Why the Solar System's First Space Elevator Will Likely be **Martian**

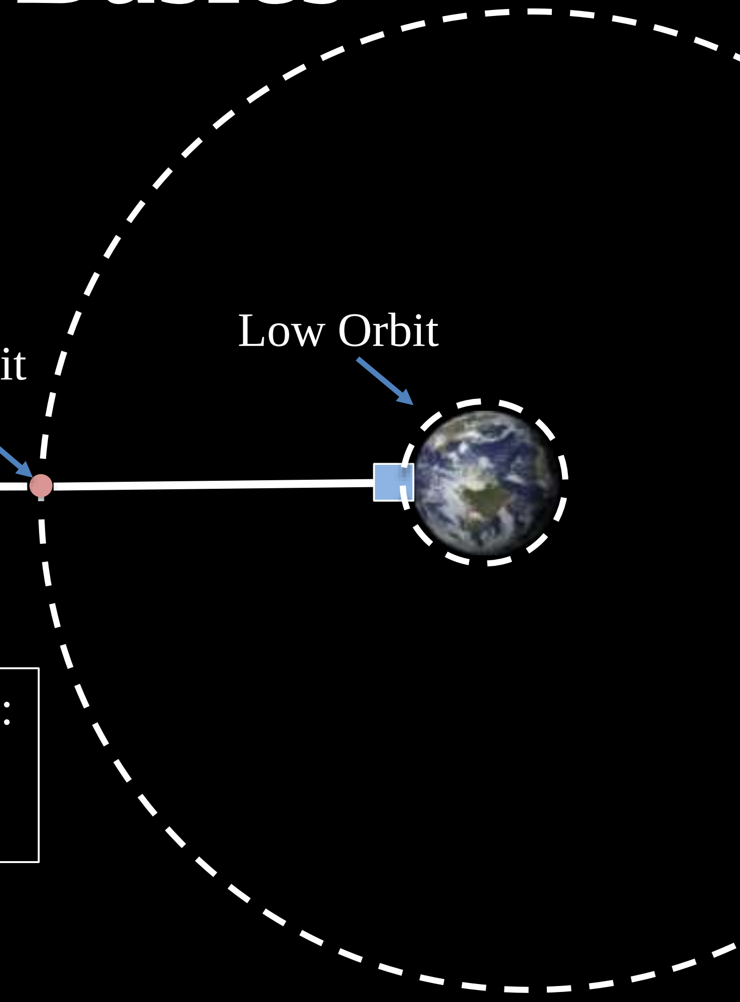
Max Fagin
Made In Space, Inc.
NASA Ames Research Center

Image credit: Erik Wernquist, "Wanderers"

Space Elevator Basics

Concept

To other planets, asteroid etc.



Need ~55 MJ per kg to Escape Earth

Space Elevators can be as efficient as a motor + solar array:
30-60% efficient
~$5 of electricity per kg

By contrast…

Rockets can only be as efficient as an explosion:
<0.1% efficient
~$15,000 of rockets per kg

Space Elevator Basics

History

1865: Idea proposed by Konstantin Tsiolkovsky

1960: Concept formalized by Yuri Artsutanov as “Electric Railroad to the Stars” but no known materials had sufficient strength.

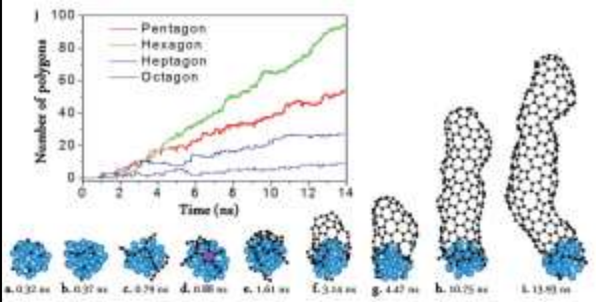
1970-80’s: Carbon Nano Tubes (CNTs) first characterized as theoretically capable of reaching the required strength.

Today: Millimeter scale CNTs of the required strength are regularly grown in labs, but we have no idea how to scale up production to industrial levels (1k-10k tonnes, ~10,000 km).

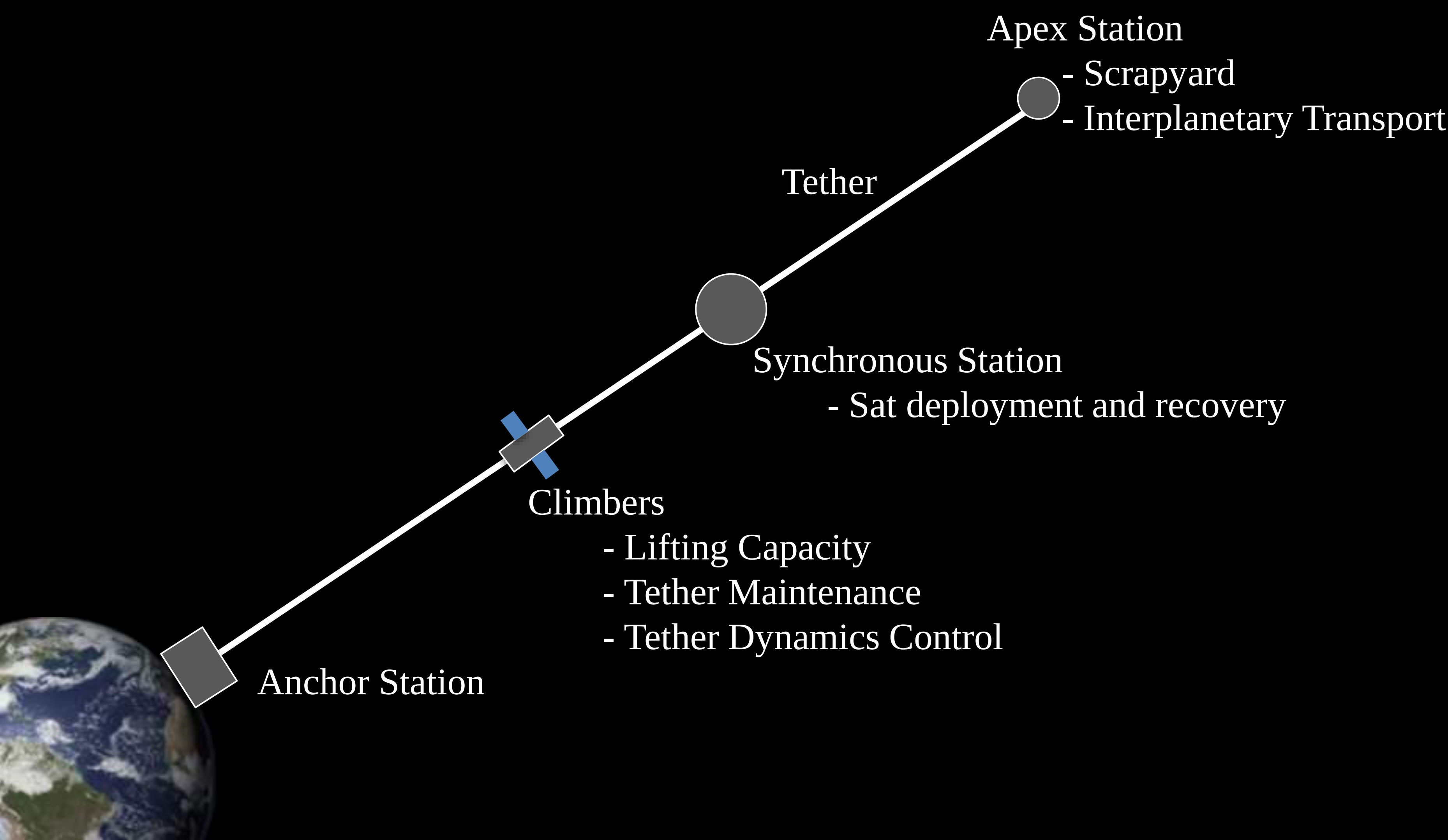
2035-2065: Predicted range when CNT experts say we will have solved the problem…

…but no one really knows.

