Drilling Deeper:

Borebots and the Search for Life Under the Ice

Quinn Morley, Planet Enterprises https://borebots.fyi/


NIAC
NASA Innovative Advanced Concepts
Planet Enterprises

Purpose

To enable access to liquid water under the great ice sheets of the solar system, in order to support the search for a second genesis of life—or to determine a panspermic origin.

Earth holds perhaps only 1/50th of the solar system's water!

- Mars has massive polar water ice caps, containing climate records and perhaps frozen samples of ancient biospheres
  - The ice at the base of the southern cap could be from 3 Gya
  - Periods of solar system evolution are surely preserved here, which elude us because Earth has had ice-free periods since
- The ocean worlds are incredibly promising
  - Europa, Callisto, Ganymede, Enceladus, Dione, Titan, Miranda, Ariel, Umbriel, Titania, Oberon, Triton, and Pluto

Some recent inspiration…

“We used to swim the same moonlight waters,
oceans away from the wakeful day.”

– Nightwish

Why borebots?

- Cable-reliant drilling systems have stagnated
- Apollo astronauts still hold the drilling record for the solar system
    - 3 meters, beating the next closest by 2.8 meters (the failed HP^3 probe)
- The search for life under the ice is simply too important to wait for existing technologies to develop, so we must innovate

https://www.planetary.org/articles/pdd-completes-second-field-test

On Thursday, Steve Banner reminded me how I got started on this…

DATELINE: Gig Harbor, WA, USA, Earth; August 2018:

- Planetary Radio episode about liquid water on Mars:
    - “If we’re going to do astrobiology, we need to not just see it, we need to get a piece of it, we need to get a sample of it. So, I think this becomes a very strong argument for deep drilling” – Chris McKay
        - https://www.planetary.org/planetary-radio/0801-2018-garvin-mckay-mars-lakeInvestigated Mars polar applications for borebots

Can a fifth grader criticize current drilling approaches?

YES. it is easy to criticize magic cables handled by magic winches or magic spools, ran by magic power sources, with a drill head that is serviced using magic techniques for which descriptions are not even attempted.

They can also criticize borebots. And I'm fine with that.

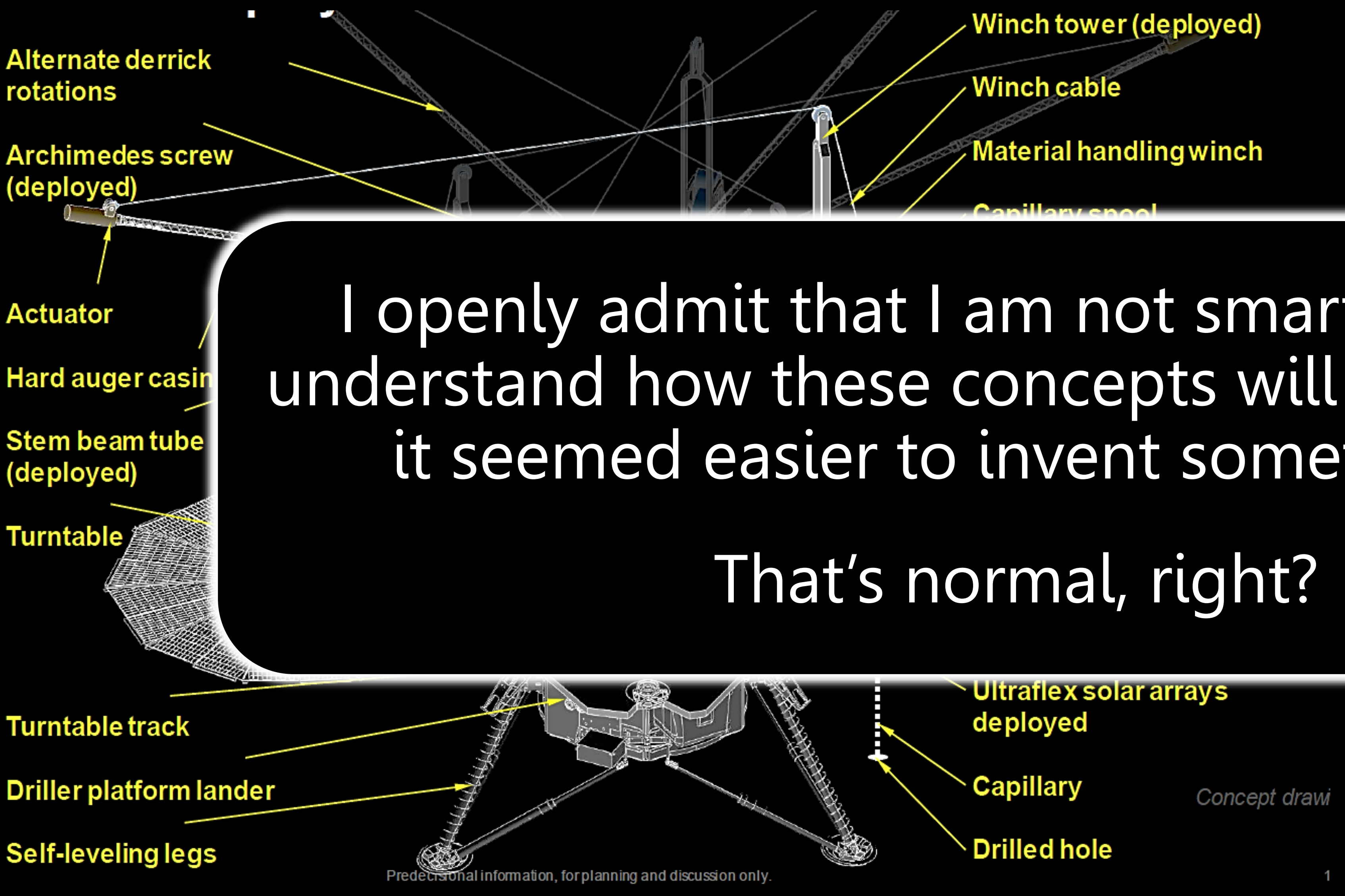
They can also ***build their own borebots***, since everything is ***fully open source***. We hope to have curriculum modules available next year.

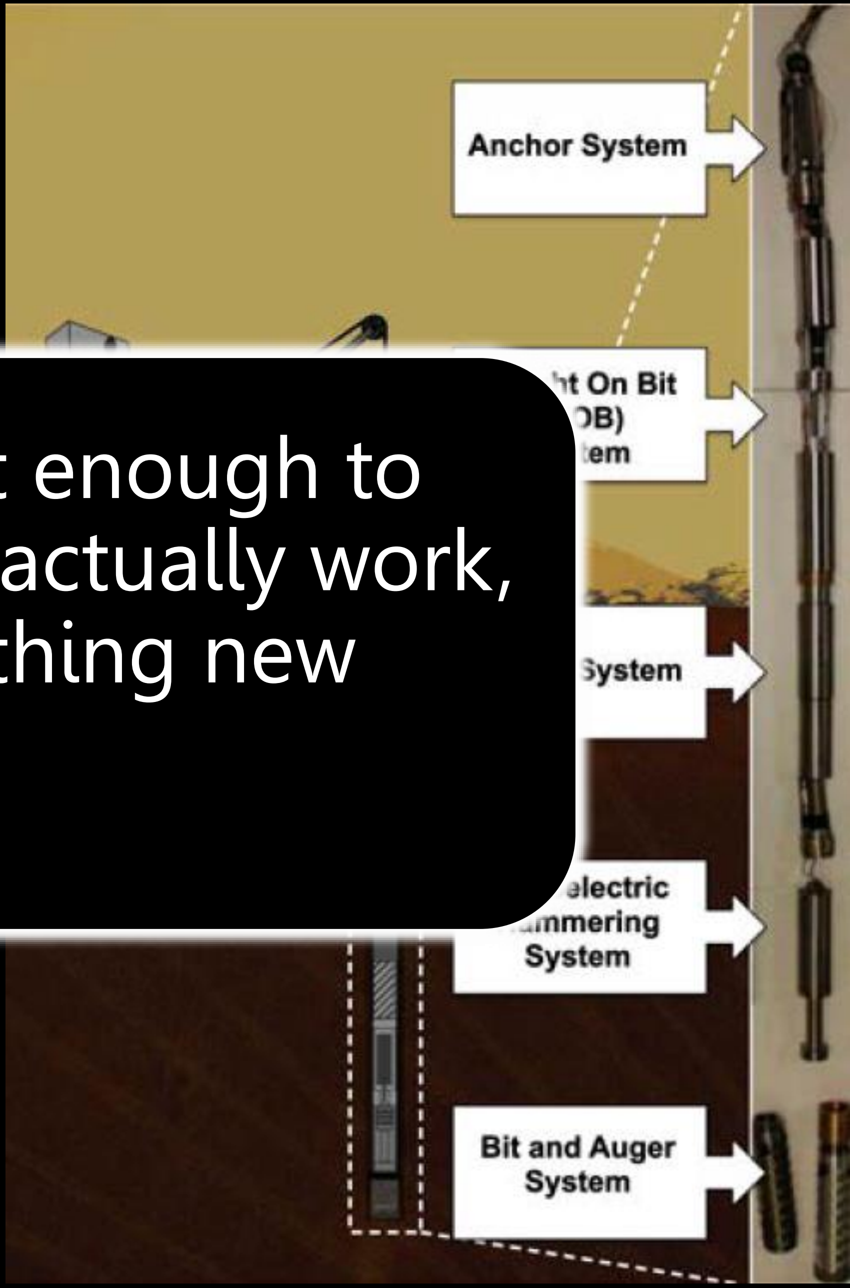
"Science is the belief in the ignorance of experts"

Evaluating Drilling Systems 101, 9AM MWF, (3 Cr.):

- Look for huge pieces of equipment which are not appropriate for the claimed mission class
- Look for grad student / intern labor for tasks which should be automated (lack of enabling technologies)
- **Look for generators**.

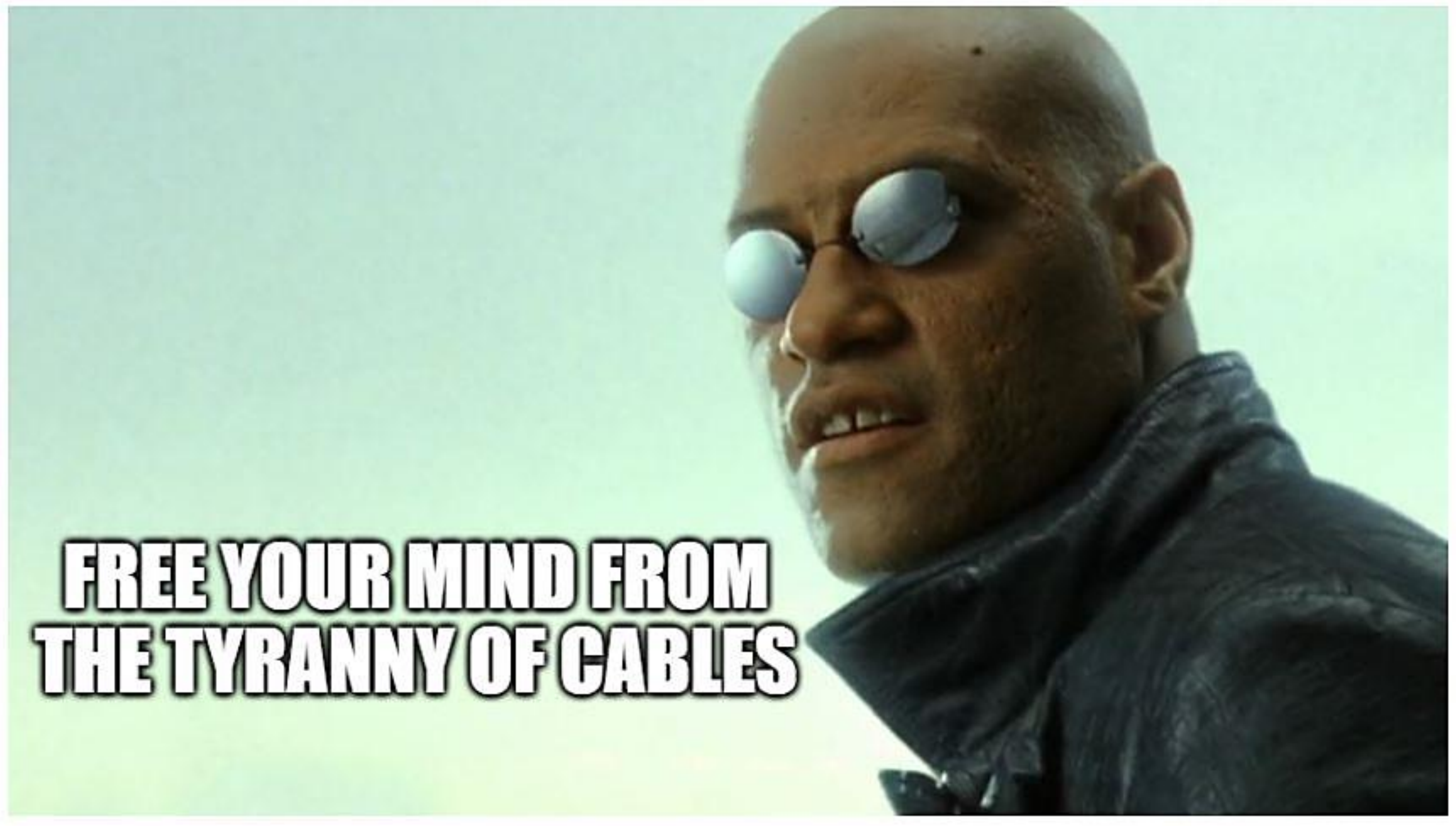

Is this vacuum for removing chips??

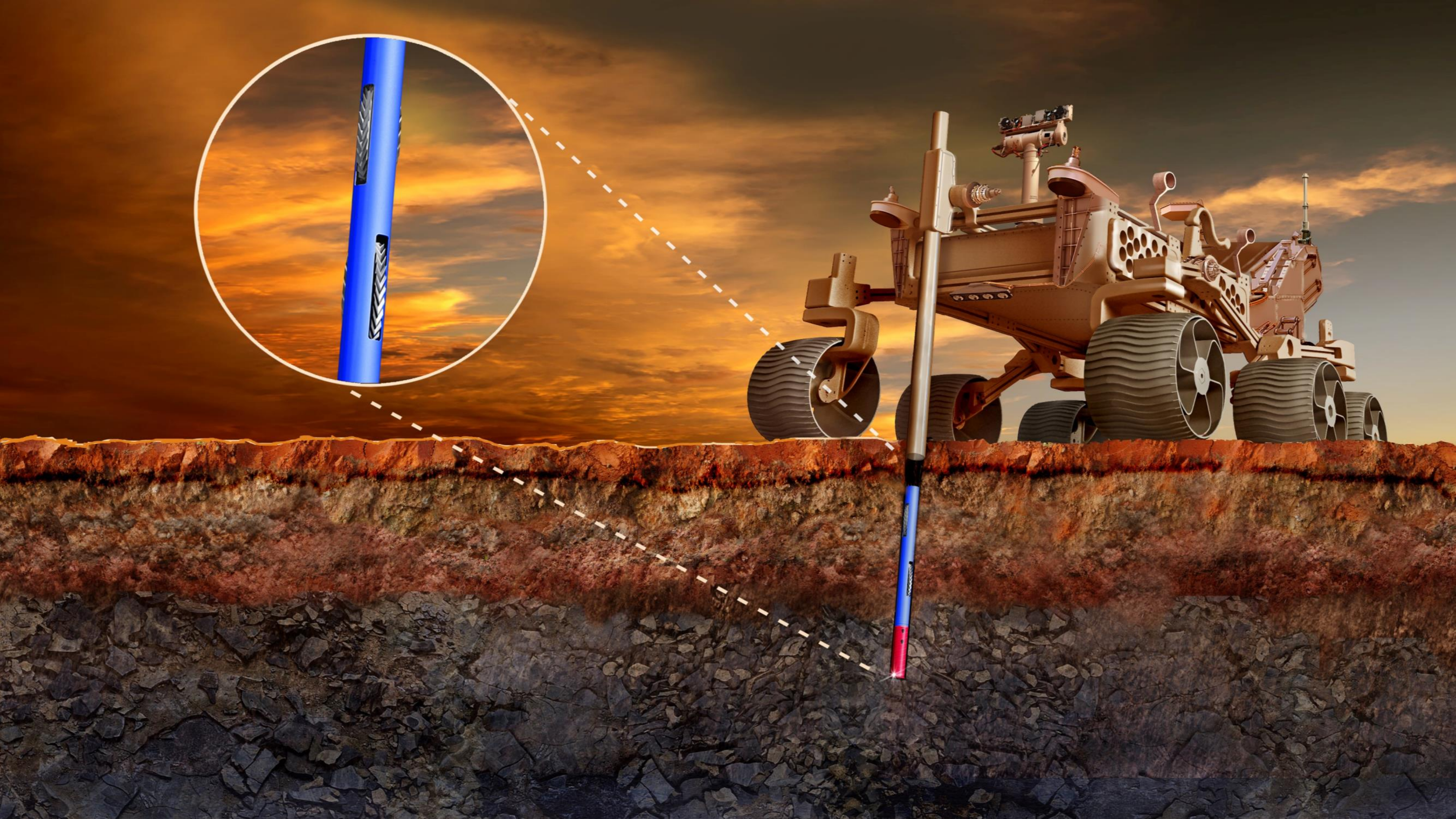




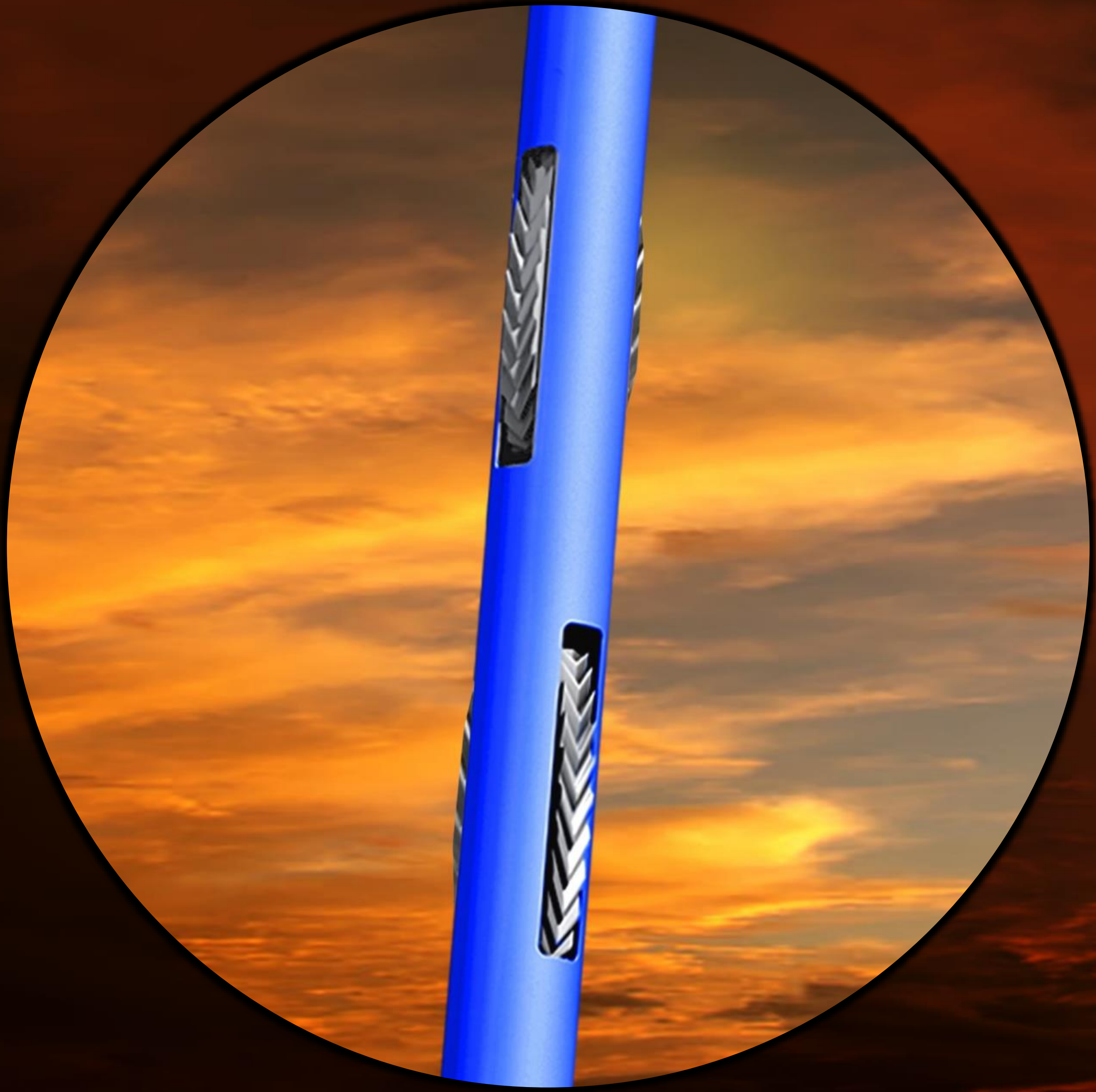
I openly admit that I am not smart enough to understand how these concepts will actually work, it seemed easier to invent something new

That’s normal, right?

