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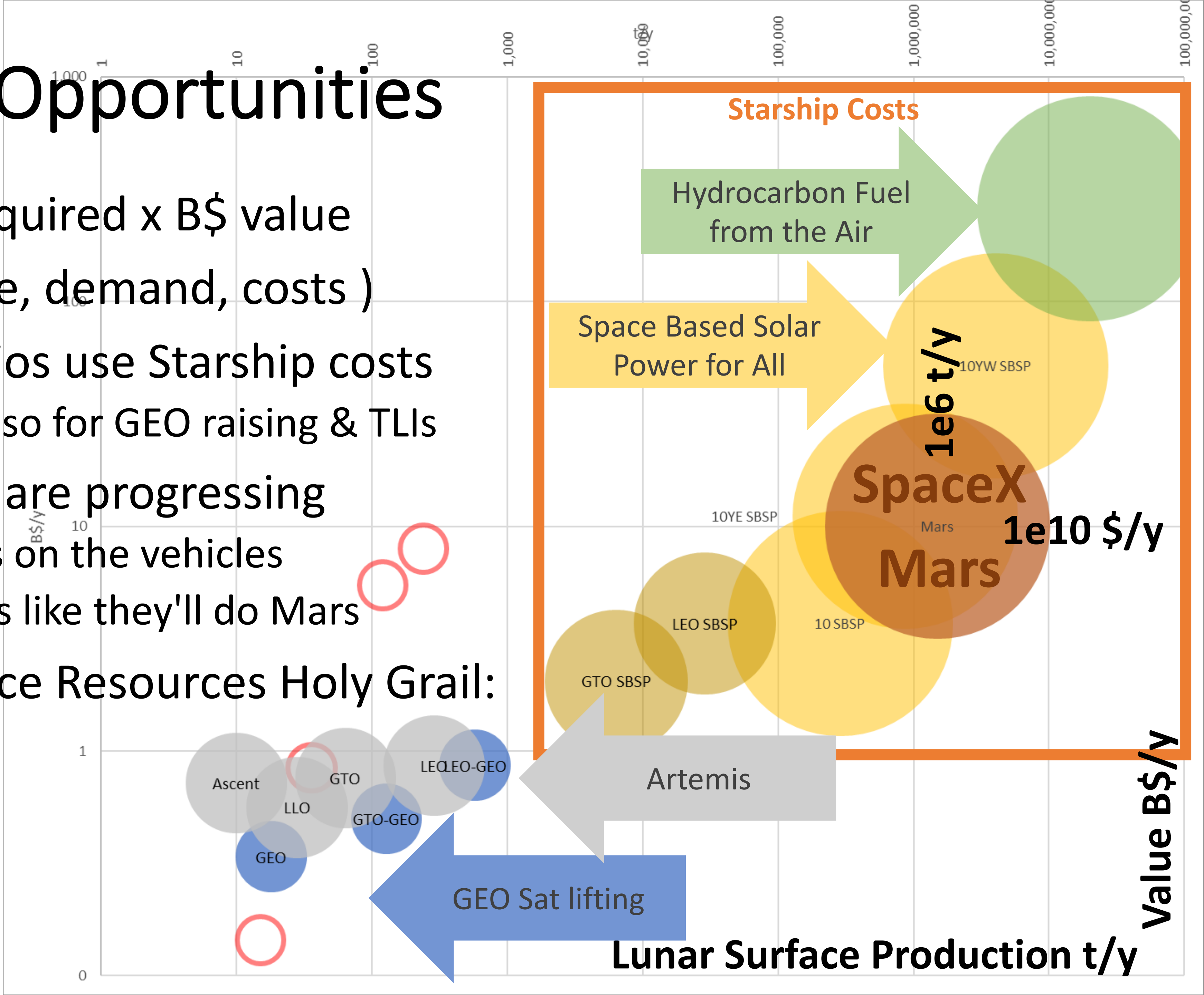
efficiently connecting Space Resources to the economy

Space Resources Group
Australian centre for Space Engineering Research
University of New South Wales

Propellant & Capital Efficient Trans-Mars Injections Using Lunar Propellant For The SpaceX Mars Project

1 Lunar Water Opportunities

- log annual: tons required x B$ value
- Bubble = f(use case, demand, costs)
- Orange box scenarios use Starship costs
  - Today's CONOPs also for GEO raising & TLIs
- Starship & Booster are progressing
  - Artemis now relies on the vehicles
  - SpaceX talks & acts like they'll do Mars
- SpaceX Mars = Space Resources Holy Grail:
  - Large!
  - Long Term!
  - Funded?

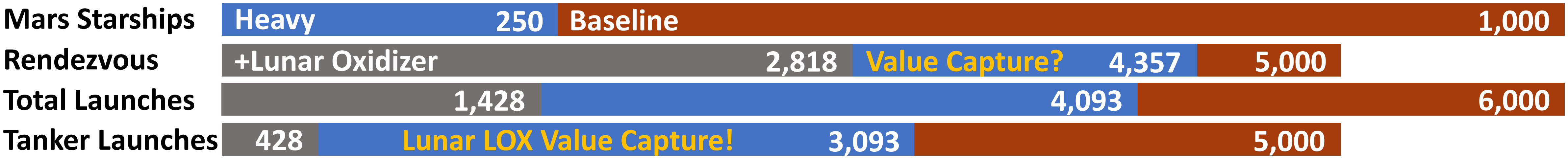


2 Features Overview, detail to follow…

- Luna can deliver to GTOs cheaper than to LEO, **especially LOX**
  - **For GTO: water = transport LH2LOX + deliverable LOX**
  - Return to LLO = LEO’s - 2.5 km/s
- GTO trans-Mars Injection of a fully fuelled Starship?
  - **Cargo Aggregation required to match Mars transfer delta-V**
  - Earth return opportunity 2/day, low periapsis ⇒ 10s m/s @ apoapsis
  - vs LEO TMI: "pre-paid” 60% delta-V 40% energy, & more impulsive
  - Marshal over entire synodic, reduce bursty launch cadence
- Lunar LOX deliveries?
  - Consumer incremental periapsis orbit pumping to GTO
  - **Just-In-Time LOX delivery, for next burn only!**
  - Eliminate **85%** of Earth propellant launches (CH4LOX is **78%** LOX)
  - Lower lunar production required & higher $/kg
  - Would also benefit a regolith oxygen operation’s CH_4 import
- **Model entire fleet collaboration**

3 Results: *Baseline*, *Heavy*, *Heavy Luna*

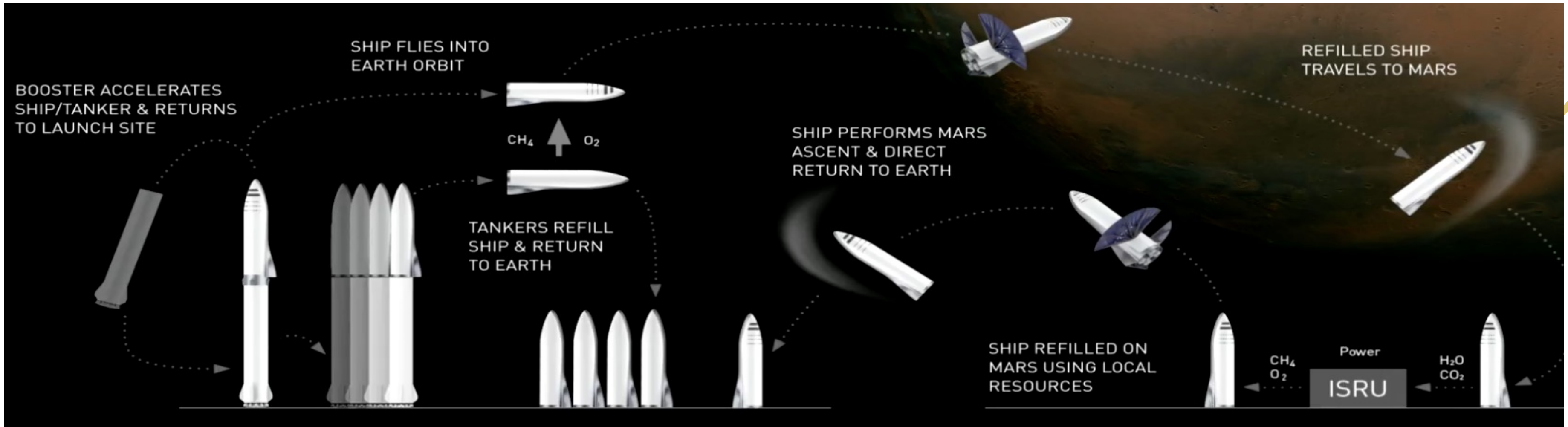
- **Baseline SpaceX Mars Project**: 1000 Starships to Mars every 26 months
- ***Heavy***: 4x cargo on Mars Starships, GTO TMIs, easier to supply lunar LOX
  - **Reduce Mars Starships & Mars Propellant to 25% of Baseline**
  - **Reduce Tanker launches to 62% of Baseline**
  - **Propellant moving cargo? *Baseline* 50%, *Heavy* 80%**
  - Less expensive and higher value for SpaceX & more convenient for lunar LOX supplier
- ***Heavy Luna***: ***Heavy*** + ***Lunar Oxidizer***
  - **Reduce Total SpaceX Launches to 24% of Baseline**
  - **Reduce SpaceX Tanker launches to 9% of Baseline**
  - **Cargo Launches? *Baseline* 17%, *Heavy Luna* 70%**
  - **Capture up to 53% of *Baseline* Tanker costs, 5...25 Billion USD/synodic**