Image Credit: Roger Gilbertson



Space Elevator Basics
Elements

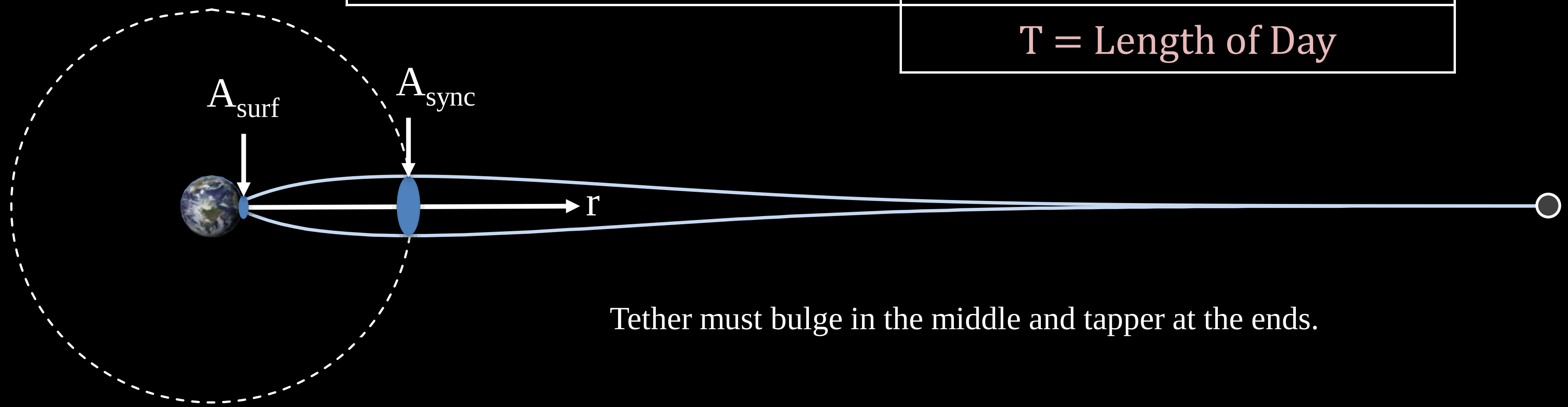


Space Elevator Basics
Tether

To be self supporting, the tether must be able to survive gravity ($\sim r^{-2}$) and centrifugal force ($\sim r$)

$$\text{Thether Thickness} = A(r) \propto \exp\left(\frac{\rho}{\sigma_y} GM \left[\frac{1}{R} + \frac{4\pi^2}{GMT^2}\left(R - \frac{r^2}{2}\right) - \frac{1}{r}\right]\right)$$

Tether Material Properties	**Planet Properties**
ρ = Density	M = Mass
σ_y = Yield Stress	R = Radius
	T = Length of Day



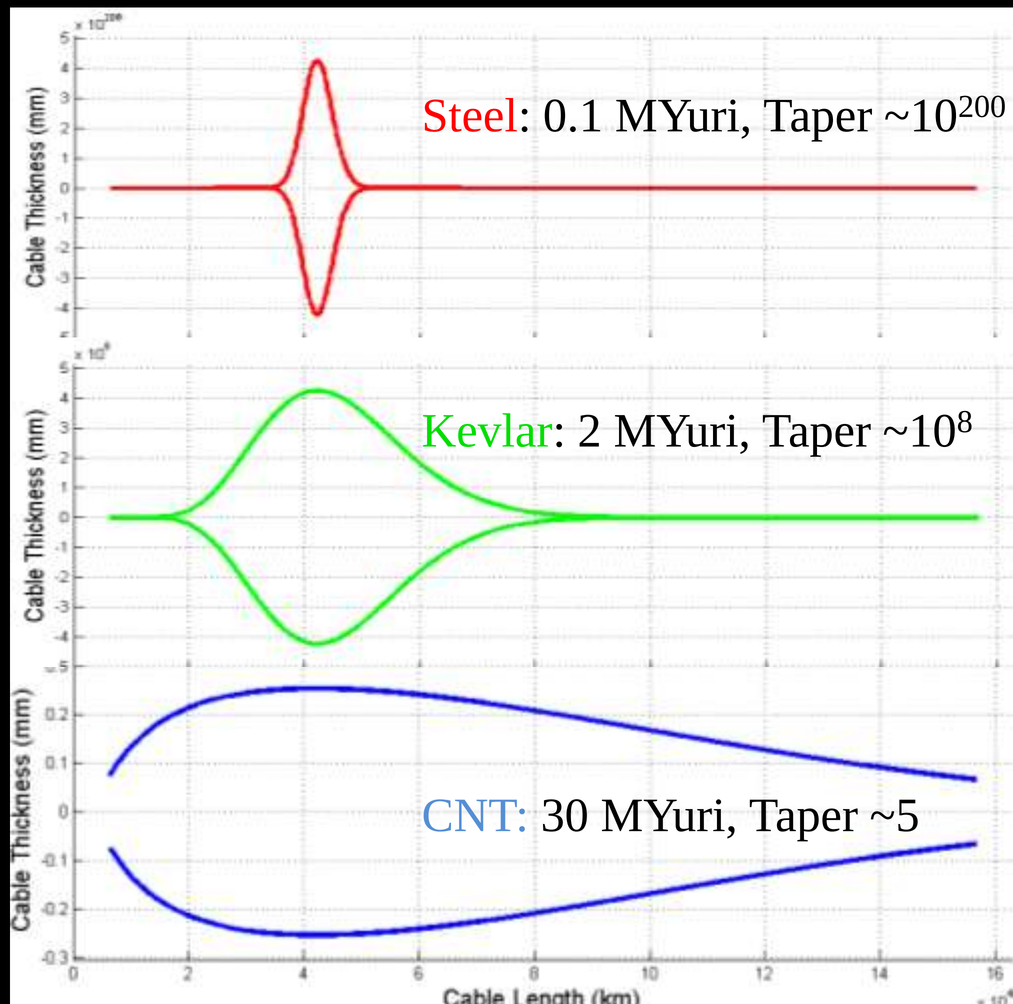
Tether must bulge in the middle and tapper at the ends.

$$\text{“Taper Ratio”} = \tau = \frac{A_{sync}}{A_{surf}} = \frac{\text{Cross Sectional Area at Synchronous Altitude}}{\text{Cross Sectional Area at Surface}}$$

Space Elevator Basics
Tether

Taper Ratio is determined by material:

