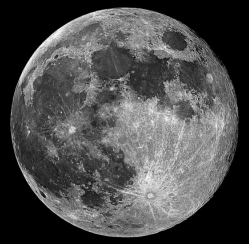
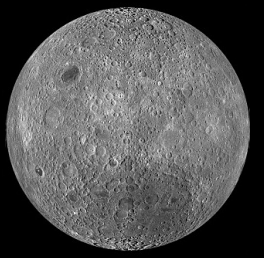


The International Lunar Resource Prospecting Campaign (ILRPC): Growing the Collaboration



C.R. Neal[1], A. Abbud-Madrid[2], J.D. Carpenter[3], T. Chakraborty[4], A. Colaprete[5], B. DeWitt[6], B. Ehlmann[7], C.D. Espejel[8], K. Hadler[9], D. Heather[3], C.A. Hibbitts[10], K. Kim[11], J. Kleinhenz[12], S. Li[13], M. Link[14], M. Ohtake[15], G. R. Osinski[16], N. Petro[17], A. Salmeri[18], G.B. Sanders[19], with R. Patterson[20], H.C. O'Brien[19], L. Galien[1], & J. Valenciano[1].

1 = University of Notre Dame, IN, U.S.A.

2 = Colorado School of Mines, CO, U.S.A.

3 = European Space Agency, ESTEC, Netherlands

4 = Space Applications Centre, ISRO, Ahmedabad, India

5 = NASA Ames Research Center, CA, U.S.A.

6 = Lunar Station, Cambridge MA 02142, U.S.A.

7 = CalTech, Pasadena CA 91125 U.S.A.

8 = iSpace Europe, Inc., 1811 Luxembourg, Luxembourg

9 = Director of ESRIC, 41 Rue du Brill, Luxembourg

10 = Johns Hopkins University Applied Physics Lab, MD, U.S.A.

11 = KIGAM, Daejeon, Republic of Korea

12 = NASA Glenn Research Center, OH 44135, U.S.A.

13 = University of Hawaii, Honolulu, HI 96822, U.S.A.

14 = Luxembourg Space Agency, 2449 Luxembourg, Luxembourg

15 = University of Aizu, Tsuruga, Fukushima, 965-8580, Japan

16 = University of Western Ontario, London, Ontario N6A 5B7, Canada

17 = NASA GSFC, Greenbelt MD 20771 U.S.A.

18 = Lunar Policy Platform, 22 Calle De Valdesangil, Spain

19 = NASA Johnson Space Center, TX 77058, U.S.A.

20 = Astralytical Consulting, U.S.A.

Motivation – Artemis Architecture Segments (from Jerry "Magnum" Sanders)

HUMAN LUNAR RETURN

Initial capabilities, systems, and operations necessary to reestablish human presence and initial utilization (e.g., science) on and around the Moon.

FOUNDATIONAL EXPLORATION

Expansion of lunar capabilities, systems, and operations supporting complex orbital and surface missions to conduct utilization (e.g., science) and Mars-forward precursor missions.

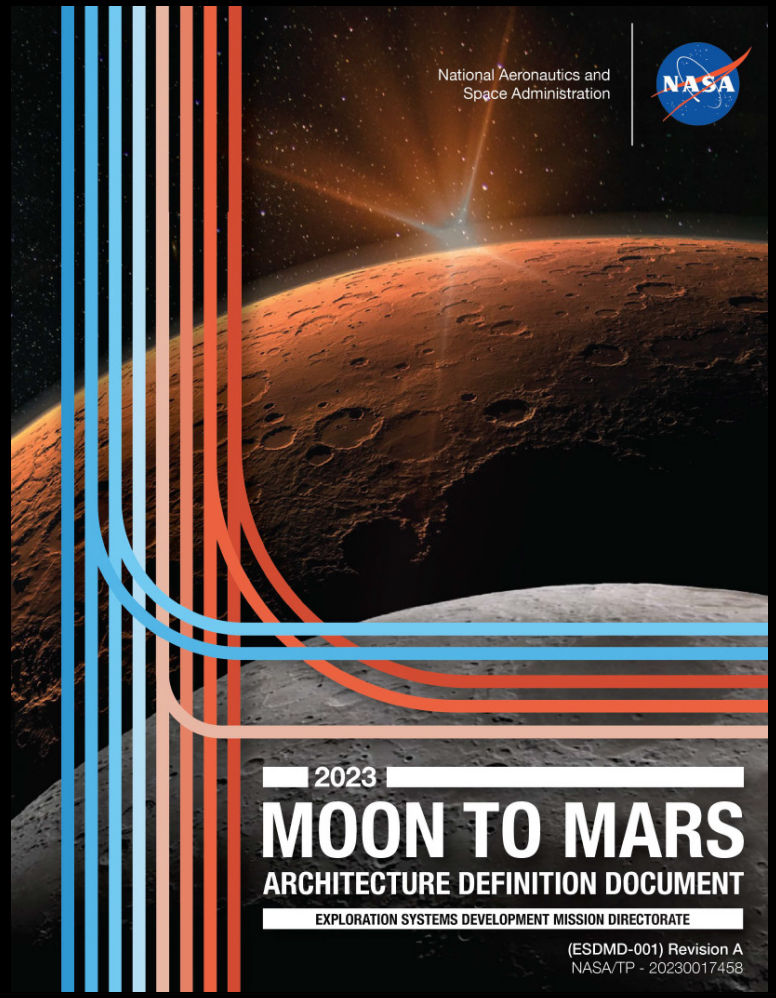
SUSTAINED LUNAR EVOLUTION

Enabling capabilities, systems, and operations to support regional and global utilization (e.g., science), economic opportunity, and a steady cadence of human presence on and around the Moon.

HUMANS TO MARS

Initial capabilities, systems, and operations necessary to establish human presence and initial utilization (e.g., science) on Mars and continued exploration.

Motivation – Artemis Architecture Definition Document 2023



The current Architecture document states:

P. 22 of the PDF: "*To minimize the risk to the Artemis campaign and ISRU product customers, NASA and its partners must plan a transition of Earth-delivered to ISRU-derived products, along with adequate resource mapping and demonstration of the ISRU processes and product quality*."

P. 145 of the PDF: "*The shift from reconnaissance, initial resource assessment, and sampling to resource reserve estimation, acquisition, and processing occurs in this segment* [Foundational Evolution]."

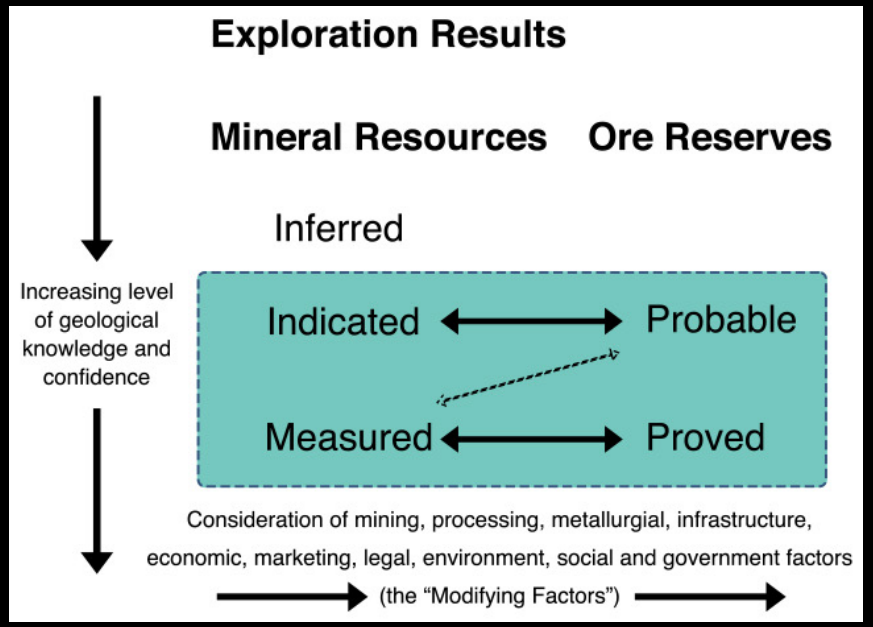
HOW?