4 *Baseline*: SpaceX Mars Project

- 1000 Mars Starships per synodic
- 150 ton vehicle, 150 ton Cargo, 1200 ton propellant ⇒ 6 km/s
- 5 Propellant Tankers in LEO to fill a Mars Starship

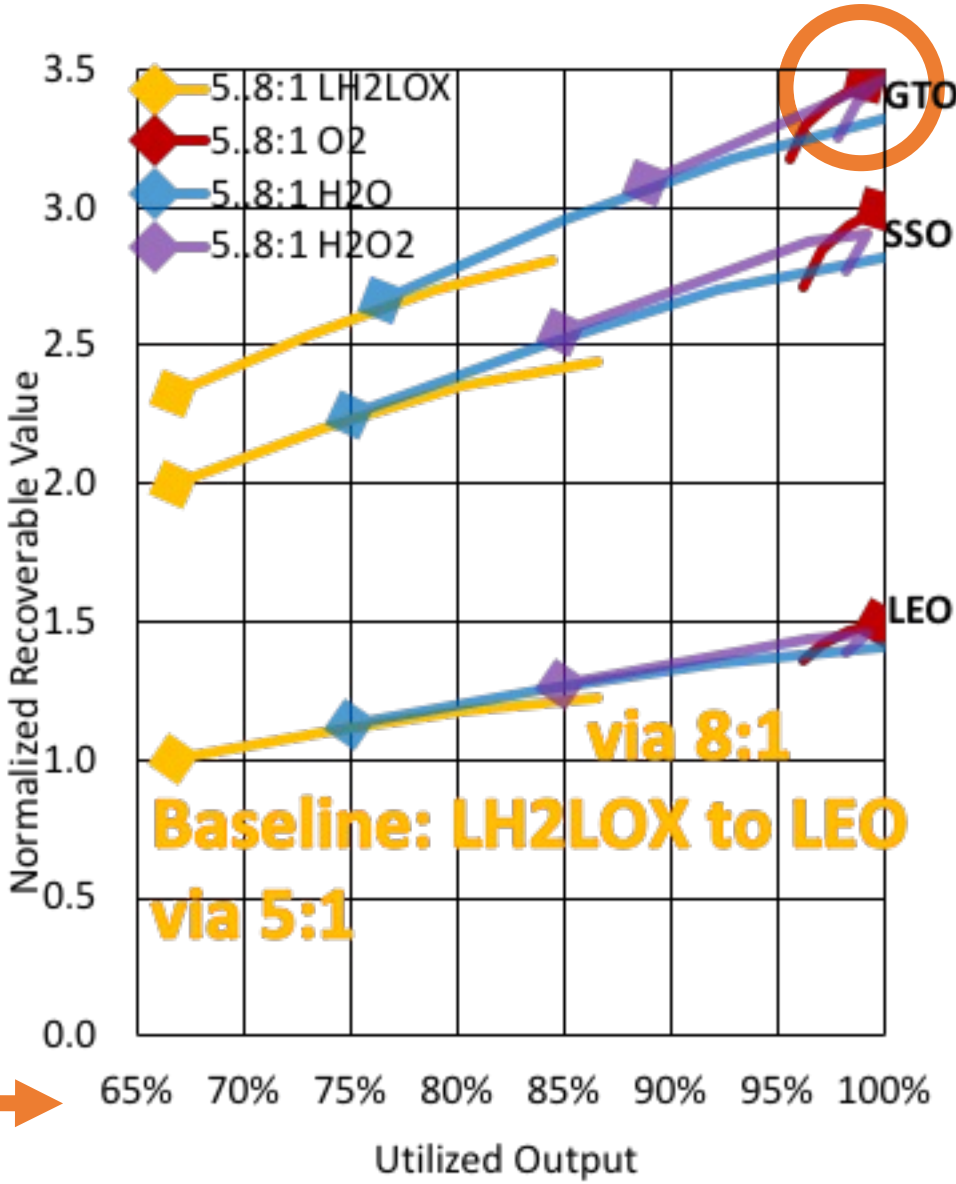
- Implications:
  - **50% of the propellant is "wasted" moving vehicle mass**
  - **100 Mars Starships per Tanker**: Synodic 780 days ⇒ 6.4 Tanker flights/day
  - **Cost drivers: Mars Starship mfg., Prop Tanker flights, Mars ISRU**