Strength per density = Pa/(kg/m^3) = "Yuri" = (m/s)^2

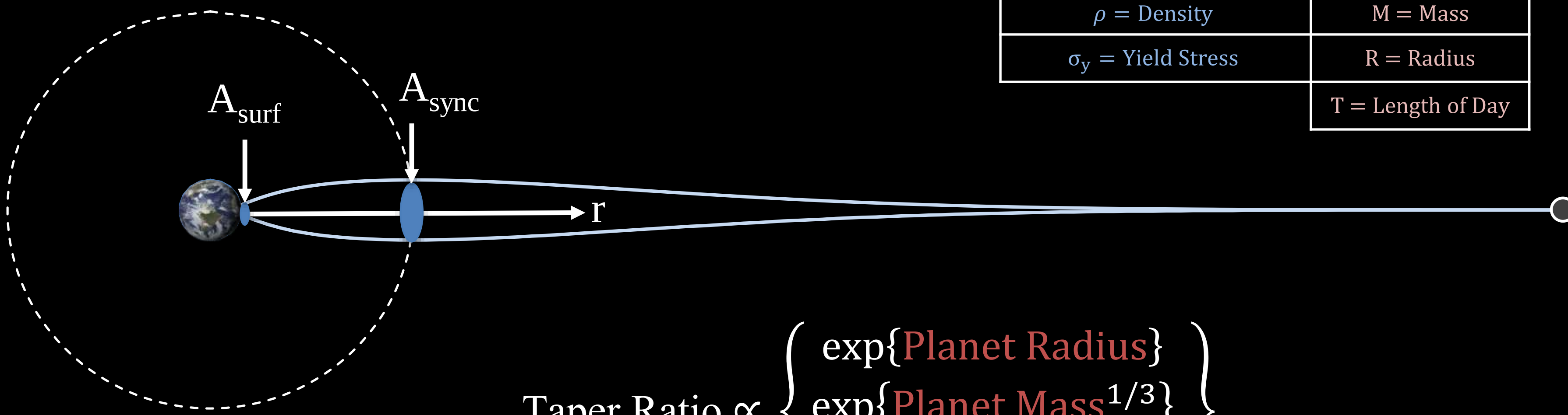


Space Elevator Basics

Tether

$$\text{Taper Ratio} = \frac{A_{sync}}{A_{surf}} = \exp\left\{\frac{\rho}{\sigma_y}\frac{GM}{R}\left[1 - R\left[\frac{GMT^2}{4\pi^2}\right]^{-\frac{1}{3}}\right]^2 + \left[1 + \frac{R}{2}\left[\frac{GMT^2}{4\pi^2}\right]^{-\frac{1}{3}}\right]\right\}$$

Tether Material Properties	Planet Properties
ρ = Density	M = Mass
σ_y = Yield Stress	R = Radius
	T = Length of Day

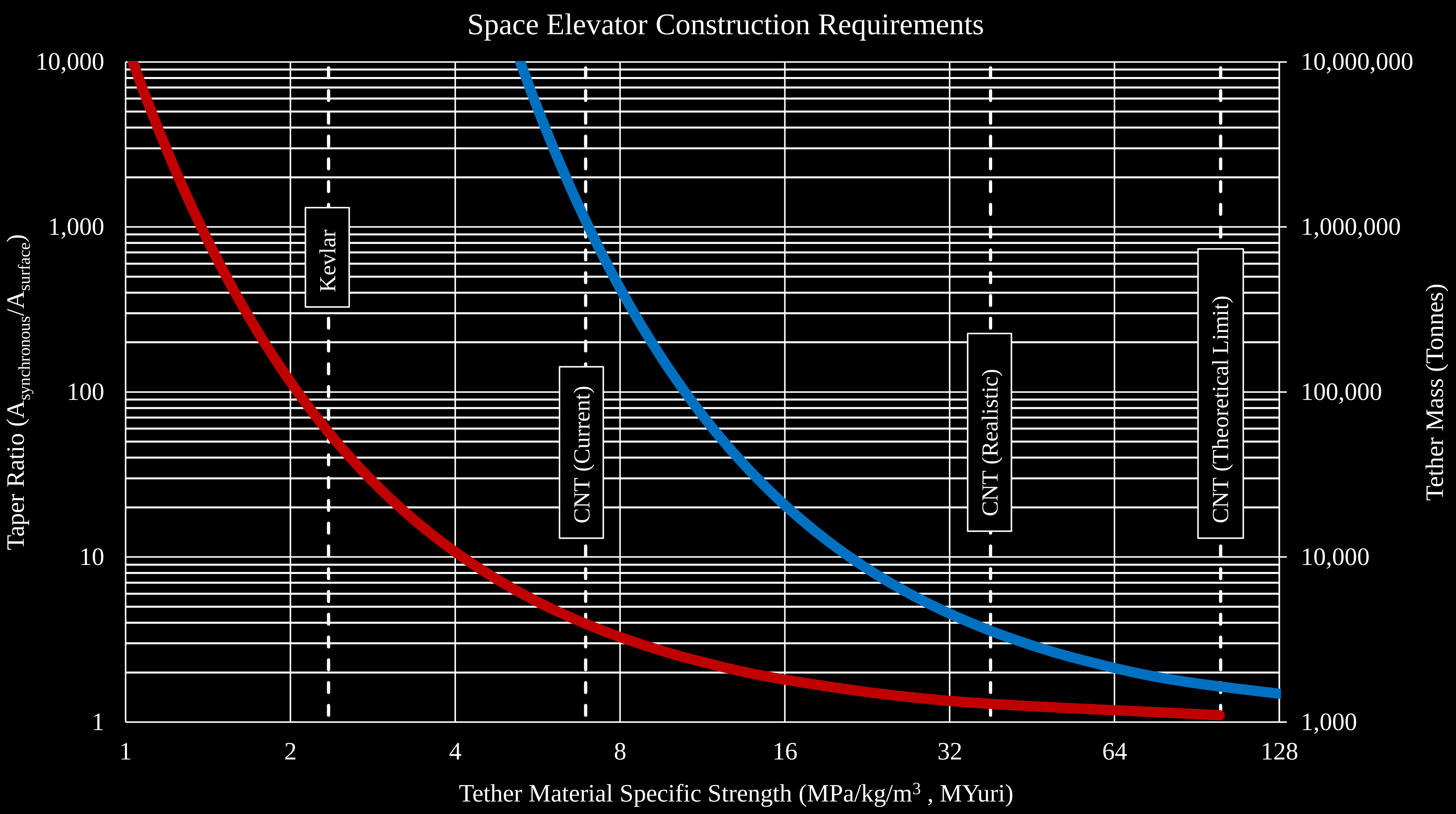


$$\text{Taper Ratio} \propto \begin{Bmatrix} \exp\{\text{Planet Radius}\} \\ \exp\{\text{Planet Mass}^{1/3}\} \\ \exp\{\text{Day Length}^{-4/3}\} \end{Bmatrix}$$

It is currently **250 times easier** to build a space elevator on Mars than on Earth

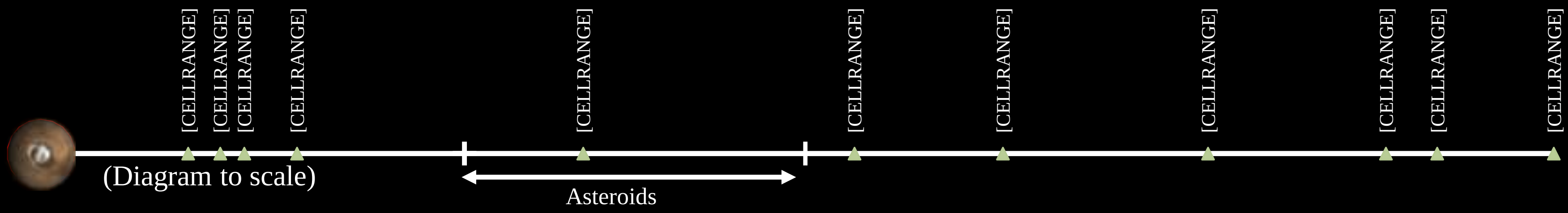
Mars vs. Earth

Tether Mass



Mars vs. Earth

Accessible Destinations



If Mars is serving as an exporter to the outer solar system/asteroids, a space elevator is a means of reducing ΔV requirements to every destination.