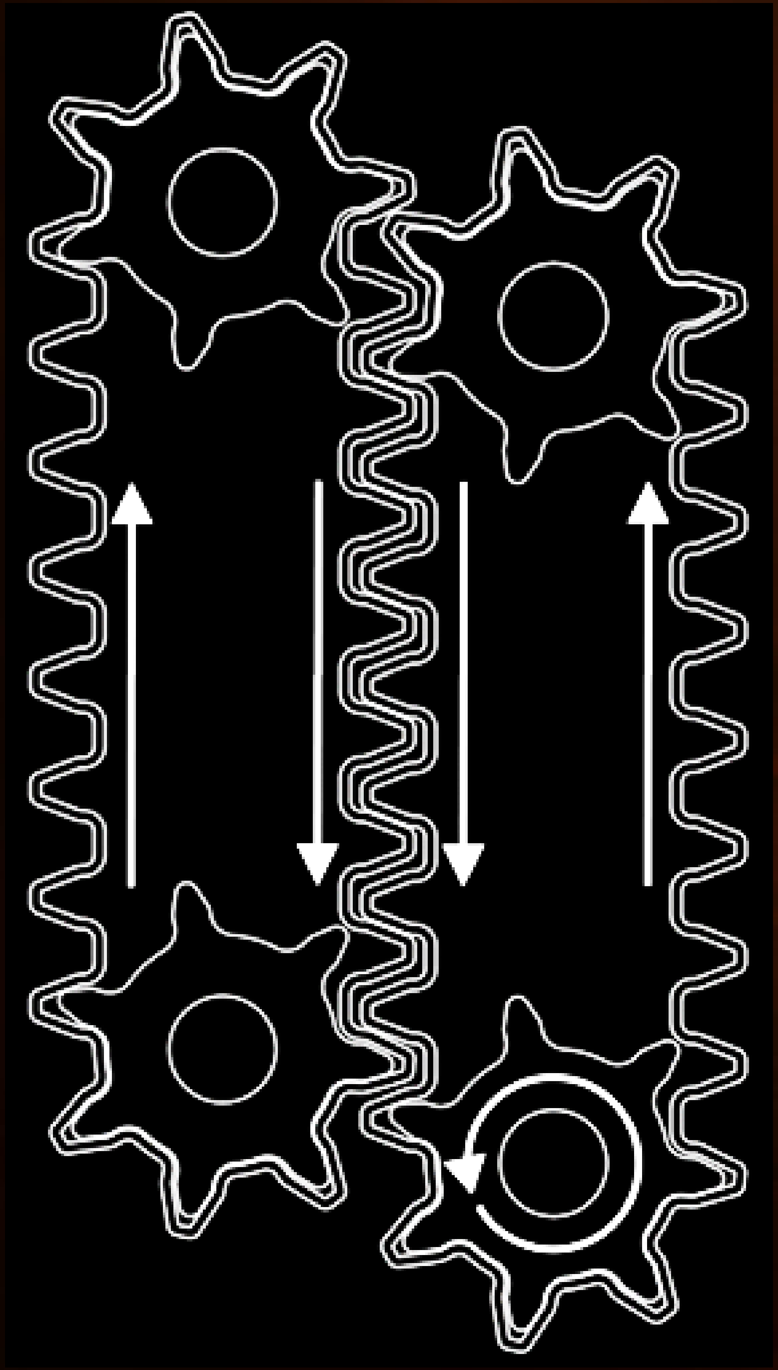

FREE YOUR MIND FROM
THE TYRANNY OF CABLES



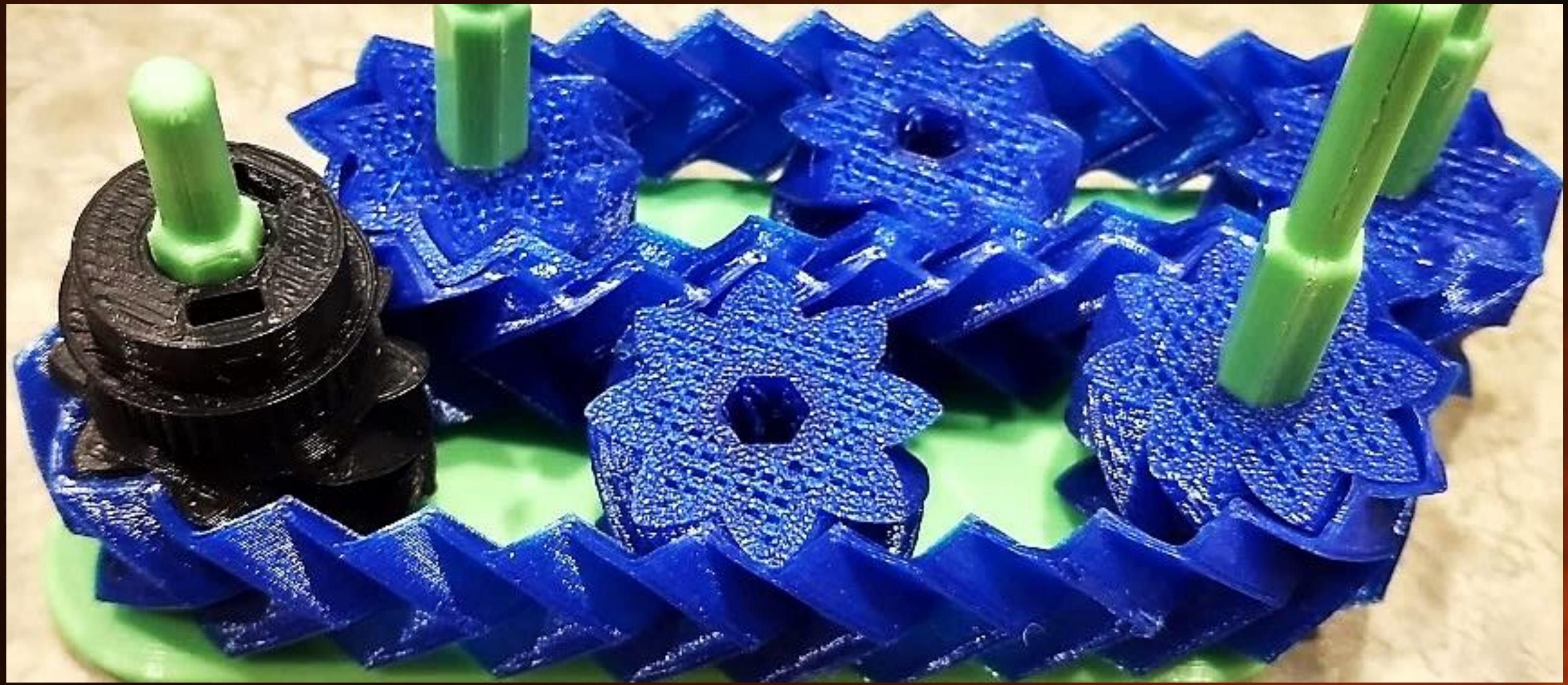
Borebot Drivetrain



Borebot Drivetrain



- Replace tether cables with driving apparatus
- Staggered tank tracks mesh together
- When components are squished, drive belt tension increases
- Geared belts, zipper-like belts, and smooth belts are all feasible options
- Drivetrain frictional losses are the largest energy budget item
    - Low friction favors smooth belts



https://github.com/Shootquinn/ARD3/blob/master/ZipperDrive%20Traction%20Belt%20System.pdf

https://youtube.com/shorts/fARg3XMnxzk

Background

During our Phase I NIAC Study, we:

- Evaluated the feasibility of the borebots concept
- Modeled the energy demands of tripping drills
  - This means any drill which hauls material to the surface
- Investigated Mars polar applications for borebots
- Briefly considered applications for icy moons and Earth

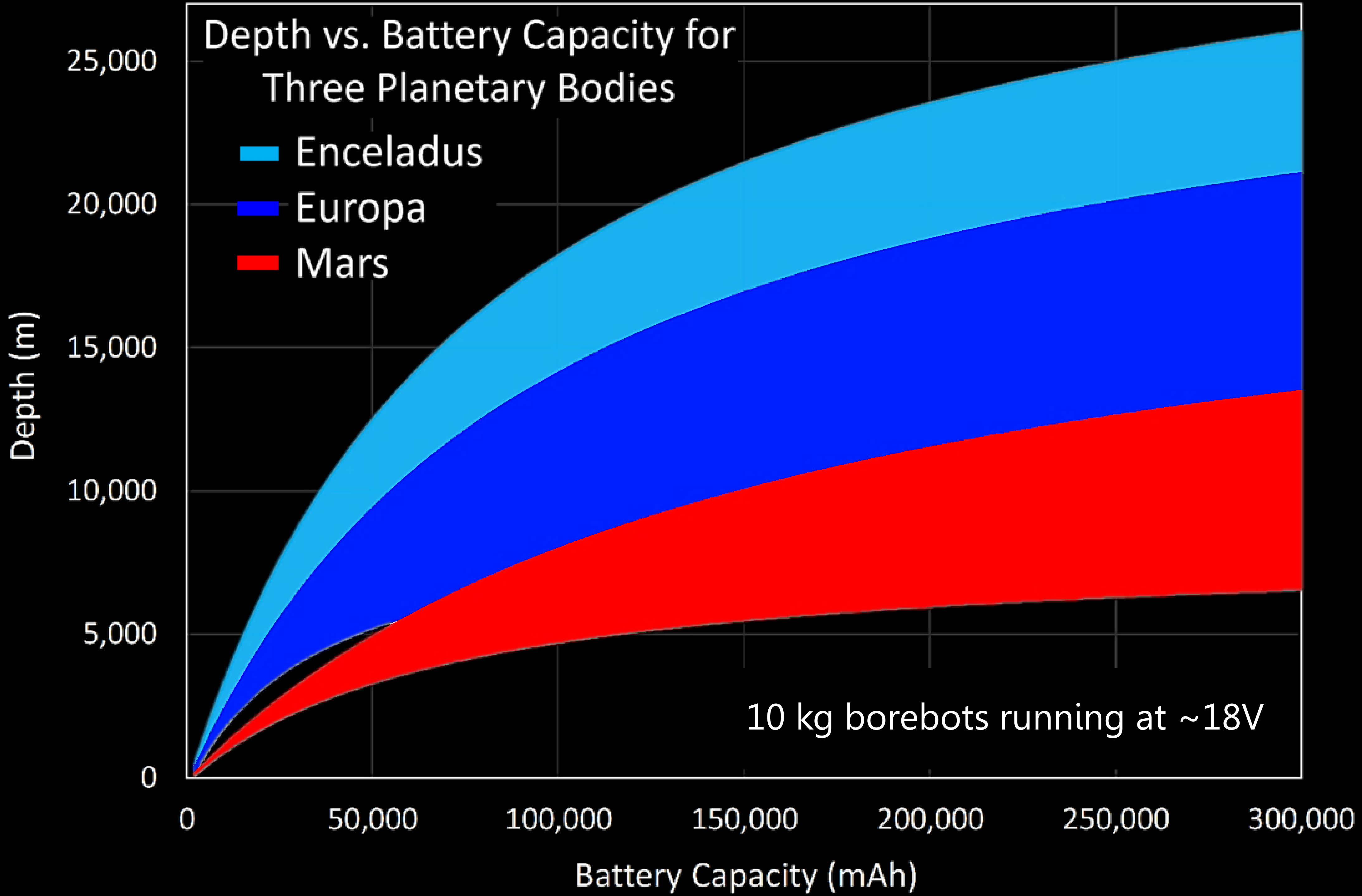
Trips-to-Depth Formula:

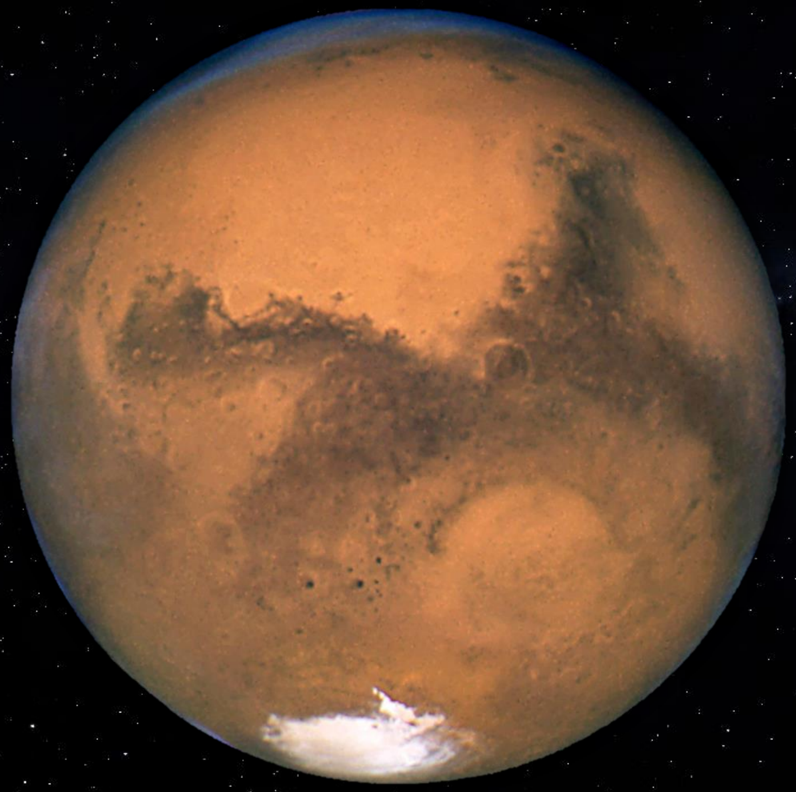
Required trips to the surface = desired depth / core length

- This is fundamental. Wirelines have to deal with this too
- If you aren’t taking a core, it’s worse, because you are hauling 100% fluff back up (drill 0.25 m to fill a 0.50 m container, etc.)
- The numbers, although obvious, are usually surprisingly large

NIAC Phase I Key Findings

- Driving up and down a borehole is a fundamentally feasible alternative to wireline drilling, but is depth limited
- Energy efficiency is a critical factor, which is especially sensitive to power draw from electronics and drive system
- High-efficiency drill heads can add margins to power budget, but may not be required (i.e., we can use drill heads of others)
- Significant downhole science instruments exist and can be repurposed; some will require dedicated borebots and trips


Depth vs. Battery Capacity for Three Planetary Bodies
Enceladus
Europa
Mars
10 kg borebots running at ~18V
Depth (m)
25,000
20,000
15,000
10,000
5,000
0
0
50,000
100,000
150,000
200,000
250,000
300,000
Battery Capacity (mAh)

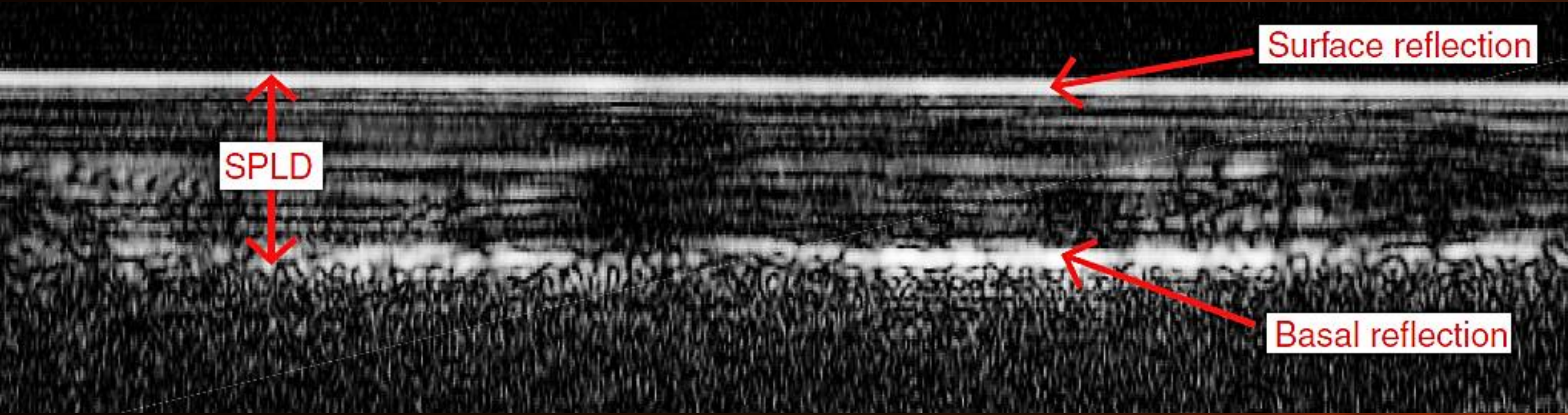


Why Mars?

There is potentially a subglacial lake (i.e., **liquid water**) 1.5 km below the South Polar Layered Deposits (SPLD) on Mars

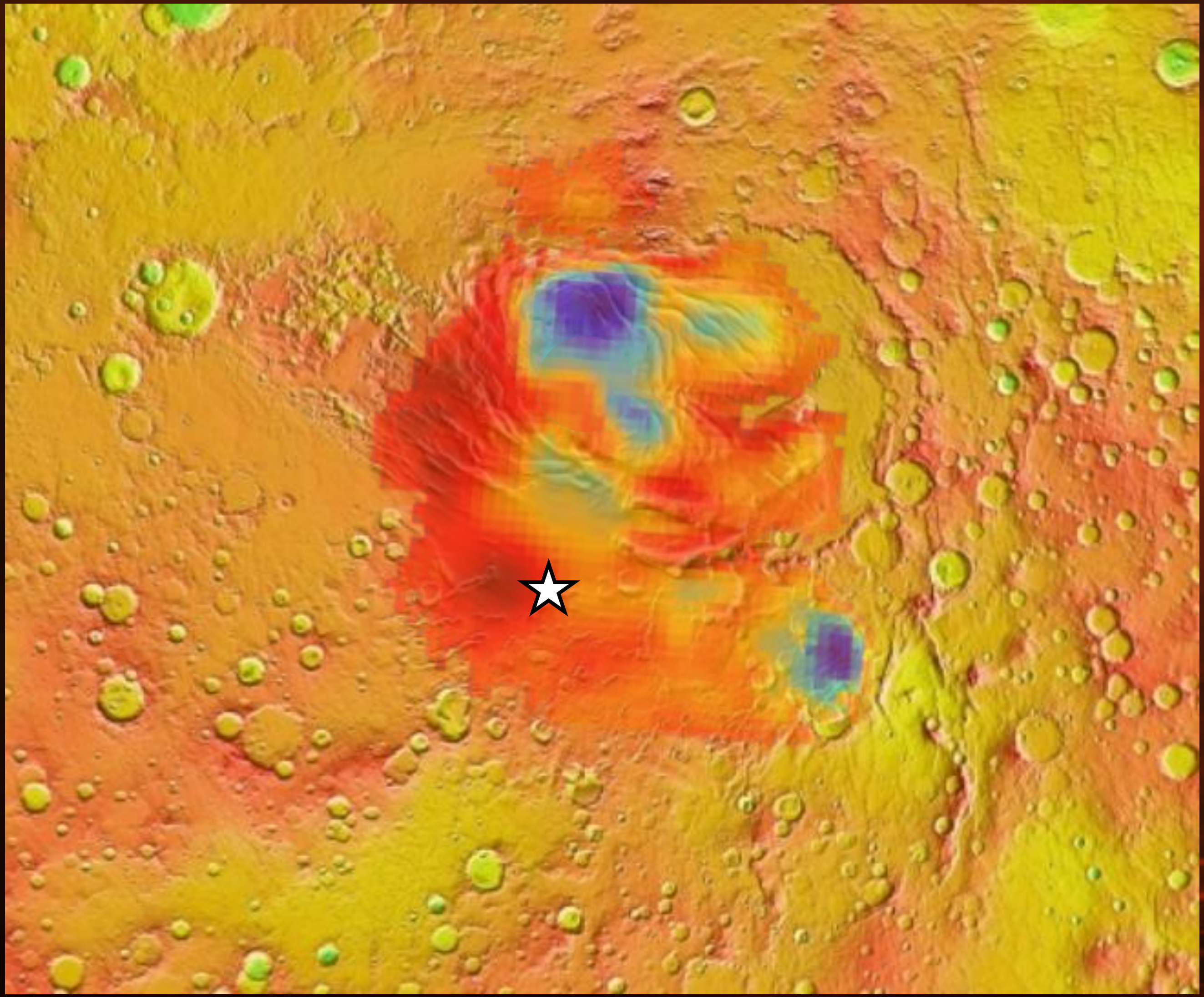
The SPLD is like a polar ice cap, except it is layered dust and ice.

Potential Subglacial Lake Under the SPLD



MARSIS radargram showing the High-Reflectance Area (HRA; potentially liquid water) at the base of the SPLD. From Orosei, et al. 2018 (Figure 2A, p. 3).

Location of potential subglacial lake; ice density map



Overlay gradient is ice density; figure 6-d, Li et. al 2012

Mars

Mars-specific findings from our NIAC Phase I:

- A Mars 2020/Perseverance-class mission would need only modifications to the rover, not a full redesign
- The Mars SPLD has a hard, ice-cemented duricrust which should take well to this type of drilling (20-40 m thick)
- Cryptic terrain (seasonal CO_2 ice) may be a problem
- Borebots are easily adapted to other mission classes

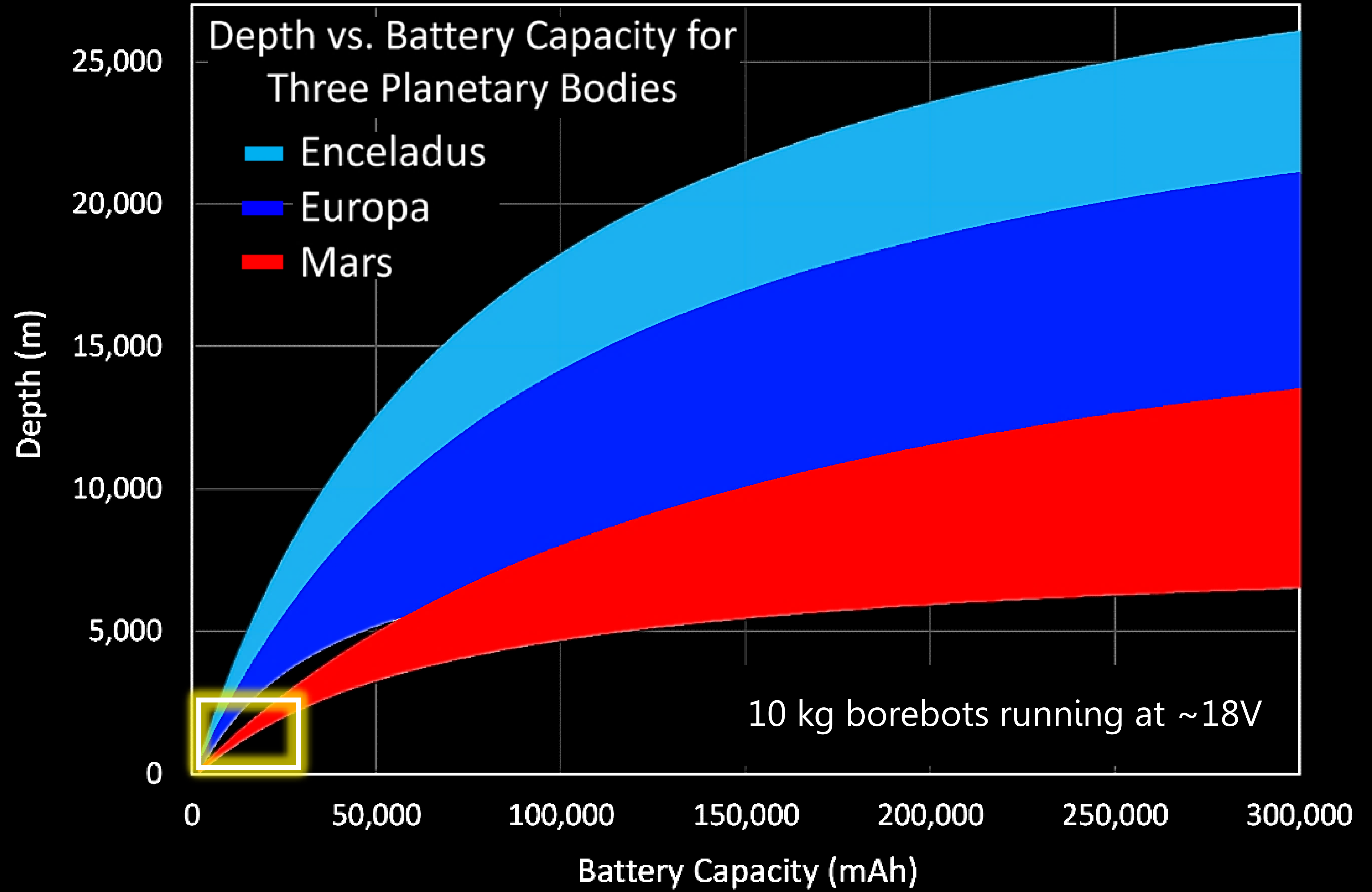
Power Model Details

- Power is the derivative of the work done by the borebot (or, derivative of work done by the winch, on a wireline drill)
- Lithium-iron-phosphate batteries for low-temp reliability
- Max discharge rate of 0.5C for balancing power draw / longevity
- We assume that thermal balance is achievable (ala Ingenuity)
- Evaluated microcontrollers/components for real-world demands
- Drive speed analysis done iteratively with efficiency in mind