https://www.nasa.gov/moontomarsarchitecture-architecturedefinitiondocuments/

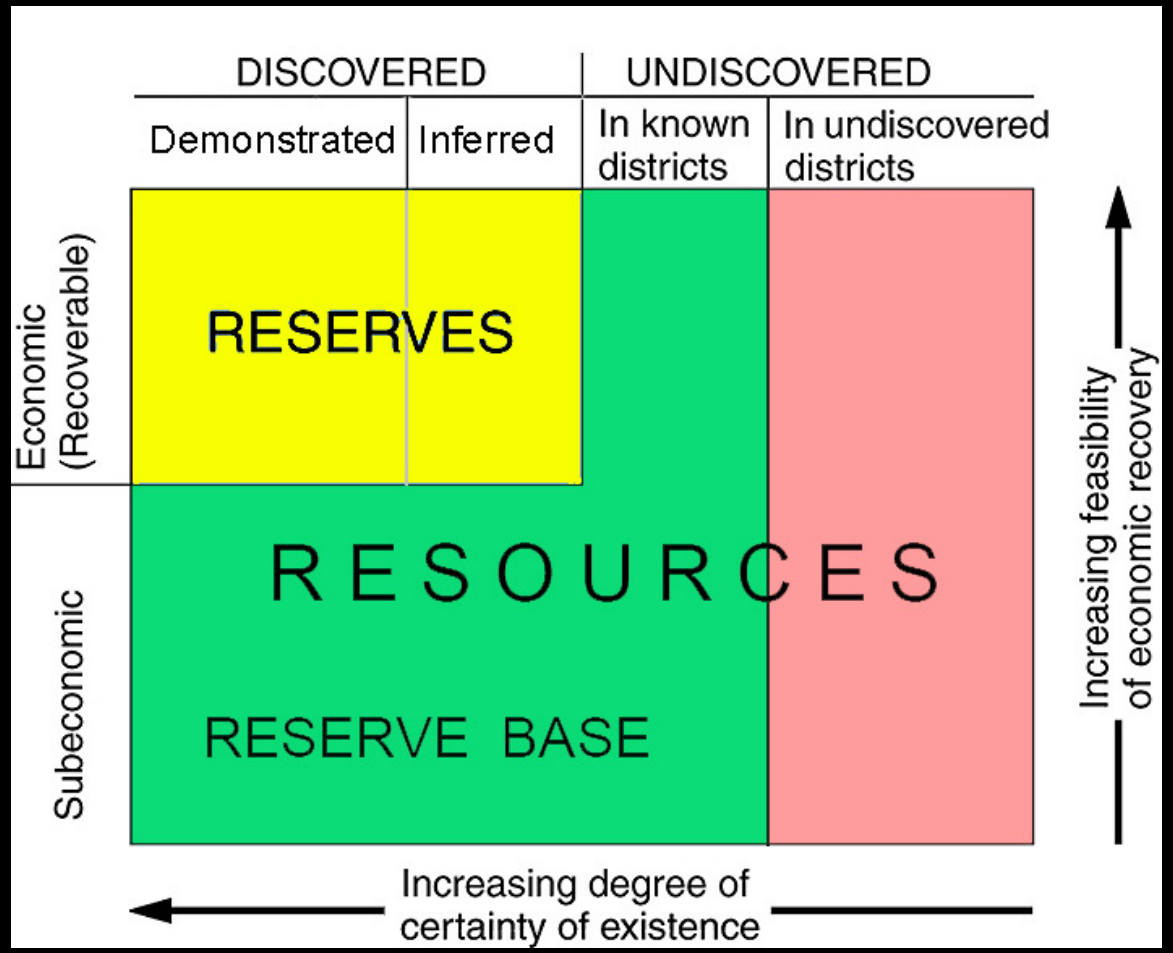
Resources vs. Reserves

Resource: A concentration of natural materials in/on the crust such that economic extraction is feasible.

Reserve: A portion of a resource from which a usable mineral or energy commodity can be economically and legally extracted.



For the Moon, initial exploration results require more granular data



Cannon & Britt (2020) Icarus 347, Article 113778

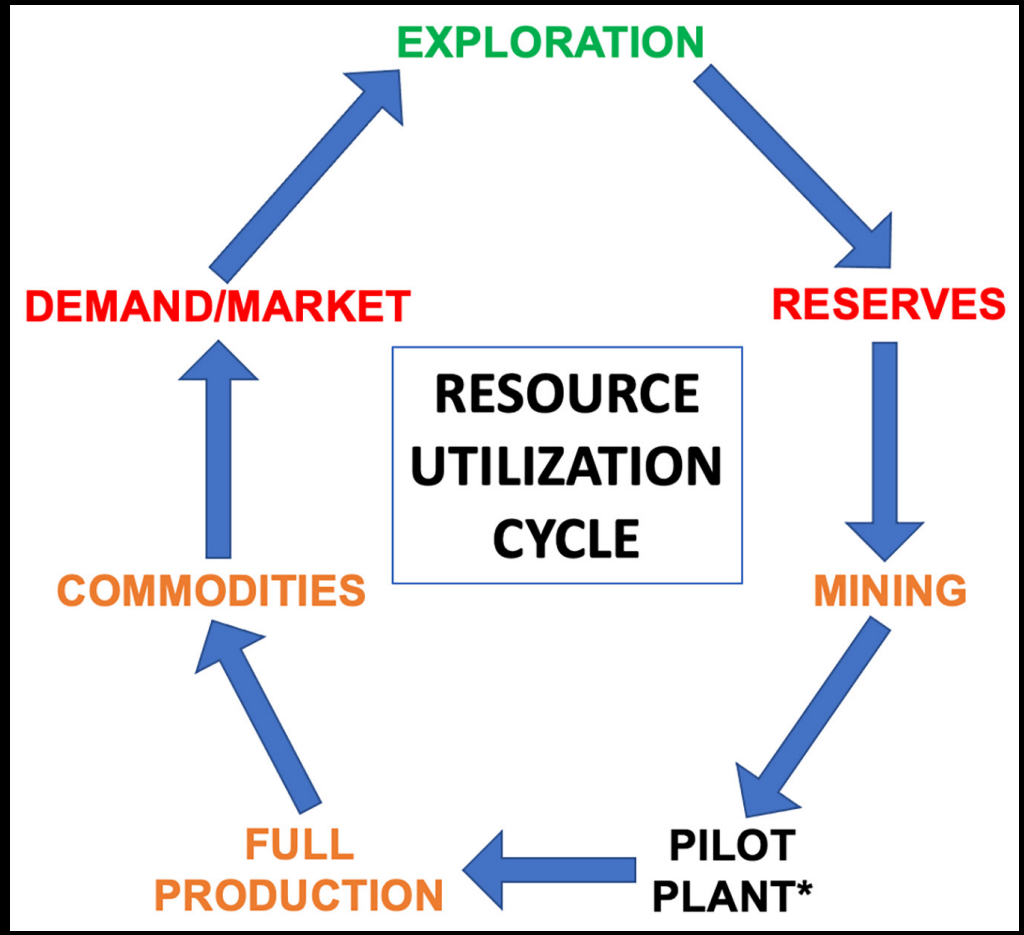
United States Geological Survey (1980) Geol. Survey Circ. 831. https://pubs.er.usgs.gov/publication/cir831

Resources vs. Reserves

Road-blocks in the ISRU value chain:

Reserve Potential ⟷ Demand/Market(s) (Customers)

Ground-truth Data & Demand/ Market(s) need to be obtained/ established to understand if lunar resources are reserves.



- Kleinhenz et al. (2020) Lunar Water ISRU Measurement Study (LWIMS) NASA/TM-20205008626
- Kleinhenz (2022) ISRU Potential Water Mine Site Preliminary Evaluation for NASA Artemis Campaign. https://isruinfo.com/public/index.php?page=srr_22
- Espejel et al. (2023) Lunar Ore reserves standards 101 (LORS-101), in: V. Badescu, et al. (Eds.), Handbook of Space Resources, Springer, 2023, pp. 999–1022.
- Brown et al. (2022) Resource potential of lunar permanently shadowed regions. *Icarus* **377**, Article 114874.

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https://doi.org/10.1016/j.actaastro.2023.11.017

Table 1: Datasets for lunar volatile resource evaluation

Dataset	Specific Data	Use	Measurement
Composition	Concentration of the resource Concentration & composition of impurities	Evaluate potential investment needed for refining the product	Required Fidelity?
Form	Cement in pore space; Layers; Irregular blocks; Loose ice grains with regolith	Develop efficient extraction techniques	
Distribution	Horizontal Vertical	Variability needs to be documented to understand the volume of the resource	
Geotechnical	Torque and power required for any drills to penetrate the deposit; Energy required to move loose regolith; Hardness of the deposit;	Understand the effort required to mine the deposit and investment needed in developing extraction capabilities.	
Near-surface Regolith Stratigraphy	Buried and surface rock populations Ice block/layer distribtuion	Will impact the extractibility of the regolith resource	
Accesibility	Traverse paths;	Ease of accessibility has an impact on cost of developing robotic miners.	

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The Moon needs an international lunar resource prospecting campaign

Clive R. Neal [a,*], Antonino Salmeri [b], Angel Abbud-Madrid [c], James D. Carpenter [d], Anthony Colaprete [e], Karl A. Hibbitts [f], Julie Kleinhenz [g], Mathias Link [h], Gerald Sanders [i]

[a] Department of Civil & Environmental Engineering & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, USA
[b] Lunar Policy Platform, 22 Calle De Valdesangil, Spain
[c] Center for Space Resources, Colorado School of Mines, Golden CO 8040, USA
[d] European Space Agency, European Space Research and Technology Centre, Keplerlaan 1, 2201AZ, Noordwijk, the Netherlands
[e] Space Science Division, NASA Ames Research Center, Moffett Field, Mountain View, CA 94035, USA
[f] Johns Hopkins University – Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723, USA
[g] NASA – Glenn Research Center, 21000 Brookpark Rd, Cleveland, OH 44135, USA
[h] Luxembourg Space Agency, 19-21 Boulevard Royale, 2449 Luxembourg, Luxembourg
[i] NASA – Johnson Space Center, 2101 E NASA Pkwy, Houston, TX 77058, USA