Destination	Detach Altitude (km)	Required ΔV (km/s)
Asteroids	39,172 – 73,404	1.198 - 3.296
Earth	51,094	3.236
Venus	78,343	6.073
Jupiter	93,246	4.087
Saturn	113,854	4.461
Uranus	131,736	4.093
Neptune	136,897	3.733

Mars vs. Earth

Construction Requirements

Assuming tether is to be manufactured:

- In synchronous orbit
- Using a carbon rich (C-type) asteroid as feedstock
- Density 2700 kg/m^3
- 3% Carbon Content
- 80% Process Yield
- Present day cutting edge CNT bundle strength (~7 MYuri) and manufacturing rates
- 5000 CNT reactors working at 1.0 kg/month/reactor (2019 Industry expert prediction by 2019)

	Mars	**Earth**
Tether Mass	4,000 tonnes	13,000,000 tonnes
Tether Length	69,000 km	151,000 km
Required Asteroid Mass	170,000 tonnes	540,000,000 tonnes
Required Asteroid Diameter	50 m	725 m
Manufacturing Time	35 years	210,000 years

*Industry expert prediction of achievable by end of 2018

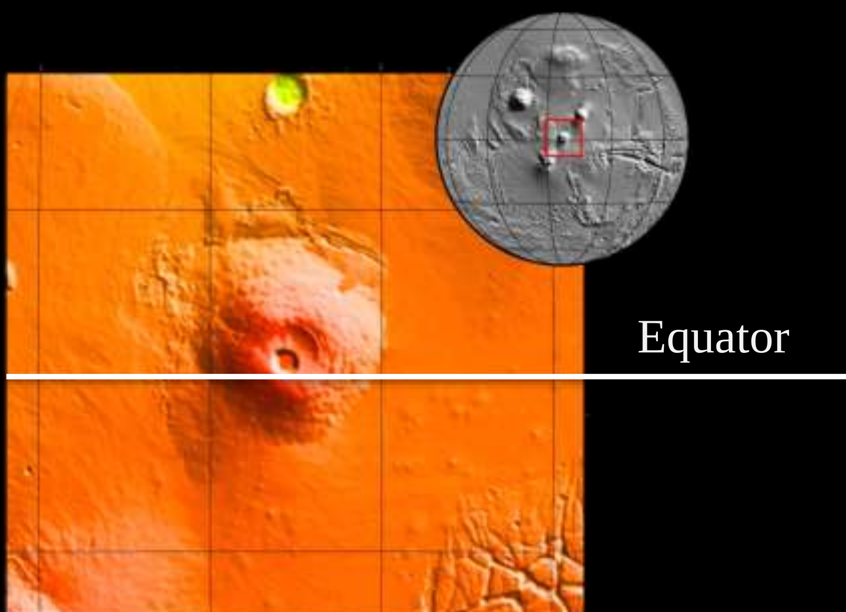
Mars vs. Earth

Terrestrial Concerns

On Earth, base station, climbers and tether must survive:

- Hurricanes
- Wind shear
- Lightning strikes
- Atomic oxygen in the ionosphere
- Induced ionospheric currents (CNTs are conductive)
- NIMBYs

Image Credit: ISEC



On Mars, *none* of these problems apply. Tethers and climbers can be optimized for *one* environment (space).

Potential Issues

Power Availability

Climbers will probably use solar power to ascend the tether.
1370 W/m^2 of solar power available on Earth, only 590 W/m^2 at Mars (57% reduction)

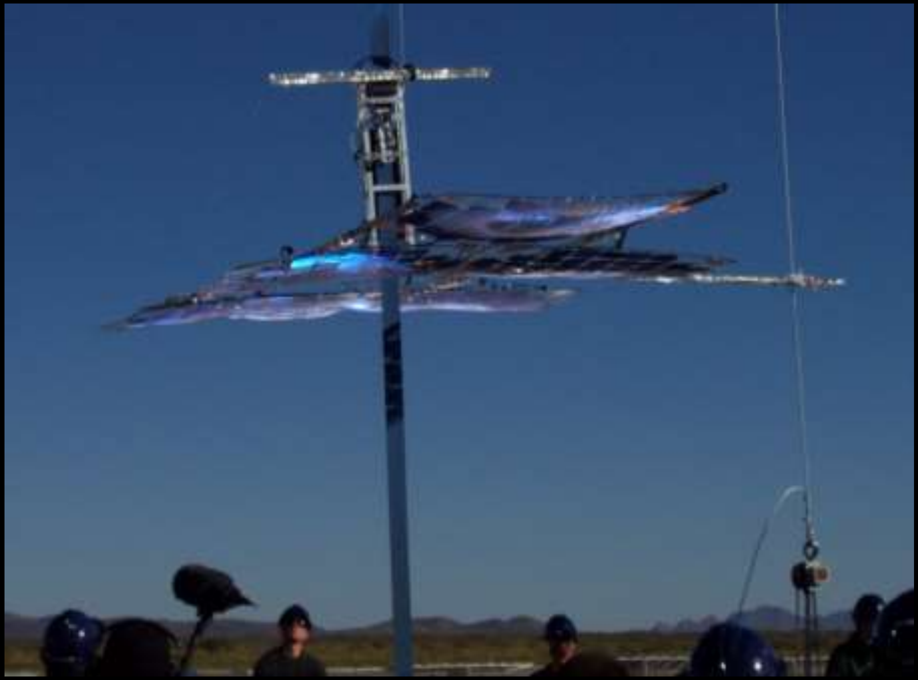


Image Credit: ISEC

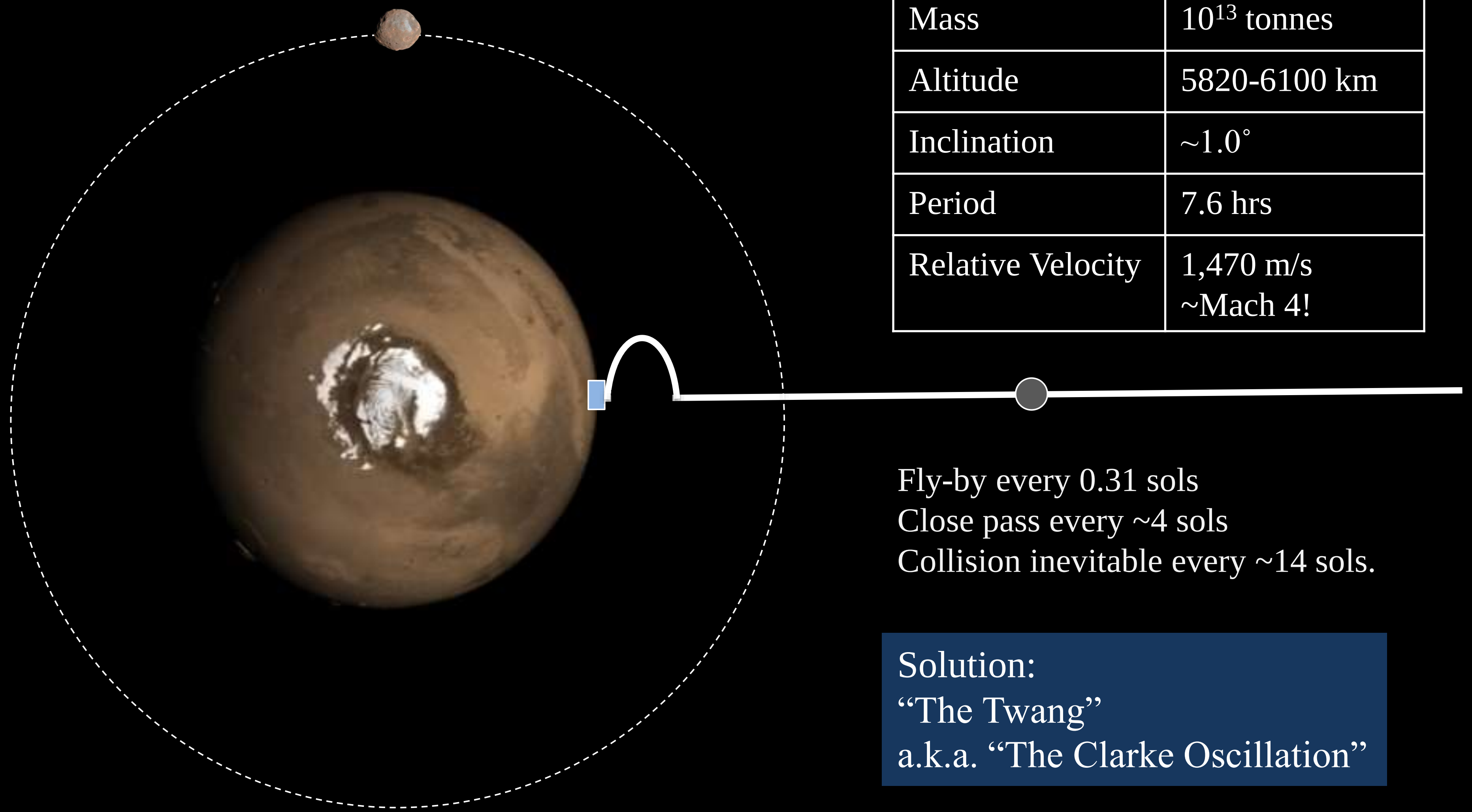
57% irradiance reduction at Mars, but also 62% reduction in gravity.
A climber designed for Earth would be +14% faster on Mars.

