Economic Modeling Of The Competitiveness Of Lunar Water Over Earth-launched Water, Including Wright's Law, Optimization Of Reliability, And Economies Of Scale

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Motivation

- Reusable Launch Vehicles lowering the cost
- Claims made by some in the space community
- Those claims need to be rebutted

Overview

- Optimization of Reliability
- Experience Curve (Wright’s Law)
- Economies of Scale
- Economies of Scope
- Results

Optimization of Reliability

- NASA pays a very high ”reliability penalty”
  - Space agencies affect national pride
  - Competence sends geopolitical signals
- Space agencies optimize for those benefits
- Commercial space optimizes for profit
- How does this affect cost?

Reliability is Exponentially Expensive

- Testing for reliability drives cost
- The rule of 9’s
  - 10X cost for each additional 9 in the decimal place
- Saying in NASA:
  - The last 10% of reliability is 80% of the cost
- There is empirical data for this

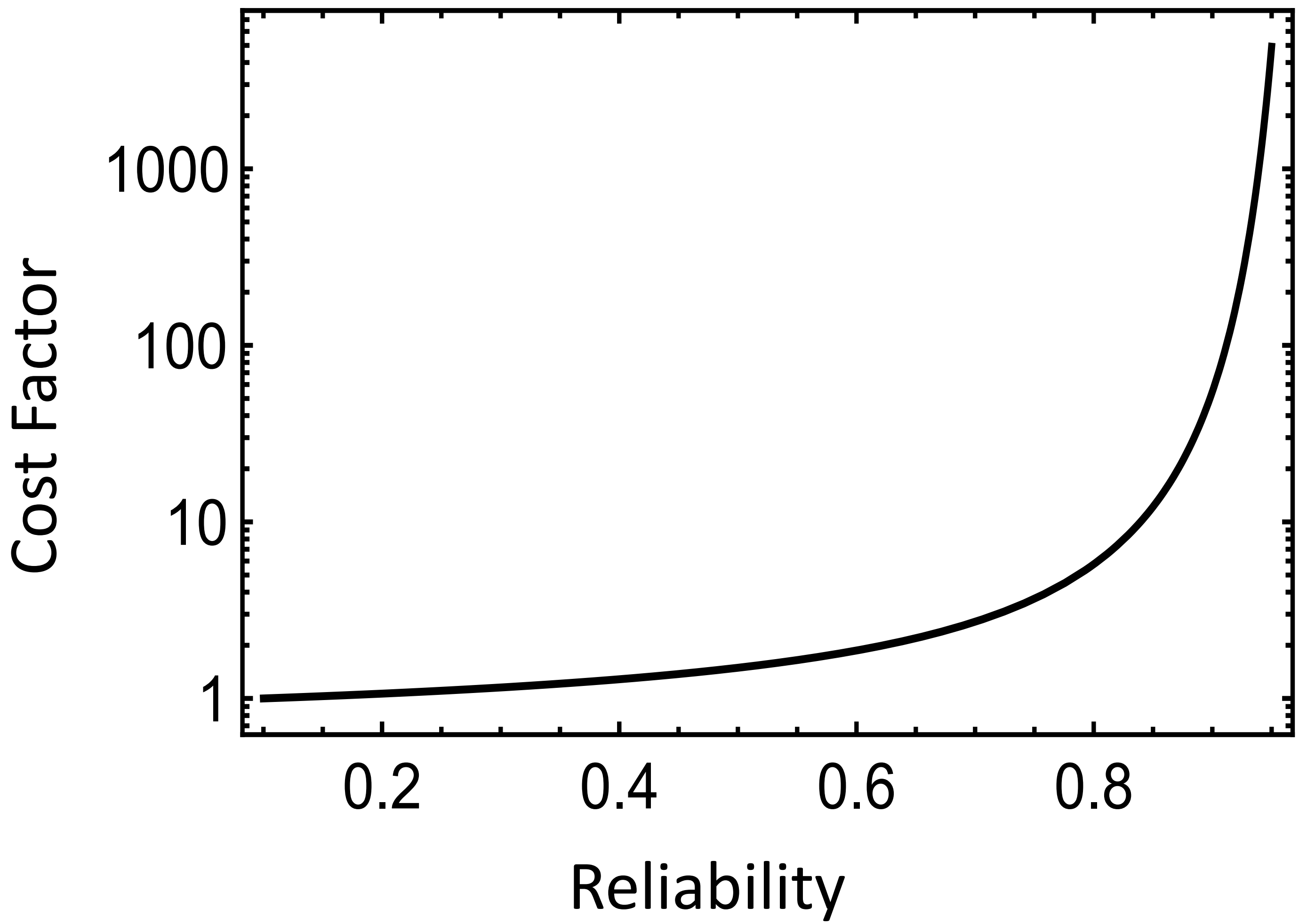
Reliability Cost Model

- Model by Mettas, Stancliff, et al. (2000, 2006, 2007)
  - Based on real engineering data
  - Appied to lunar rovers

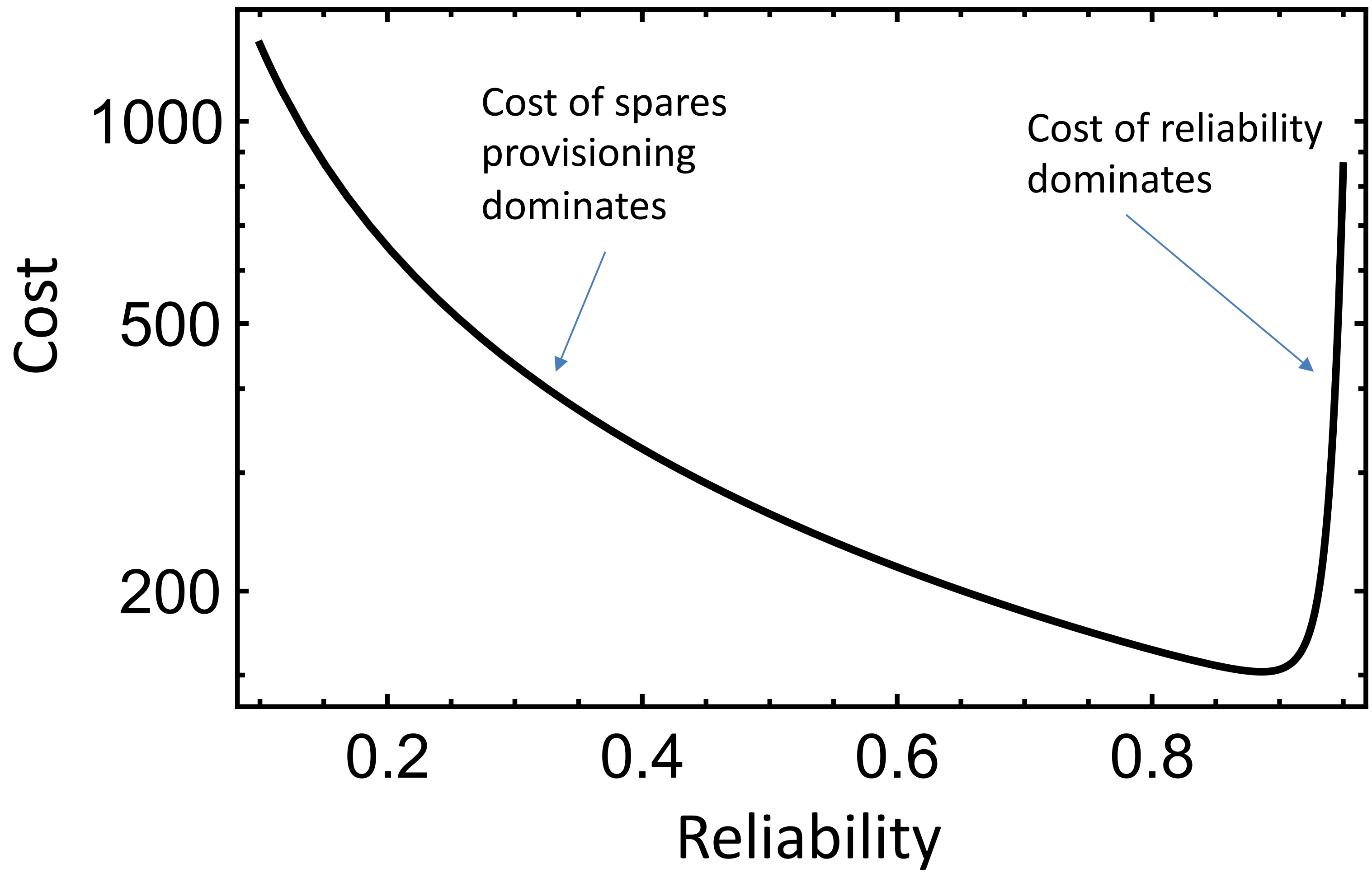
$$c_i = \exp\left[(1-f)\ \frac{R-R_{\min}}{R_{\max}-R}\right]$$