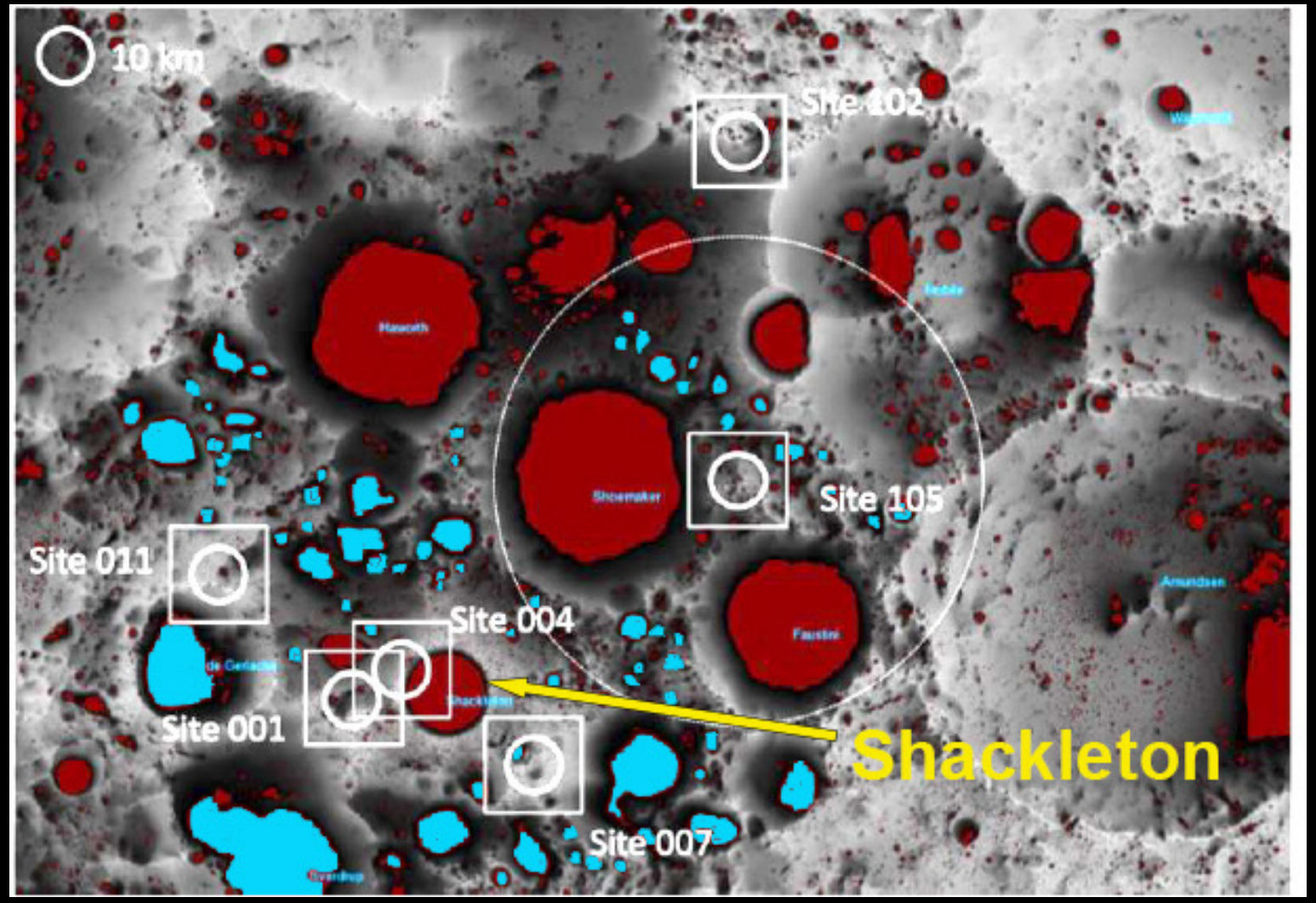
Data types needed for understanding if lunar resources are reserves.

Required Fidelity:

- **Thoroughness** of coverage
- **Accuracy** of surface & subsurface measurements (e.g., +/- 5% for species ≥ 0.5 wt.%)
- **Coordination** between surface missions (easily comparable data sets – could VIPER be the benchmark?)
- Many of these new data types would need to be taken via surface mobile assets.
- BUT the 10 most promising sites for polar volatiles cover an area >6,000 km^2 [Brown et al., 2022, Icarus 377,114874]

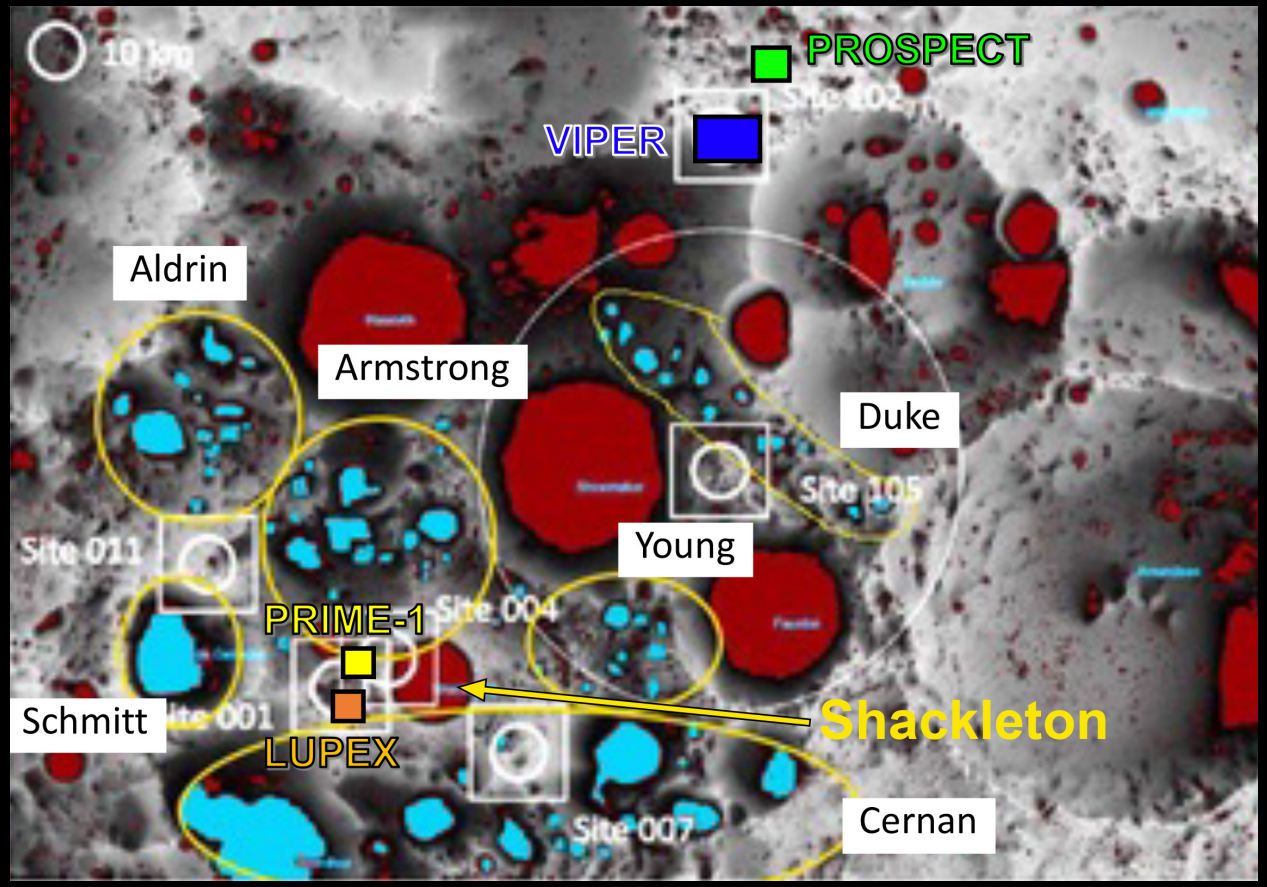
The Way Forward

- Focus on south pole volatiles in PSRs (+/- 5% on species ≥ 0.5 wt.%)
- Use existing data sets to define targets
- Conduct sensitivity analyses on combined data set results to inform future measurement needs
- Focus on small-to-medium PSRs – more accessible(?)
- ”Close” to Artemis sites of interest

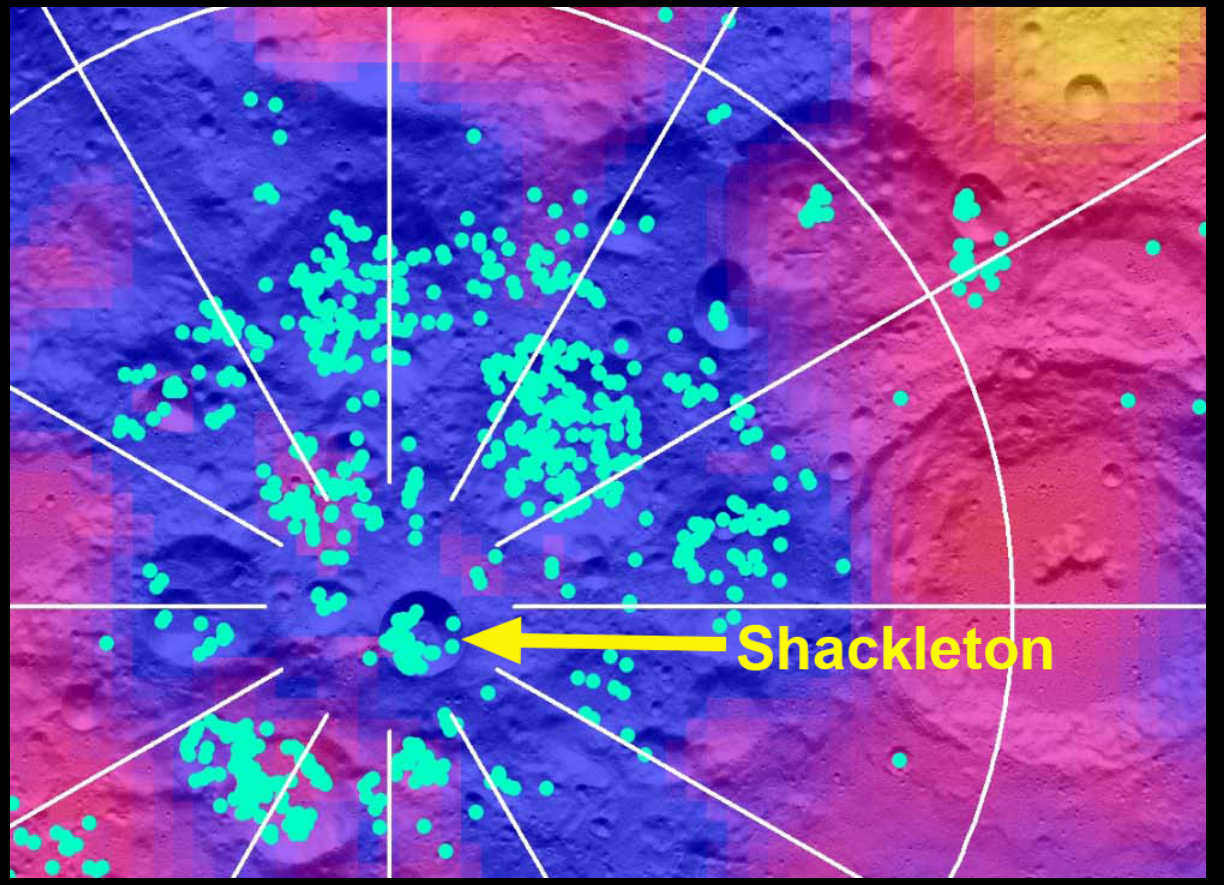


The Way Forward

South Pole PSR Map[1] with proposed Artemis landing sites and targets for orbital data gathering & ground-truthing (blue).