Potential Issues

What about Phobos?

Potential Issues

What about Phobos?



Phobos Properties	
Size	27 x 22 x 18 km
Mass	10^{13} tonnes
Altitude	5820-6100 km
Inclination	~1.0˚
Period	7.6 hrs
Relative Velocity	1,470 m/s ~Mach 4!

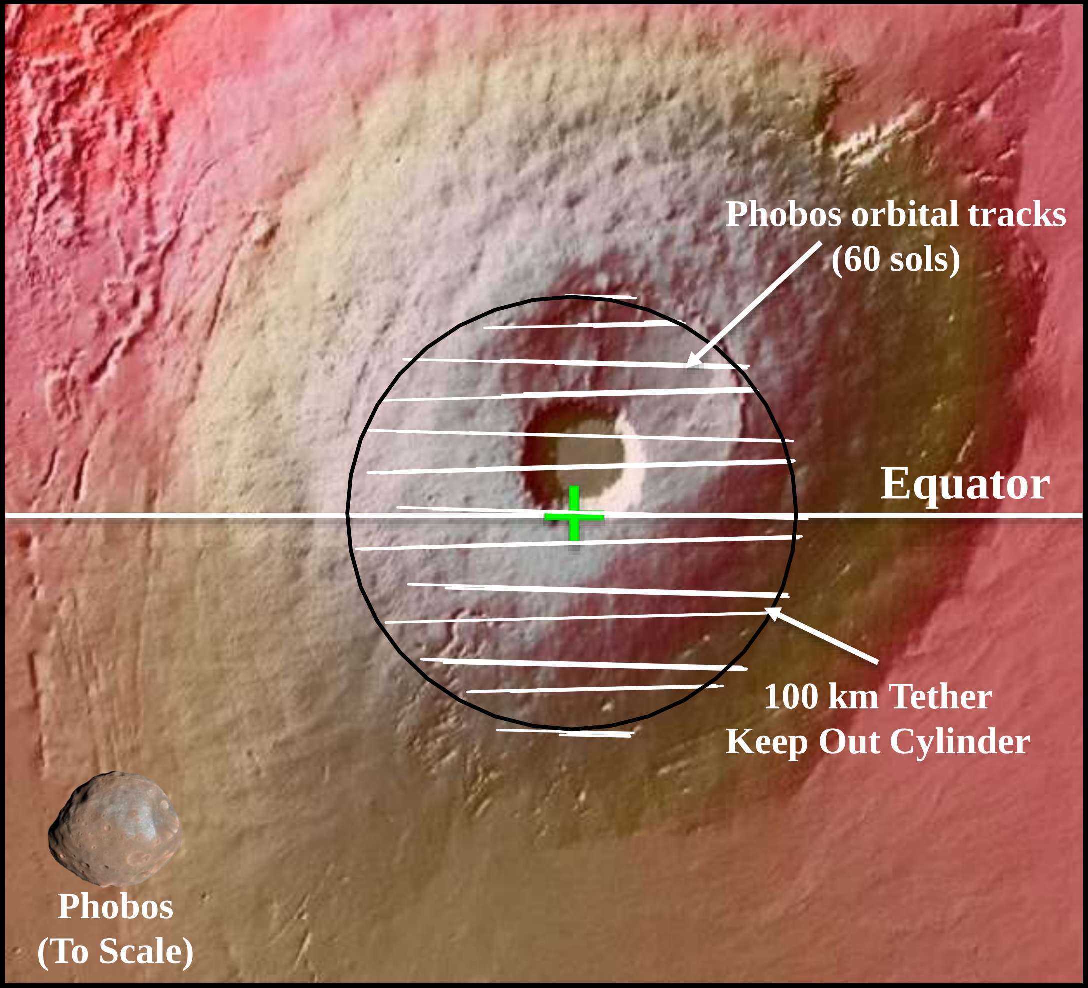
Fly-by every 0.31 sols
Close pass every ~4 sols
Collision inevitable every ~14 sols.

Solution:
"The Twang"
a.k.a. "The Clarke Oscillation"

Potential Issues

What about Phobos?

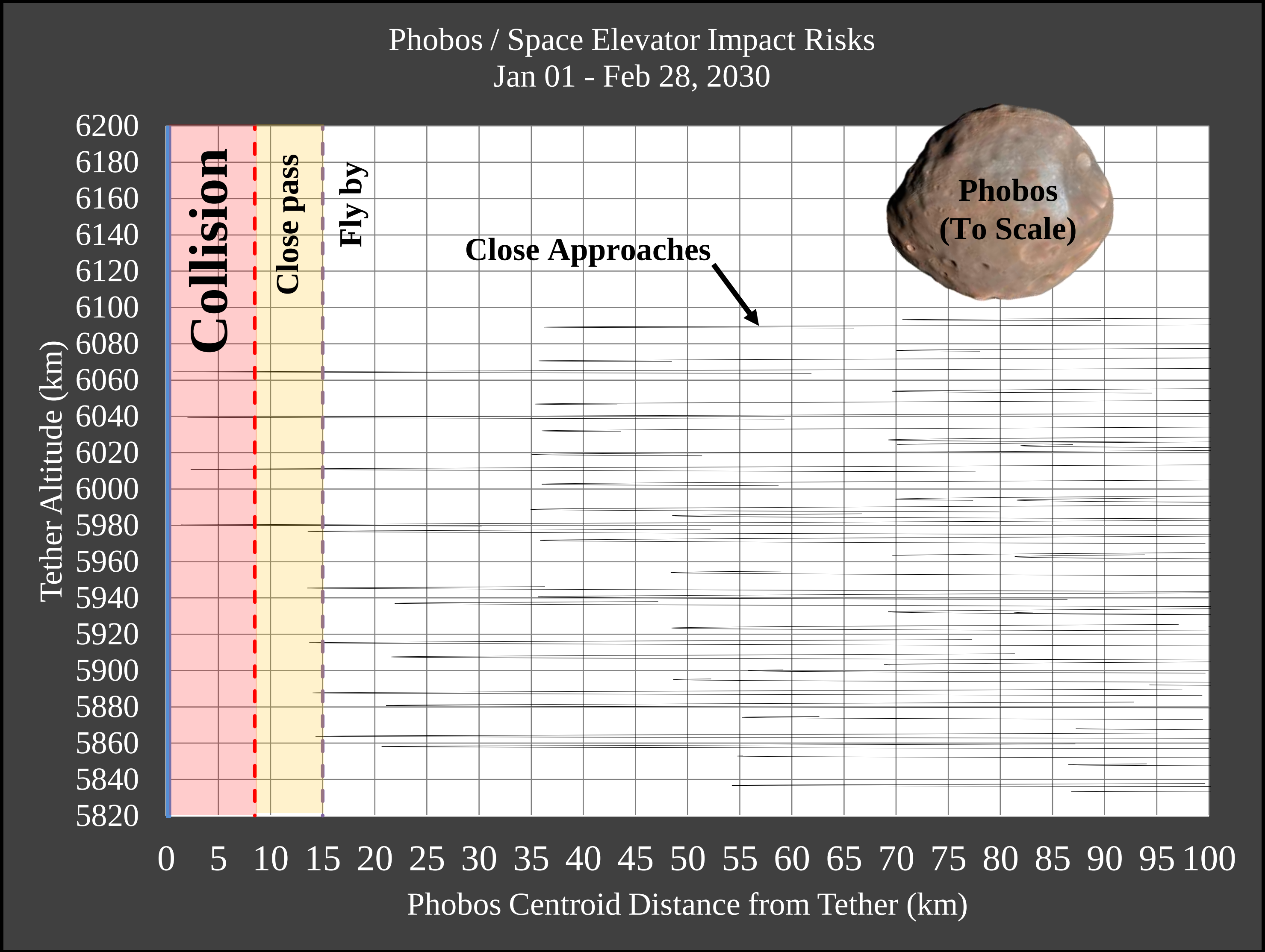
Phobos / Space Elevator Impact Risks
Jan 01 - Feb 28, 2030