- Mettas A. Reliability allocation and optimization for complex systems. In: Annual Reliability and Maintainability Symposium, 2000 Proceedings, International Symposium on Product Quality and Integrity, IEEE, 2000, pp. 21.-221
- Stancliff DB, Stephen B, Dolan JM, Trebi-Ollennu A. Mission reliability estimation for multirobot team design. In: 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, 2006, pp. 2206-2211
- Stancliff, S., John Dolan, and A. Trebi-Ollennu. Planning to fail: reliability as a design parameter for planetary rover missions. In: Proceedings of the 2007 Workshop on Performance Metrics for Intelligent Systems, 2007, pp. 204-208

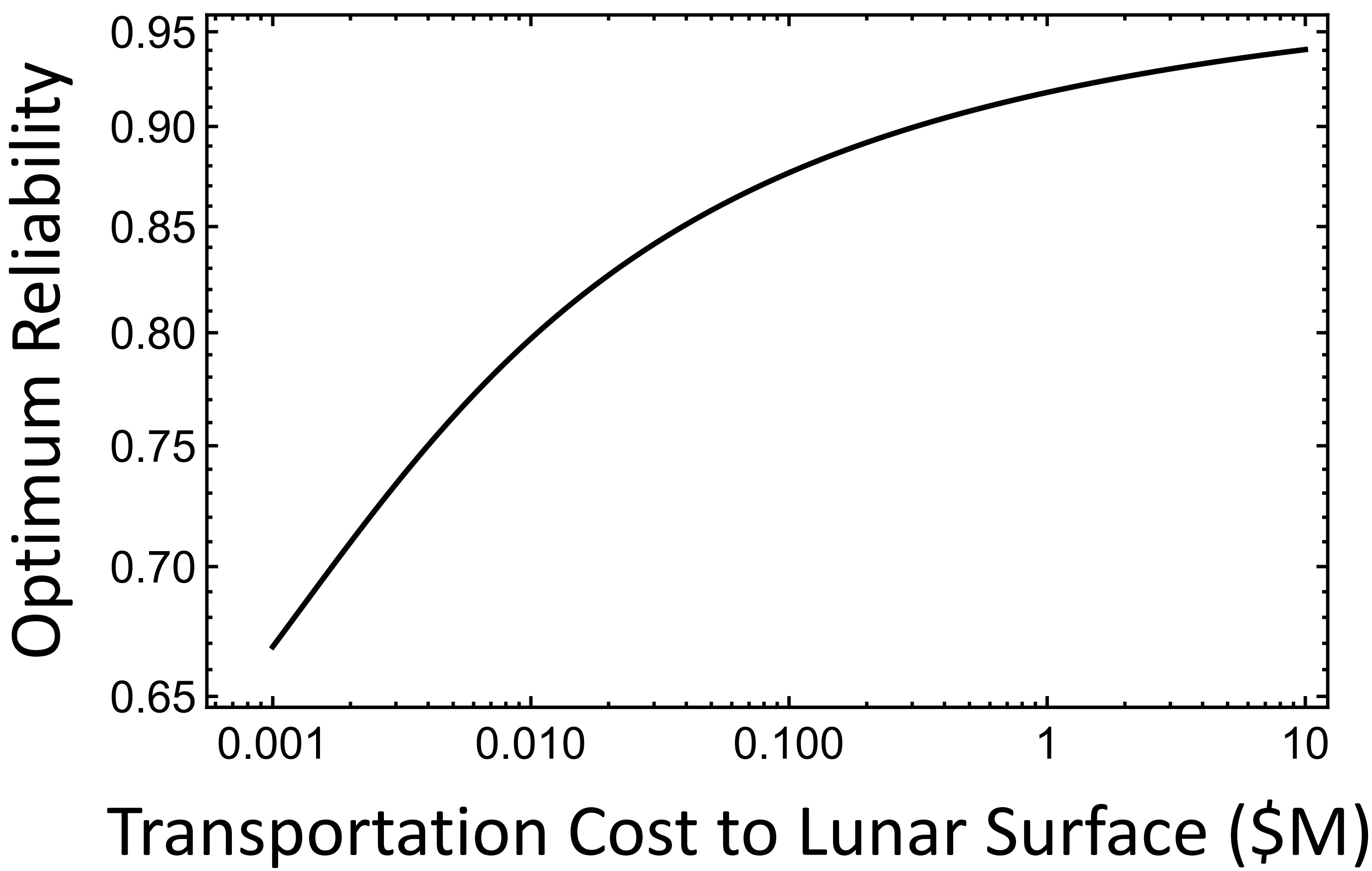
Reliability Cost Factor



An Optimum Exists



Optimum Reliability Depends on Transportation Cost



Experience Curve

- Based on centuries of industrial data
- Production costs drop as we gain experience
  - Management
  - Capital
  - Labor
  - Supply Chain

Wright's Law

$$c_{\mathrm{WL}} = \left(\frac{\int_0^t P(t)\mathrm{d}t}{S(0)} \right)^{\mathrm{Log}_2(b)}$$