Efficiency Estimates

We use three methods for estimating wasted energy:

1. Mechanical efficiency
   - 50% nominal estimate, down to 25%
2. Track system friction – sometimes called “drivetrain friction”
   - Can only be determined experimentally!
3. “Hotel loads” – power draw from electronics and heaters inside the borebot itself, just to “keep the lights on”
   - This has a huge impact on drive speed; can’t go too slow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Three Planetary Bodies
Enceladus
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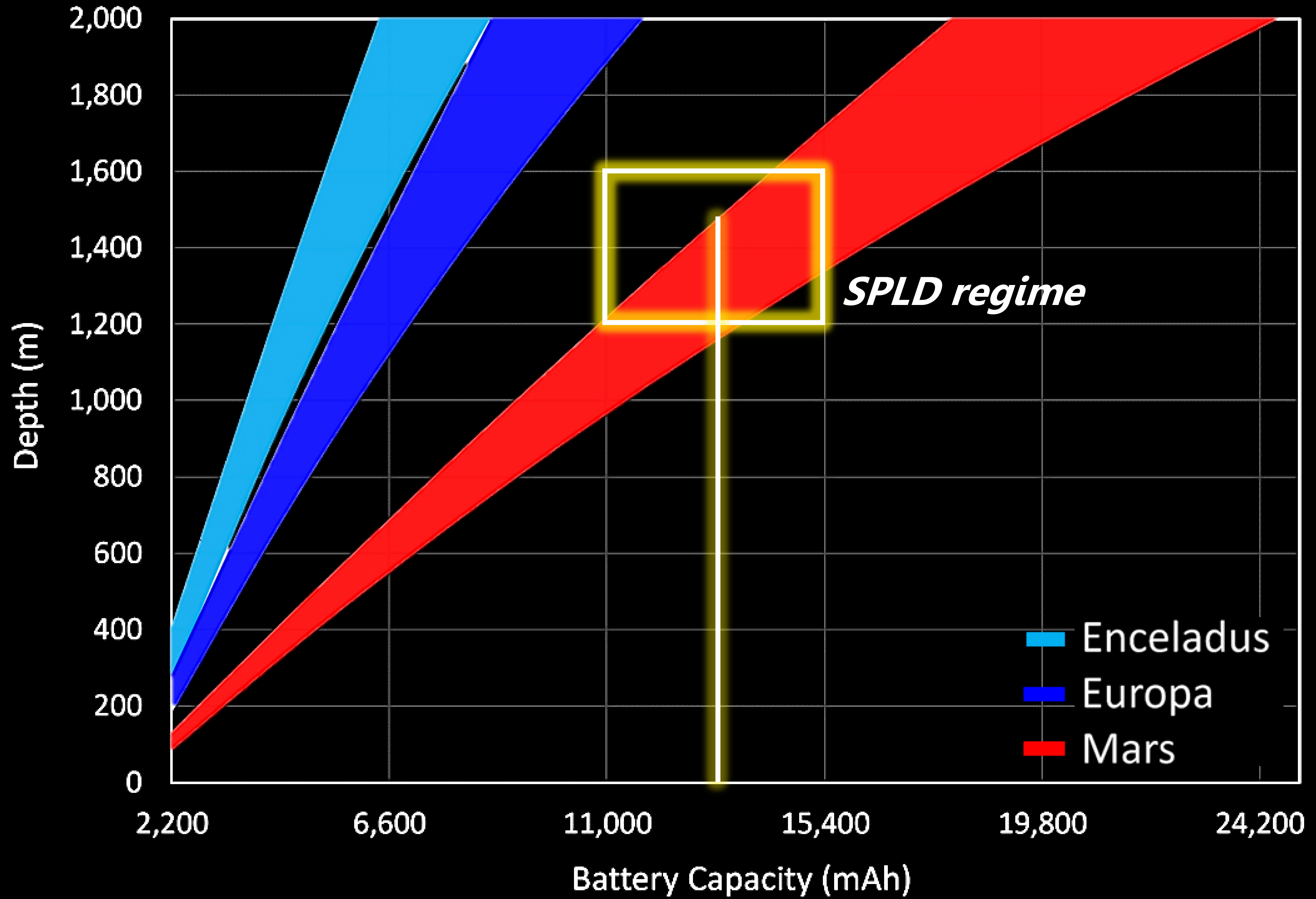
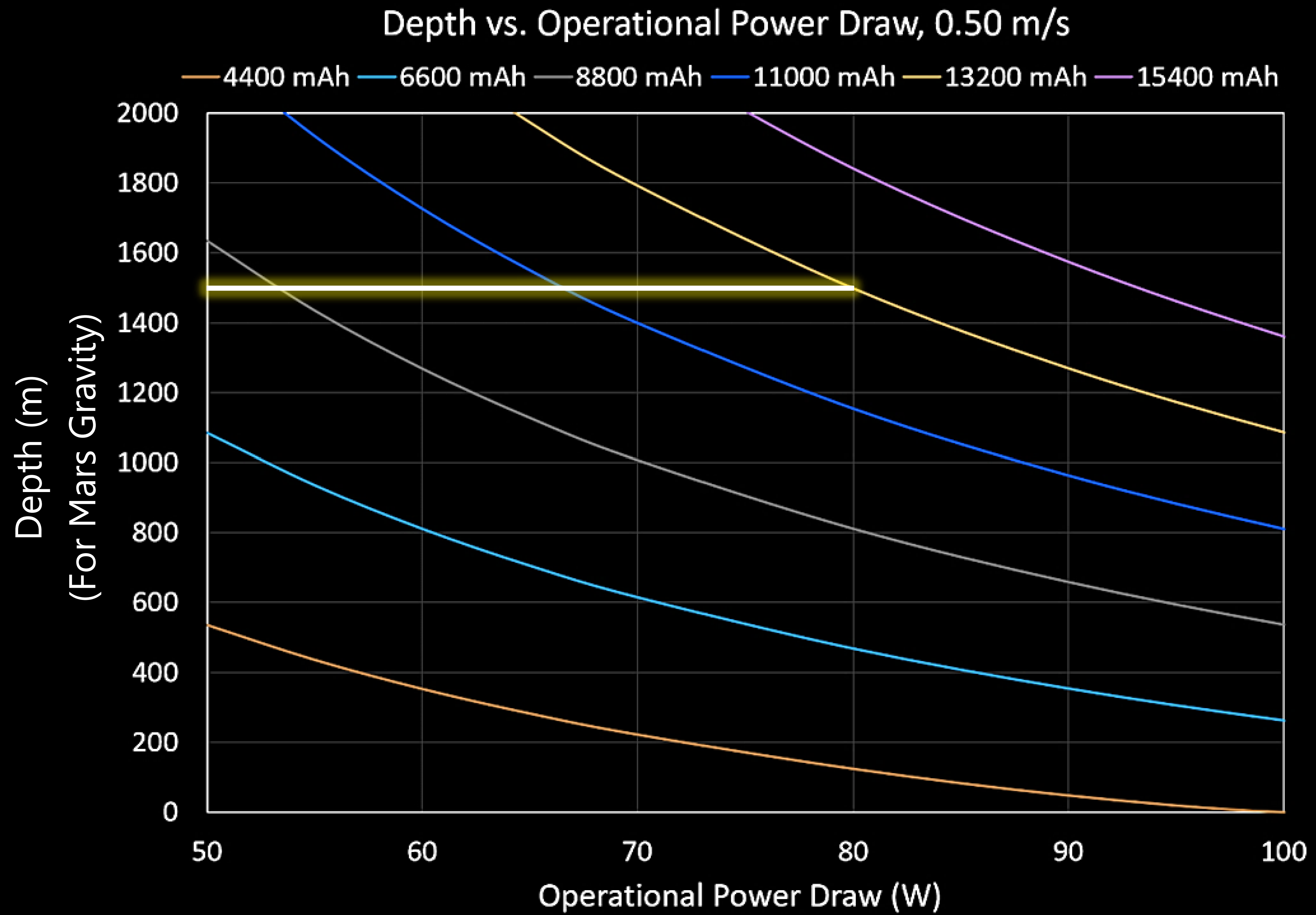
10 kg borebots running at ~18V
Depth (m)
25,000
20,000
15,000
10,000
5,000
0
0
50,000
100,000
150,000
200,000
250,000
300,000
Battery Capacity (mAh)



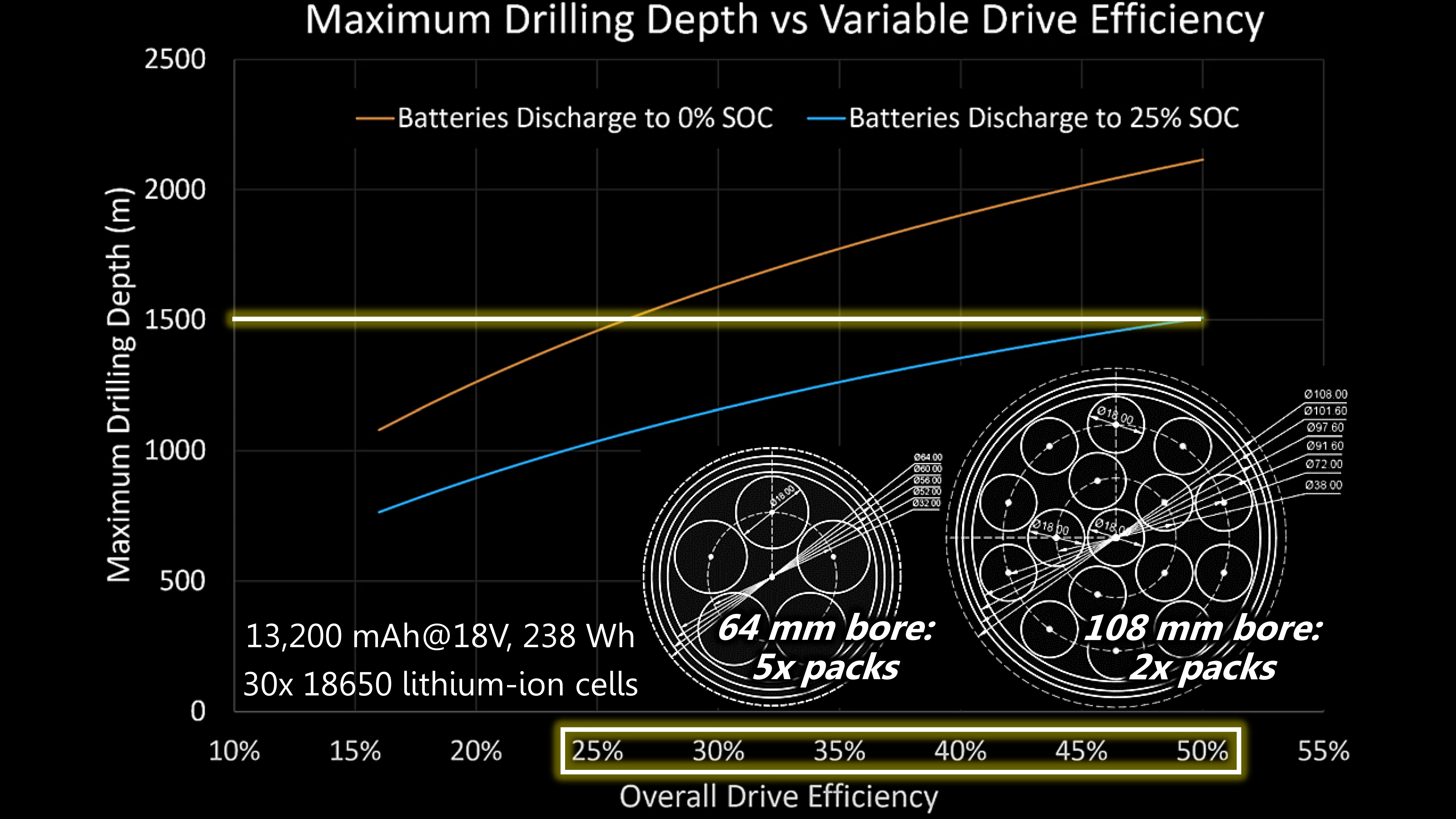
Depth (m)
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
2,200
6,600
11,000
15,400
19,800
24,200
Battery Capacity (mAh)
SPLD regime
Enceladus
Europa
Mars



Depth vs. Operational Power Draw, 0.50 m/s
4400 mAh
6600 mAh
8800 mAh
11000 mAh
13200 mAh
15400 mAh
Depth (m)
(For Mars Gravity)
Operational Power Draw (W)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
50
60
70
80
90
100

The previous plot is designed to be verifiable!

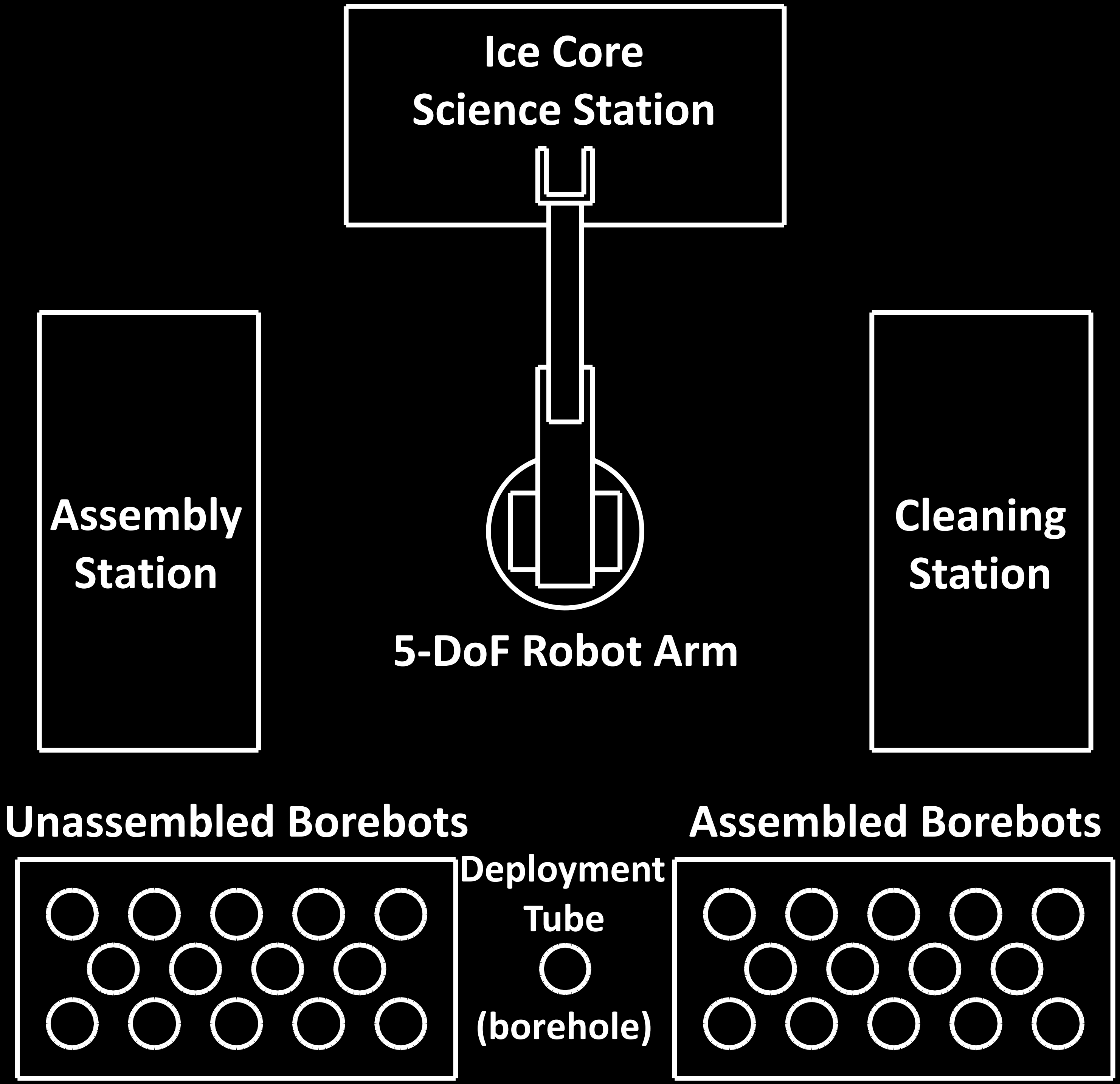
- Drive power = (gravity · borebot mass · velocity) / (system efficiency) + (friction · velocity)
- Depth in meters as a function of power is then:
  - Depth = (velocity/2) · [battery Joules / (power draw) – cumulative drilling time]
- Standard assumptions: 20-watt electronics loads, core length of 0.15 m, fixed bot mass of 10 kg, 12 borebots, 37.5 minutes of drilling time per trip, 18 V battery packs, minimum state of charge (SoC): 25%



Maximum Drilling Depth vs Variable Drive Efficiency
Batteries Discharge to 0% SOC
Batteries Discharge to 25% SOC
Maximum Drilling Depth (m)
2500
2000
1500
1000
500
0
10%
15%
20%
25%
30%
35%
40%
45%
50%
55%
Overall Drive Efficiency
13,200 mAh@18V, 238 Wh
30x 18650 lithium-ion cells
64 mm bore:
5x packs
108 mm bore:
2x packs
Ø108.00
Ø101.60
Ø97.60
Ø91.60
Ø72.00
Ø38.00

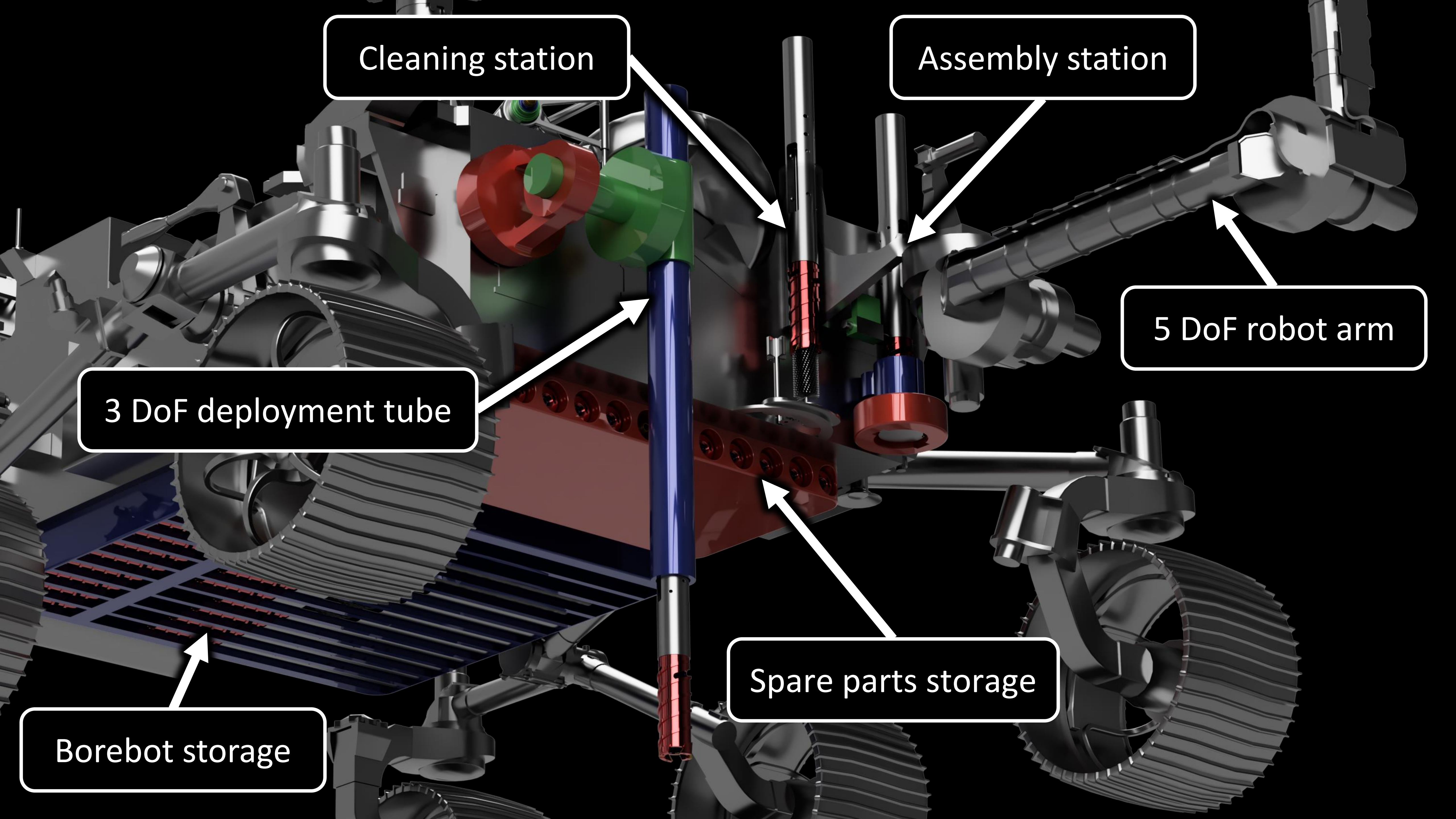
How to Turn a Lander into a Borebot Drill Rig:

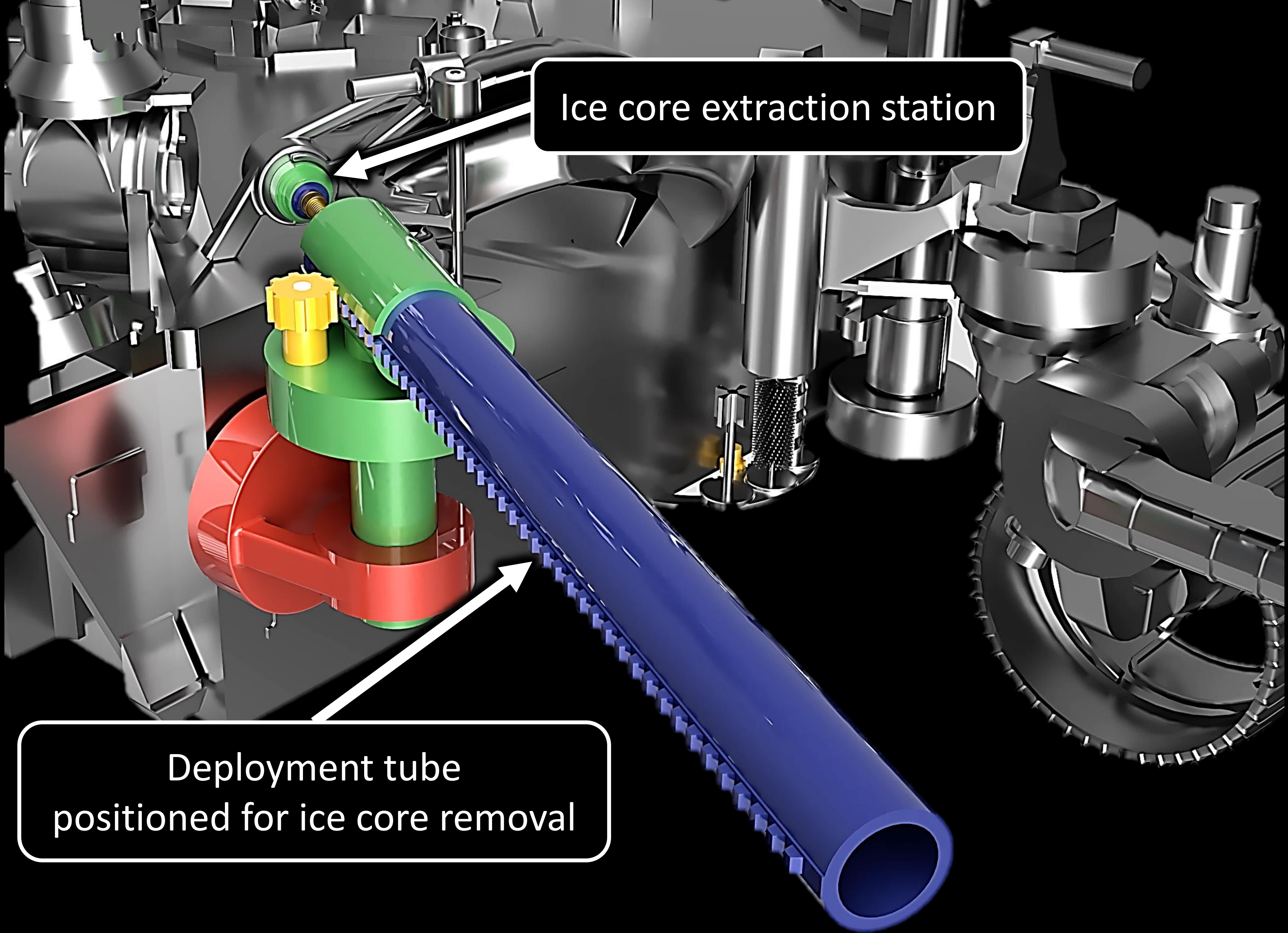
First, picture a state-of-the-art ice drilling facility on Earth, perhaps Antarctica, with a work cell which is centered around a 5 Degree of Freedom (DoF) robot arm.

