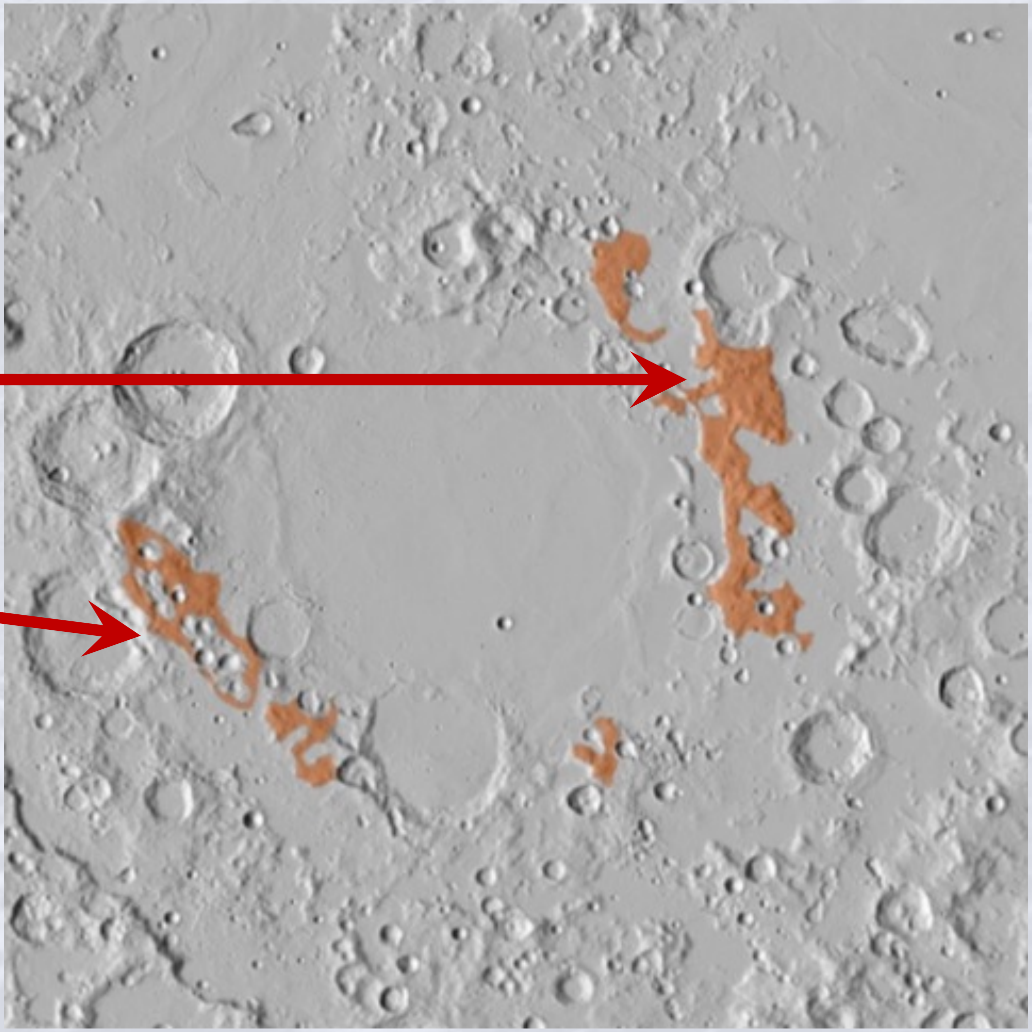
- Ongoing work on samples in the last decade, presented at Solar System Bombardment workshops in 2008, 2012, 2015
- What we thought were Serenitatis impact-melt rocks actually have strong affinity to Imbrium samples, and their origin in the Descartes Fm has been geologically linked to Imbrium. Oops.
- Crisium samples from Luna 20 are small and discordant, no agreement on whether they are impact melt.
- Impact-melt samples from Apollo 16 give ages for Nectaris from 3.85 Ga-4.2 Ga depending on who interprets them – no agreement on what is from Nectaris. Oops.
- **Samples thrown from basins don’t come tagged with their origin. Norman (2009) called this ”Pulling the pin” on the start of the Cataclysm!**

So, how can we resolve this?