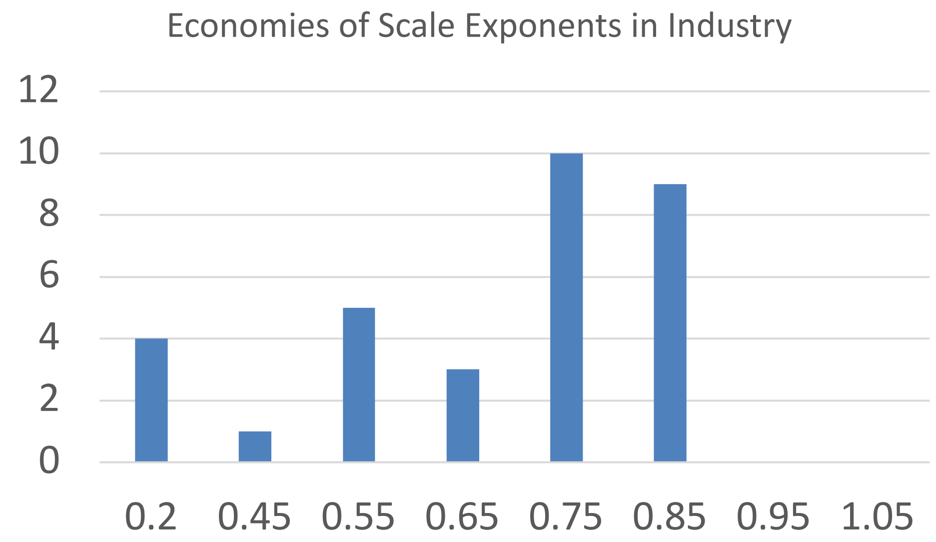
- *b* is typically 0.75 to 0.90
- This describes empirical experience of industry

Economies of Scale

- Production cost is less for larger operations
  - Geometric scaling
  - Efficiencies
- Distinct from the experience curve

Economies of Scale

- $c_{\mathrm{EoS}} = \left(\frac{X}{X_0}\right)^{a-1}$
- *a* is typically 0.2 to 0.85 in industry
- weighted average *a* = 0.66



Economies of Scope

- Additional business activities
  - Overlap of assets, skills, processes, etc.
  - Enables additional gains in experience curve
  - Enables additional scaling efficiencies
  - Enables vertical integration
- Examples for Lunar Water
  - Lunar metal
  - Construction

Predictions

$$L > \frac{\omega}{1 - G^2\phi - x}$$

- for lunar water to compete in LEO
- $\phi =$ mass ratio of water extraction h/w over water it produces in its lifetime
- $G \approx 4$ for LLO to lunar surface
- Probably can achieve $G^2\phi \ll 1$
- $x =$ cost ratio of fabricating lunar surface h/w (per water it delivers) over launch cost (per water it delivers)
- Probably can achieve $x \ll 1$

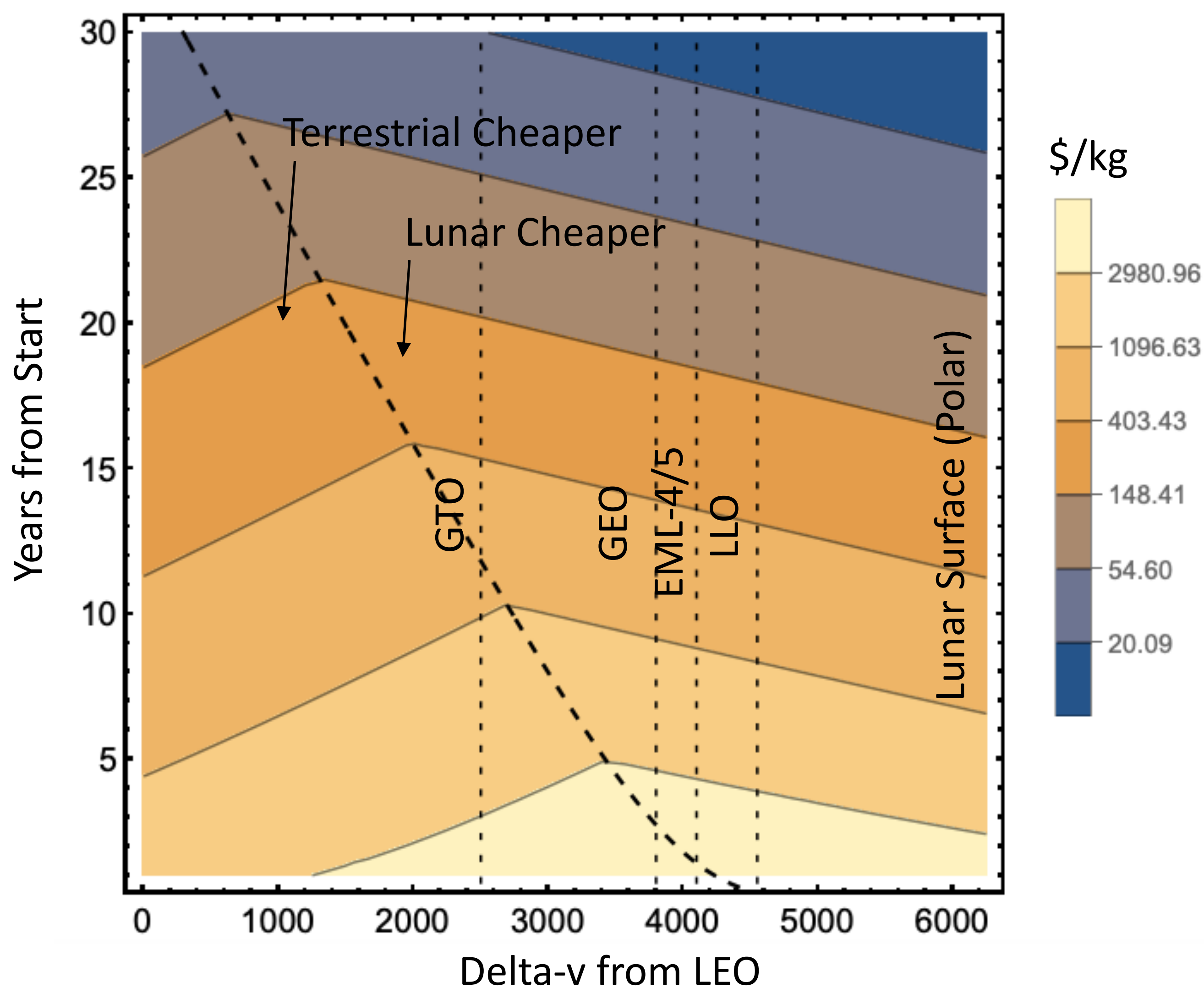
Starship Launch Costs

- “Optimistic” Starship projections
  - Going down to \$30/kg to LEO
- Assume SpaceX successfully settling Mars by 30 years with 1 Starship launch per day
- Assuming industry average a = 0.66, then the cost projections are do-able if b = 0.92.
  - Not very aggressive!
  - Launch costs might go much lower than the “optimistic” projections