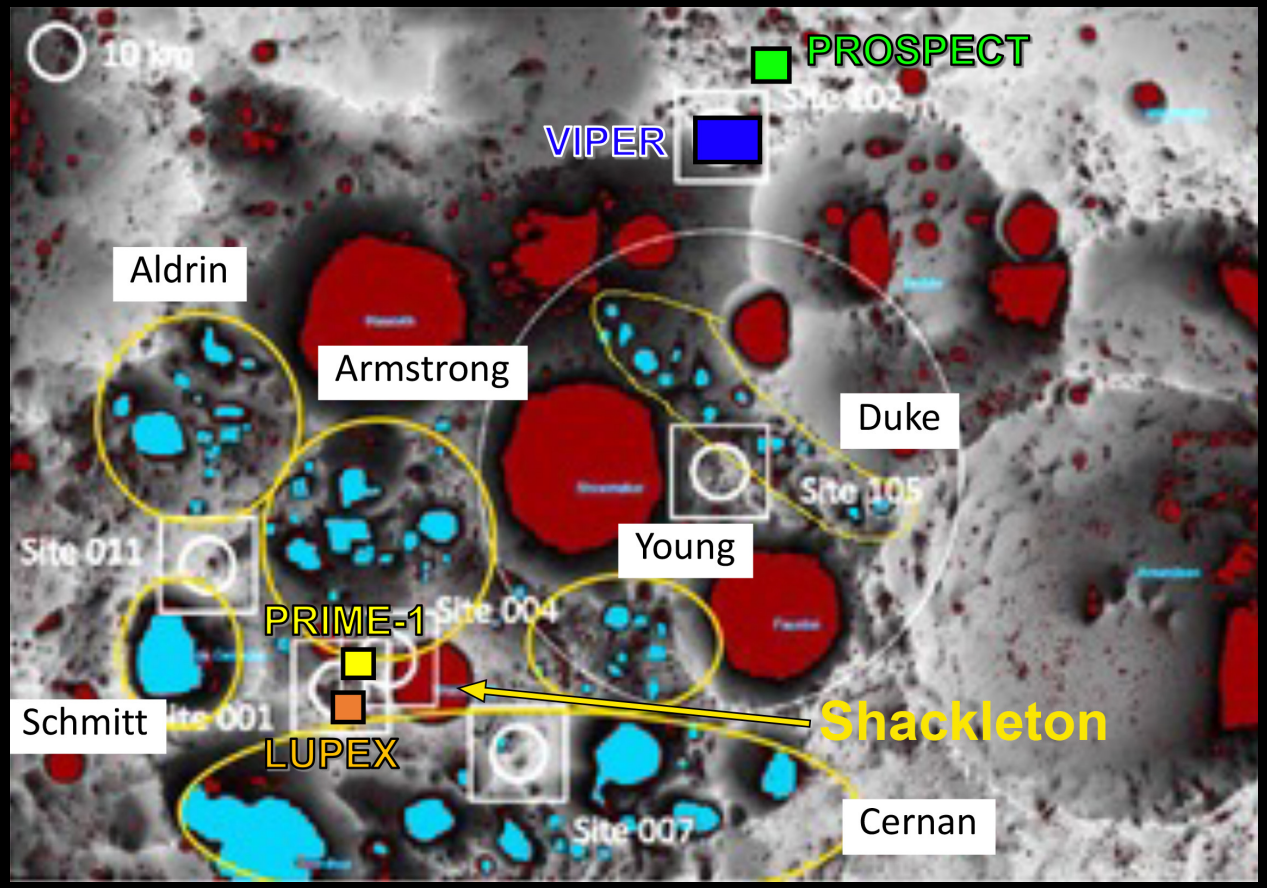
Surface water ice[2] overlain on Lunar Prospector neutron data (cooler colors represent buried H)[3], adapted from Li et al.[4].

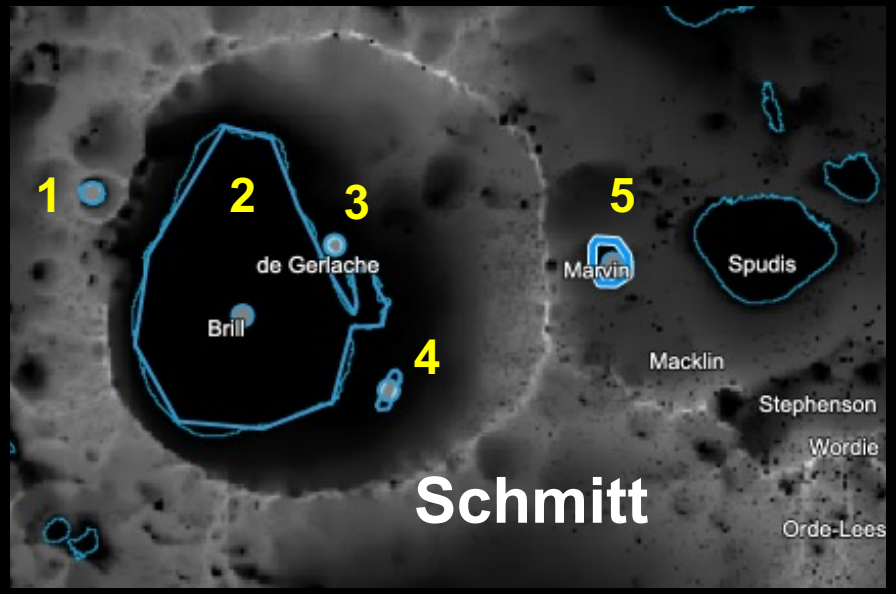


1: Mazarrico et al. (2011) Icarus 211, 1066–1081; **2**: Li et al. (2018) PNAS 115, 8907-8912; **3**: Elphic et al. (2007) GRL 34, L13204; **4**: Li et al. (2023) LPSC-55, abstract #2537

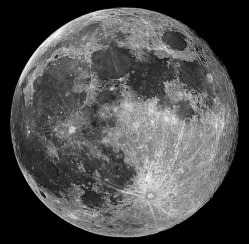
The Way Forward

Example: “Schmitt” area

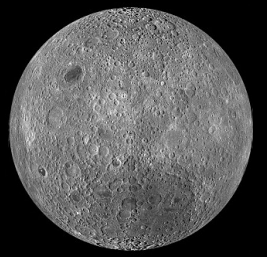




#	Latitude	Longitude	Area (km²)	Name
1	-87.9518	276.06422	1.677	
2	-88.3084	267.67894	229.654	de Gerlache
3	-88.5209	273.69554	0.953	
4	-88.6278	259.86796	2.354	
5	-89.1669	273.61880	6.406	Marvin



Coordinating an International Lunar Resource Prospecting Campaign



- Campaign = series of missions. Expensive!
- 21st Century renaissance for the Moon!
  - 27 lunar missions, 4 lander failures
- Between now and the end of the decade – **30** robotic lunar missions are funded and under development, and **16** more have been proposed, but not yet funded.
- Coordinate existing missions rather than starting new mission lines.

NAME	Mission Type	Agency/Company	LAUNCH DATE
SMART-1	Orbiter/Tech. Demo.	ESA	27 Sept 2003
ARTEMIS	Orbiters	NASA	17 Feb 2007
SELENE	Orbiter	JAXA	14 Sept 2007
Chang'e 1	Orbiter	CNSA	24 Oct 2007
Chandrayaan-1	Orbiter	ISRO	22 Oct 2008
LRO	Orbiter	NASA	18 June 2009
LCROSS	Impactor	NASA	18 June 2009
Chang'e 2	Orbiter	CNSA	1 Oct 2010
GRAIL	Orbiters	NASA	10 Sept 2011
LADEE	Orbiter	NASA	7 Sept 2013
Chang'e 3	Lander/Rover	CNSA	1 Dec 2103
Chang'e 5 TI	Tech. Demo.	CNSA	23 Oct 2014
Queqiao	Comm. Sat.	CNSA	21 May 2018
Chang'e 4	Lander/Rover	CNSA	7 Dec 2018
Beresheet	Lander	SpaceIL	22 Feb 2019
Chandrayaan-2	Orbiter/Lander	ISRO	22 July 2019
Chang'e 5	Sample Return	CNSA	23 Nov 2020
KPLO	Orbiter	KARI	4 Aug 2022
Artemis 1	Orbiter	NASA	21 Nov 2022
HAKUTO-R-1	Lander/Rover	iSpace	11 Dec 2022
Chandrayaan-3	Lander/Rover	ISRO	14 July 2023
Luna 25	Lander	Roscosmos	10 Aug 2023
SLIM	Lander	JAXA	6 Sept 2023
Peregrine 1	Lander	Astrobotic	8 Jan 2024
Odysseus	Lander	Intuitive Machines	15 Feb 2024
Queqiao-2	Comm. Sat.	CNSA	20 Mar 2024
Chang'e 6	Sample Return	CNSA	3 May 2024

Coordinating Ongoing & Scheduled Missions

Orbital Missions

- Lunar Reconnaissance Orbiter (**LRO** - U.S.A.)
- Korean Pathfinder Lunar Orbiter (**KPLO aka Danuri** – Korea)
- Chandrayaan-2 (India)
- Lunar Trailblazer (U.S.A.)