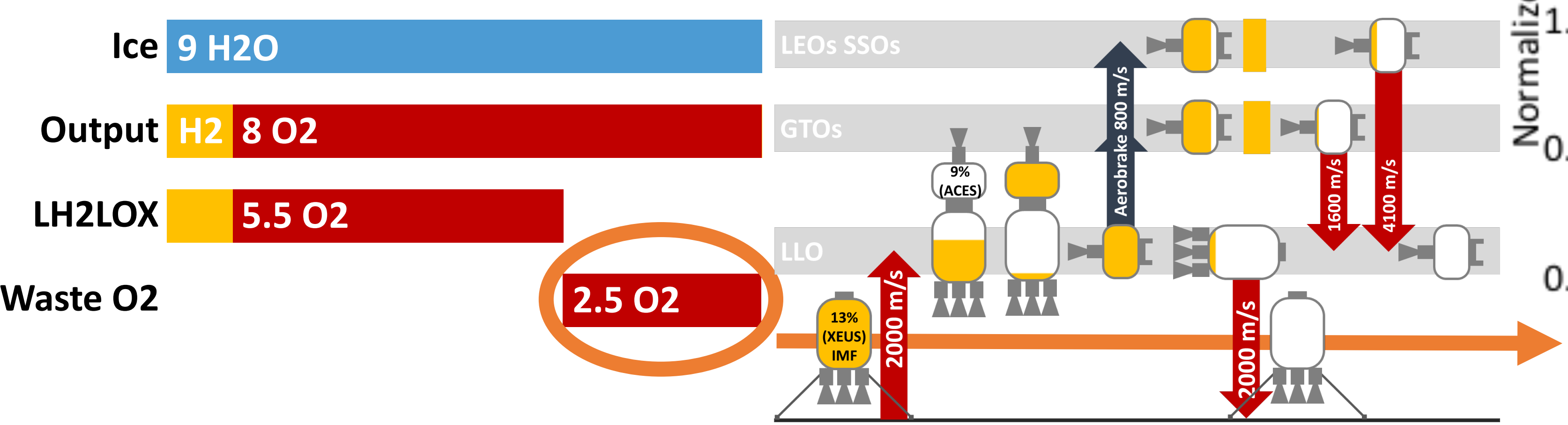


5 Got Lunar Water? Deliver LOX in GTOs!

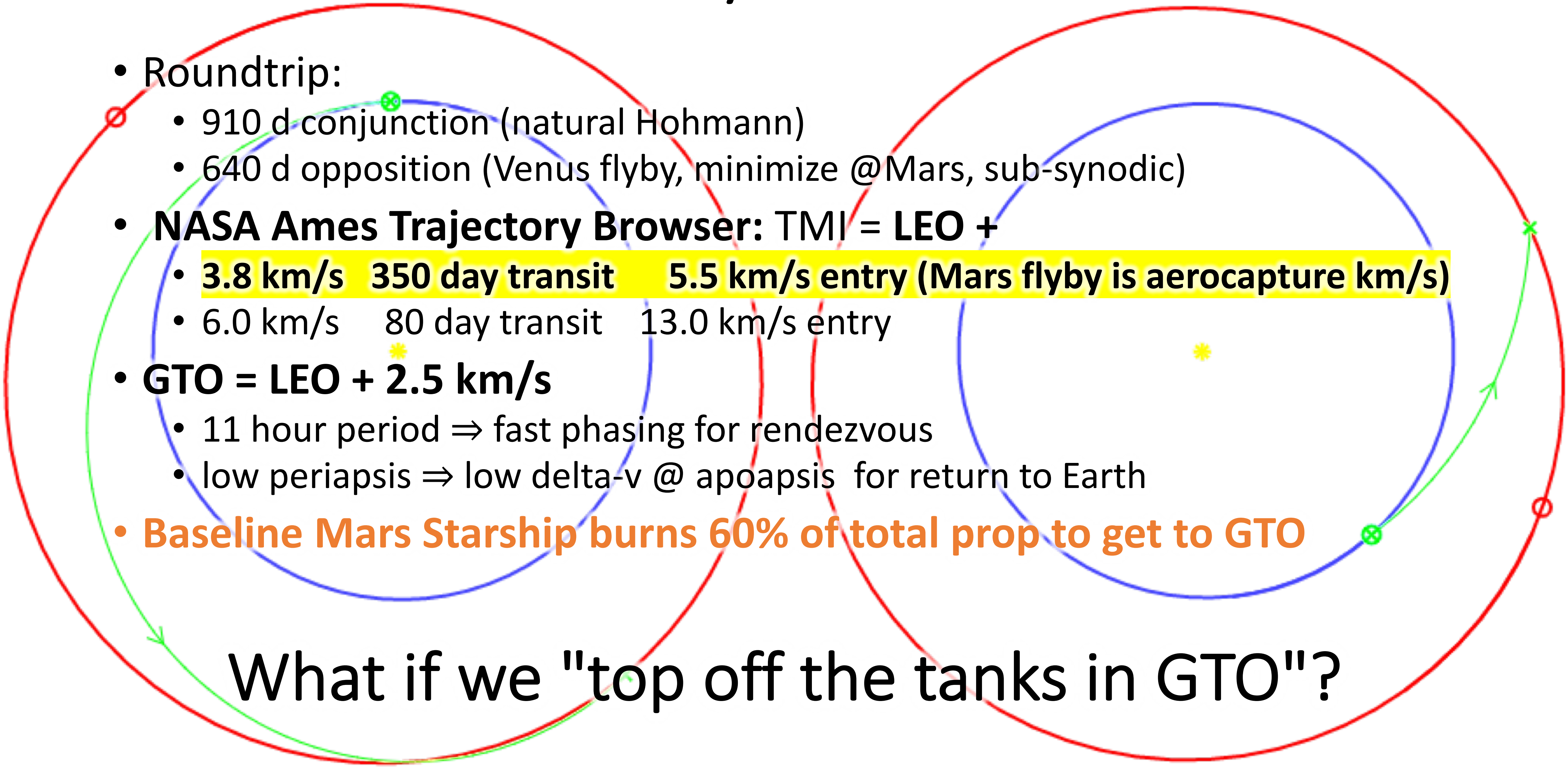
Lunar LOX in GTOs

- Physics based logistics model + value proxies
- Resource, Product, Market, Transport
- H2O, LOX, GTO, LH2LOX
- **LOX from lunar water in GTOs:**
  - high value
  - low transport cost
  - high mine output utilization





6 Earth to Mars Astrodynamics



- Roundtrip:
  - 910 d conjunction (natural Hohmann)
  - 640 d opposition (Venus flyby, minimize @Mars, sub-synodic)
- **NASA Ames Trajectory Browser:** TMI = **LEO +**
  - **3.8 km/s 350 day transit 5.5 km/s entry (Mars flyby is aerocapture km/s)**
  - 6.0 km/s 80 day transit 13.0 km/s entry
- **GTO = LEO + 2.5 km/s**
  - 11 hour period ⇒ fast phasing for rendezvous
  - low periapsis ⇒ low delta-v @ apoapsis for return to Earth
- **Baseline Mars Starship burns 60% of total prop to get to GTO**

What if we "top off the tanks in GTO"?

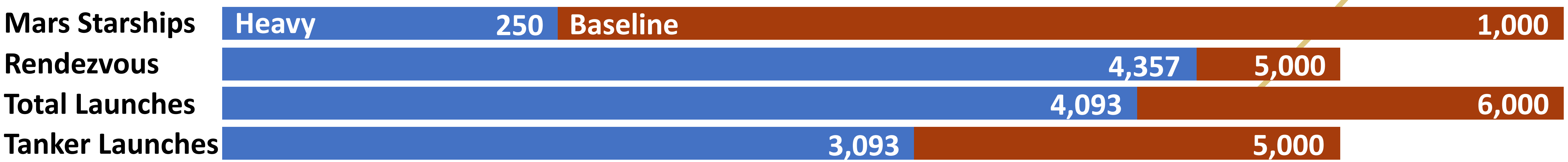
7 *Heavy*: Reduced Mars Starship CAPEX

- **Heavy**: A full Mars Starship in GTO can land 4x Baseline cargo on Mars
  - 250 Mars Ships to LEO, 750 Cargo ferries overload Mars Ship cargos, Mars Ships & Tankers to GTO, Tankers top up Mars Ships & reenter, 250 TMIs…
- Implications:
  - **1,000** ↓ **250** Mars Starships, (Starship Manufacture & Mars ISRU)/4
- Risks:
  - Aerocapture Heat?
    - **Hohmann Mars:** = 5.5 km/s entry = **1 unit heat flux**
    - **Heavy Cargo: + kg** = (1360/544)^0.5 = **1.6x**
    - **LEO: +m/s** = (LEO/Hohmann)^3 = (7.8/5.5)^3 = **2.9x**
  - Thrust for EDL? 4x Cargo = 2.5x Mars entry kg, +3 Raptors = +4.5t = 1% of added cargo kg

Mars Starships	Heavy 250	Baseline 1,000

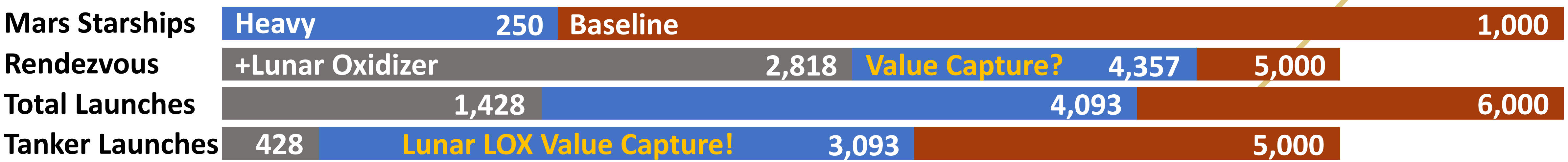
8 *Heavy*: Reduced Propellant Tanker Flights

- -750 Starships ⇒ ↓ 62.5% Baseline TMI dry mass ⇒ less prop
- Tanker math for 4xCargo "Heavy" Starships:
  - 3 to get a 4x Cargo Starship into GTO
  - 9.375 for a full Tanker in LEO, to top off 1.14 Starships in GTO
  - 3093 Tanker Launches = 1250 LEO for Cargo + 220 GTO bound (= 1843 in LEO)
- ↓ **38% reduction of Tanker flights**
- 750 Cargo Logistics, ↓ **32**% reduction in Total Launches
- **4x Cargo ⇒ prop that moves Cargo was 50% now 80%**



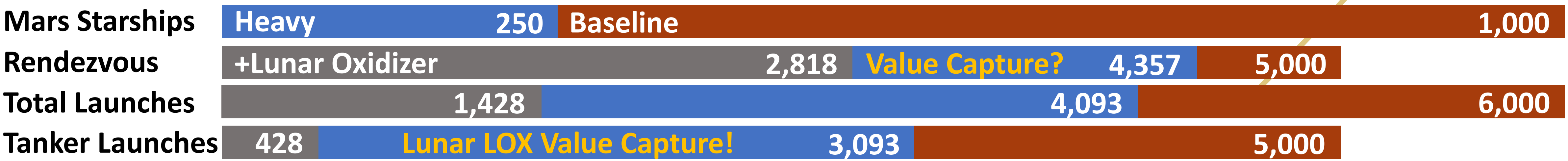
9 *Heavy Luna: Heavy* + Just In Time Lunar LOX

- CH4LOX is **78%** LOX, but, also don't need the CH_4 that lifts the LOX
- Repeat(take on 500 m/s of lunar LOX & boost) until GTO
  - LEO Tanker Launches: **3,093** ↓ **428**
  - GTO Tankers: **220** ↓ **21**
- Tanker Launches: **9%** ***Baseline***, **14%** ***Heavy***
- Tanker Rendezvous: **56%** Baseline
- Value Capture up to **53%** of Baseline Tanker costs
- Payload Launches? ***Baseline 17%***, ***Heavy Luna 70%***
  - Maybe changes vehicle optimization focus