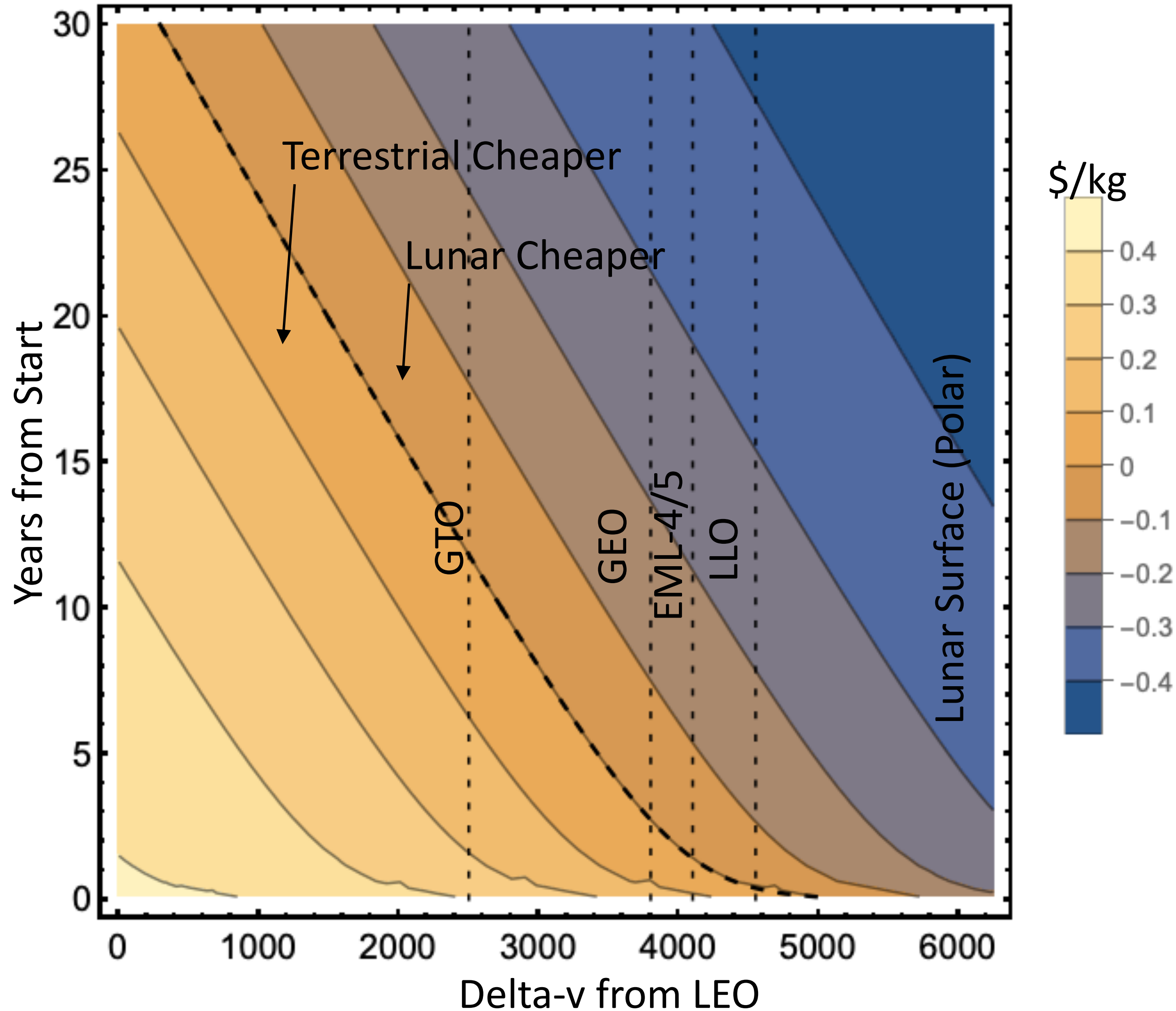
Lunar Water Scaling

- ISRU Pessimists:
  - Assume lunar water uses current transportation costs ($300K/kg to the LS)
  - BUT…Assume Earth-water launches $2000/kg to LEO dropping to $30/kg
  - Assume lunar extraction system based on supporting NASA with reliability premium
  - BUT…assume Earth-water architecture is optimized for commercial

Modeling with Pessimistic Assumptions



Discuss Comparative Advantage



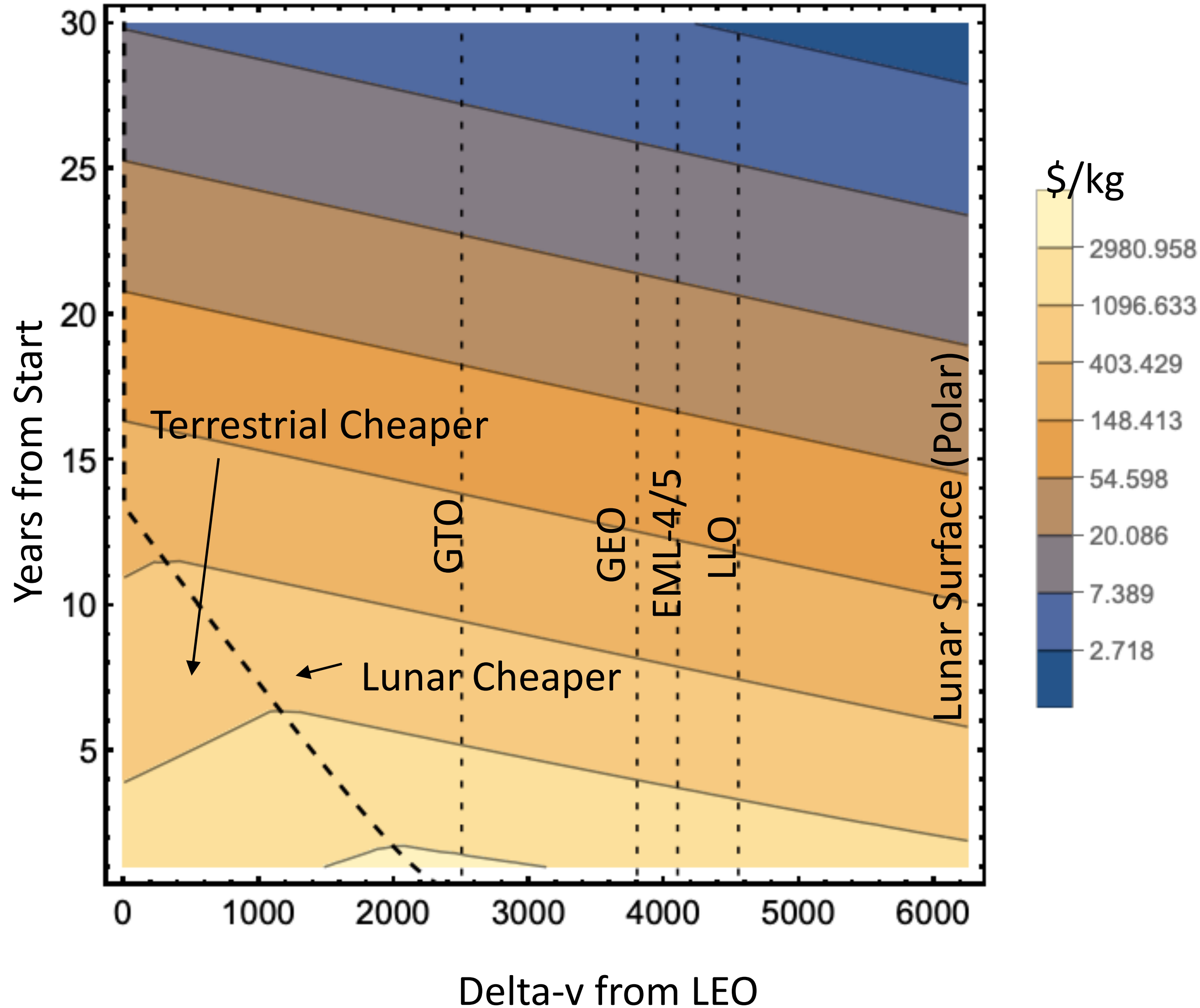
Using Aqua Factorem Starting Point

- 2019/2020 NASA Innovative Advanced Concepts (NIAC) study
- Demonstrate that we can design lunar water extraction for small-scale so a single investor could fund it
  - Create revenue and profit* immediately
  - Scalable up to large-scale systems
  - Allows risk to be bought-down incrementally
- "Actionable" in current economic environment