Close pass every ~4 sols. Collision is inevitable every ~14 sols.

Potential Issues

What about Phobos?



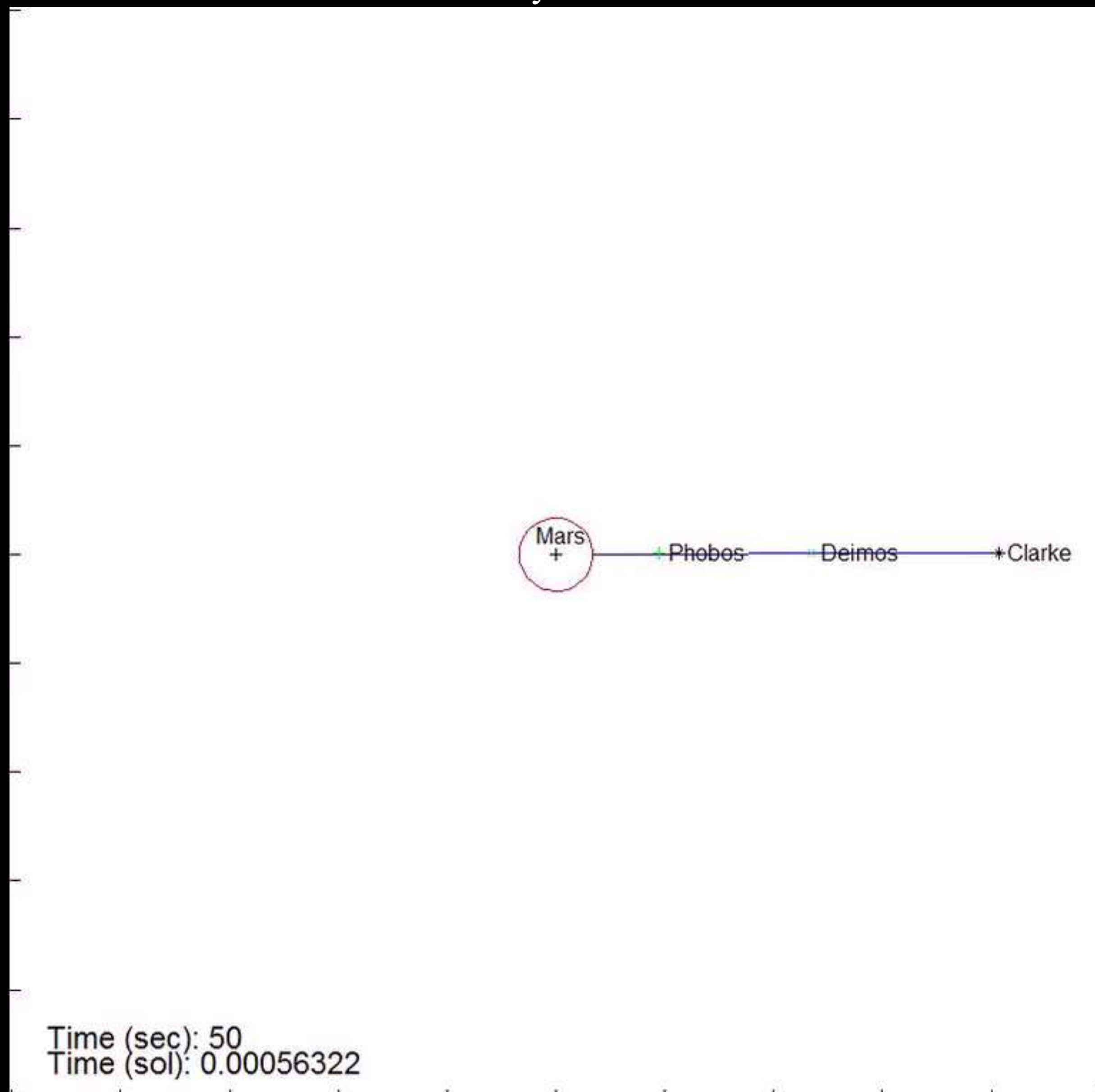
Collisions can be avoided provided one climber every ~14 sols is devoted to collision avoidance