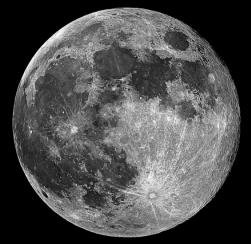
Other Relevant Planned missions

China: Chang'e 7, 8

Russia: Luna 26, 27

Surface Missions (lander & rover)

- Volatiles Investigating Polar Exploration Rover (**VIPER** – U.S.A)
- Polar Resources Ice Mining Experiment-1 (**PRIME-1** – U.S.A.)
- Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation (**PROSPECT** – European Space Agency)
- Lunar Rover Mission (Canada)
- LUnar Polar EX mission (**LUPEX** – Japan & India)



Coordinating Ongoing & Scheduled Missions: Integrating Da

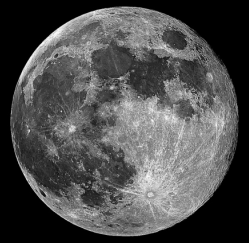
Brown et al. (2022) Resource potential of lunar permanently shadow… 114874

DATASET	
Diviner annual maximum bolometric temper…	
LRO Diviner average bolometric wint…	240
LRO Diviner ice depth stability …	240
LRO LAMP FUV off-band/…	240
LRO LOLA active n…	500
Chandrayaan-1…	280
LRO Mini…	150 & 30
LR…	~10,000
…	15,000 to 45,000
…maging	10 to 40

Conduct sensitivity analyses on combined data set results to inform future measurement needs

…ar PSRs – data also available for smaller PSRs

…set integration from different missions requires collaborations:
…nar Station, European Space Resources Innovation Centre (ESRIC),
Academic Institutions, Mining Industry



Coordinating Ongoing & Scheduled Missions: Integrating Da

KPLO:

- ShadowCam – 1.7 m/pixel;
- Gamma Ray Spectrometer – 70,000 &

Chandrayaan-2:

- Dual Frequency Synthet SAR) – collects data of the lunar surface at ~0 ted by Kumar et al., 2022, Adv. Space Res.

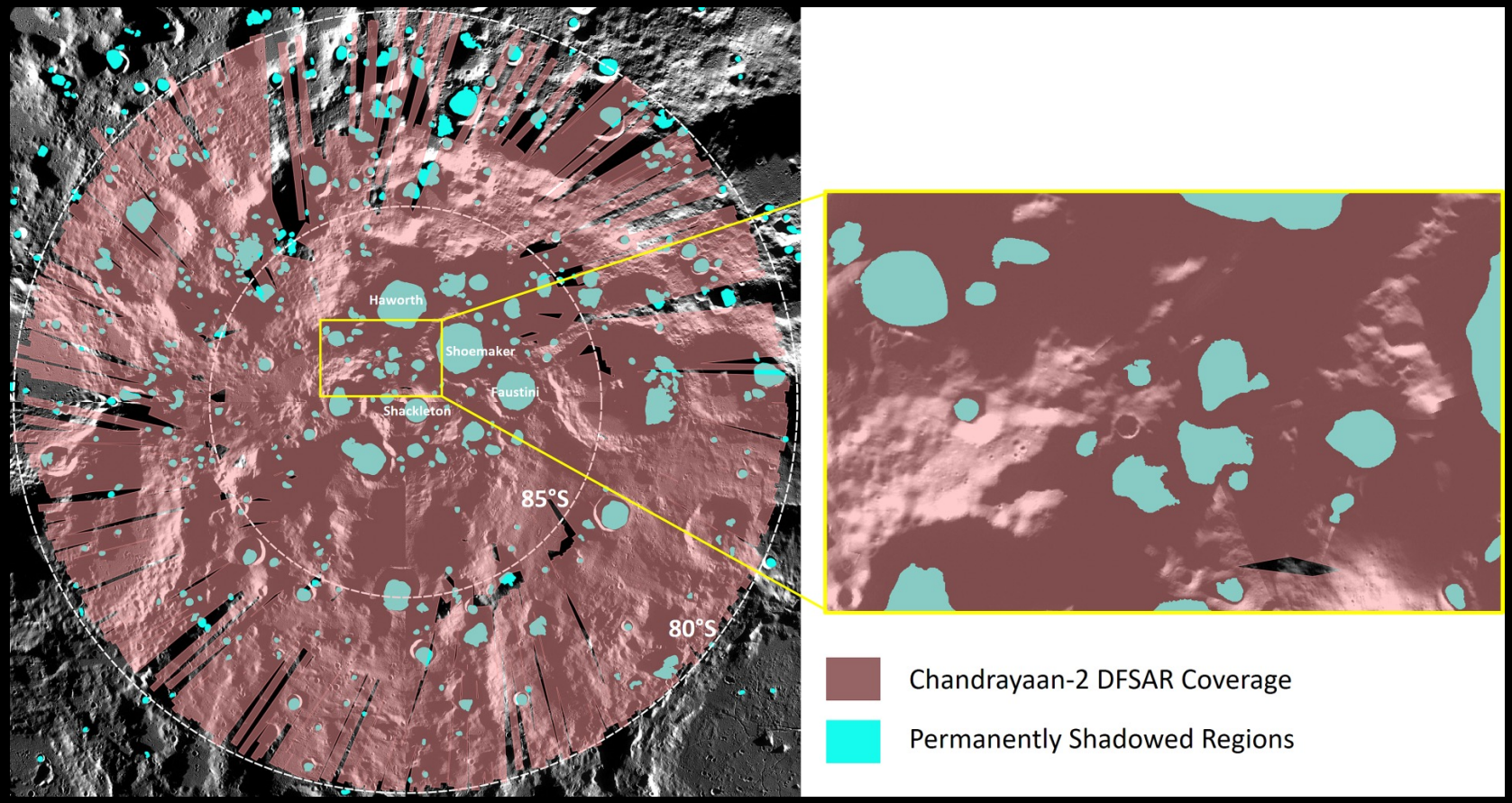
Lunar

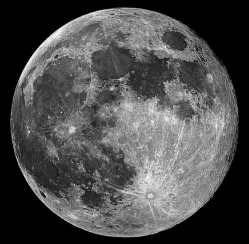
- es and Minerals Moon Mapper (HVM^3) – 50-90 m/pixel.
  apper (LTM; a multispectral thermal infrared imager to measure e, composition, and thermophysical properties) – 40-70 m/pixel.

Conduct sensitivity analyses on combined data set results to inform future measurement needs

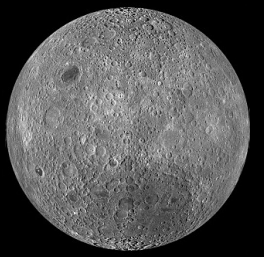
Coordinating Ongoing & Scheduled Missions: Integrating Data

March 2023 Chandrayaan-2 DF-SAR coverage of the south pole





The Way Forward: Policy Recs.

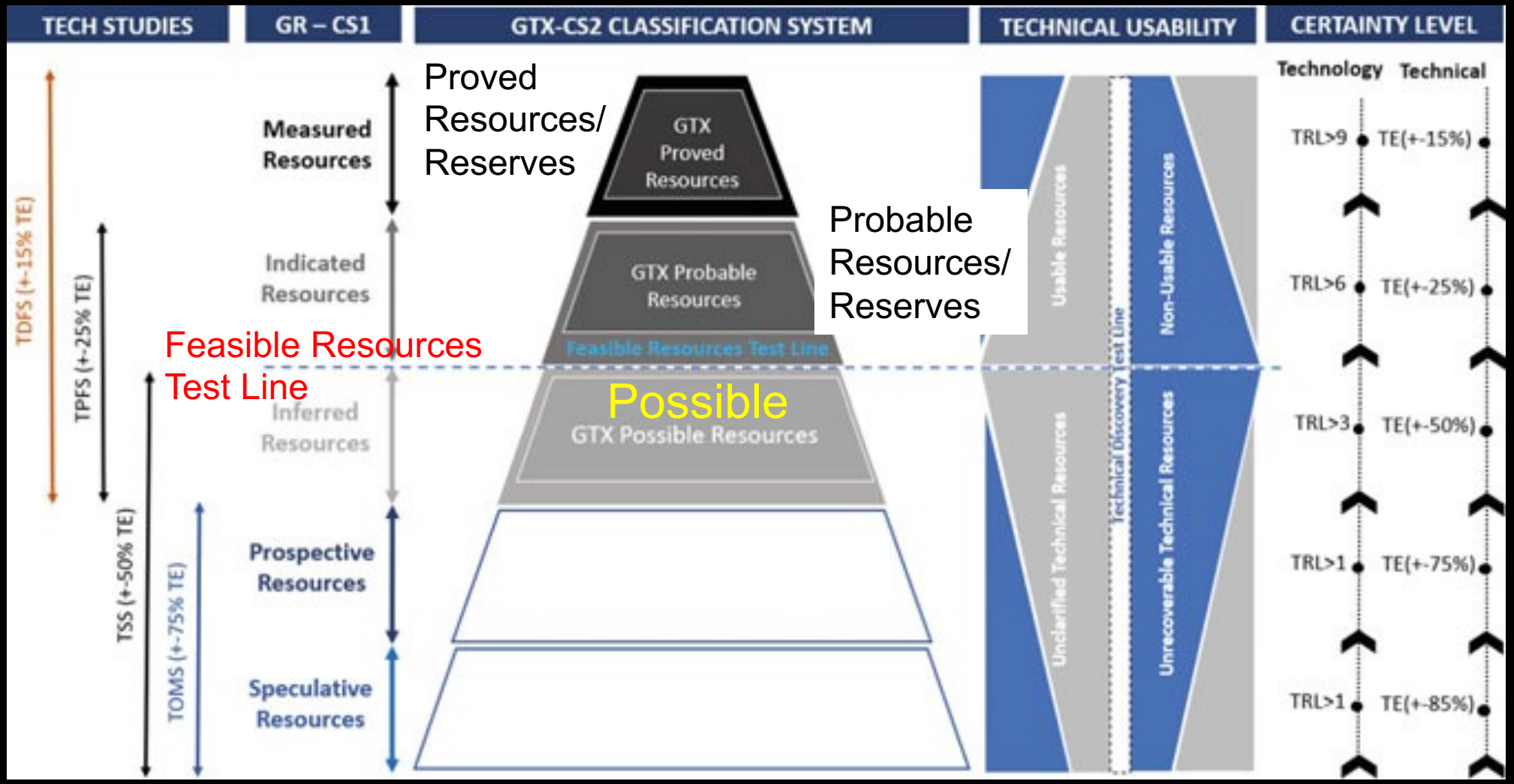


ILRPC opportunity to test the applicable legal framework and be intentional about setting precedents positively shaping the conduct of lunar (and space) resource activities in accordance with the Outer Space Treaty.