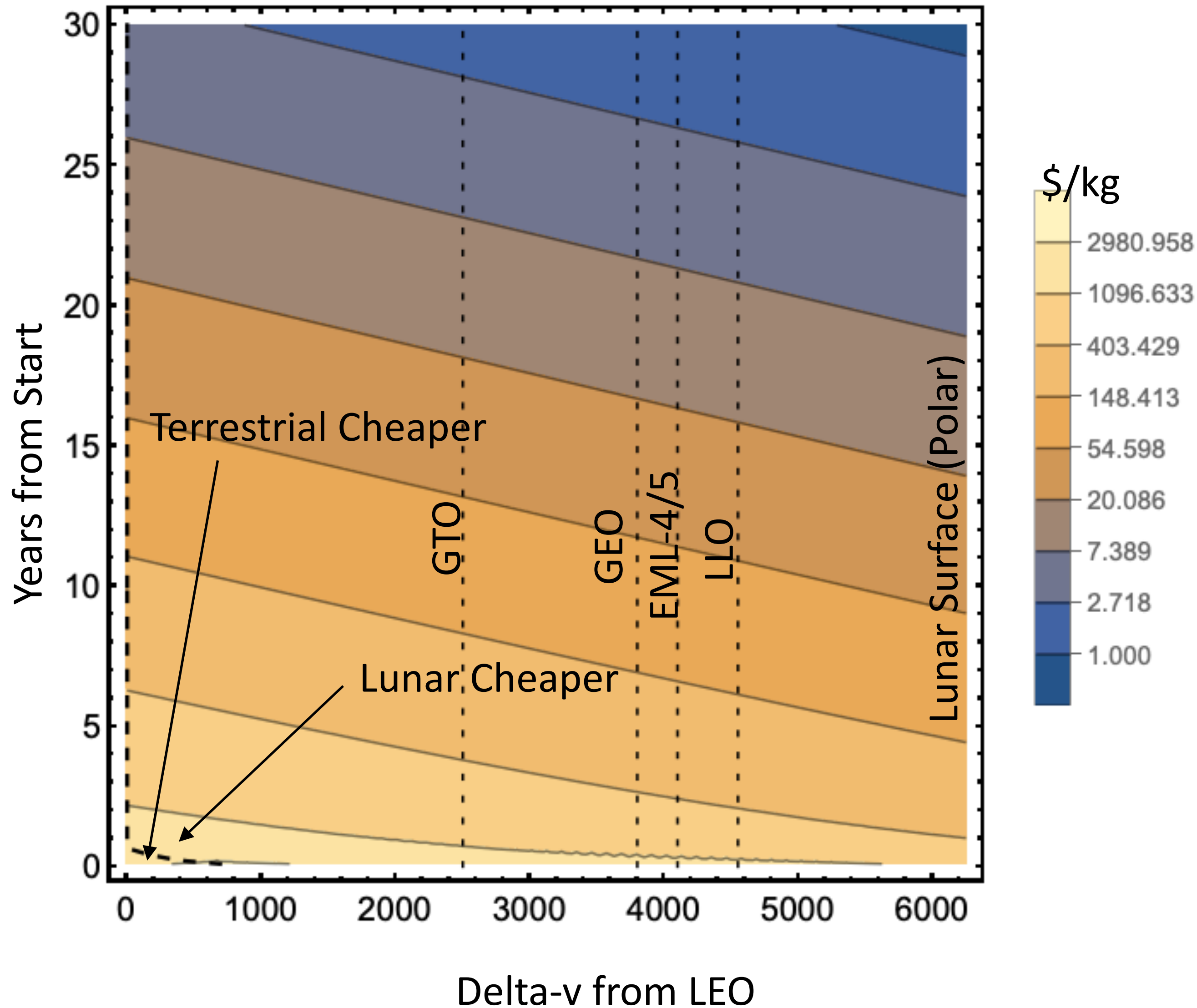
Using Aqua Factorem Assumptions

- Mass of h/w 2500 kg (without spares)
- Produces 27,900 kg/water per year
- Assume 5 year life-cycle
- Still using expensive transportation