- Date the melt sheet of a well-known, pre-Imbrian basin!
- **South Pole – Aitken Basin** is far from Imbrium, records impact history since its formation (including Apollo, Ingenii, Poincare)
  - New Frontiers class mission – farside, comsat, sample return
- Near side basins generally have mare covering their impact-melt sheets, but impact-melt kipukas may have been identified!
- **Nectaris** is a stratigraphic horizon - the Nectarian Epoch defines the onset of the cataclysm
- **Crisium** is also pre-Imbrian and may also have promising sites

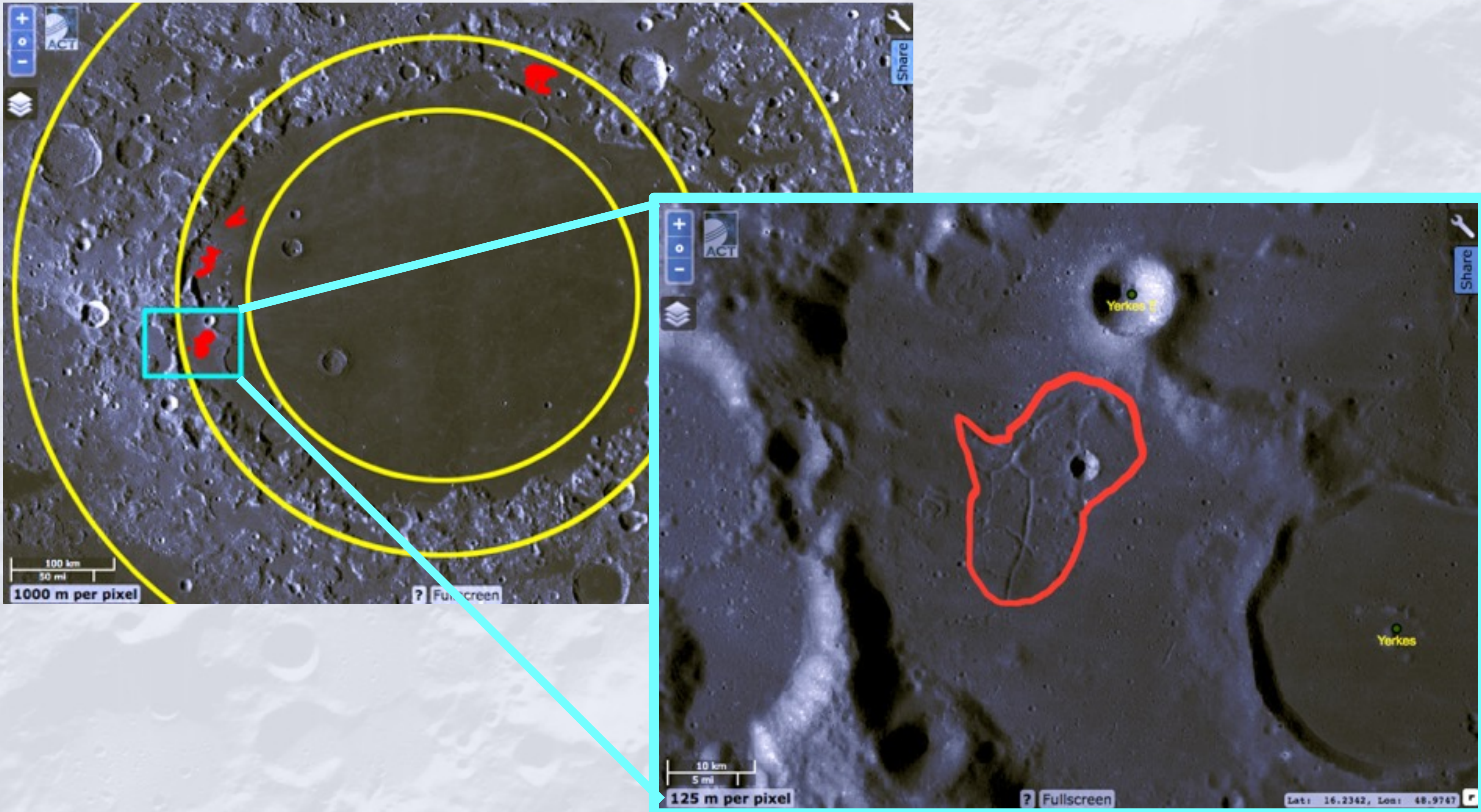
Nectaris in-place impact melt identified