We suggest the following three features:

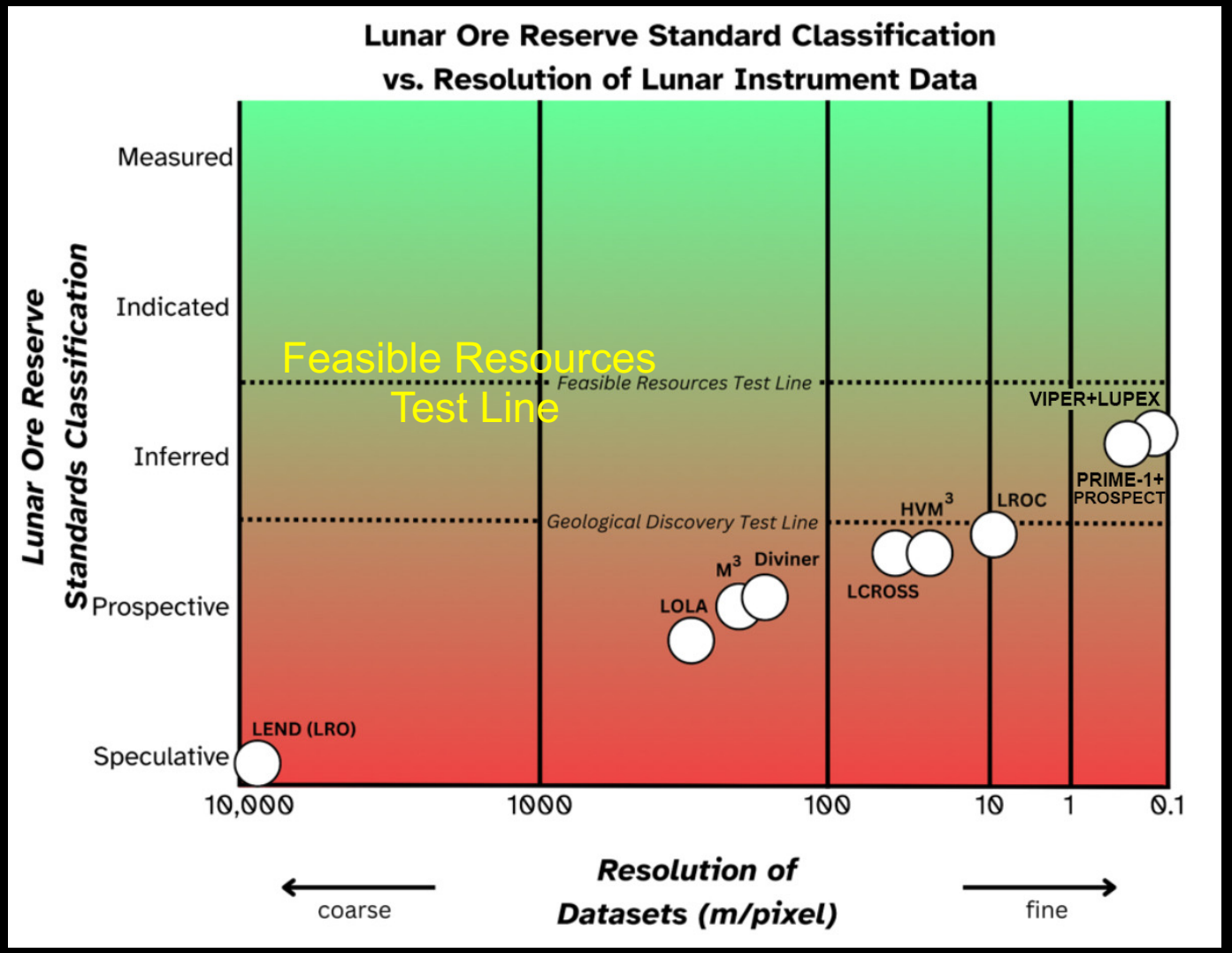
- **Organize the campaign as an international joint venture:** Define an incremental set of mission goals building on one another, to allow for inclusive and diverse participation, based upon objective criteria, with international cooperation being a preferential factor.
- **Adopt a multi-purpose data policy:** Foresee different levels of access to different datasets, depending on the contributions provided and including at least one level of open access available to the broader science community.
- **Develop shared standards:** Invite participants to develop and respect shared standards for prospecting lunar resources and evaluating their potential as lunar reserves.

Resources vs. Reserves



Espejel C.D., Casanova, S. Saydam, Lammy J.-A. (2023) Lunar Ore reserves standards 101 (LORS-101), in: V. Badescu, et al. (Eds.), Handbook of Space Resources, Springer, pp. 999–1022.

Resources vs. Reserves



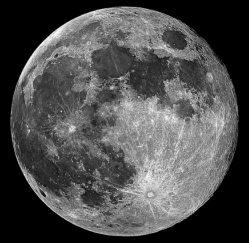
Current landed missions

- VIPER
- PROSPECT
- PRIME-1
- LUPEX

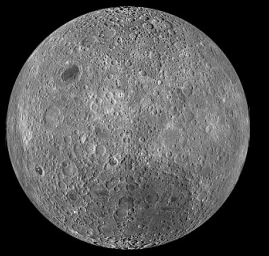
Will not yield "Indicated Resources" or "Probable Reserves".

More needs to be done.

Patterson R, O'Brien H., Galien L., Vaenciano J., Neal C.R. (2024) Examining the Reserve Potential of Lunar Polar Volatiles. Space Resources Roundtable, Colorado School of Mines; 4-7 June 2024