10 Summary & Future *Heavy Luna* Work

- Future Work? Capture & EDL, **lunar logistics**, Venus flybys, Gateway TMIs, **precession**, sensitivity/optimisation: TMI apoapsis, Cargo/Prop, Pumps
  - **Mars Starships (Cargo) & GTO Tankers (CH_4) provisioned in LEO**
  - **Starships incrementally boost to GTO taking LOX from Lunar Tankers**
  - **Lunar LOX Tankers top off Mars Starships, TMI...**
- Only Astrodynamic complexity added! **(& Lunar Propellant...)**
- **25%** Mars Starships & ISRU, **9%** Earth Tanker launches, **56%** Rendezvous
- Recover up to **53%** Baseline Tanker costs, 5-25 Billion USD/synodic
- Propellant moving cargo? Baseline **50%**, Heavy **80%**
- Cargo Launches? Baseline **17%**, Heavy Luna **70%**



11 Cargo, Boil-off, the Landing...

- Unoptimized: tune eccentricity, pumping, ???
- The Starlink "PEZ Dispenser" is also used for loading
  - orbital exchange of palletised cargo
  - Many cargos > 3.8 t/m^3
- Boil-off: SpaceX has to “solve” for Artemis & Mars
  - LEO with coatings and orientation about a year
  - HEEOs reduce Earth flux, + MLI parasol?
- Mars Aerocapture, Entry, Descent, & Landing:
  - Probably peak heat is okay but...
  - Higher terminal velocity at Landing initiation, aero trajectory "details"...
  - **Let’s avoid aero-capture & EDL altogether…**

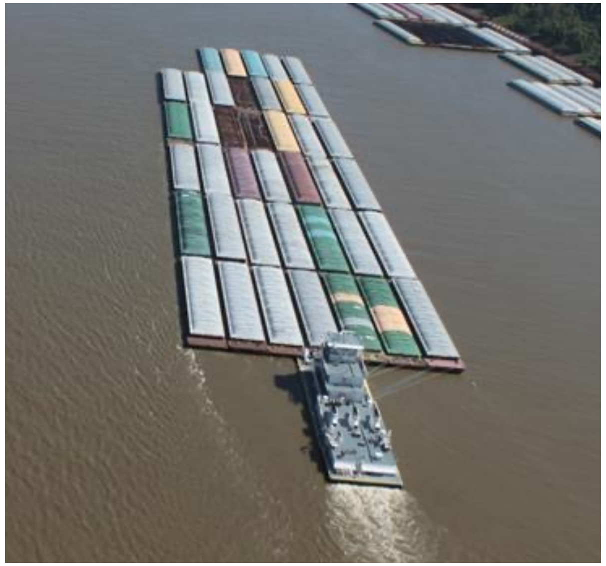
12 End Game... *Maximum Heavy*

- **Maximally eccentric TMI & capture orbits + Mars aerobrake = 800 m/s**
  - **28x** cargo per TMI Starship; **36 TMI Starships can deliver *Baseline* mass flow**
  - 8 min TMI burn, 2 min Mars capture burn
  - Classic ”Lifters, Haulers, & Landers" CONOPs...
  - But, all & only "Standard” Starships! All maintenance is ground segment!

Baseline

Heavy

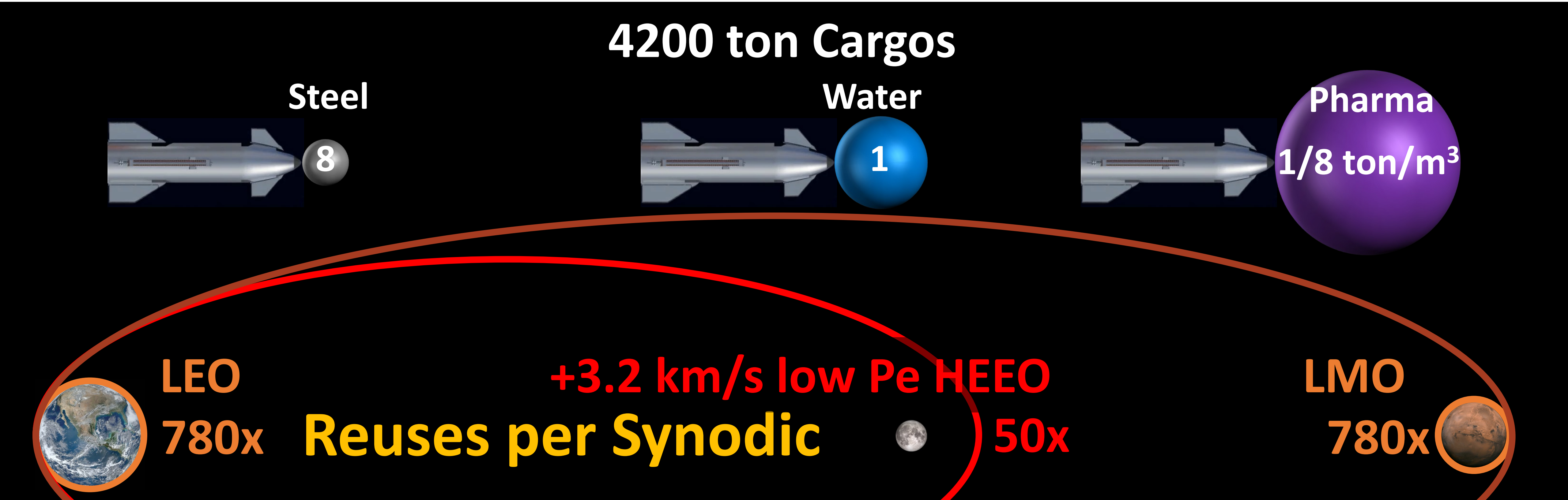
Maximum Heavy



Heritage

13 End Game... *Maximum Heavy*

- **Maximally eccentric TMI & capture orbits + Mars aerobrake = 800 m/s**
  - Cargo < 3.8 t/m^3 ⇒ outside the fairing... Mississippi barge style
  - Cislunar & areocentric Starships reused 50x to 780x the TMI Starships
  - Maximize work done where reusability is highest



14 ESA Solaris

- Getting SBSP on Europe's Net Zero Carbon Technology Roadmap
- Two big funded studies; Frazer-Nash (UK) & Roland Berger (Germany)
  - SBSP could compete with high cost end of renewables
  - Against storage & firming the grid, not the next installed panel
  - Studies used SpaceX Starship transport, **60%** of total costs
  - Fraser-Nash used direct to GTO from “the user guide” composed to GEO

- SpaceX Starship User Guide with LEO propellant & Cargo aggregation
  - Reduce Direct GTO cost by factor **3x** to **6x**
  - The effect should compound into GEO.
  - Reduce 60% of total SBSP costs by factors of more than 3x to 6x…