- Small plains near inner basin ring massifs and intermassif “draped” deposits mapped as Nectaris basin impact melt sheet remnants (Spudis and Smith 2013)

Crisium in-place impact melt identified

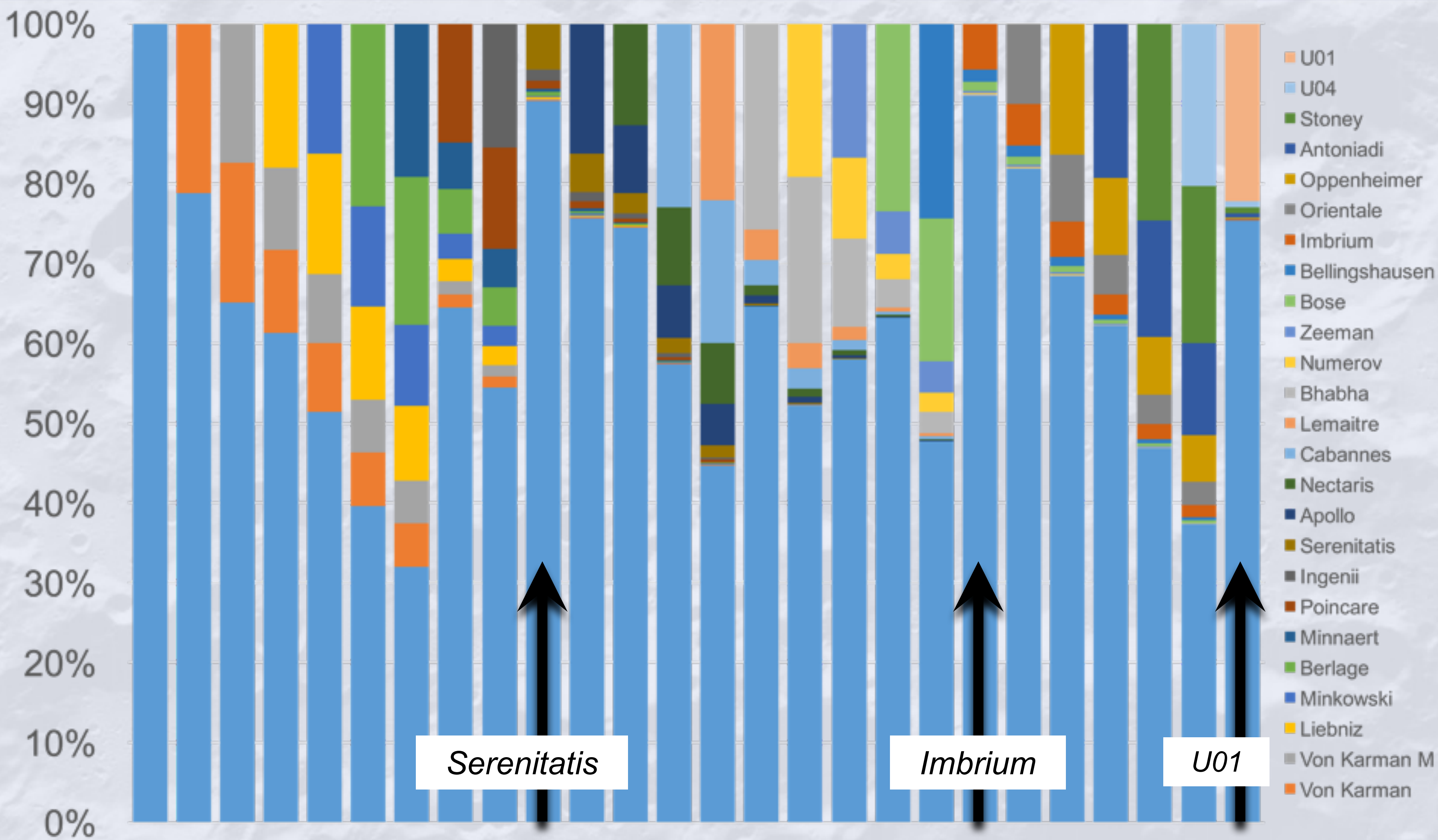


- Low FeO, cracked texture, higher crater density (Spudis & Sliz 2017)