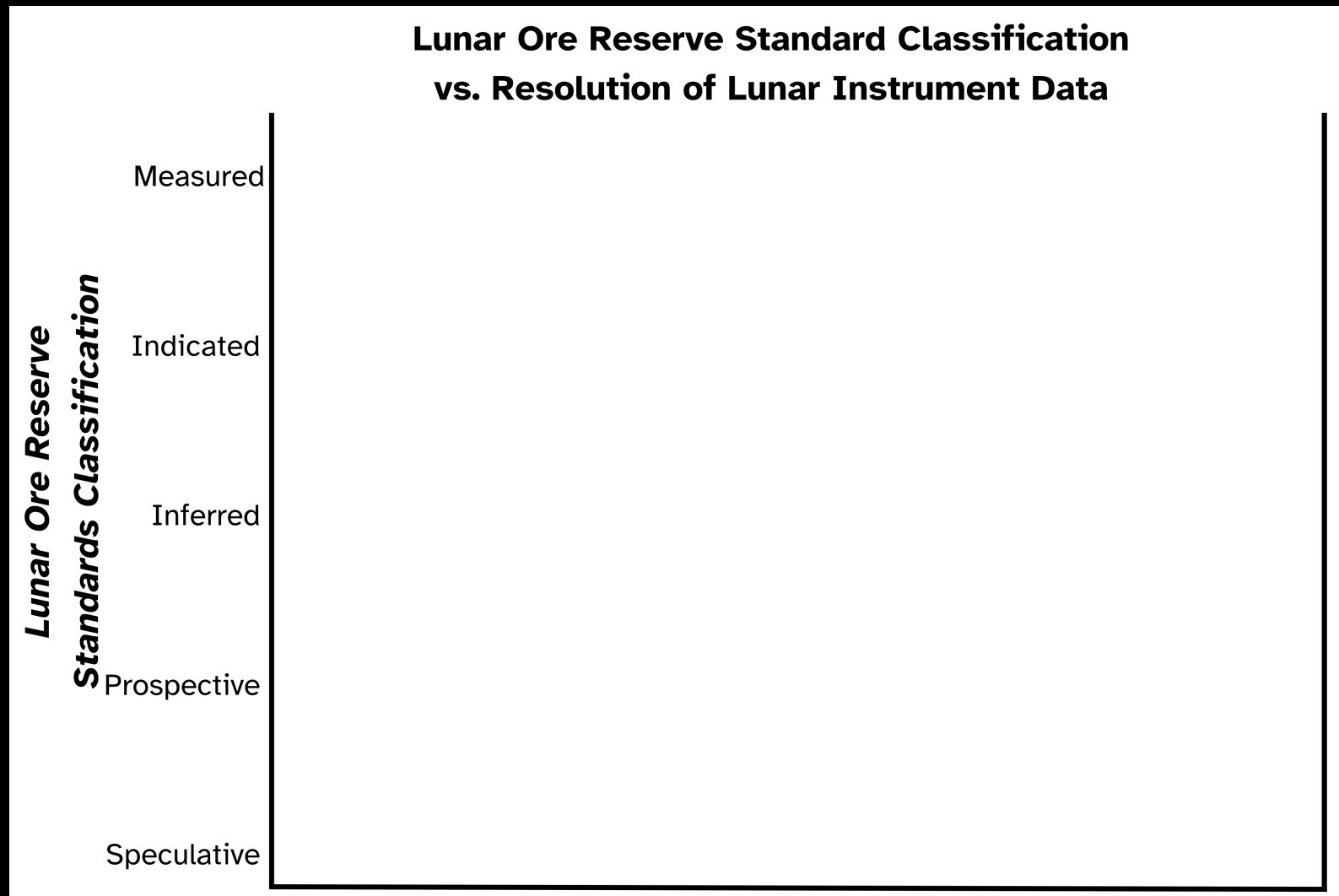


ILRPC

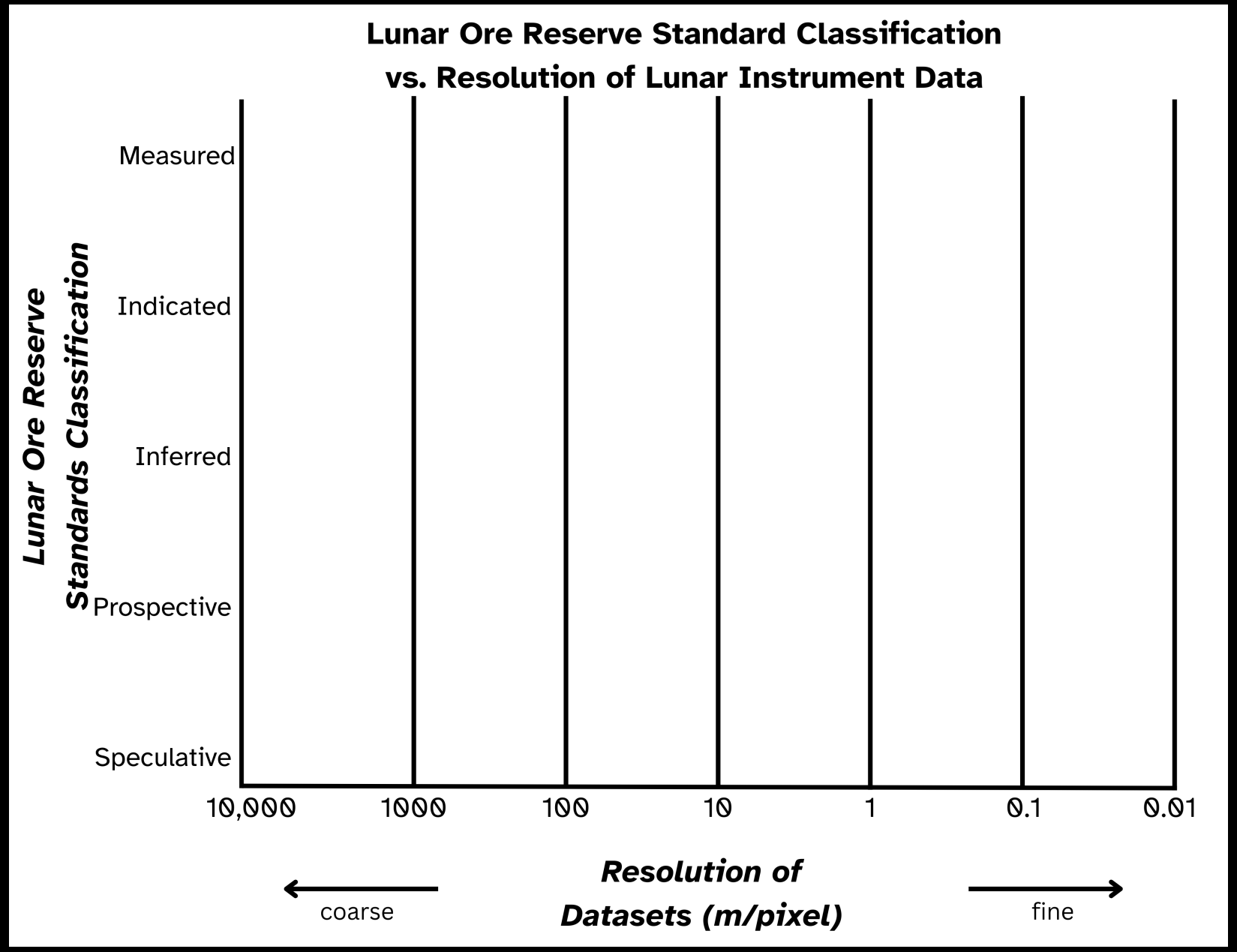


There is more to come…….

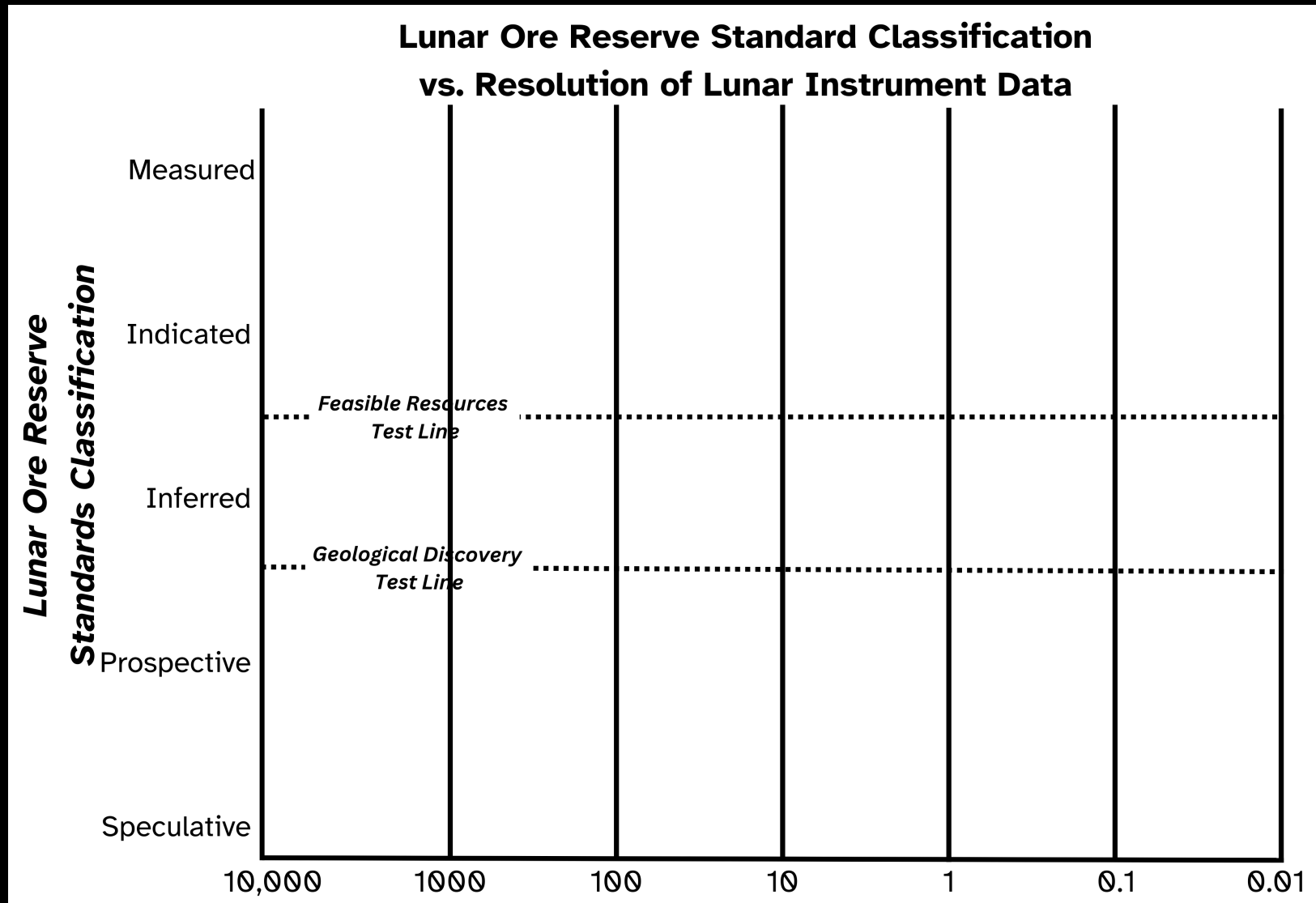
LORS Classification vs. Resolution of Lunar Data



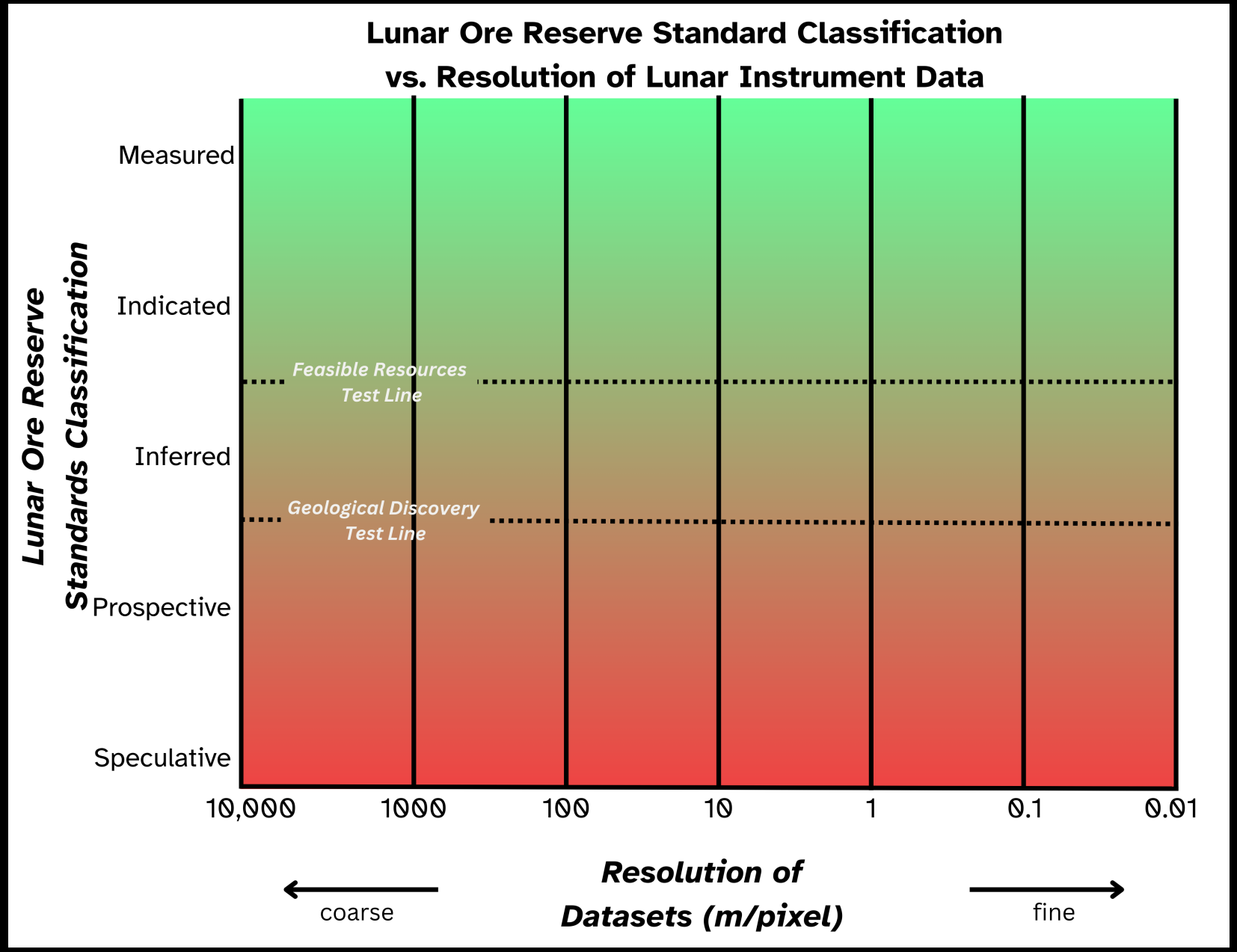
LORS Classification vs. Resolution of Lunar Data