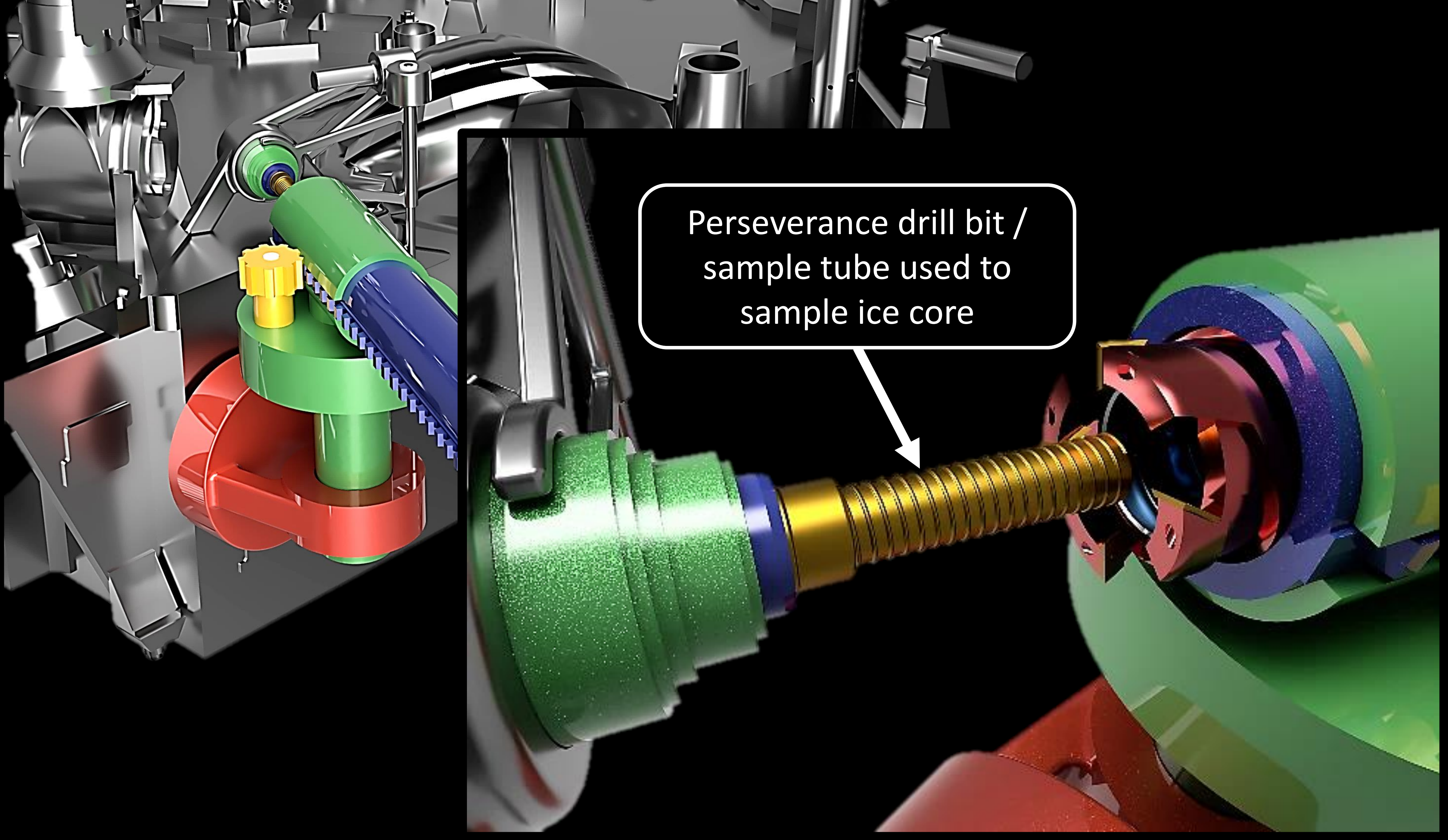

Ice Core
Science Station
Assembly
Station
Cleaning
Station
5-DoF Robot Arm
Unassembled Borebots
Assembled Borebots
Deployment
Tube
(borehole)

Now, let’s turn the Perseverance rover into a drill rig:

- We need to add a “station” on/in the rover to account for each step in the drilling workflow
- We elect for a fancy movable deployment tube, so it can fold out of the way (3 DoF should be enough!)
- We need storage space

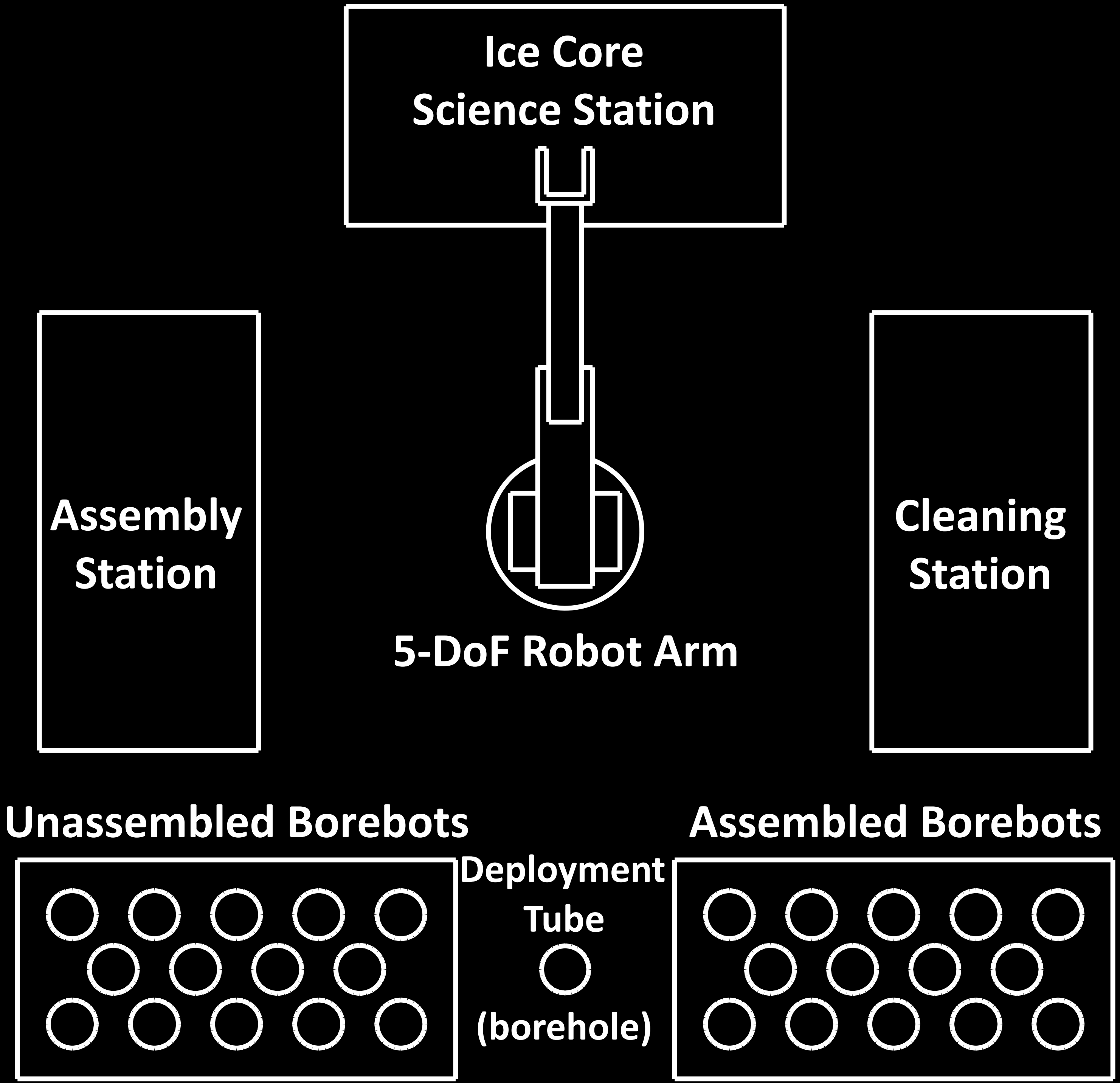

Cleaning station
Assembly station
5 DoF robot arm
3 DoF deployment tube
Spare parts storage
Borebot storage


Ice core extraction station
Deployment tube
positioned for ice core removal

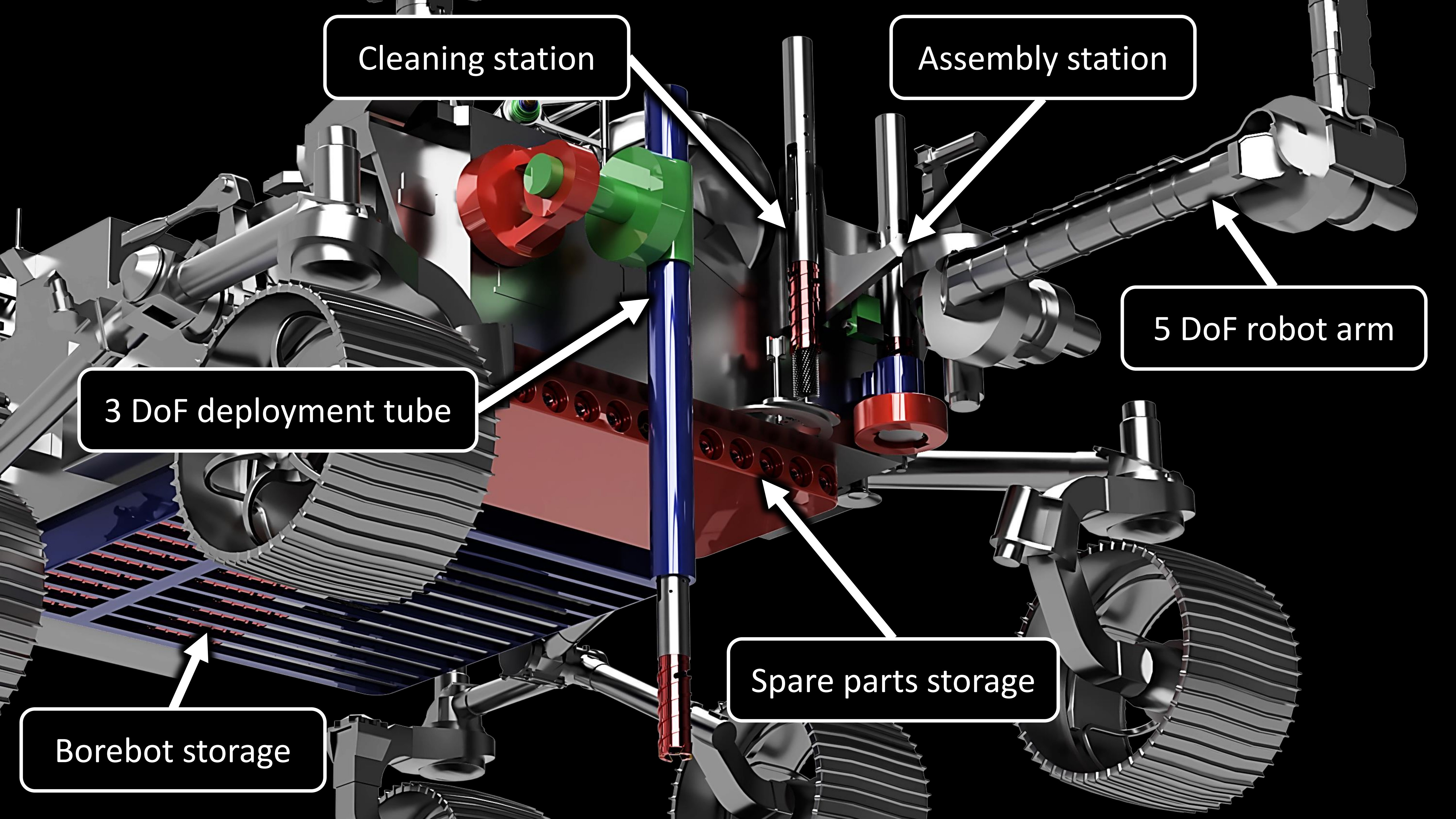

Perseverance drill bit / sample tube used to sample ice core

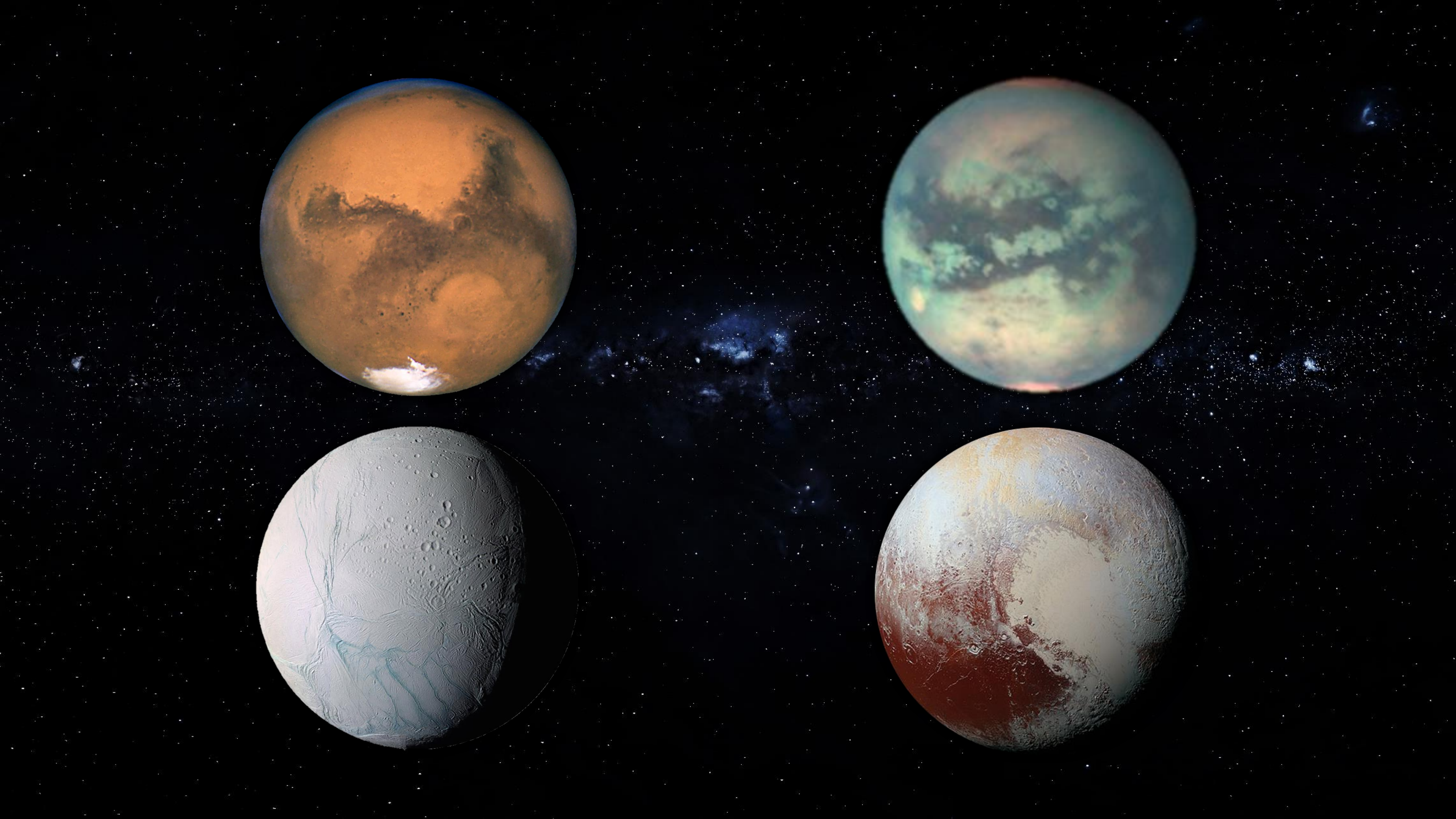
Aside: a better way to sample:

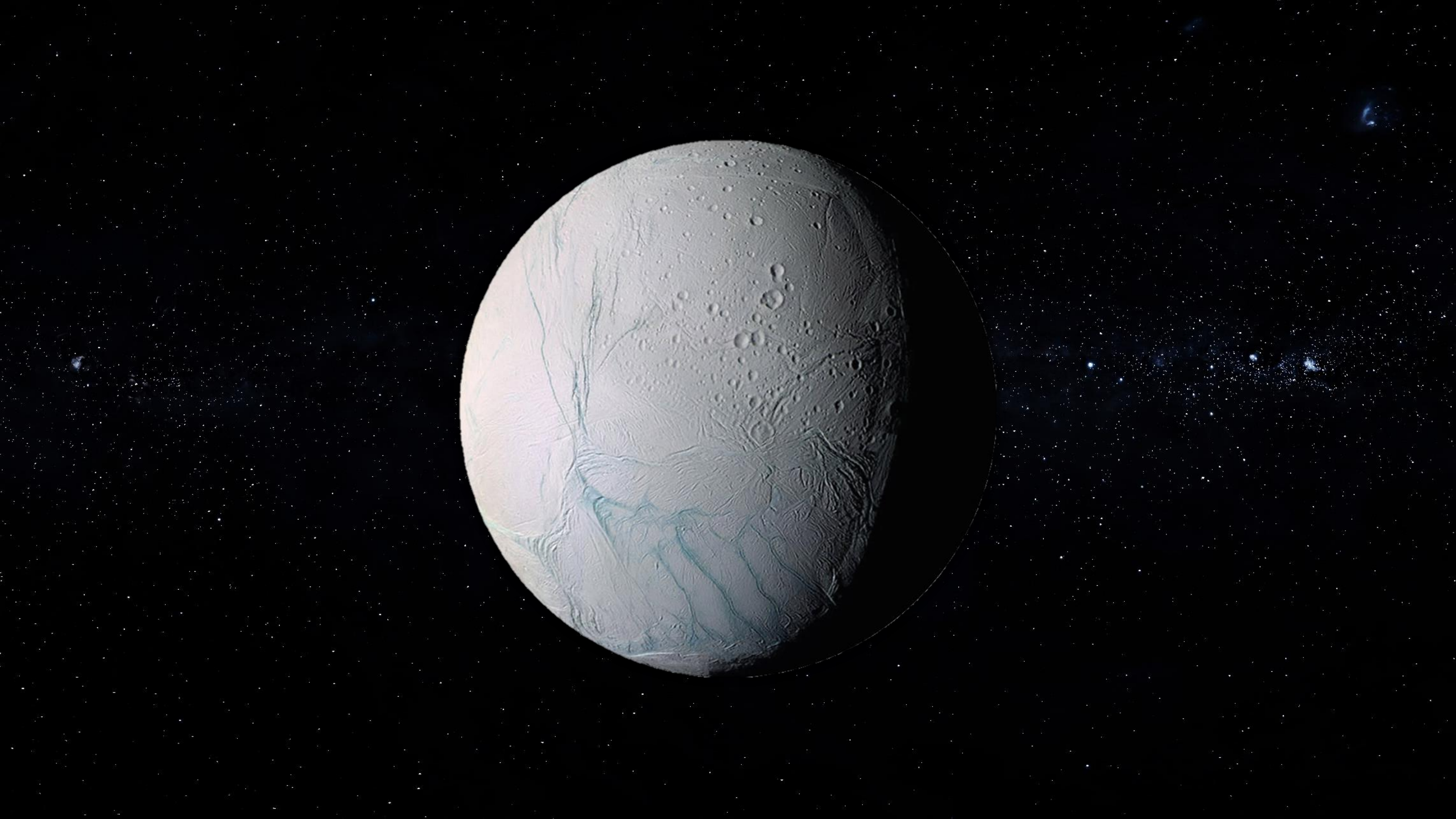
- Use the assembly station to install a Perseverance drill chuck on the end of a borebot
- Take an ice core from the virgin material at the bottom of the borehole
- Offer the drill bit and sample tube to the Adaptive Caching Assembly (ACA) in the same way that the Turret Corer does on Perseverance today



Ice Core
Science Station
Assembly
Station
5-DoF Robot Arm
Cleaning
Station
Unassembled Borebots
Deployment
Tube
(borehole)
Assembled Borebots


Cleaning station
Assembly station
5 DoF robot arm
3 DoF deployment tube
Spare parts storage
Borebot storage





Enceladus

- Enceladus became a star of the Cassini mission about 7 months after arrival at Saturn:
  - Feb. 17th 2005 first flyby found that Enceladus disturbed the magnetic field of Saturn in unexpected ways
  - The second flyby in March discovered the south polar plumes, which were confirmed in July 2005
  - Cassini flew through the plumes in 2015
- At its thickest, the water ice crust is 26 km thick