Regolith scoop sampling

- Much of the present debate about the ages of the nearside basins arises because of the difficulty in understanding the relationship of distal samples to their parent basin
- Melt sheets are a fundamentally different geologic setting than the Apollo sites
- Regolith formed on the basin impact-melt substrate, diluting but not destroying native impact-melt rocks
- Geochemical signatures are evident from orbit
- 1% of the lunar regolith is rocklets 1-3 cm; need a scoop/sieve strategy (well-developed for MoonRise)

Regolith scoop sampling



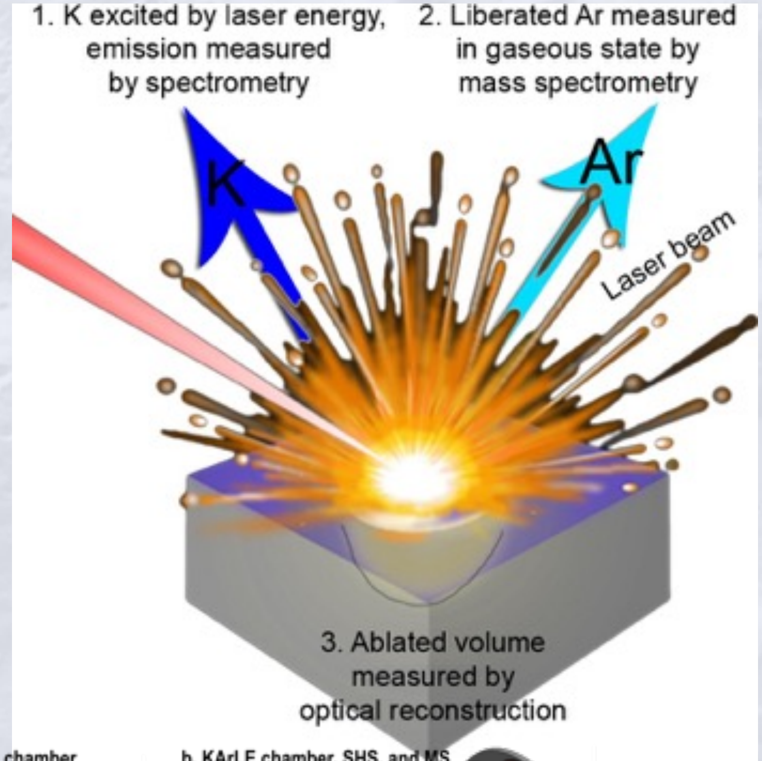
Proportion of material from different craters in the upper 1 m at Bhabha site in SPA

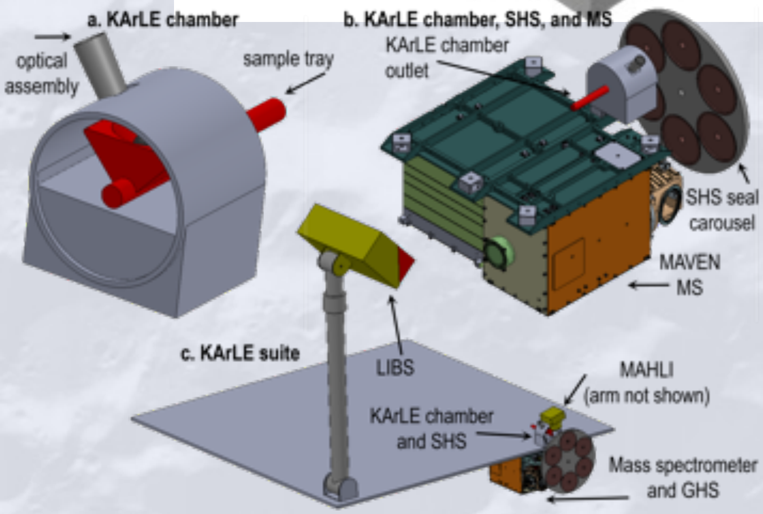
Science Instrument Payload (~30 kg)