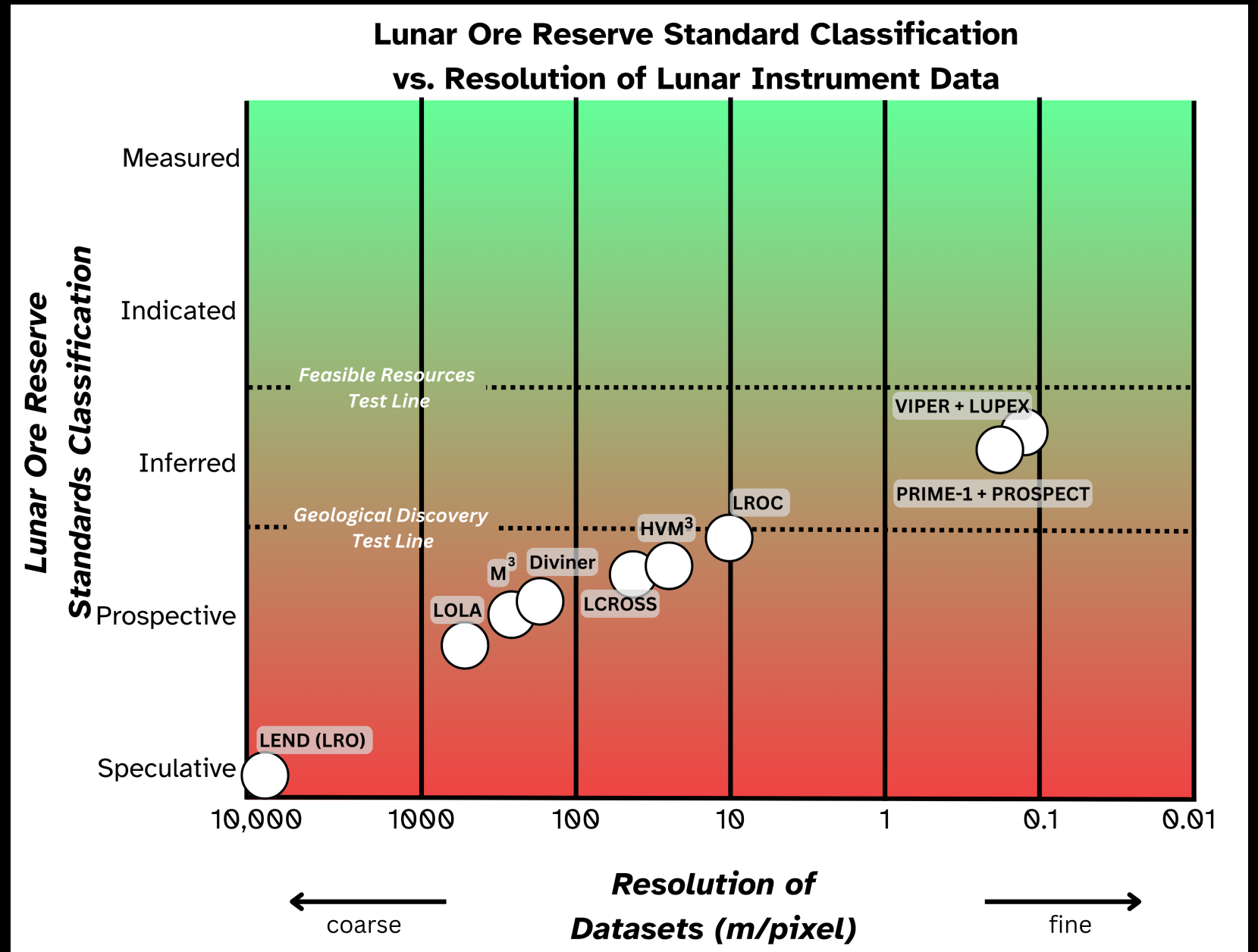
LORS Classification vs. Resolution of Lunar Data

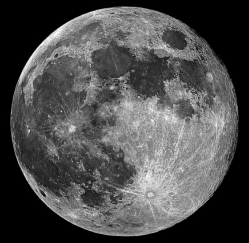


LORS Classification vs. Resolution of Lunar Data

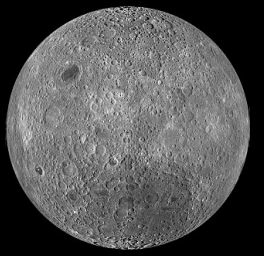


LORS Classification vs. Resolution of Lunar Data



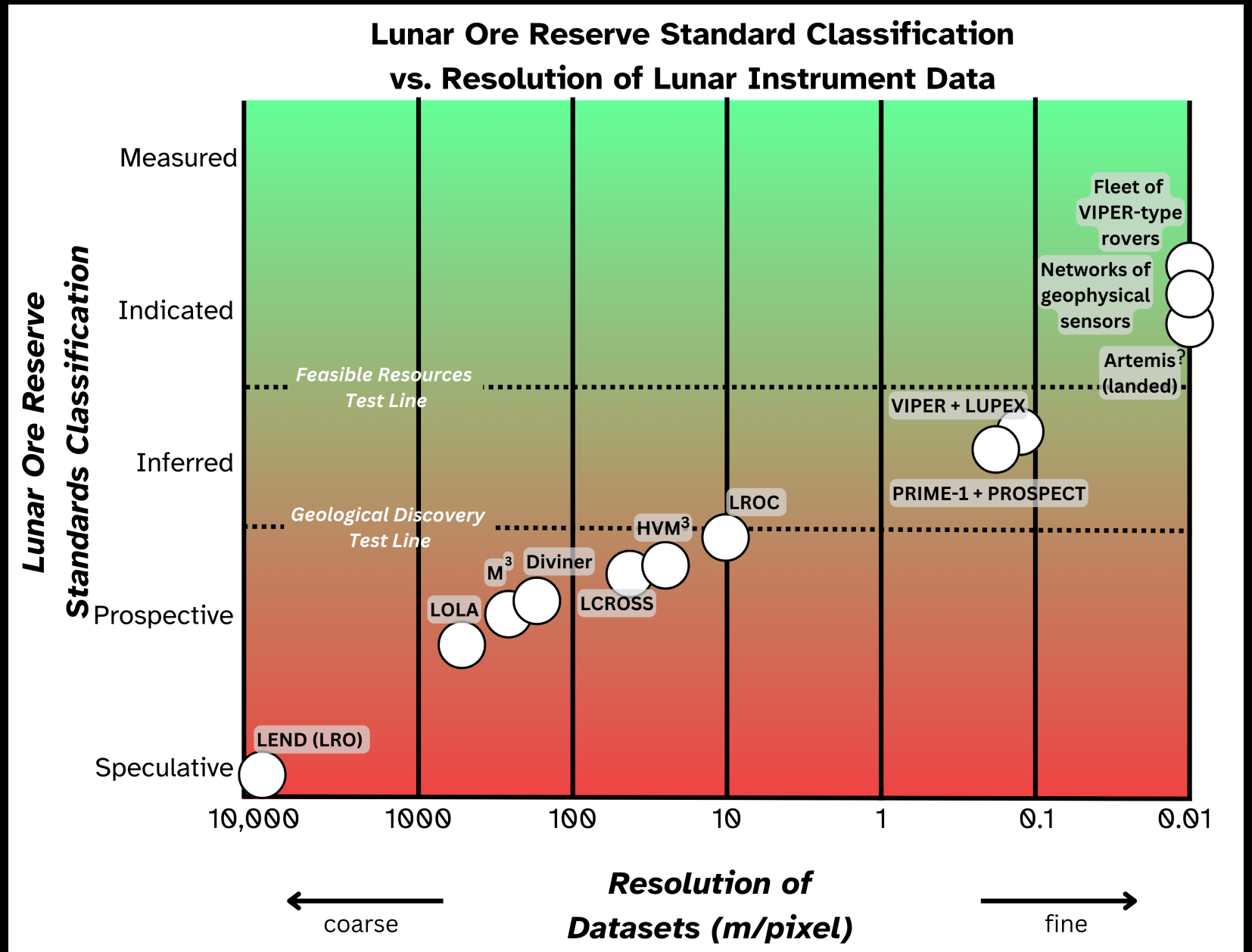


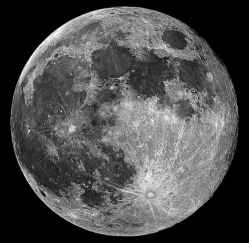
LORS Classification vs. Resolution of Lunar Data

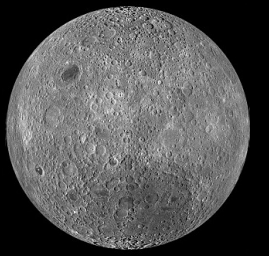


What would it take to cross
the *Feasible Resources Test Line*?

LORS Classification vs. Resolution of Lunar Data







Find us at the posters tonight!

Examining the Reserve Potential of Lunar Polar Volatiles

Hannah O’Brien & Ruby Patterson, NASA JSC & Astralytical Consulting