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Supplementary Material

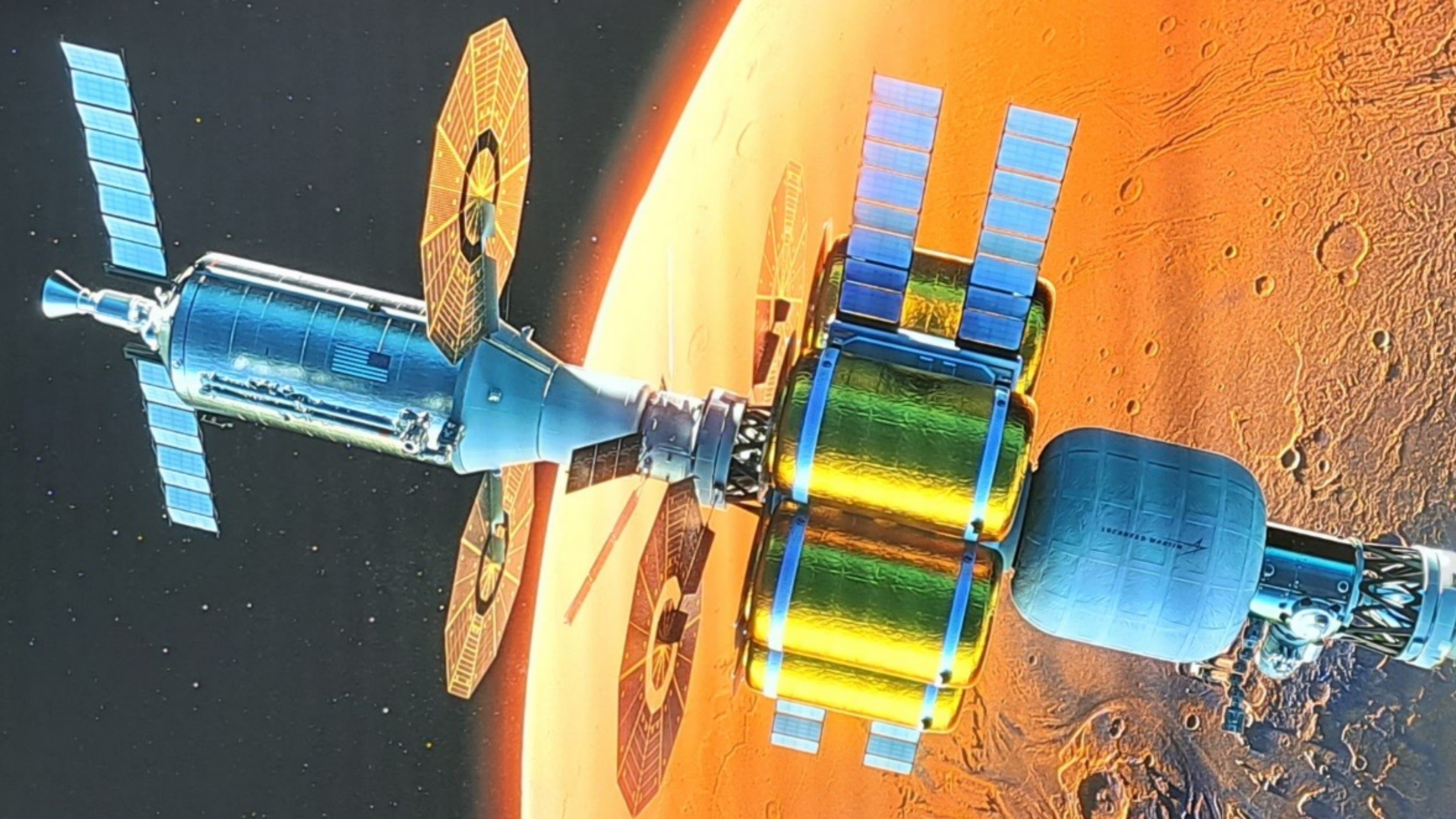
Leveraging industrial scale lunar derived propellant & impulse

- Sketch for a **Human Jupiter System Outpost** program architecture
- Prop required is a rounding error compared to SpaceX Mars Project
- LH2LOX or CH4LOX
- no Nuclear Thermal or Nuclear/Electric Propulsion

A Human Jupiter System Outpost

Discussion Deck

- High Jupiter Orbit (HJO) outpost for *humans in the loop* teleoperation
- Cargo dV < lunar surface. Crew dV 1.07 * lunar surface, 3 y return TOF
- Lunar sourced prop & impulse pumping to LEO+3.2 km/s (MaxEEO)
- Jupiter Exploration Stack: TJI, DSM, powered Earth flyby, JOI, ISRU, TEI
- Crew hyperbolic orbit rendezvous from MEEO to JES at Earth flyby
- Bunk room = storm shelter shielded by foodstuff (basically (CH2)n)
- High icy Moon radiation shielding for the outpost, 2 tours are safe
- Direct re-entry of small crew capsule after 700 m/s TEI from HJO

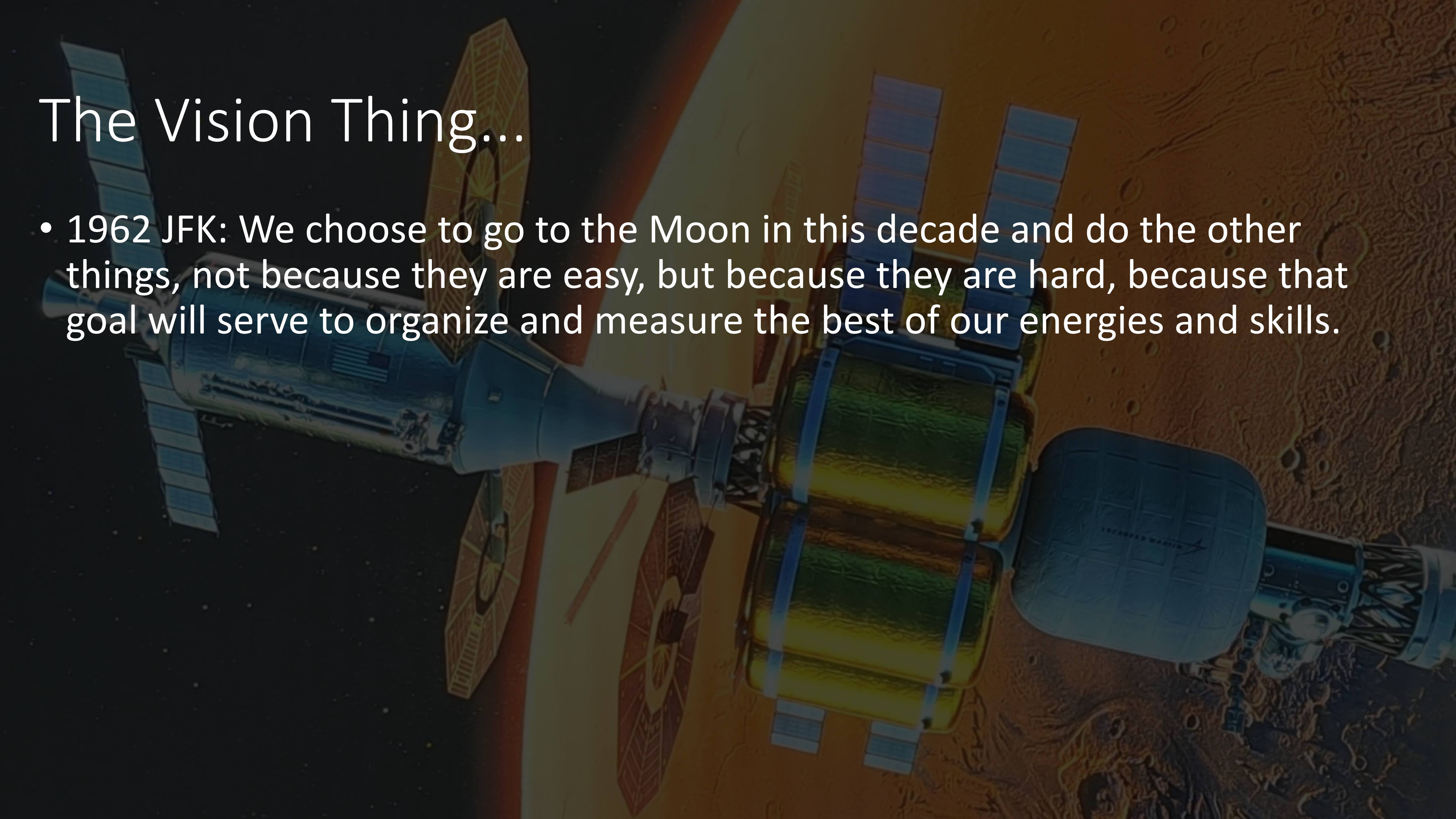


Aspirational Human Exploration Programs...

- Aerospace Companies:
  - an exciting landscape for capability and technology conversations...
- Academia:
  - a source of research problems that harmonize with industry...
- Public:
  - Forward looking inspiration...

The Vision Thing…

- 1962 JFK: We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills.



The Vision Thing... Competing Mars Visions

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Von Braun Mars 1952 (Das Marsprojekt), Stuhlinger Mars 1954–1957, Von Braun Mars 1956 (The Exploration of Mars), Martian Piloted Complex 1958–1962, TMK-1 1959 (flyby), Bono Mars 1960,NASA Lewis Mars 1960, TMK-2 (TMK-E), EMPIRE Aeronutronic 1962, Stuhlinger Mars 1962, EMPIRE General Dynamics 1962, EMPIRE Lockheed 1962, Faget Mars (chemical) 1963, Faget Mars (nuclear) 1963, TRW Mars Expedition 1963, UMPIRE Douglas 1964, Project Deimos, Douglas MORL Mars Flyby 1965, NASA JAG Manned Mars Flyby 1966, NASA NERVA-Electric Mars 1966, Korolev KK (TMK) 1966, Titus FLEM 1966, Stuhlinger Mars 1966,Boeing IMIS 1968, Mars Expeditionary Complex (MEK) 1969, Von Braun Mars 1969, NASA Mars Expedition 1971, Mars in 30 Days (Ragsdale 1972), MK-700 1972, Chelomei 1975 (MK-700 flyby), British Interplanetary Society Mars 1982, Planetary Society Mars Expedition 1983, Case for Mars II 1984, NASA-LANL Manned Mars Flyby 1985, Paine 1986 (Pioneering the Space Frontier), NPO Energia Mars 1986, NASA Ride Report 1987, NASA Mars Evolution 1988, NASA Mars Expedition 1988, NASA Phobos Expedition 1988, NASA 90 Day Study 1989, NPO Energia Mars 1989, Mars Evolution 1989, NASA Mars Expedition 1989, Mars Direct (Zubrin 1991), STCAEM CAB 1991, STCAEM NEP 1991, STCAEM NTR 1991, STCAEM SEP 1991, NASA Synthesis Study 1991, International Space University 1991, NASA Design Reference Mission 1.0 1993, Kurchatov Mars 1994, Zubrin Athena (flyby), NASA Design Reference Mission 3 1997, NASA Mars Combo Lander 1998, NASA Design Reference Mission 4 1998, NASA Dual Lander Mission, Mars Society Mission 1999, Marpost (Gorshkov 2000), Boeing Mars Transfer Vehicle & Lander Concepts for Human Exploration Missions in the 2031-2038 Time Frame (2006), Mars Design Reference Mission 5, SpaceX Starship, Inspiration Mars (Tito 2013)