Mission Element	Objective	Heritage	Mass (kg)	Power (W)
Sample collection & delivery mechanism	• Scoop & sieve regolith • Present rocks to MIBS and MI for triage • Introduce individual rocks to analysis chamber	Apollo, MoonRise	15	
LIBS	• Survey landing site materials (active and passive) • Characterize and prioritize samples • Determine K for geochronology	ChemCam (MSL), SuperCam (Mars 2020)	10	65
Mass Spectrometer	• Determine Ar for geochronology • Measure other volatile compounds and their isotopic composition	NG/IMS flown on MAVEN, MSL, etc.	5	40
Microscopic imager	• Workspace documentation • Characterize and prioritize samples Measurements of LIBS pits for geochronology	MER MI, MSL MAHLI, MSSS Hawkeye	1 (for 2)	4
Possible: LIDAR	• Descent support • Workspace definition			

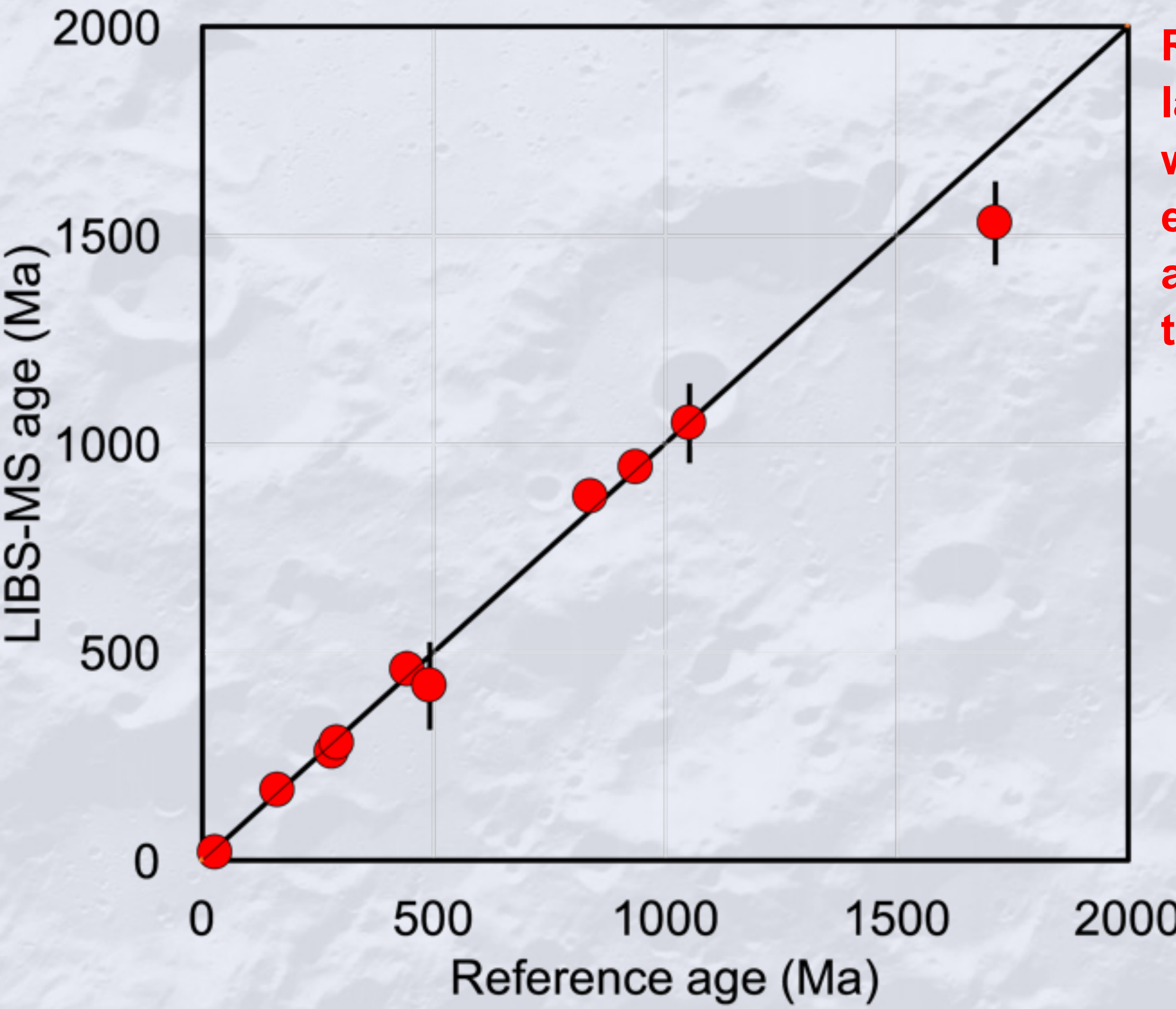
K-Ar Geochronology using LIBS-MS

- K measured using laser-induced breakdown spectroscopy (e.g. Chemcam), also ablates the rock
- Liberated Ar measured using mass spectrometry (e.g. MAVEN-MS)
- K and Ar related by volume of the ablated pit using optical measurement (e.g. MAHLI)
- All TRL 9 instruments – low risk, known cost
- Instruments do double duty – complete composition, petrology, volatiles
- Conops fits with real mission flight ops
- Precision ±100-150 Myr for a 4 Ga sample





K-Ar Geochronology using LIBS-MS



Results from multiple laboratories yield whole-rock ages within error of accepted ages and precision close to theoretical = TRL 4

Solé (2014) Chemical Geology 388, p. 9-22; Cohen et al. (2014) Geostandards and Geoanalytical Research, doi: 10.1111/j.1751-908X.2014.00319.x; Devismes et al. (2016) Geostandards and Geoanalytical Research, doi: 10.1111/ggr.12118; Cho et al. (2016) Planetary and Space Science 128, 14-29

Basin in situ dating mission

- Accomplishes solar-system wide science by visiting a stratigraphically important lunar basin
  - In situ geochronology
  - Sample and site characterization
- Accomplishes three of the four major goals of the SPA New Frontiers mission recommended in the Decadal Survey by conducting in situ dating rather than sample return
  - Single lander, no mobility
  - Nearside, subequatorial site
  - Extensively covered by LRO imaging