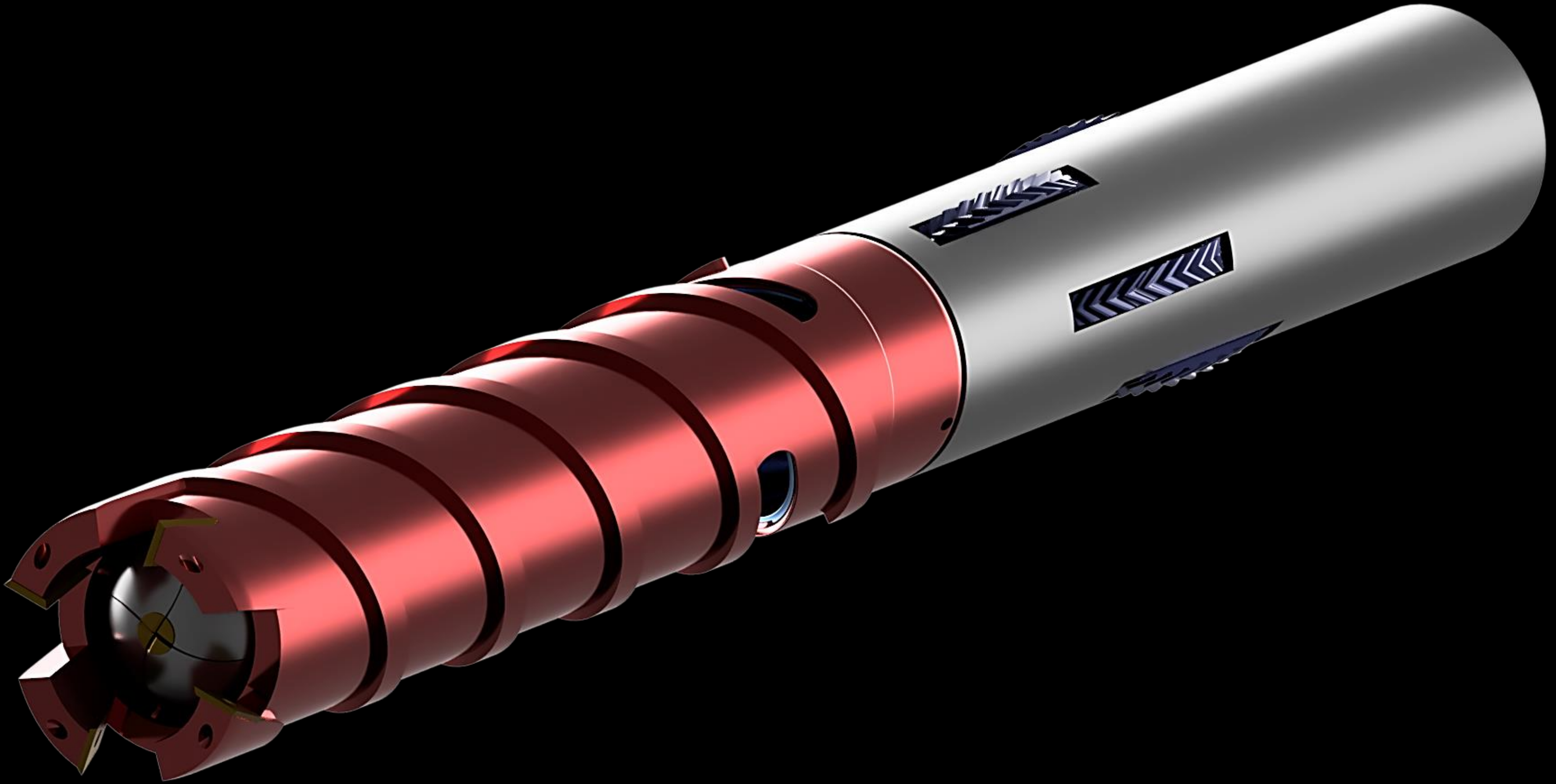
Larger borebots are possible, yet hard to handle

- The main advantage to larger borebots is extracting a longer core, reducing the number of total trips
- However, larger borebots means you can bring fewer
  - This increases the cycles-per-bot, offsetting the advantage
- Since the ice on Enceladus is about 10 times thicker than on Mars, we want a core length of around 1.5 m
- A 0.5 m * 1.5 m ice core will weigh around 290 kg (!)

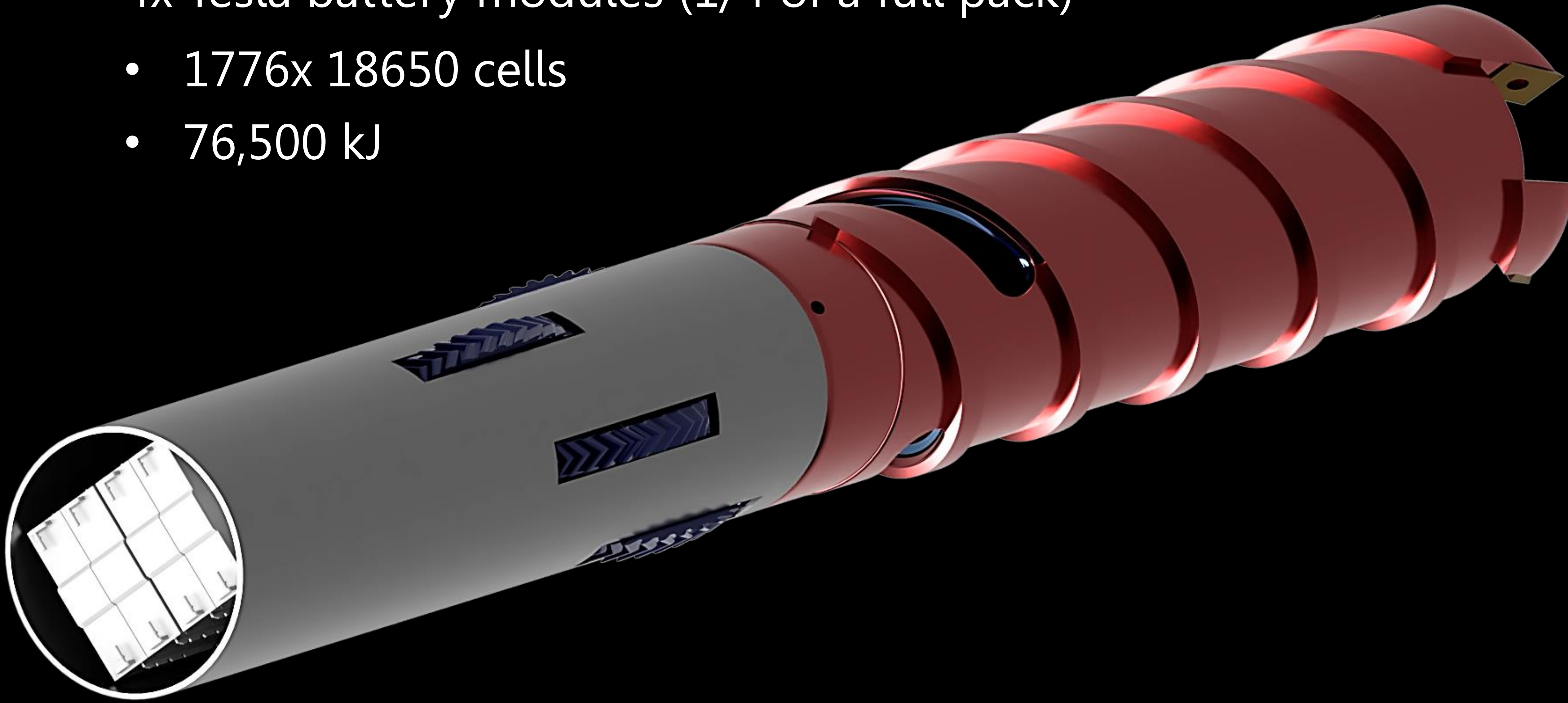
Big-bore Borebot for Enceladus

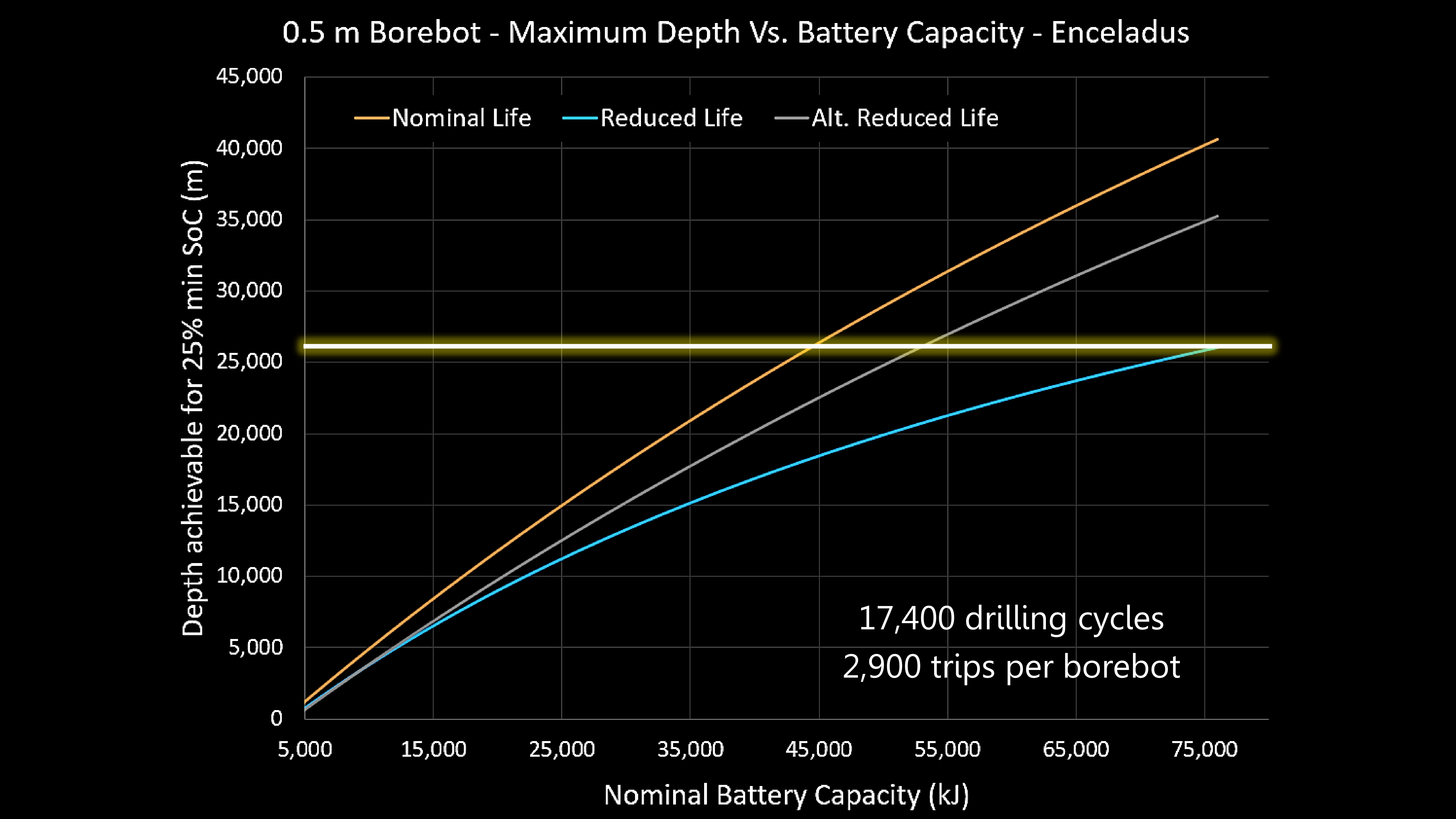
Shown at left next to a full-size fridge.

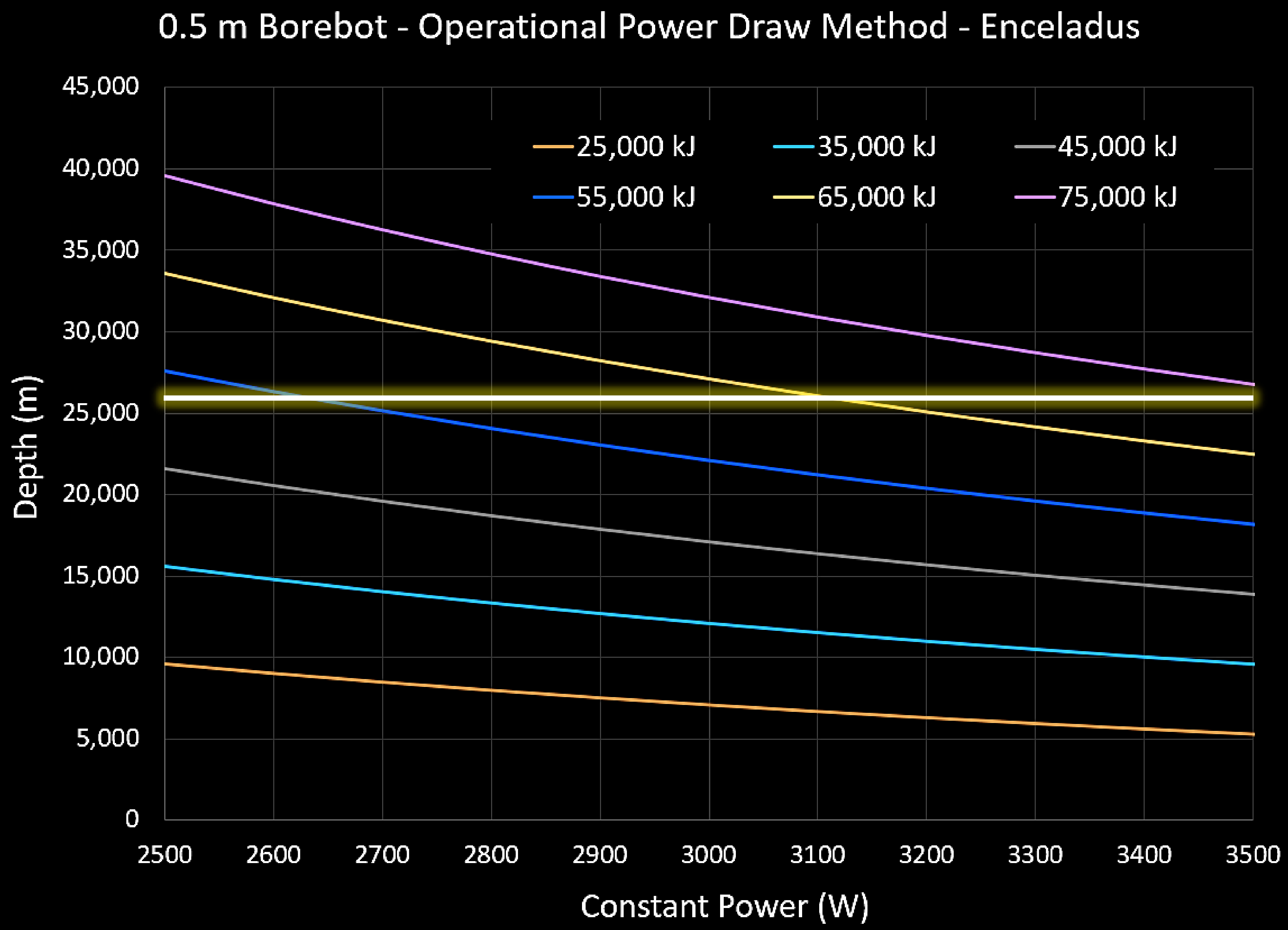
- 0.5 meters in diameter
- 4 meters long
- 600 kg fully loaded
- 6x tracks, 50 mm x 500 mm
  - 0.15 m^2 tractive area
  - 1250 N/m^2 shear loading
    - 30x less than car tires during braking



- 4x Tesla battery modules (1/4 of a full pack)
  - 1776x 18650 cells
  - 76,500 kJ




0.5 m Borebot - Maximum Depth Vs. Battery Capacity - Enceladus
Nominal Life
Reduced Life
Alt. Reduced Life
Depth achievable for 25% min SoC (m)
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
5,000
15,000
25,000
35,000
45,000
55,000
65,000
75,000
Nominal Battery Capacity (kJ)
17,400 drilling cycles
2,900 trips per borebot

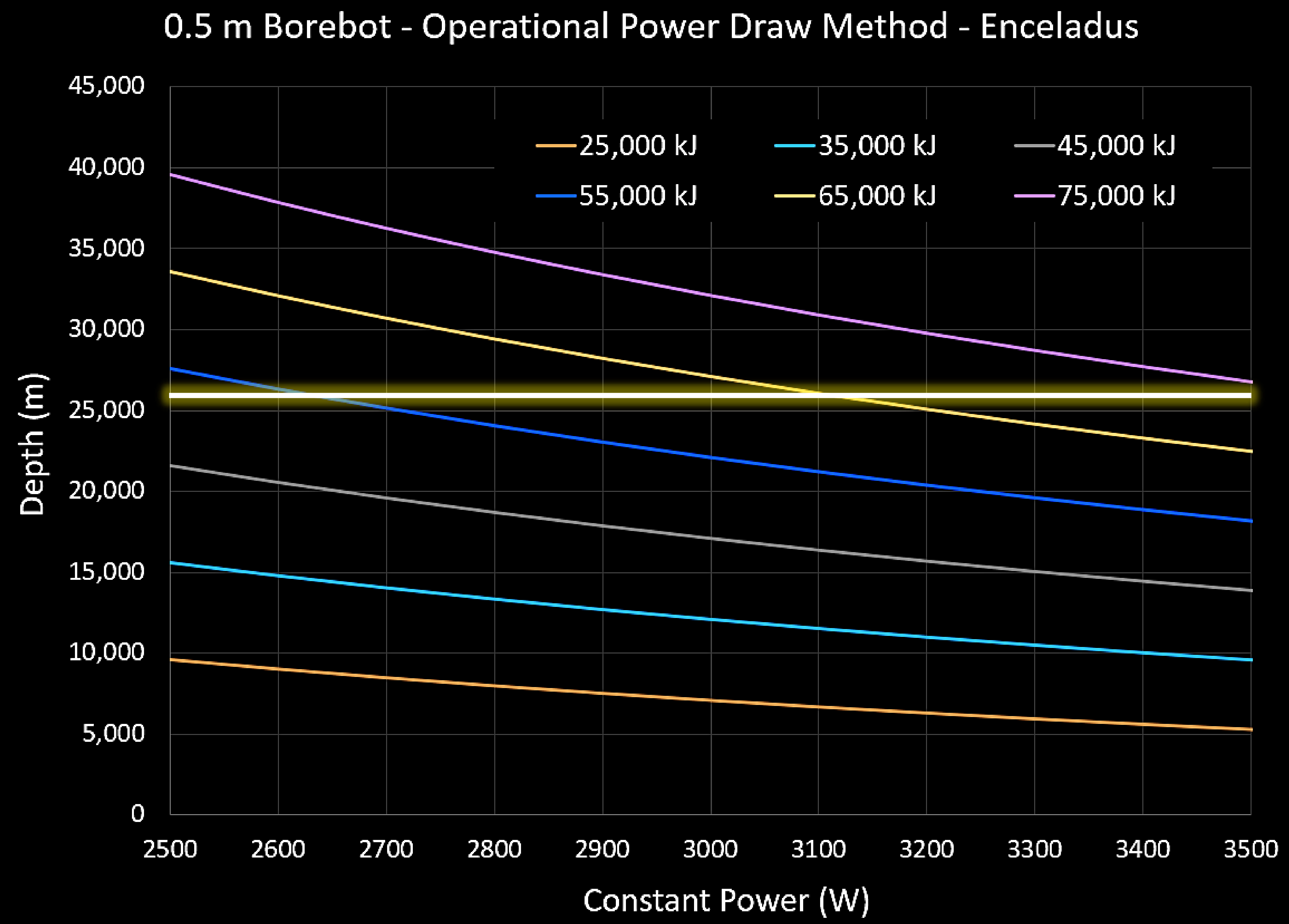

0.5 m Borebot - Operational Power Draw Method - Enceladus
Depth (m)
Constant Power (W)
25,000 kJ
35,000 kJ
45,000 kJ
55,000 kJ
65,000 kJ
75,000 kJ
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
45,000
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500

Note: the “other 100 kg” comes from our “extra battery” calculations

g	0.311	m/s^2
Bot Mass	500	kg
Gravity Force	155.5	N
Hotel Power	104.68	Watts
dH (core length)	1.5	m
Drive Speed	3	m/s
Drive Friction	100	N
Drive Eff (overall)	50%	
Est. Drive Power	1233	Watts

Number of bots	6	dim
Drill Energy total	1800000	J
Drill time	3600	seconds
Drill Power	500.000	W
Additional Hotel	100	W
Total Load Drilling	1837.68	W
Total load Driving	1337.68	W