Potential Issues

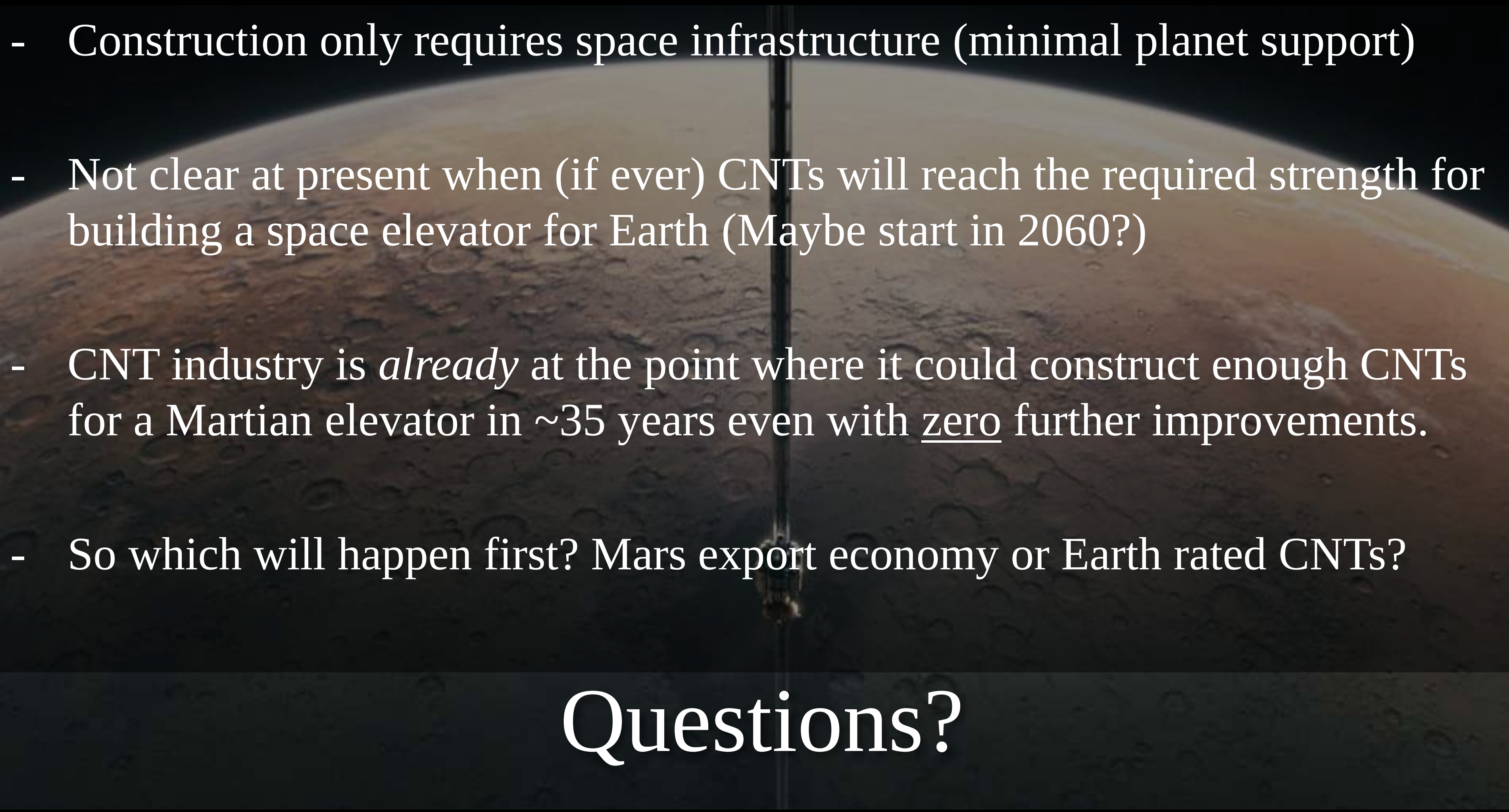
What about Phobos?

What if it falls down?

It almost certainly won't. But IF it did…



Summary



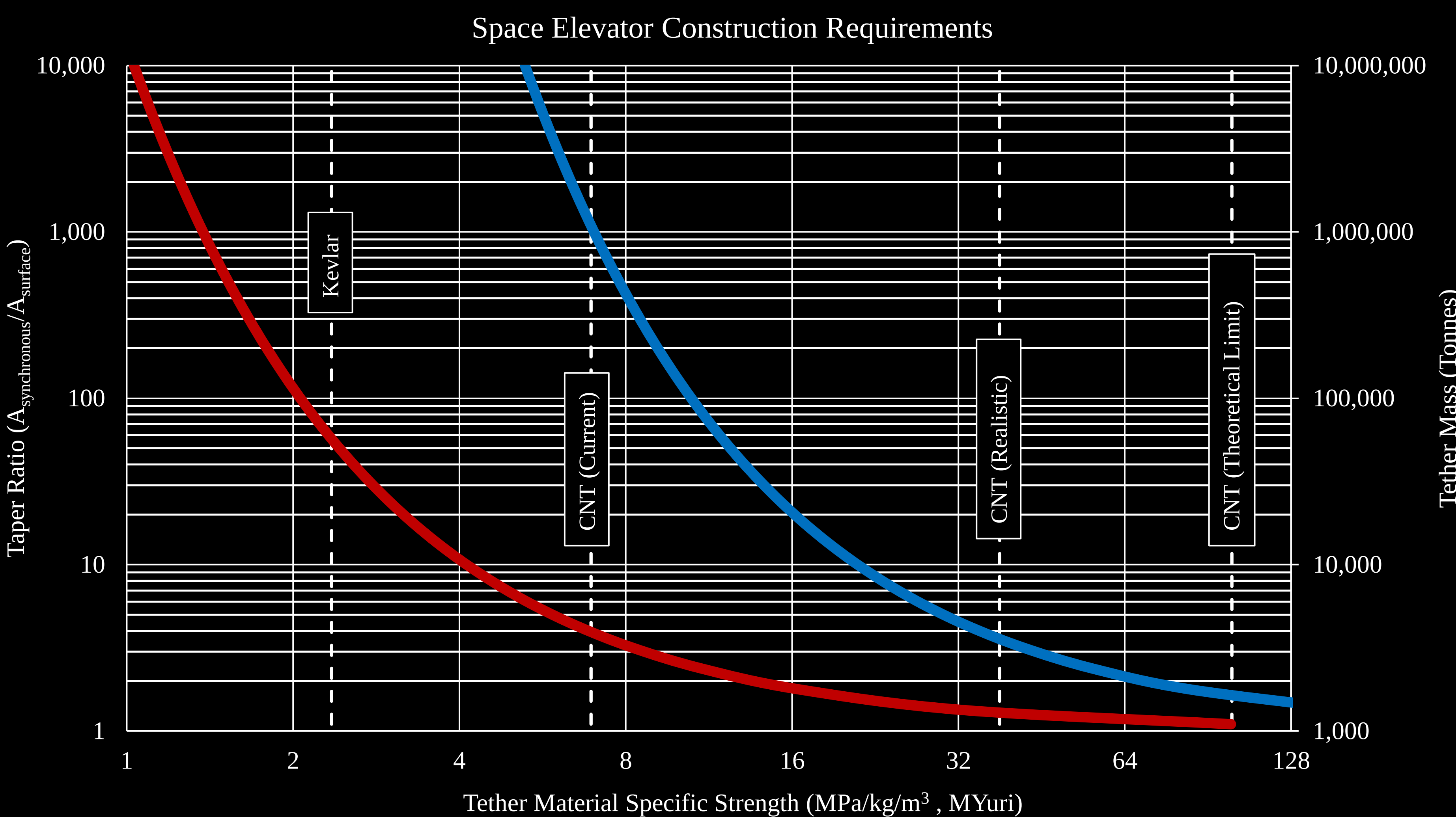
- Space Elevator construction is 250-to-30 times easier on Mars than on Earth
- Construction only requires space infrastructure (minimal planet support)
- Not clear at present when (if ever) CNTs will reach the required strength for building a space elevator for Earth (Maybe start in 2060?)
- CNT industry is *already* at the point where it could construct enough CNTs for a Martian elevator in ~35 years even with <u>zero</u> further improvements.
- So which will happen first? Mars export economy or Earth rated CNTs?

Questions?