- Extensive conceptual design work by JPL exists from MoonRise and Lunette robotic lunar lander activities
- Advances NASA investments in development of in situ geochronology measurements and science

Science Goals *from Decadal Survey*

- *Determine the chronology of basin-forming impacts and constrain the period of late heavy bombardment in the inner solar system and thus address fundamental questions of inner solar system impact processes and chronology*
  - Measure the K-Ar age of the Nectaris/Crisium basin impact-melt sheet (10-20 samples) and also KREEPy materials thrown far from the Imbrium basin (2-4 samples)
- *Determine age and compositions of basalts to determine how mantle source regions differ from regions sampled by Apollo and Luna*
  - Measure the age and composition of Mare Nectaris/Mare Crisium basalt (2-4 samples)
- *Characterize a large lunar impact basin through "ground truth" validation of global, regional, and local remotely sensed data of the sampled site*
  - Landing site characterization to correlate with orbital datasets
  - Measure the composition & petrology of samples at a site remote from the Apollo and Luna landing sites to understand their origin

Summary

- **Mission Goal:** Determine the age of a nearside basin, defining the epoch of late heavy bombardment throughout the solar system
- **Mission Status: In study for potential Discovery response**
- **Unique new science:**
  - Constrain the onset of the Cataclysm by determining the age of samples directly sourced from the impact melt sheet of a major lunar basin
  - Identify basin impact-melt samples for detailed follow-on studies using existing (& future, e.g. Chang'E) collections
  - Understand lunar evolution by characterizing new lunar lithologies far from the Apollo and Luna landing sites
  - Ground truth remote sensing measurements from orbital missions (e.g. LRO, Chandrayaan-1, Kaguya)
- **Other mission contributions:**
  - First US soft lander on the Moon since 1972
  - Conduct the first use of in situ geochronology, opening the gate to using it as a standard measurement on landed missions
  - Potential to use teleoperation and/or immersive VR environment for planning