Ice Sheet Thickness	26000	m
Trips to Bottom	17333	
Trips per Bot	2889	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25,000 kJ
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Depth (m)
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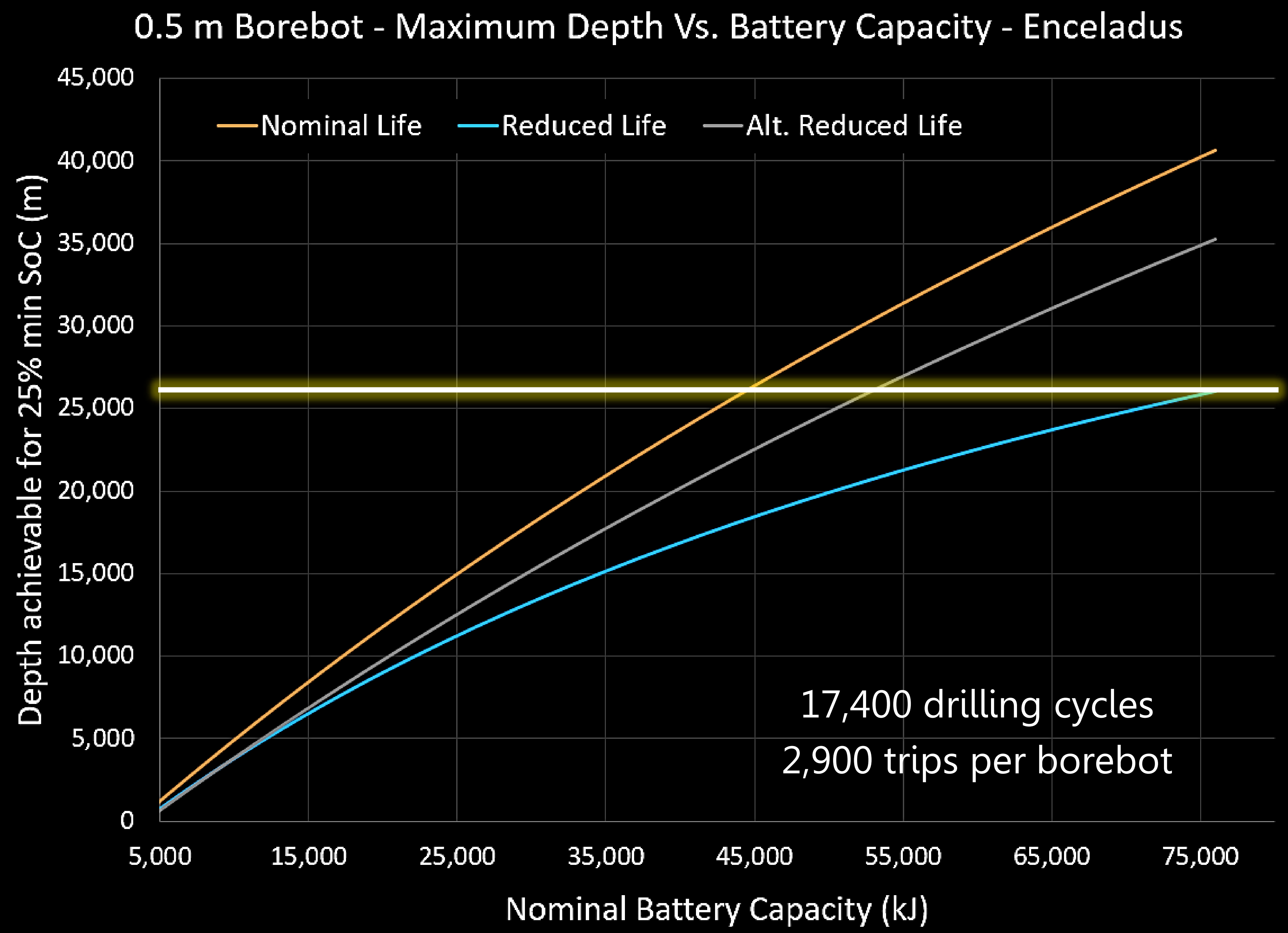
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
45,000
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500
Constant Power (W)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Reduced Life
Alt. Reduced Life
Depth achievable for 25% min SoC (m)
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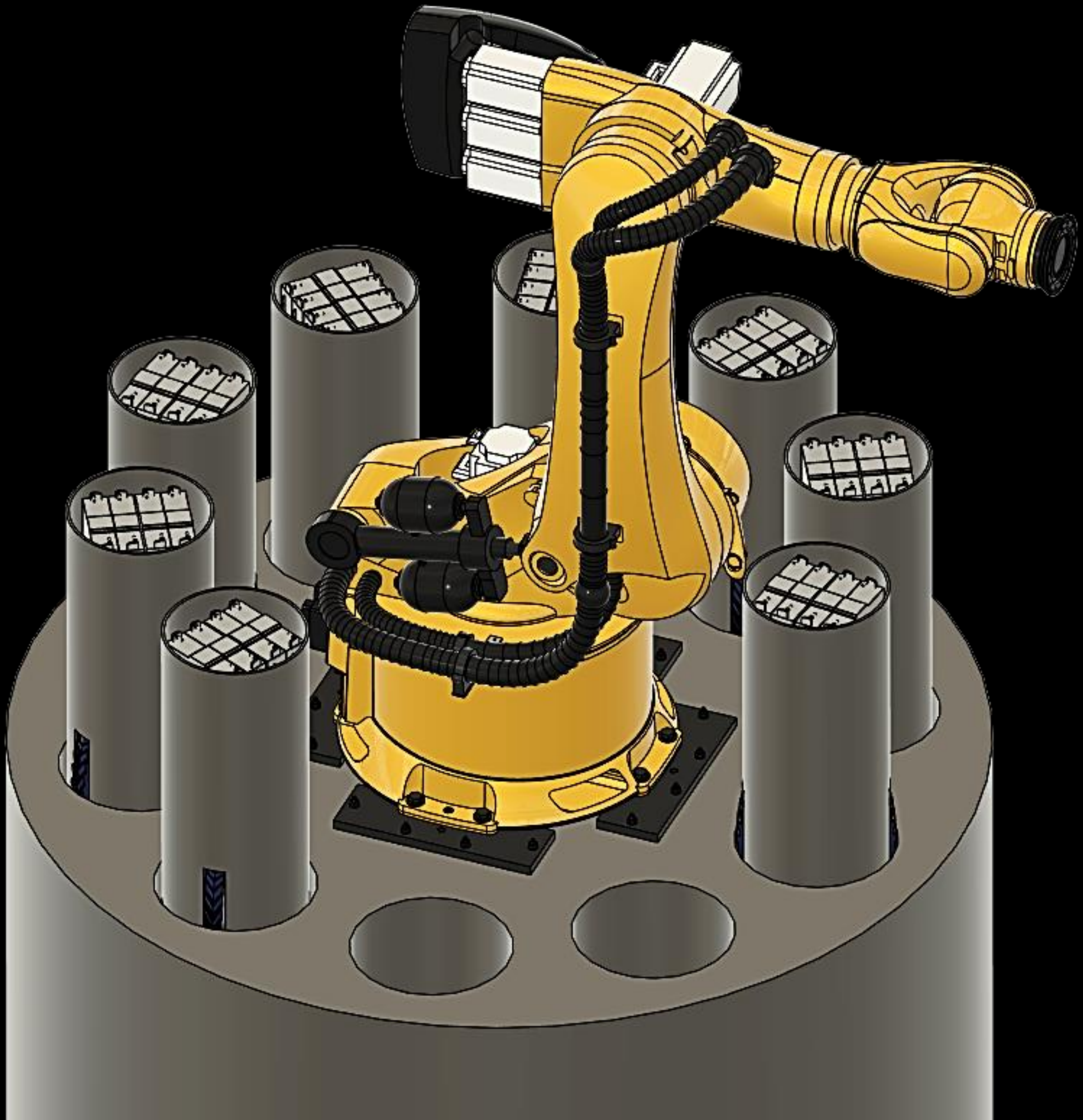
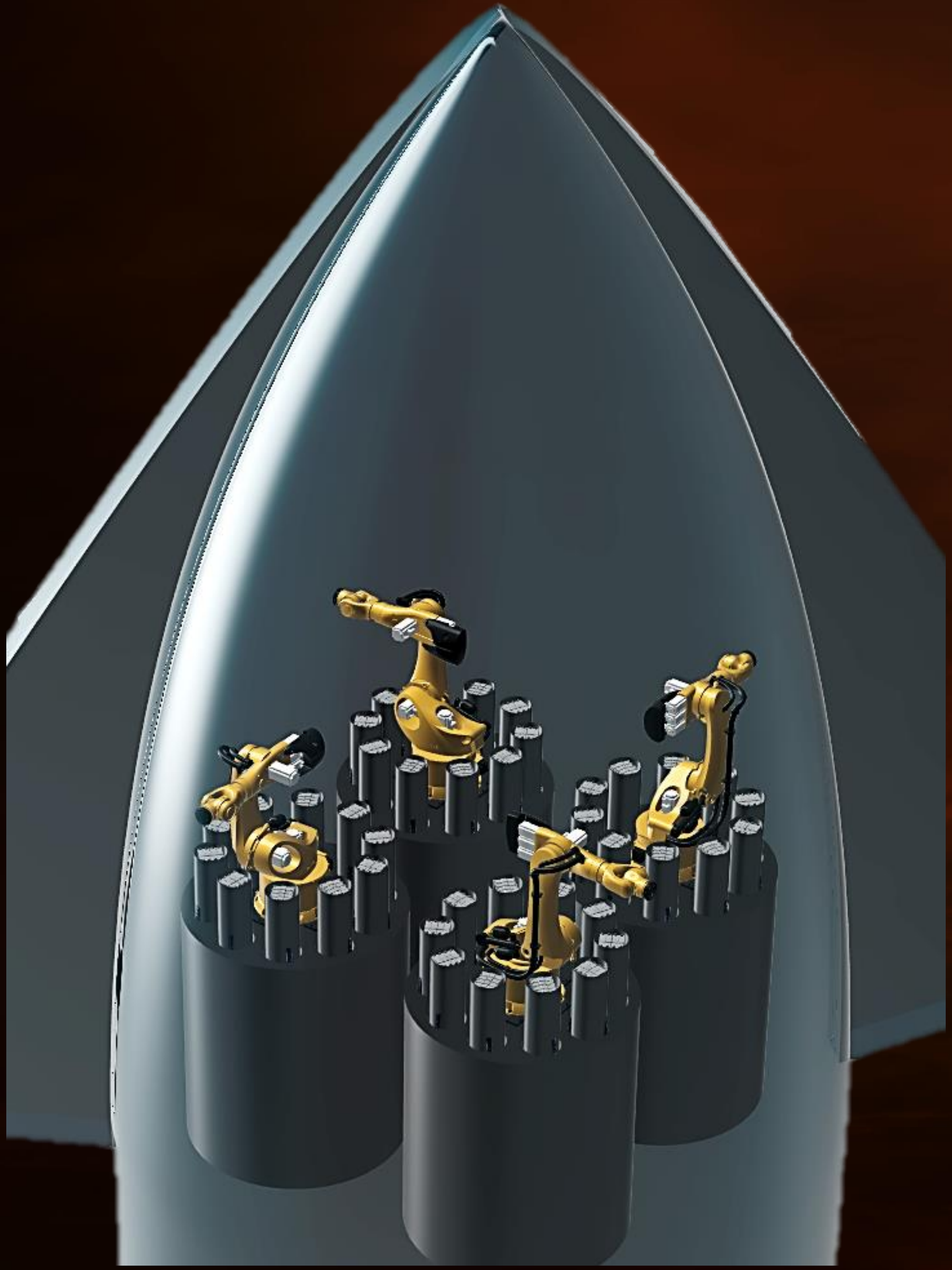
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
5,000
15,000
25,000
35,000
45,000
55,000
65,000
75,000
Nominal Battery Capacity (kJ)
17,400 drilling cycles
2,900 trips per borebot

What's the catch?

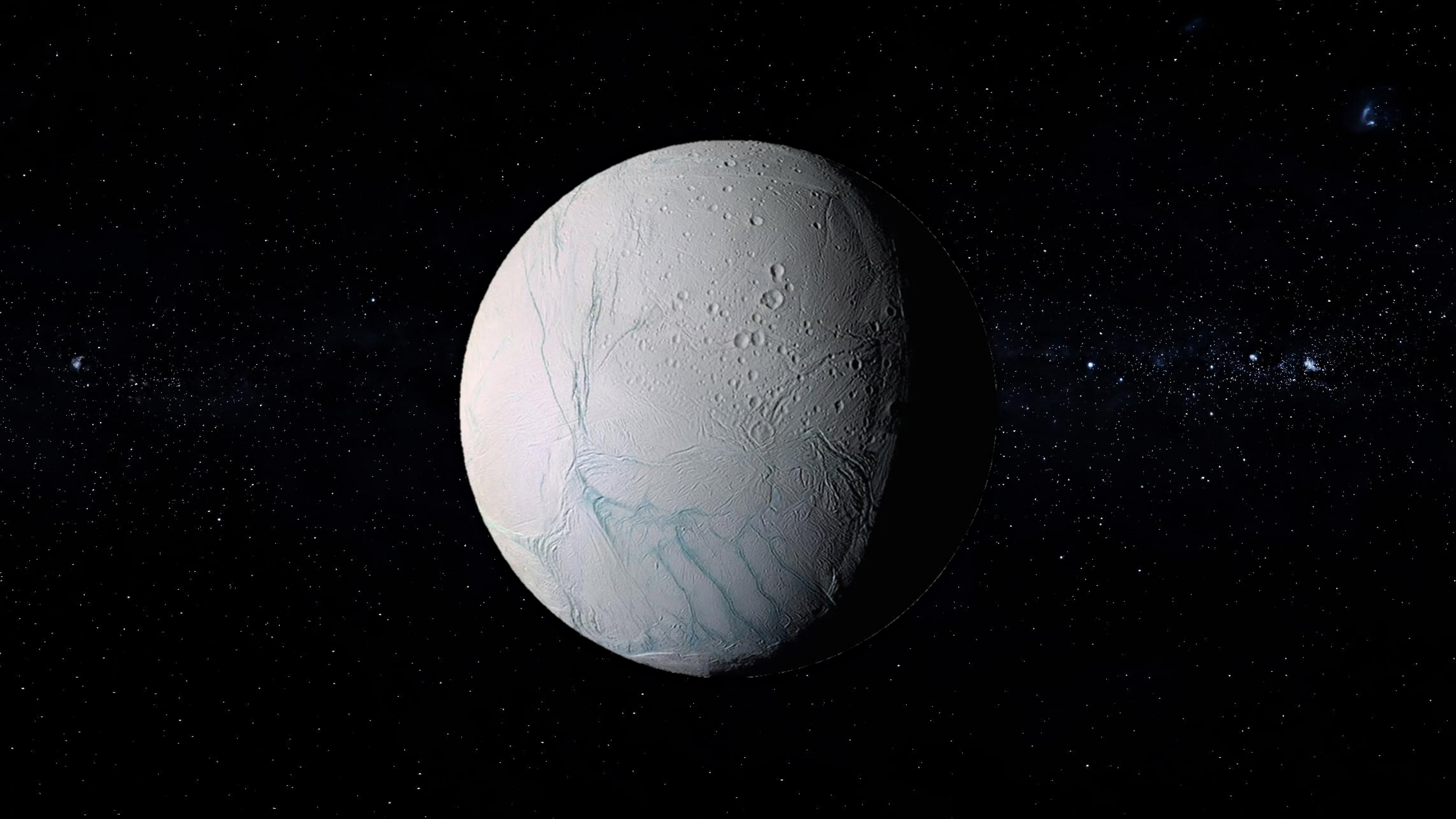
- We need a robust robotic system for handling 600 kg drilling robots that are 4-5 m long (up to 6 of them)
- The lander would need to charge borebots (~5 kW)
  - This would require some kind of reactor (RTGs are out)
  - Each borebot *could* have an RTG to trickle-charge itself

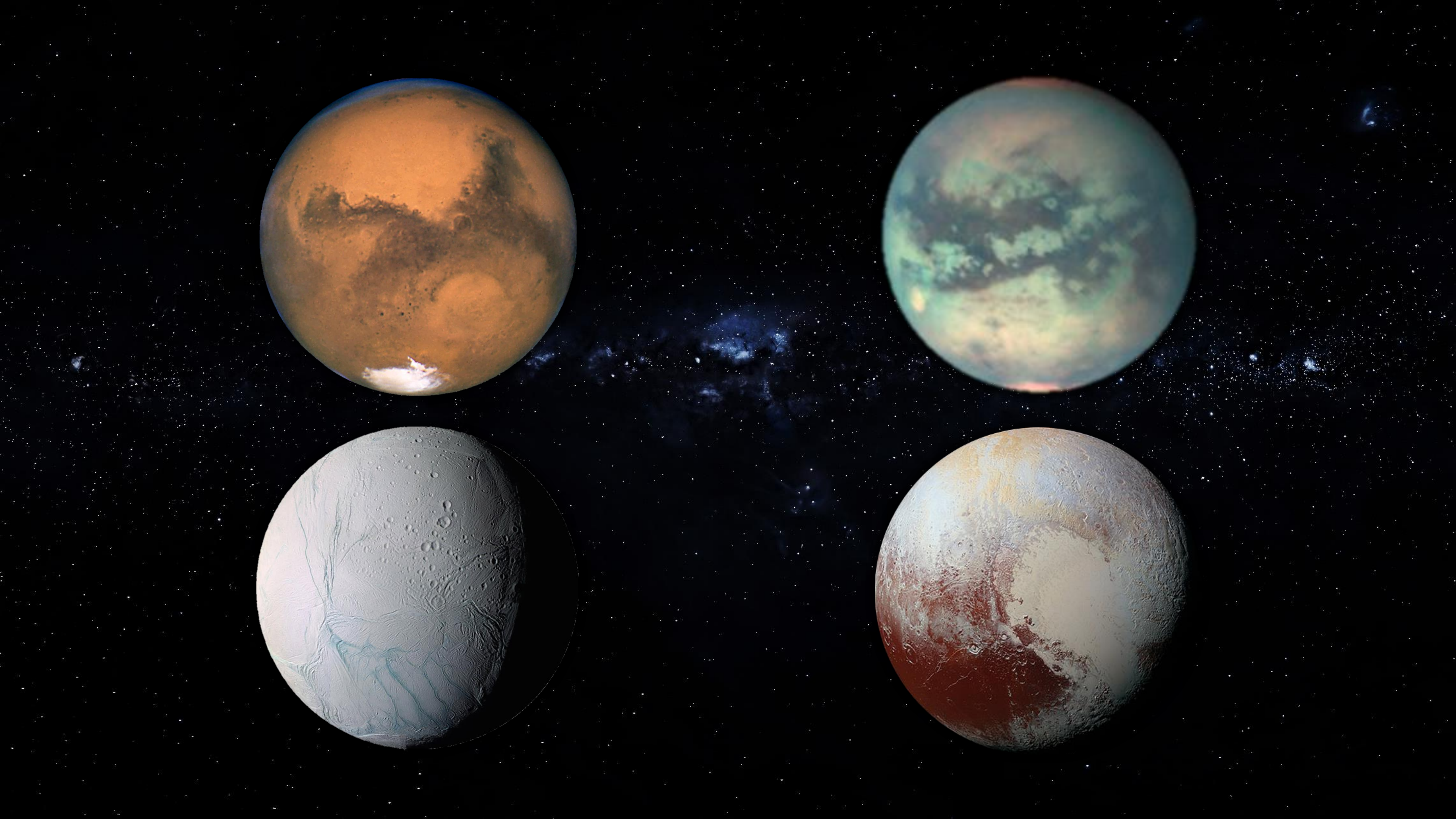


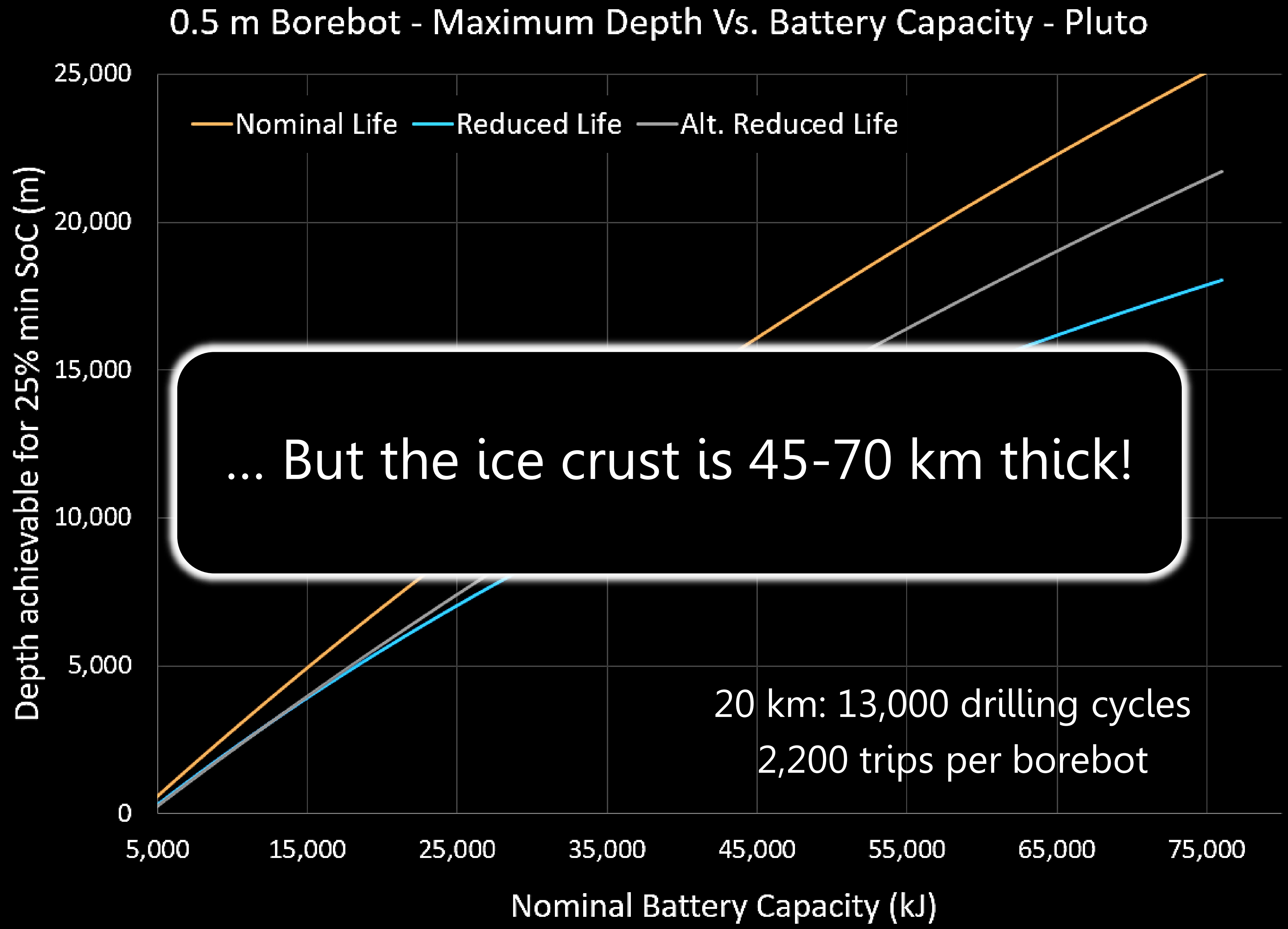


Launch vehicle context

- Starship (with orbital refueling) is a “100 tons to anywhere” rocket
- Four of these modules together (with internal systems, etc.) could weigh around 50 tons
- For Enceladus, you need a landing system that works without an atmosphere, so Starship makes sense for this





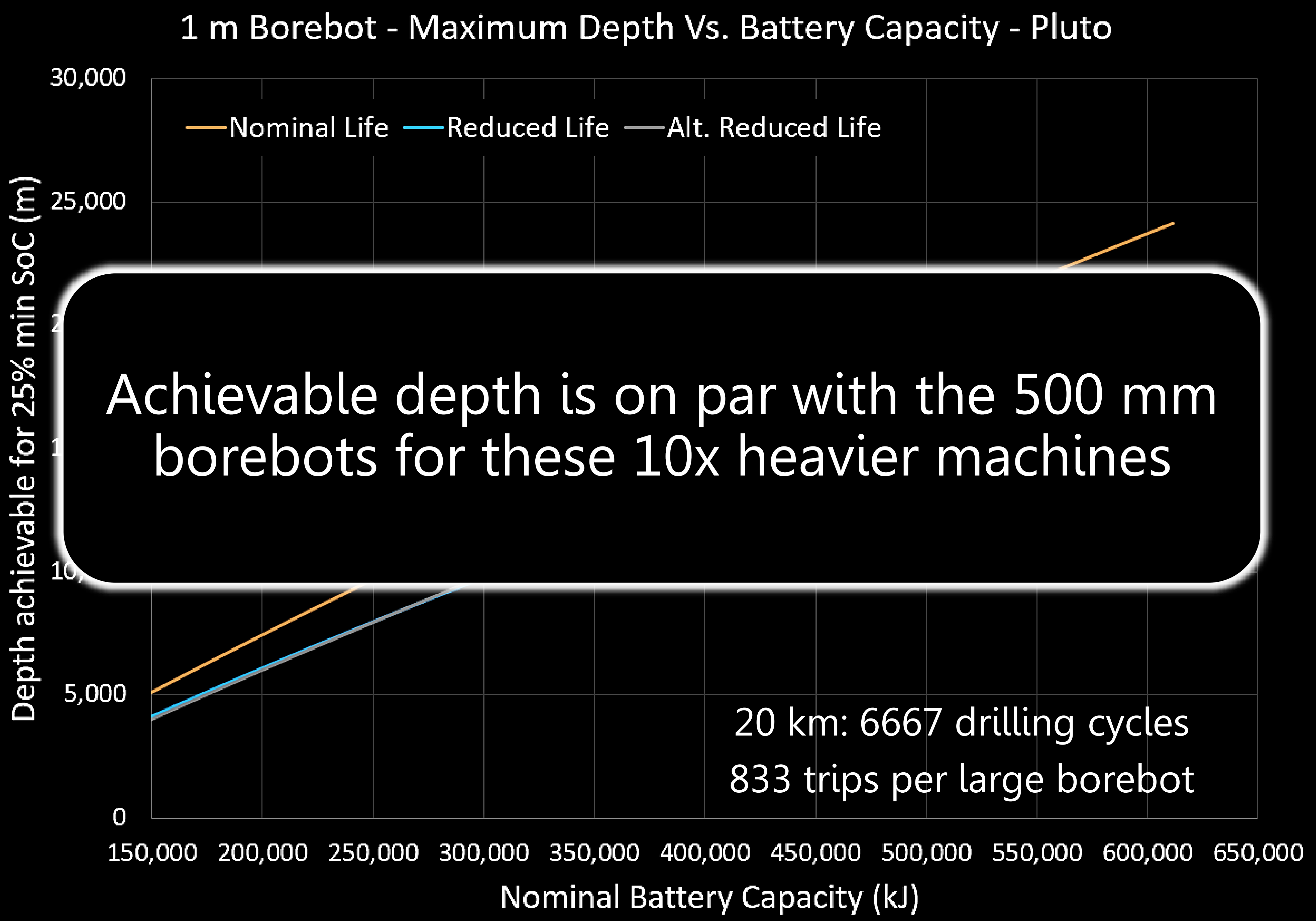

0.5 m Borebot - Maximum Depth Vs. Battery Capacity - Pluto
Nominal Life
Reduced Life
Alt. Reduced Life
Depth achievable for 25% min SoC (m)
25,000
20,000
15,000
10,000
5,000
0
5,000
15,000
25,000
35,000
45,000
55,000
65,000
75,000
Nominal Battery Capacity (kJ)
… But the ice crust is 45-70 km thick!
20 km: 13,000 drilling cycles
2,200 trips per borebot

We're about to go off the rails…

… Fifth graders, I might need you!