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- 2022 NASA Dep Admin Pam Melroy: ...Moon, Mars, & **destinations beyond...**

Human Jupiter System Outpost

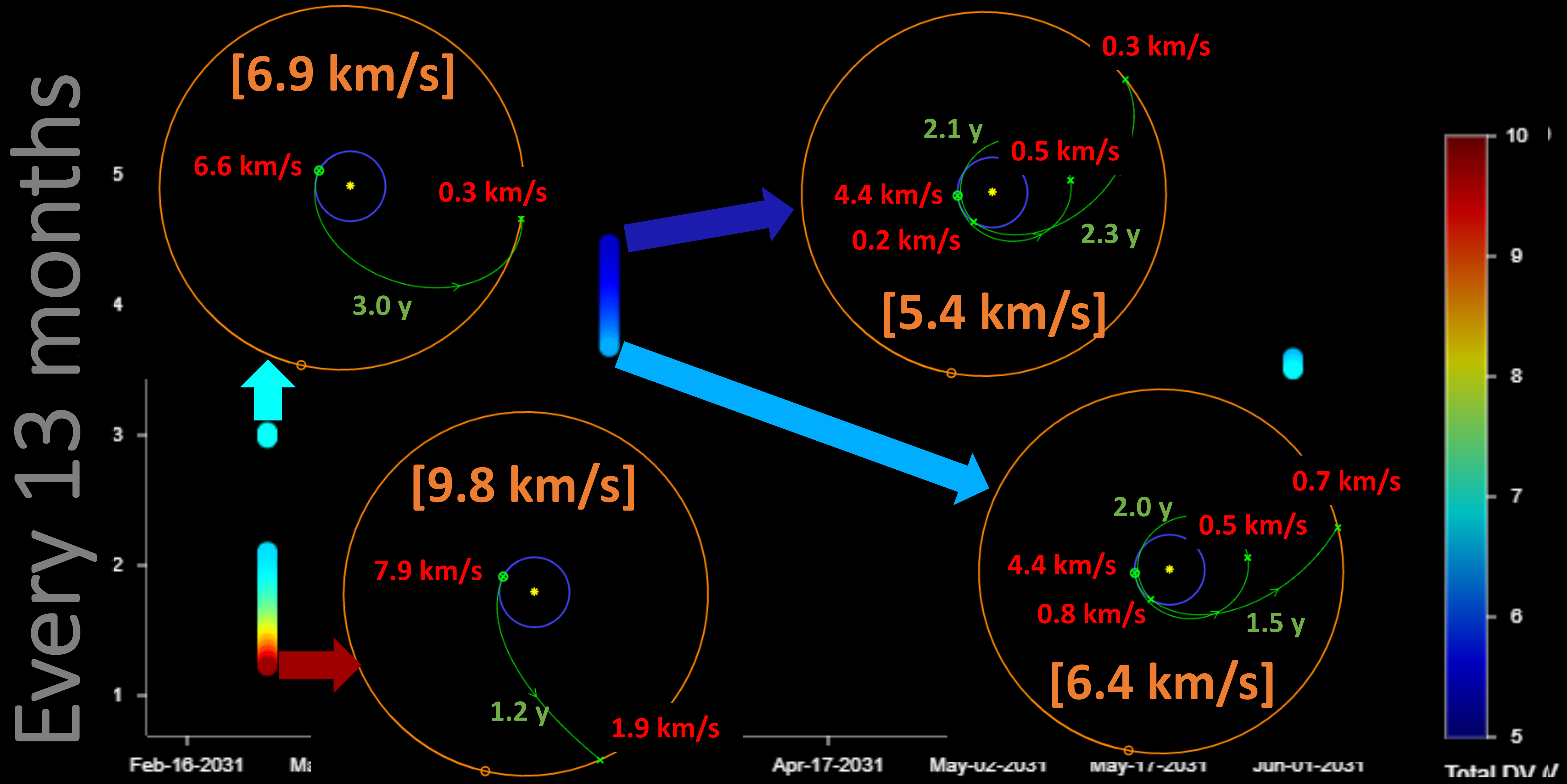
Why?...

...Epic!

Target rich science environment, but...

1 vs 60 min time of light control delay for human in the loop Jupiter robotics => 60x productivity

Deep Space Network is constrained: triage the interesting stuff, return the archive

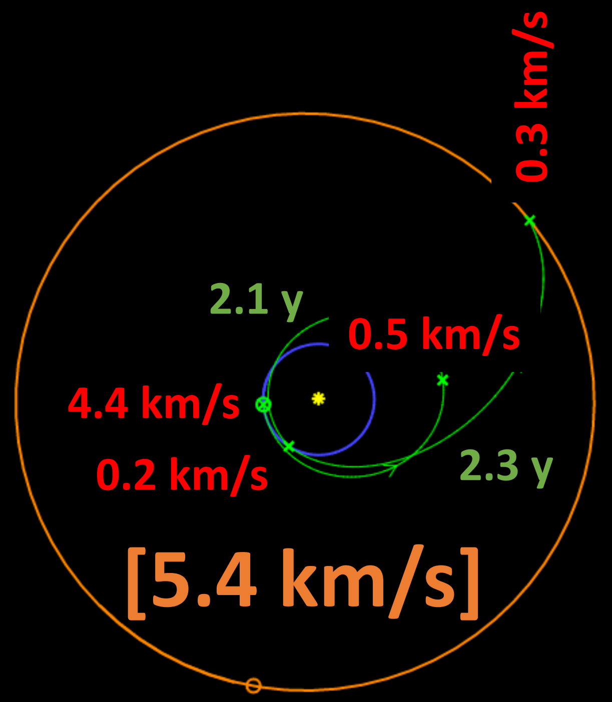


NASA Ames Trajectory Browser

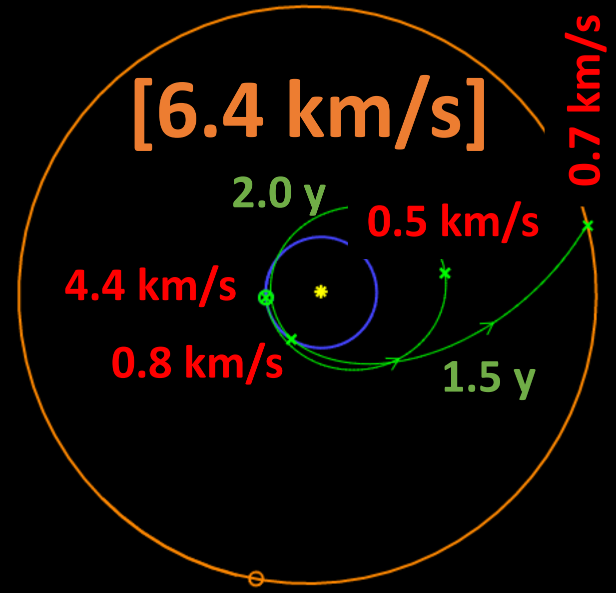
but it can't find min EJ TOF, or min post TJI dV, or EEJs - possible better trajectories options

Propulsion? Doable...

dV: Jupiter Cargo < Lunar Surface



18 month Crew Time Of Flight after
Crew Hyperbolic Orbit Rendezvous
two-way TOF = Hohmann Mars Mission



The Horrors...

Logistics...
Trajectory...
Radiation...
Consumables...
Psychology...