Image credit: Erik Wernquist, "Wanderers"

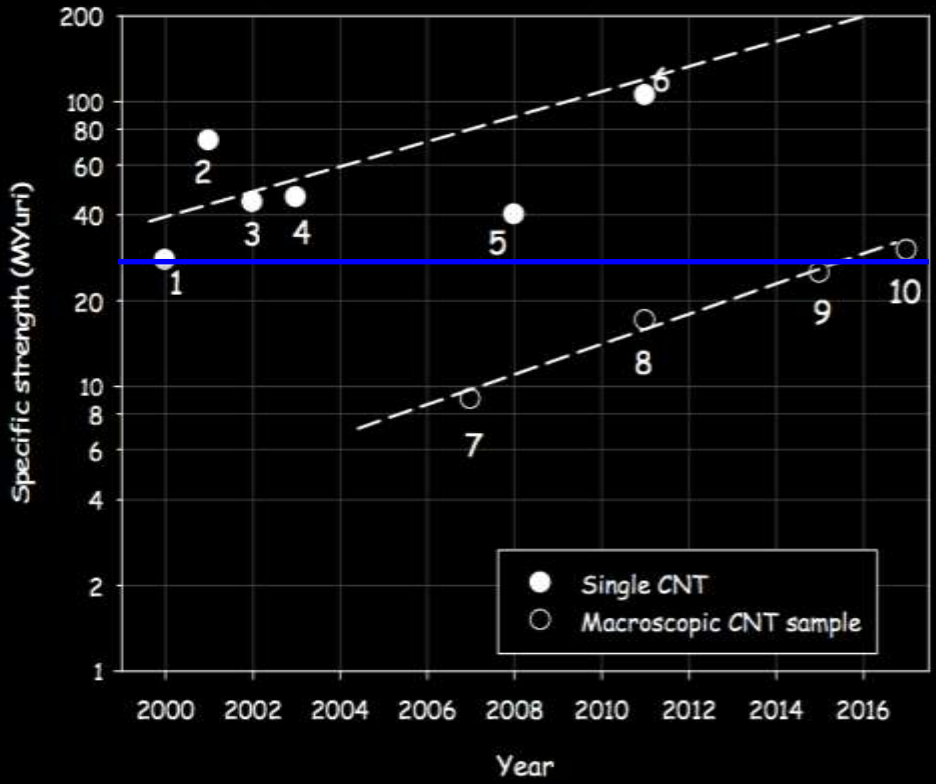
Mars vs. Earth

Tether Mass

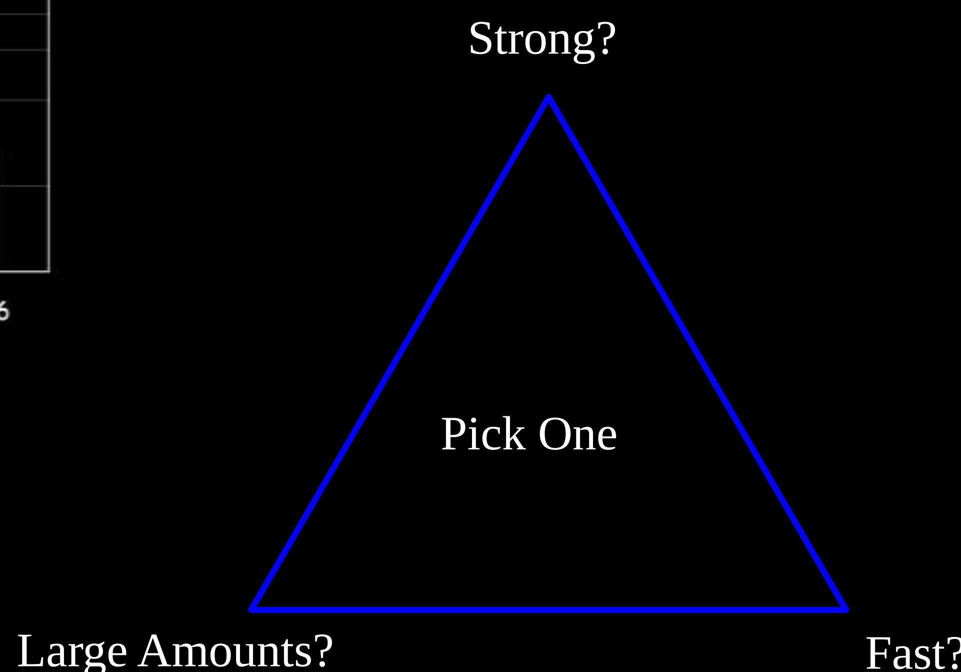


Backup Slides: CNT’s

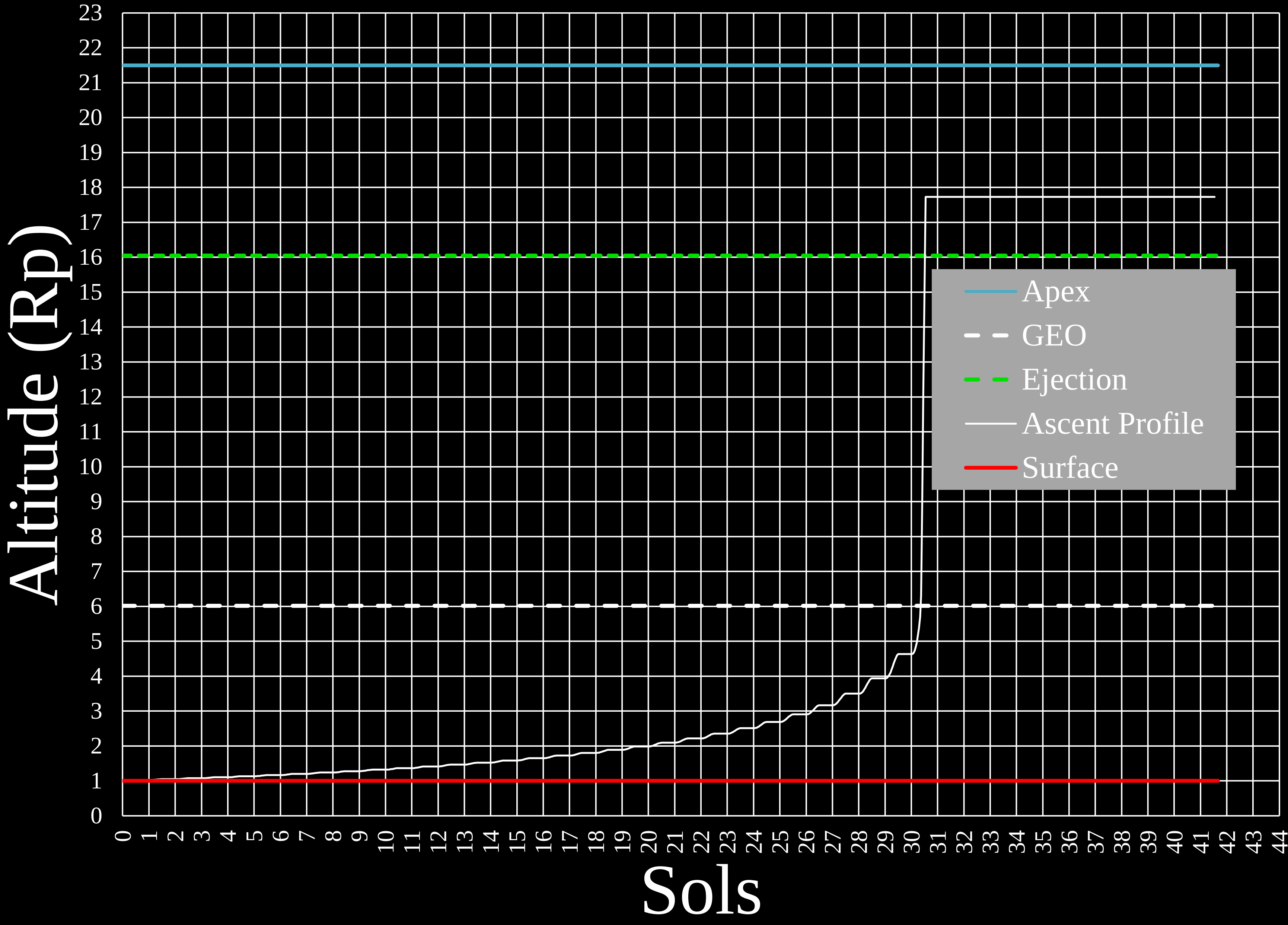
CNT’s have been made that satisfy specific strength requirements.



So what’s the hold up?



Requires 2000 tonnes of defect free CNTs.
Would take ~20,000 years to grow


Altitude (Rp)
Sols
Apex
GEO
Ejection
Ascent Profile
Surface
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44