Pluto

- Pluto’s ice is 45-70 km thick
- Our strategy centers around two core ideas:
    1. One-meter-diameter, 7-meter-long, 6000 kg borebots
        - Note: it’s 2350 kg for a 3-meter-long, 1-meter-diameter ice core
    2. Every 20 km, we drop down to a smaller borebot class
- Ocean access may be possible with a 100-ton payload


1 m Borebot - Maximum Depth Vs. Battery Capacity - Pluto
Nominal Life
Reduced Life
Alt. Reduced Life
Depth achievable for 25% min SoC (m)
30,000
25,000
5,000
0
150,000
200,000
250,000
300,000
350,000
400,000
450,000
500,000
550,000
600,000
650,000
Nominal Battery Capacity (kJ)
Achievable depth is on par with the 500 mm borebots for these 10x heavier machines
20 km: 6667 drilling cycles
833 trips per large borebot

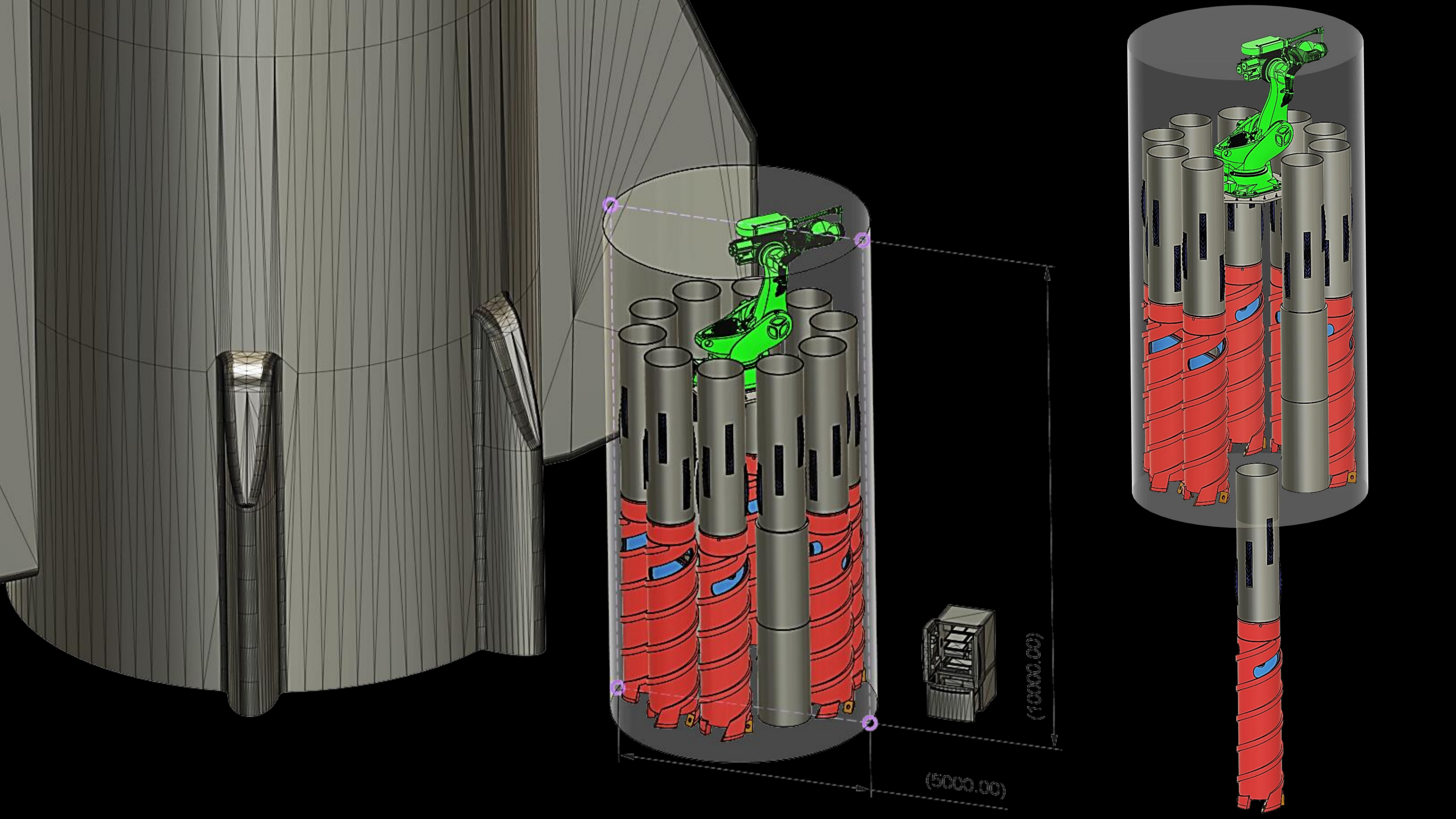
Pluto

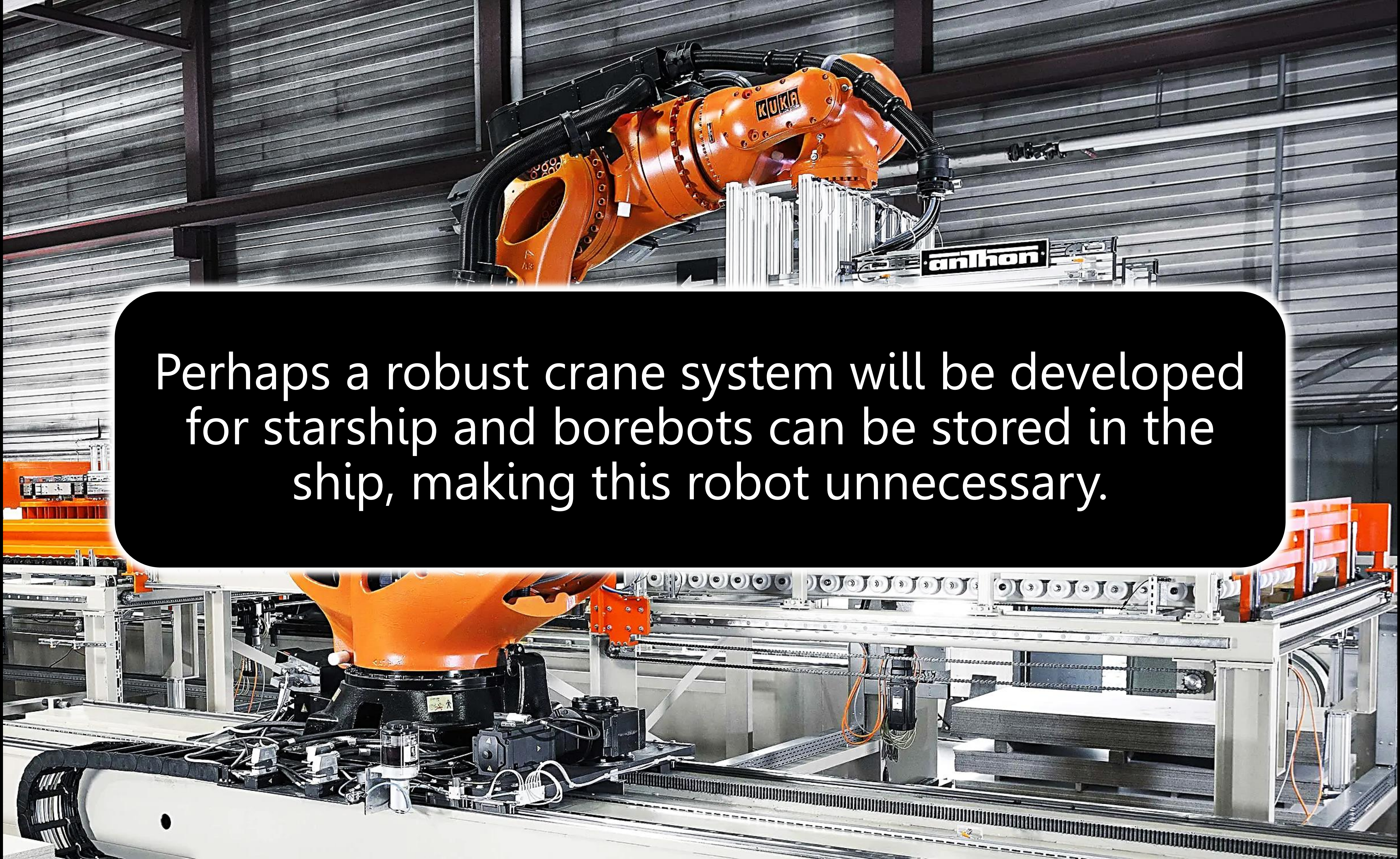
- With 8x the batteries, achievable depth is on par with the 500 mm borebots for these 10x heavier machines
- Some of our assumptions start to break down at this point, but the error is to our advantage:
  - We neglect things like regenerative braking
  - We assume mass is the same on the way down/up
    - For a 10 kg borebot, core weight *is* negligible! You also can't regen brake, you actually have to *spend energy* going down
  - We neglect the change in gravity as we descend

Pluto

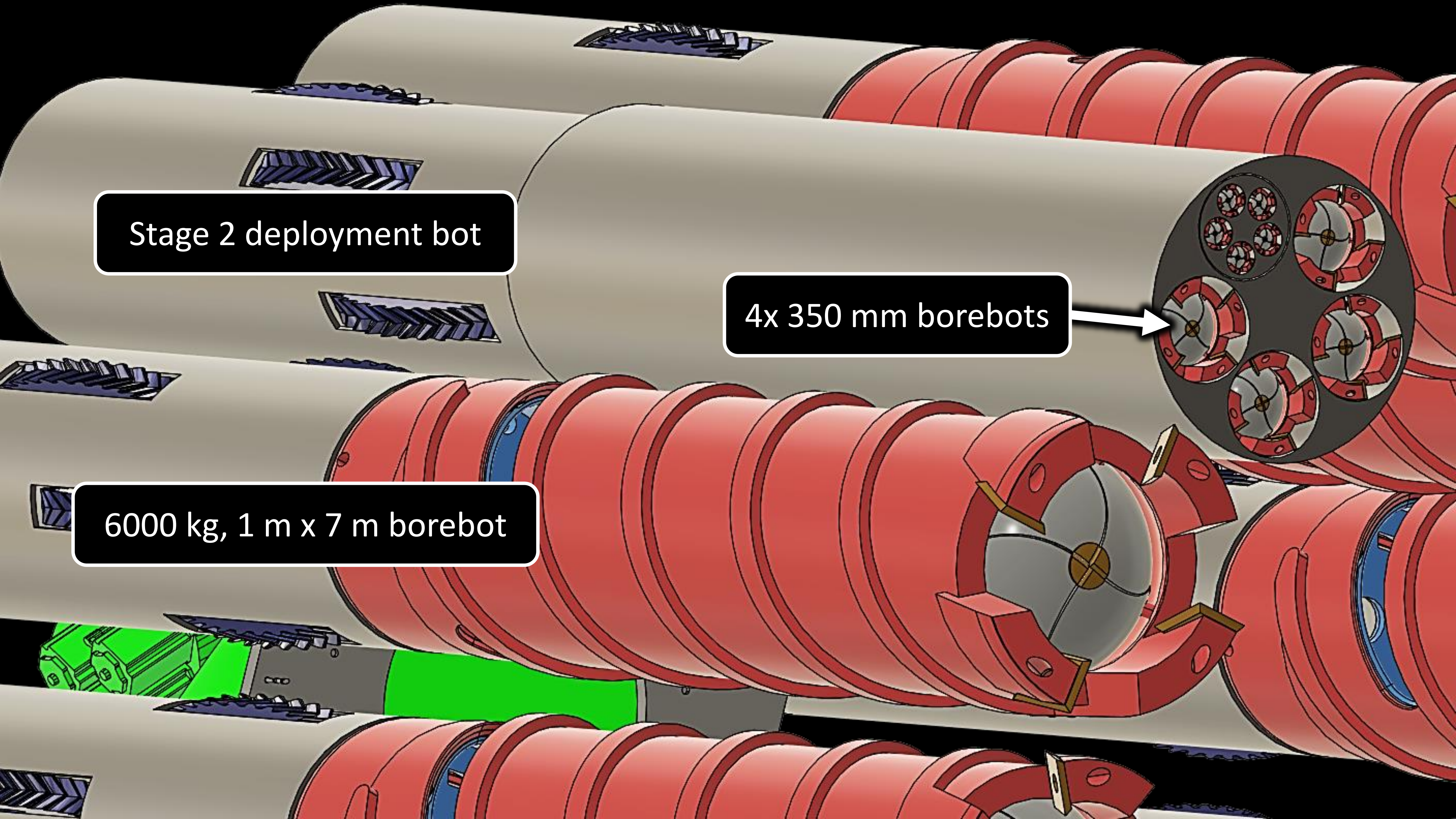
Power is a whole thing for this context

- 500 W RTG **required** to trickle charge sub-scale drills
- A small fission reactor is likely required at the surface
  - Could potentially “charge” RTG material in-situ (ref. Chris Morrison / USNC “EmberCore” NIAC tech)
    - The idea here is we would only have to permit the main reactor, and the “charged” RTG batteries could be a much hotter isotope

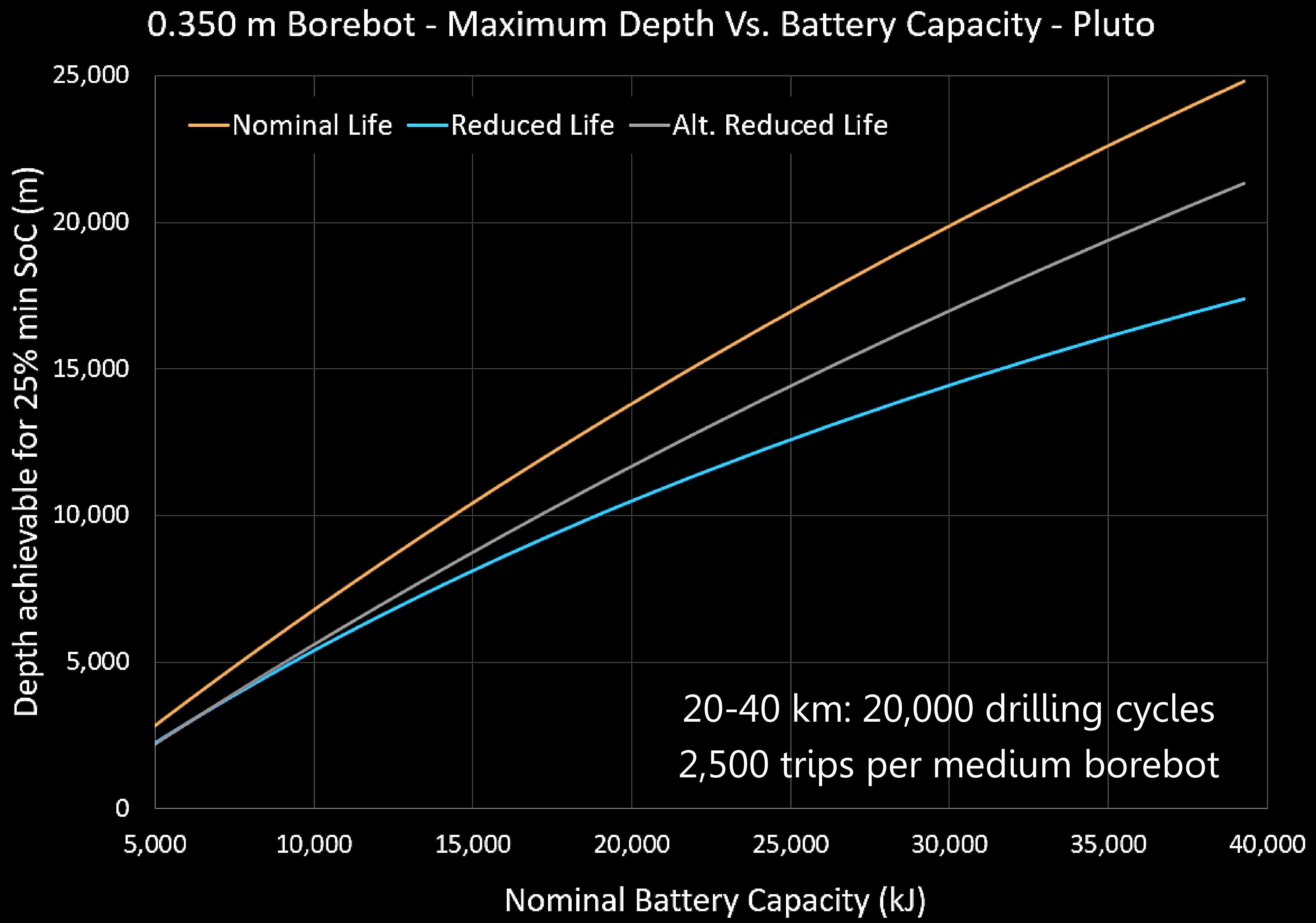

(10000.00)
(5000.00)

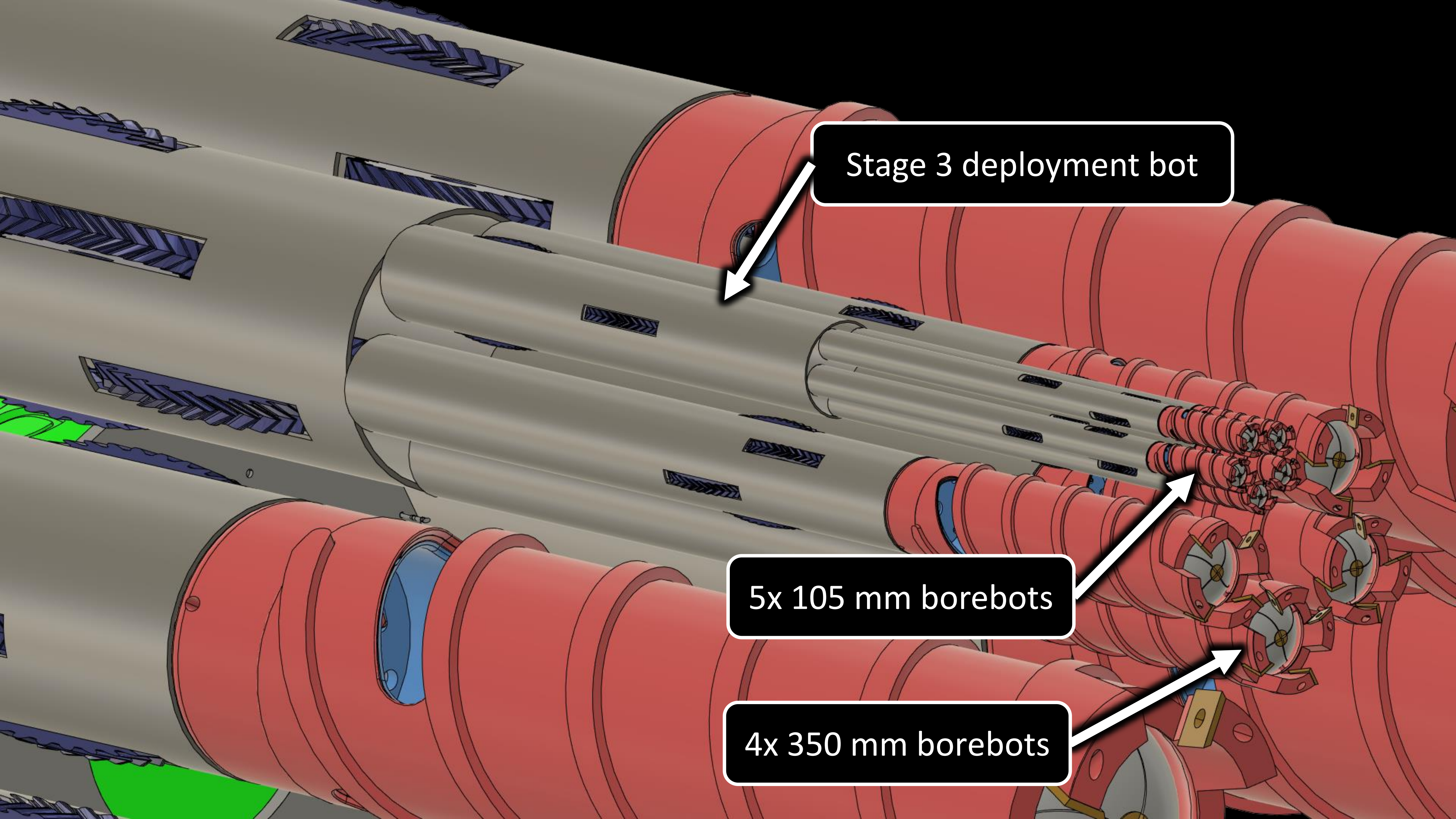


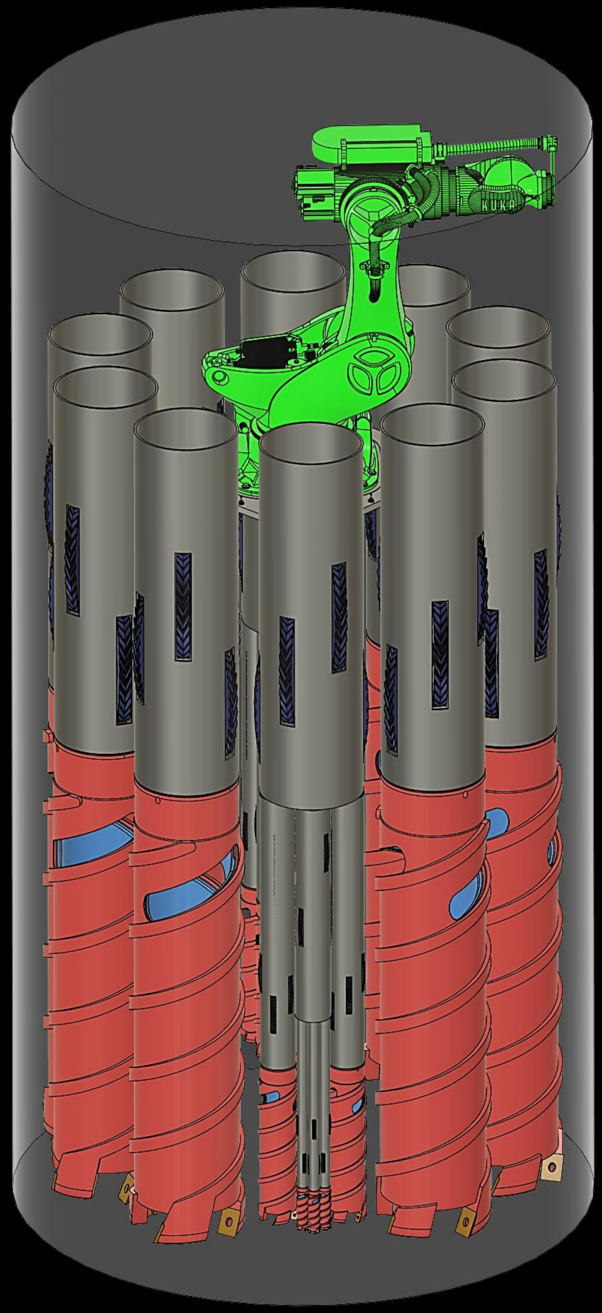
Perhaps a robust crane system will be developed for starship and borebots can be stored in the ship, making this robot unnecessary.