Same Unfair Launch Costs but Aqua Factorem

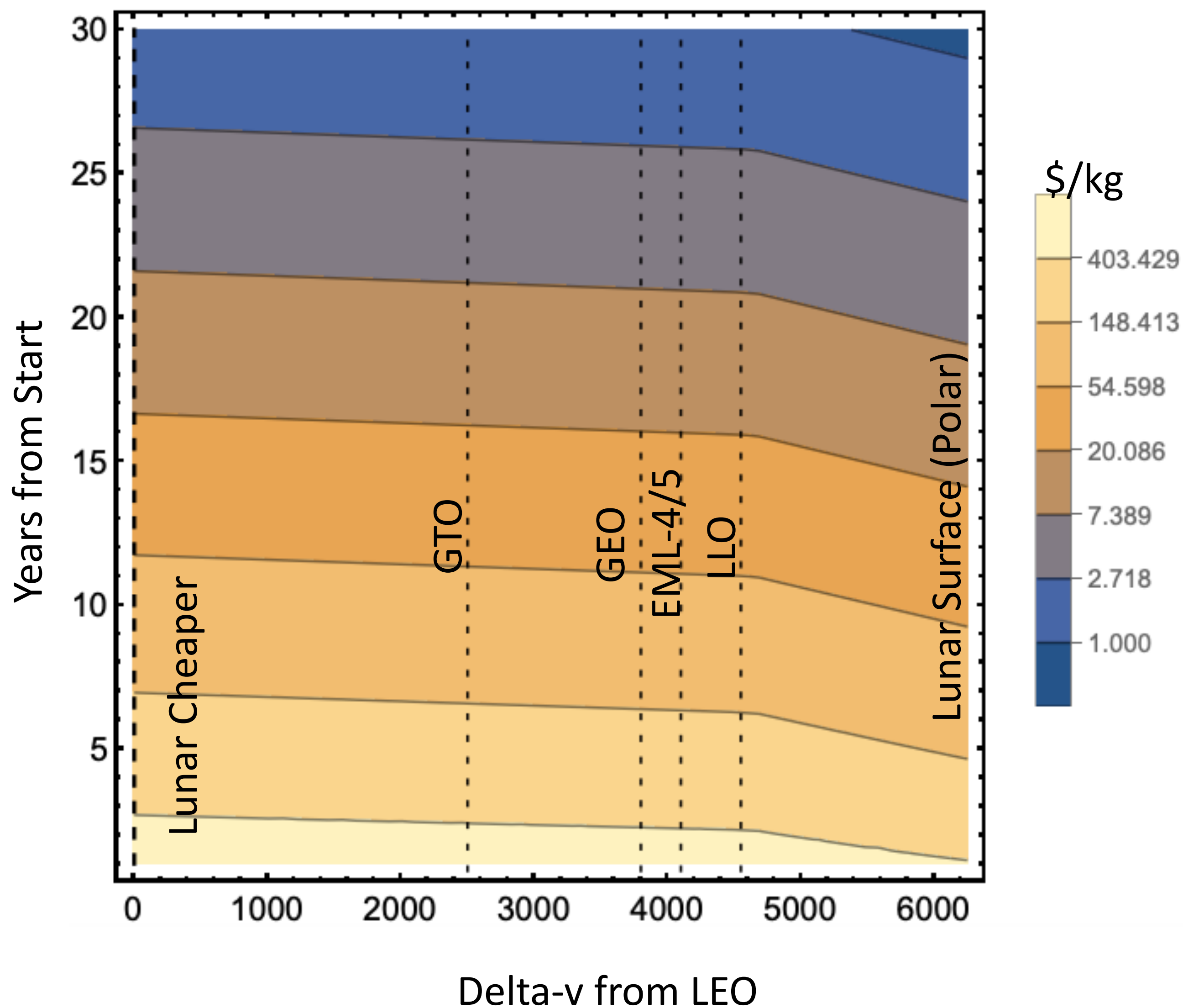


Starship Launch Costs for Aqua Factorem



…But Use Water-based Electric Thrusters to Deliver Propellant

Included 11% discount rate for the longer transit times



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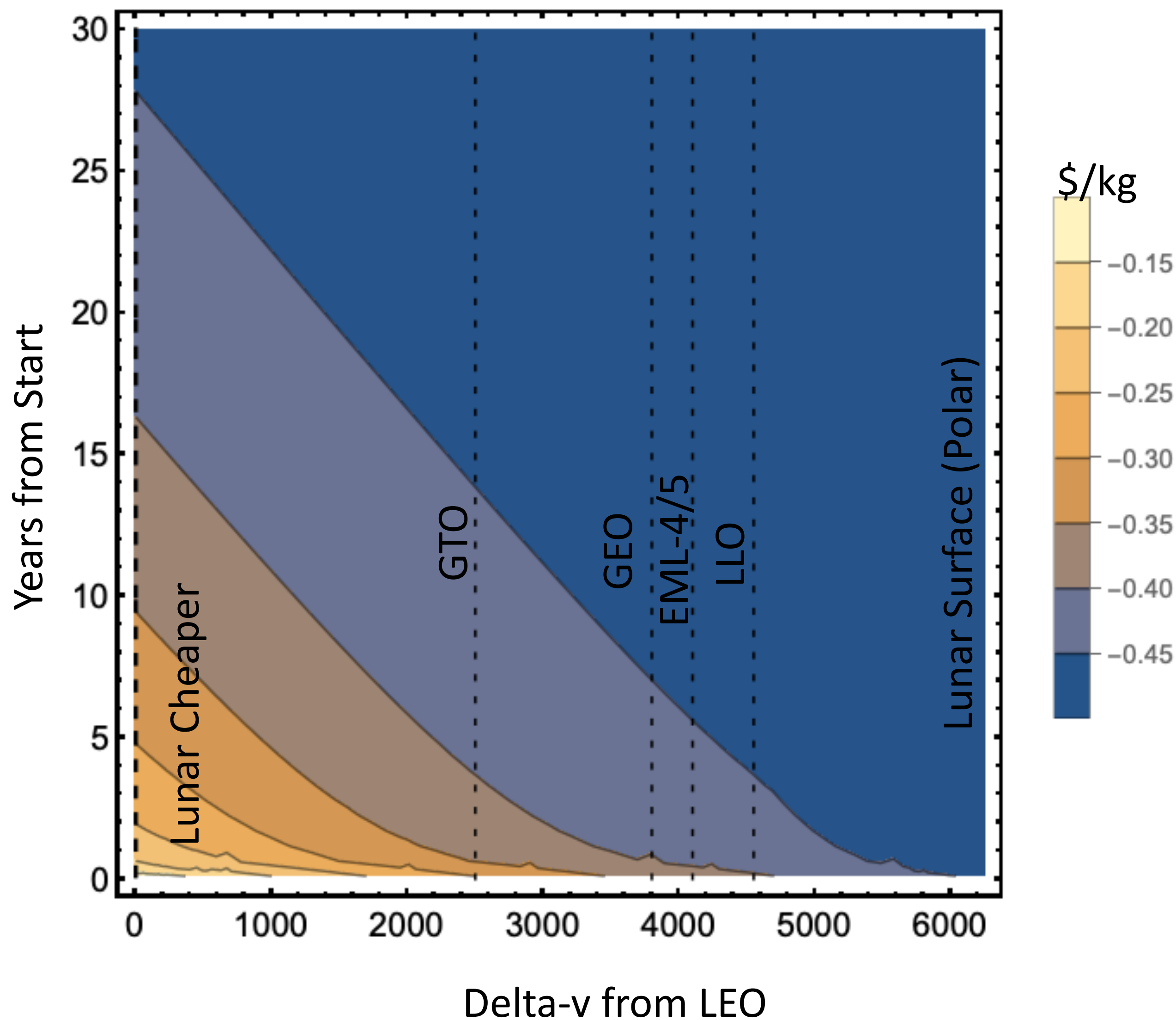
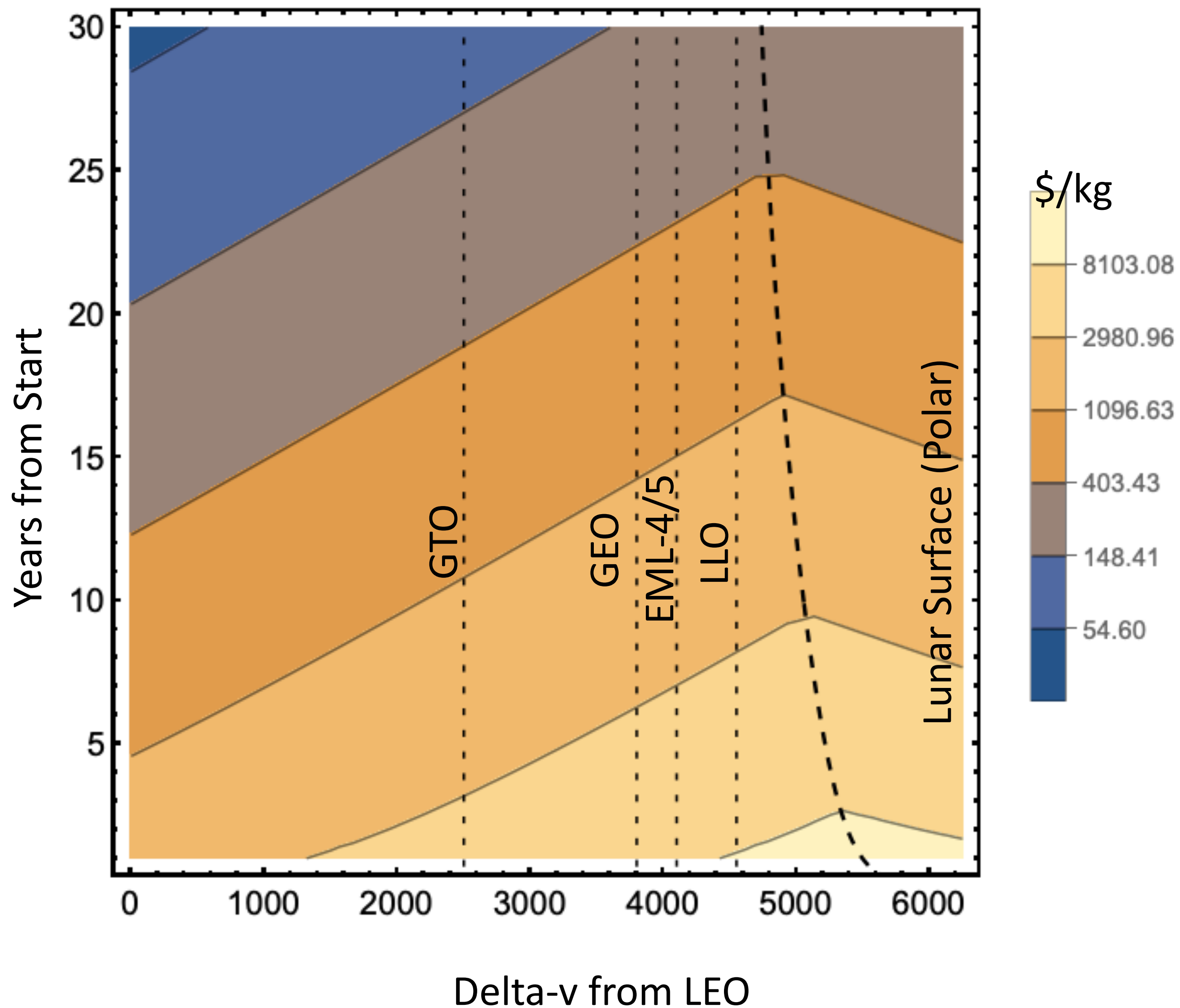