Psychology…
Peak Whaling:
average 4 year voyage, longest 10

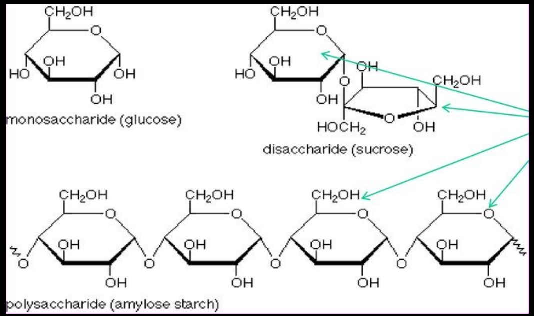
Consumables...

NASA Baseline Assumptions & Values Doc

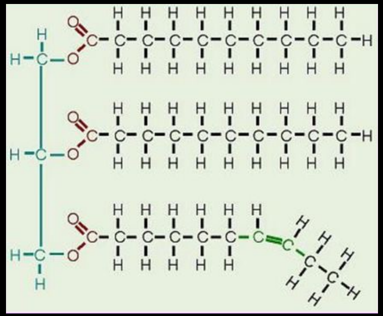
4 Crew, 6 years, bare bones metabolic

Gross: **41 t** = **35 H_2O**, 5.3 food, 0.8 O_2, but...

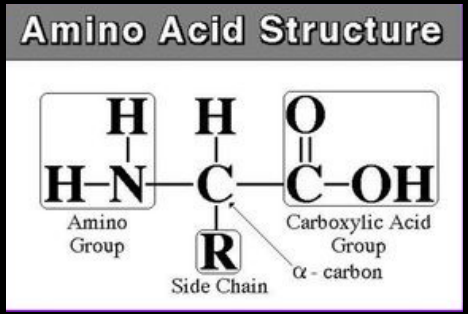
O_2 +



Carbohydrates



Lipids



Proteins

= CO_2 + H_2O

Net: **5.5 t** (metabolic output + H_2O recycle & O_2 from CO_2)

Food you must take is high H or CH_2!

Radiation...

AstroRad Vest: $(CH_2)_n$ 20 g/cm^2

Food is 5.5+ t of "CH_2" shielding

Sleep in the pantry, 50+ g/cm^2

NASA risk based lifetime exposure limits?

Those 35 years and older with 6 year TOF

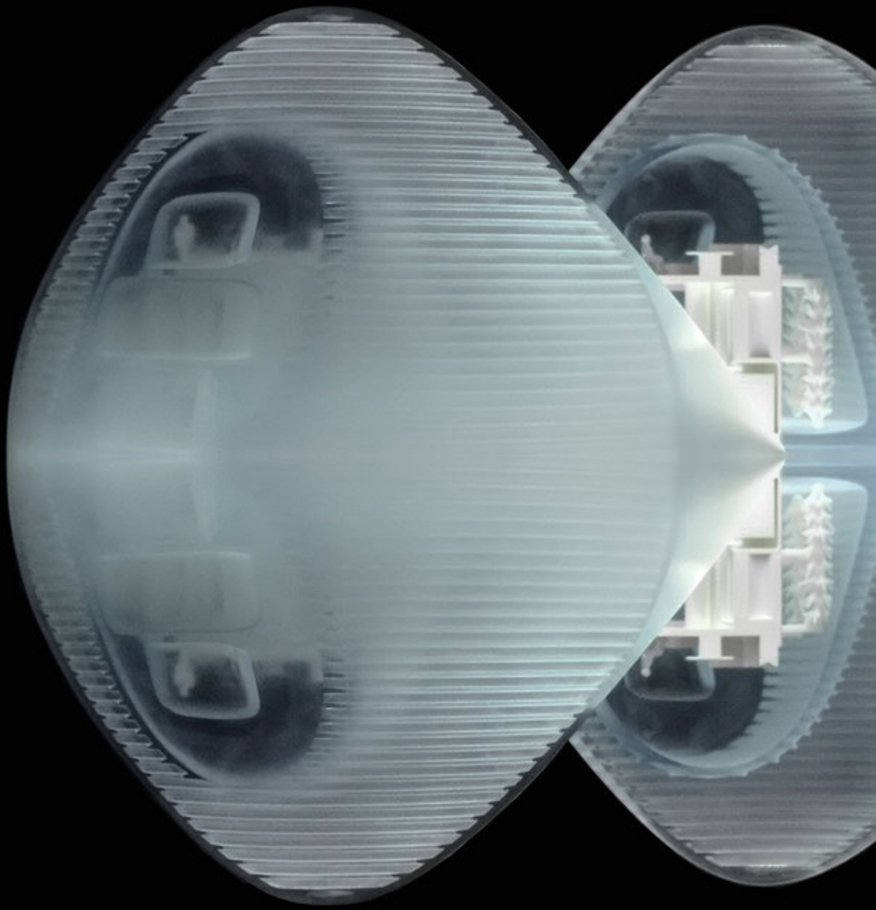
= 2 tours, because...

Radiation…

Use ISRU water ice to shield during Jupiter system residence

burrow in or construct

Jupiter radiation favours an outer moon
=> microgravity

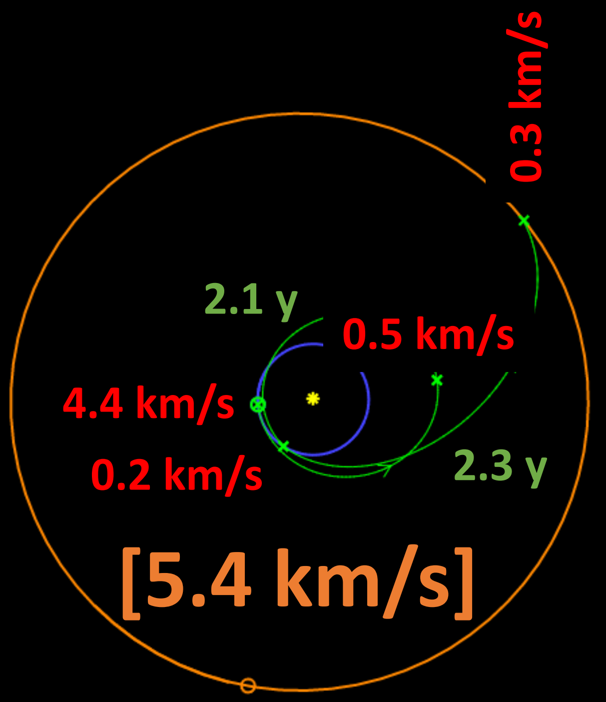


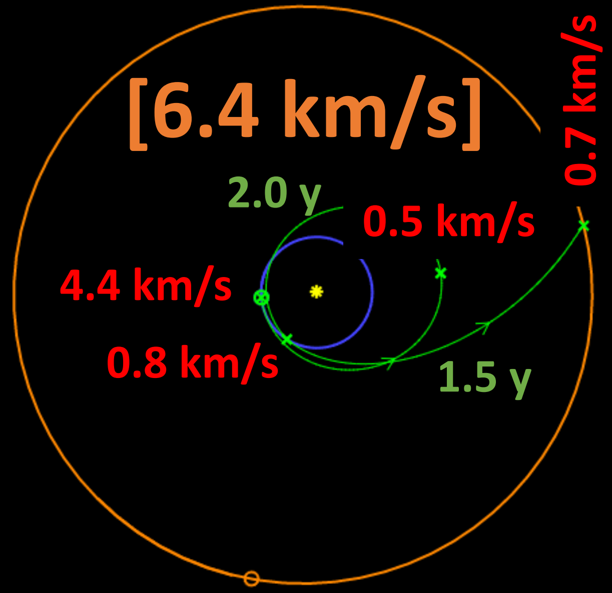
Trajectory back...

700 m/s to direct reentry return

Centaur can push **110 t**
For same water ISRU at Jupiter
Nuclear Thermal can push **30 t**

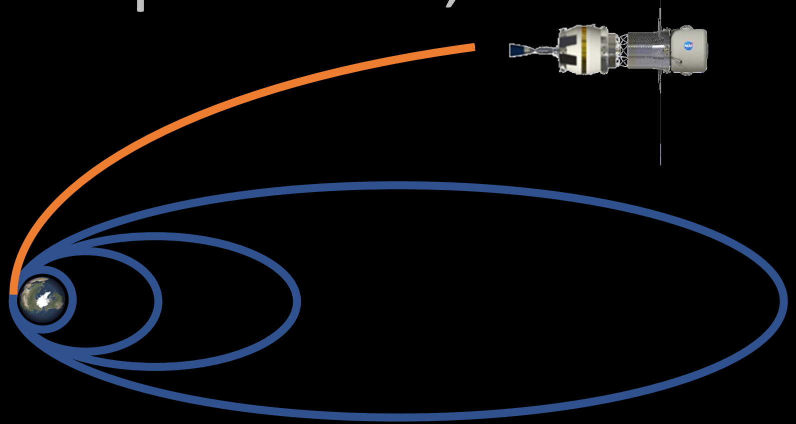
RL10s can get you home...