Stage 2 deployment bot
4x 350 mm borebots
6000 kg, 1 m x 7 m borebot

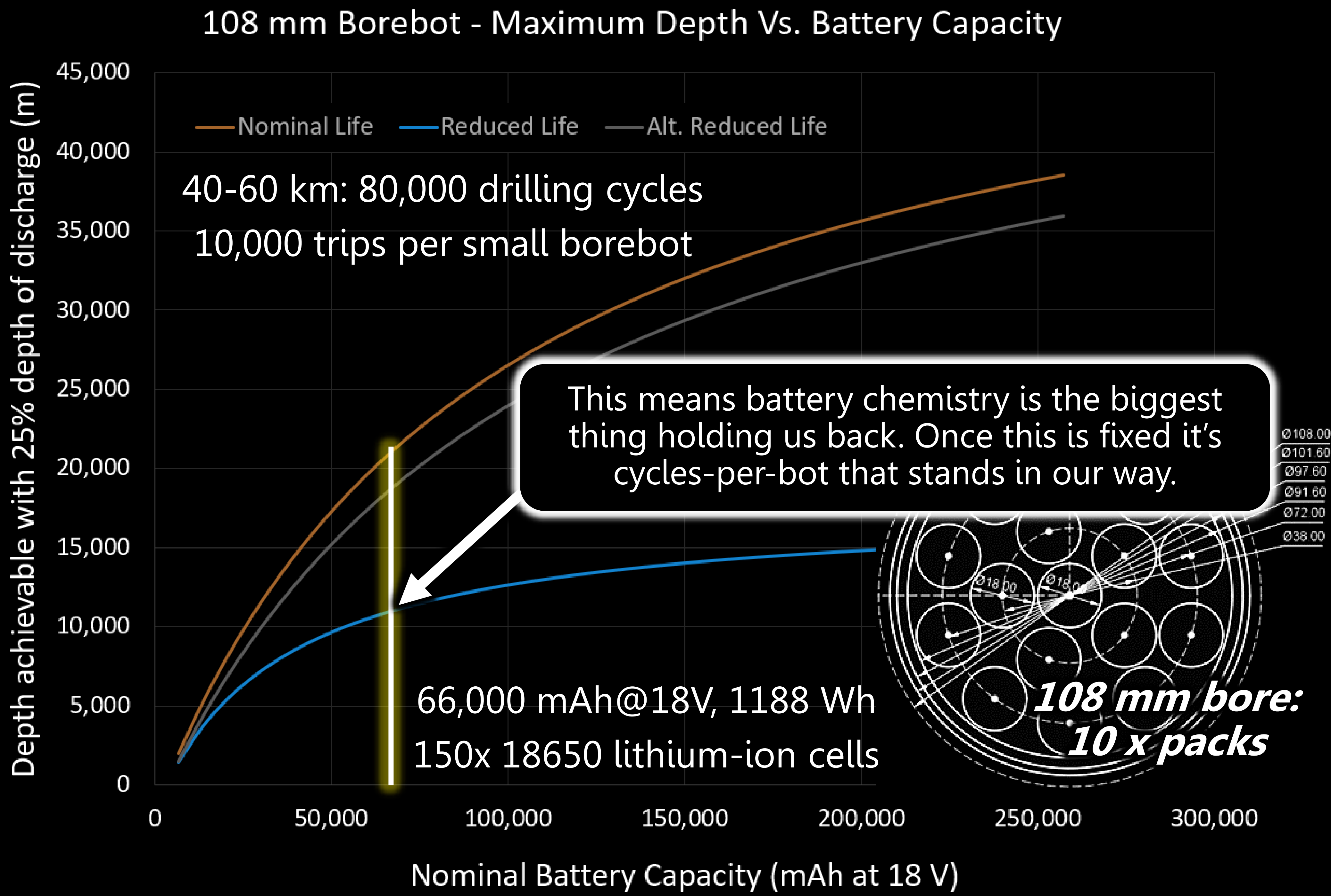

0.350 m Borebot - Maximum Depth Vs. Battery Capacity - Pluto
Nominal Life
Reduced Life
Alt. Reduced Life
Depth achievable for 25% min SoC (m)
25,000
20,000
15,000
10,000
5,000
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
Nominal Battery Capacity (kJ)
20-40 km: 20,000 drilling cycles
2,500 trips per medium borebot

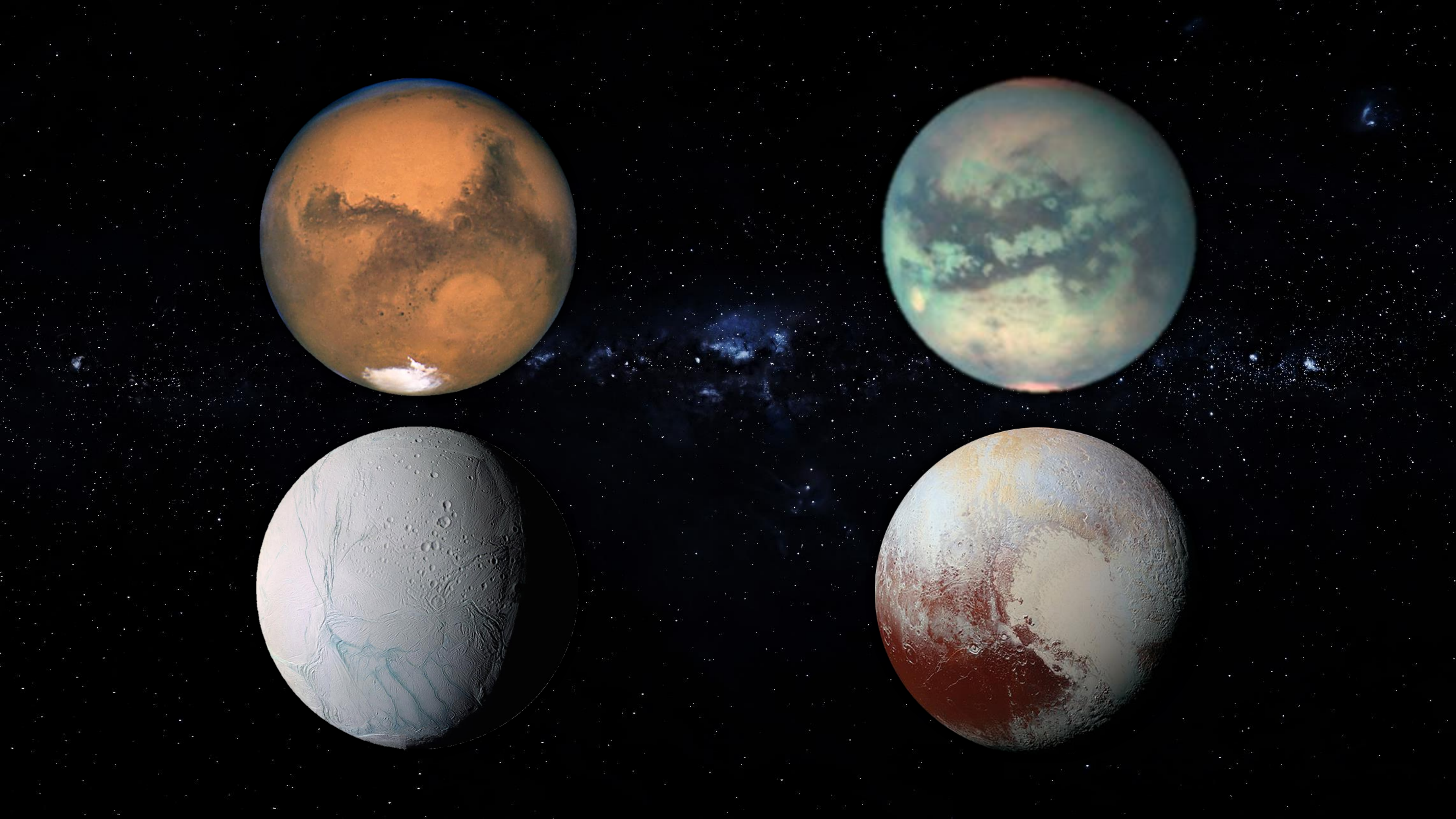

Stage 3 deployment bot
5x 105 mm borebots
4x 350 mm borebots

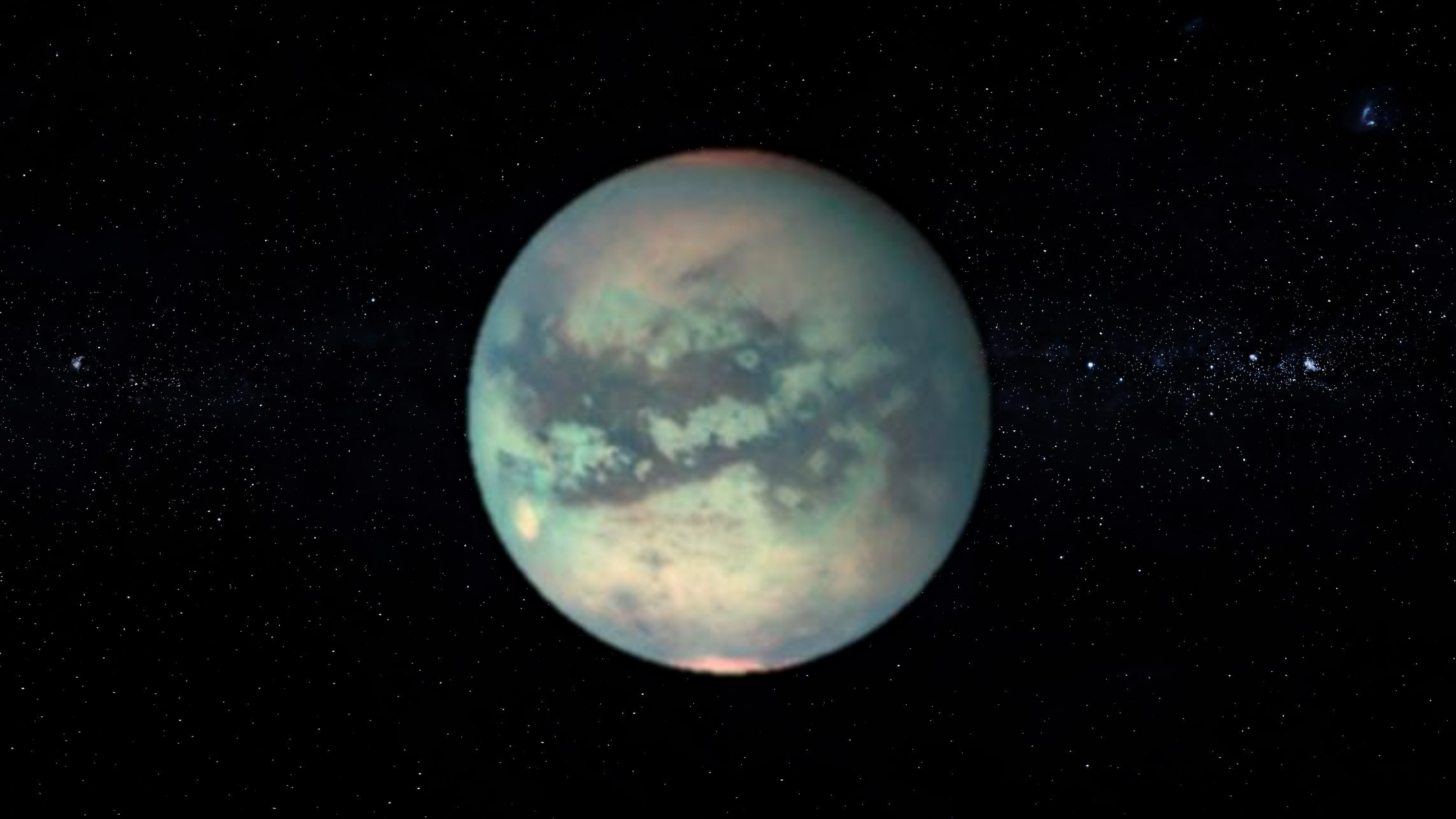


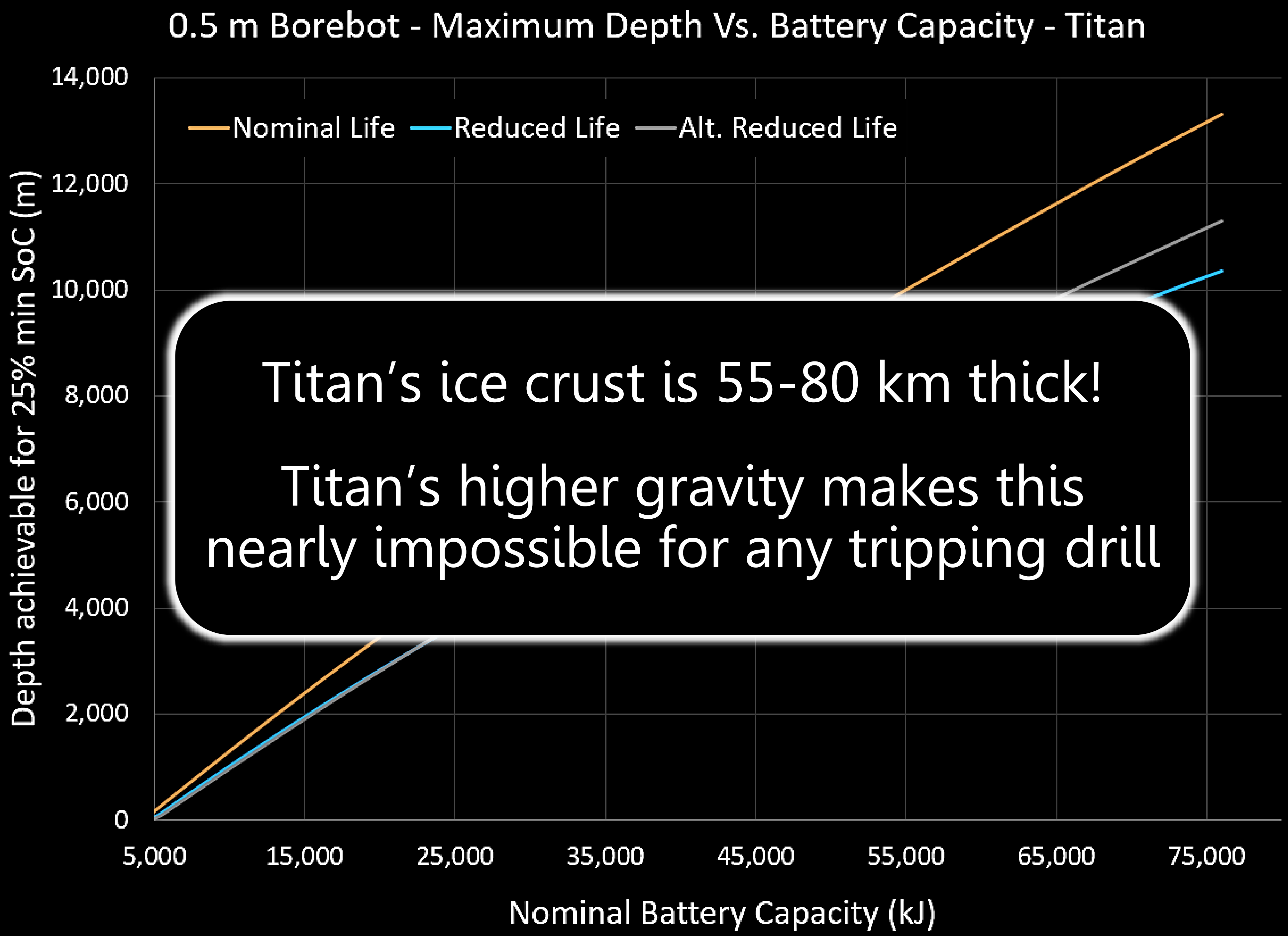
Total Surface Module Inventory

- 1x Kuka KR 1000 w/ barrel sleeve
- 8x 6000 kg x 1 m x 7 m borebots
- 2x Stage 2 deployment bots
- 8x 250 kg x 350 mm x 4 m borebots
- 2x Stage 3 deployment bots
- 8x 10 kg x 108 mm x 2 m borebots
- 2x 108 mm sub sampling borebots
  - Notionally for water sampling
- Fission reactor under Kuka robot 🙆


108 mm Borebot - Maximum Depth Vs. Battery Capacity
Nominal Life
Reduced Life
Alt. Reduced Life
40-60 km: 80,000 drilling cycles
10,000 trips per small borebot
This means battery chemistry is the biggest thing holding us back. Once this is fixed it's cycles-per-bot that stands in our way.
66,000 mAh@18V, 1188 Wh
150x 18650 lithium-ion cells
108 mm bore:
10 x packs
Ø108.00
Ø101.60
Ø97.60
Ø91.60
Ø72.00
Ø38.00
Ø18.00
Depth achievable with 25% depth of discharge (m)
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
45,000
0
50,000
100,000
150,000
200,000
250,000
300,000
Nominal Battery Capacity (mAh at 18 V)

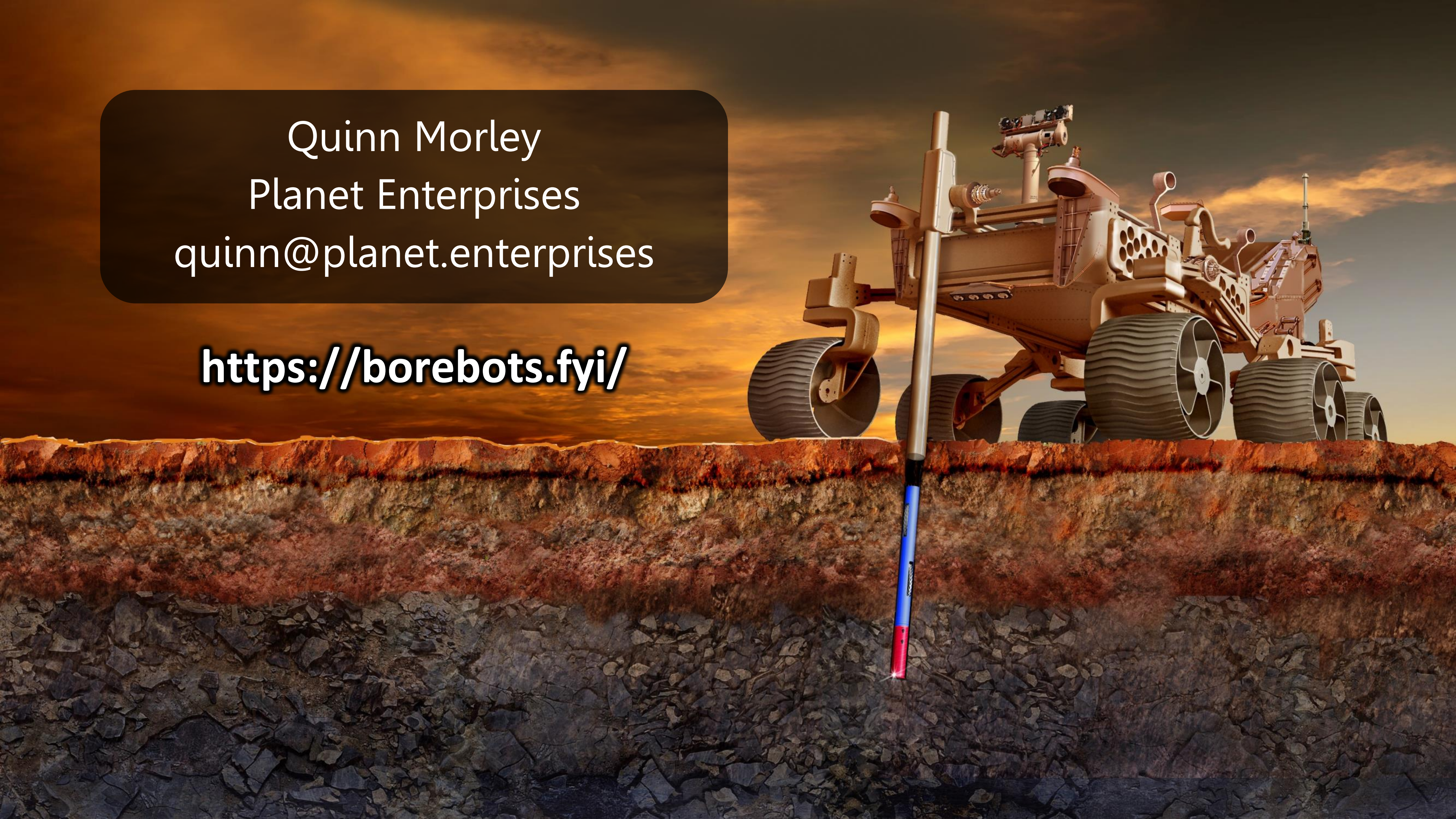





0.5 m Borebot - Maximum Depth Vs. Battery Capacity - Titan
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Depth achievable for 25% min SoC (m)
Nominal Life
Reduced Life
Alt. Reduced Life
5,000
15,000
25,000
35,000
45,000
55,000
65,000
75,000
Nominal Battery Capacity (kJ)
Titan's ice crust is 55-80 km thick!
Titan's higher gravity makes this nearly impossible for any tripping drill

We do have a method for drilling through Titan’s crust with a 10-m-class tunnel boring machine…

… which will be the topic of my next talk!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