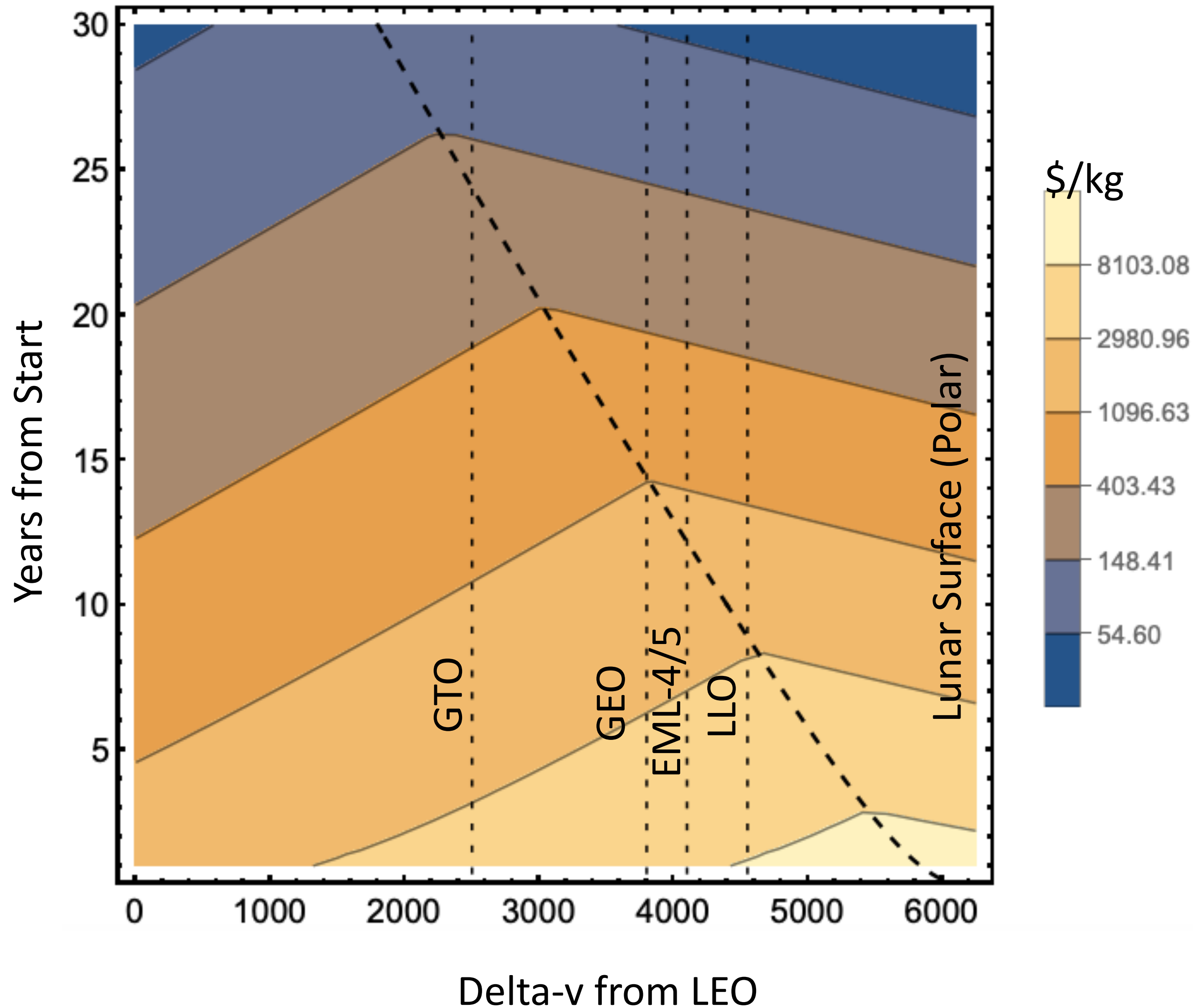
Study by Charania and DePascuale

Uses expensive transport, vs. Earth-water using cheap transport

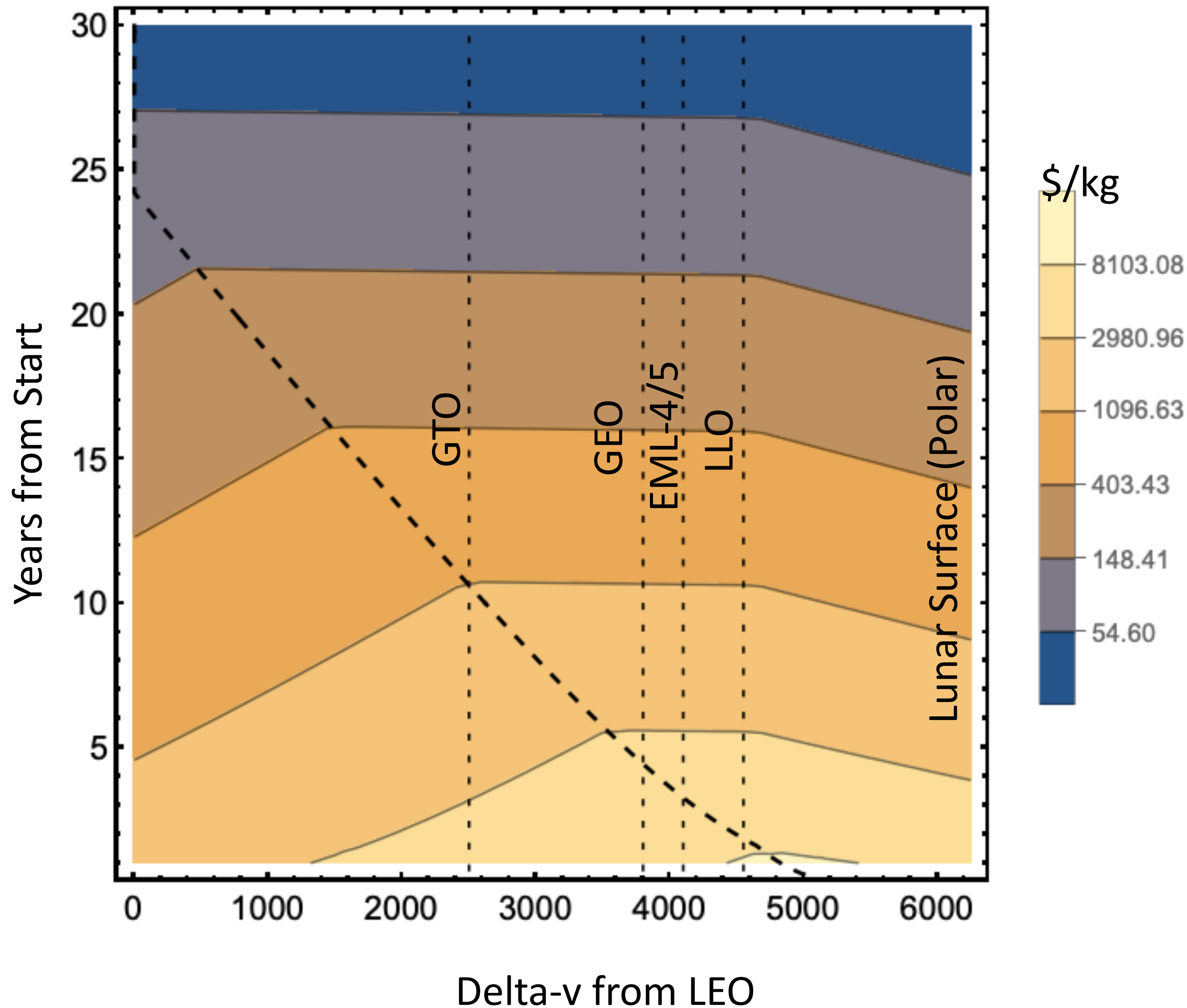


Charania & DePascuale but Same Transportation Cost as Earth-Water

I think their ops cost is too high, reflective of NASA program reliability-cost models



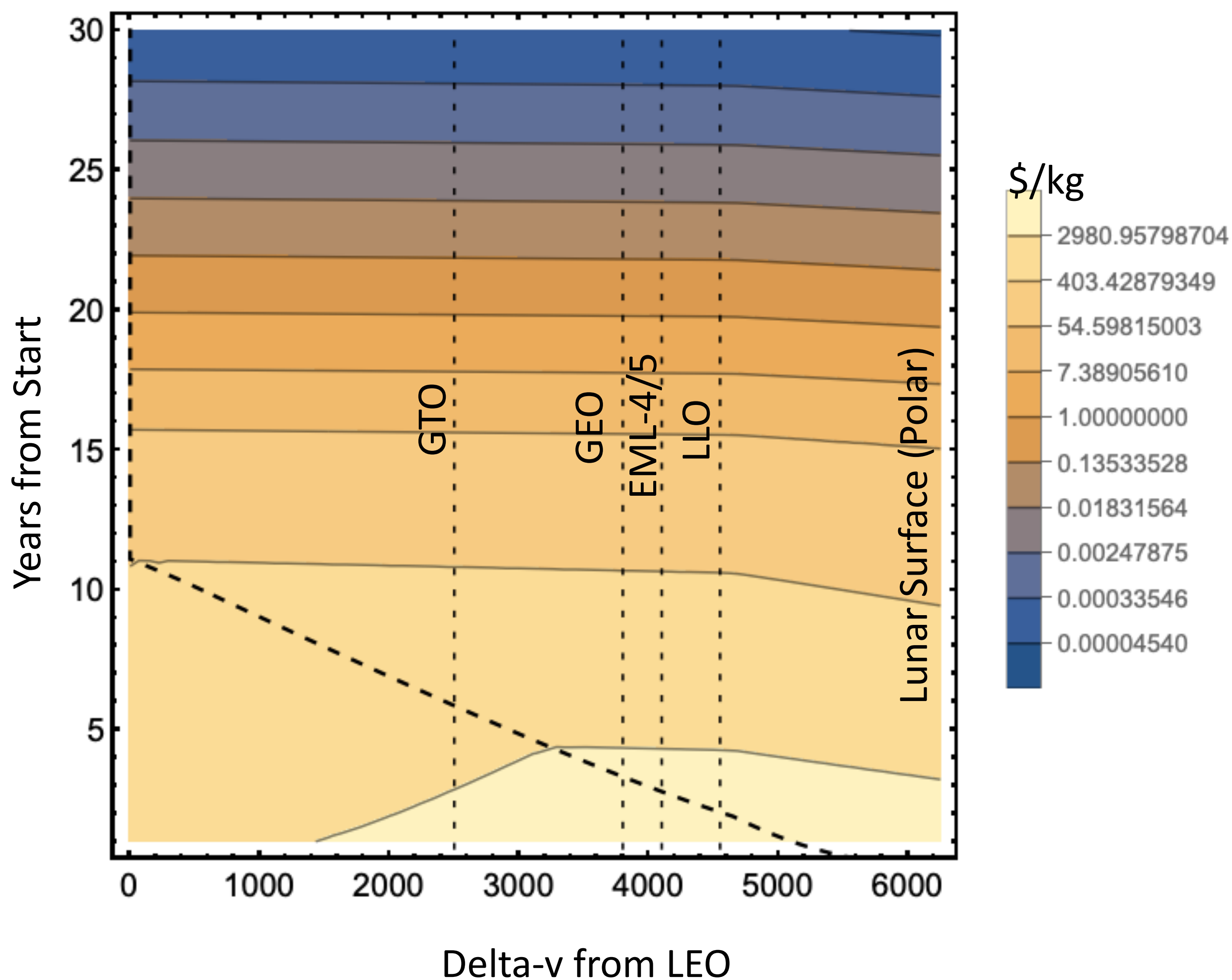
Charania & DePascuale but Solar-Electric where possible



Economies of Scope: Lunar Metal & SBSP

- Start making metal in year 10
- Start boosting SBSP in year 15
- Metal mining doubles the business of water mining
- SBSP boosting triples the business of other boost services

Aqua Factorem but 5x costs



Conclusion

- Let nobody say low launch prices will drive cis-lunar space resources out of business
- The cost of cis-lunar space resources drops *faster* than the cost of launch
- Space resources are the future