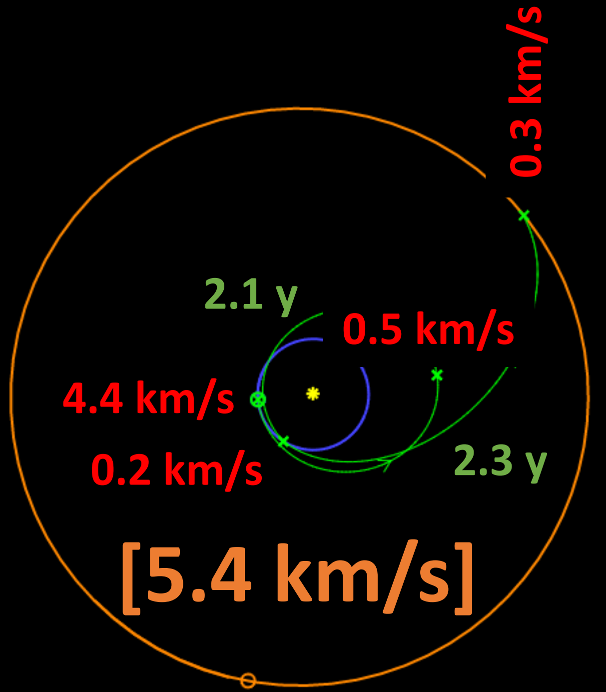


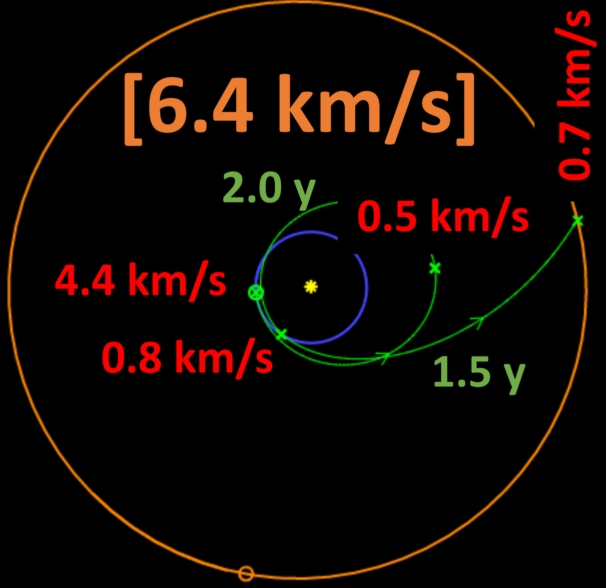
Trajectory there...

3.2 km/s via cislunar tug:
pump orbit, return, & reuse

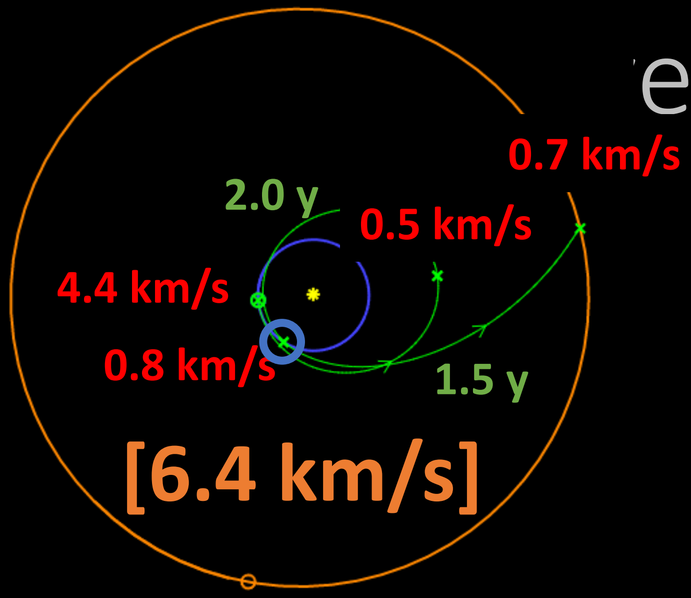


2.2-3.2 km/s by exploration vehicle
Small, cheap, disposable
(escape tugs? heliocentric tugs?)

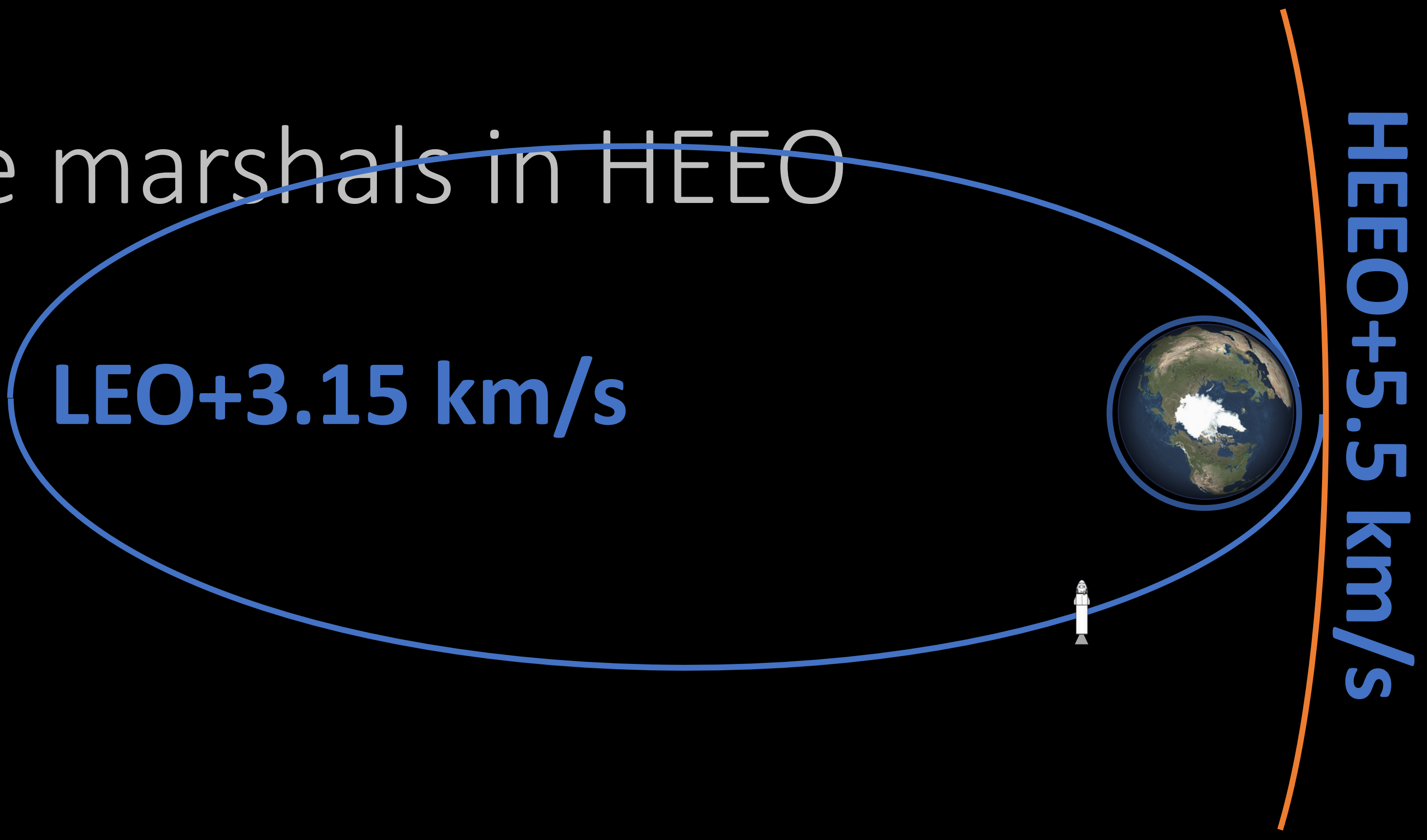


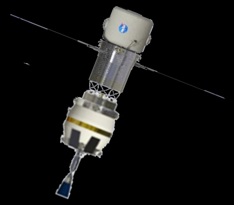


Trajectory hyperbolic orbit rendezvous



ehicle marshals in HEEO





then 5.5 km/s to catch HAB powered flyby

Lightweight reusable gateway?

Logistics… 2x a permanent lunar outpost

Out

Residence

Return