

# Some Speculation on The Future...

- Where we are, where we're going (soon)
- Predicting the future (tl;dr - we're not good at it)
- Rockets are Wrong

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<http://spacecraft.ssl.umd.edu>

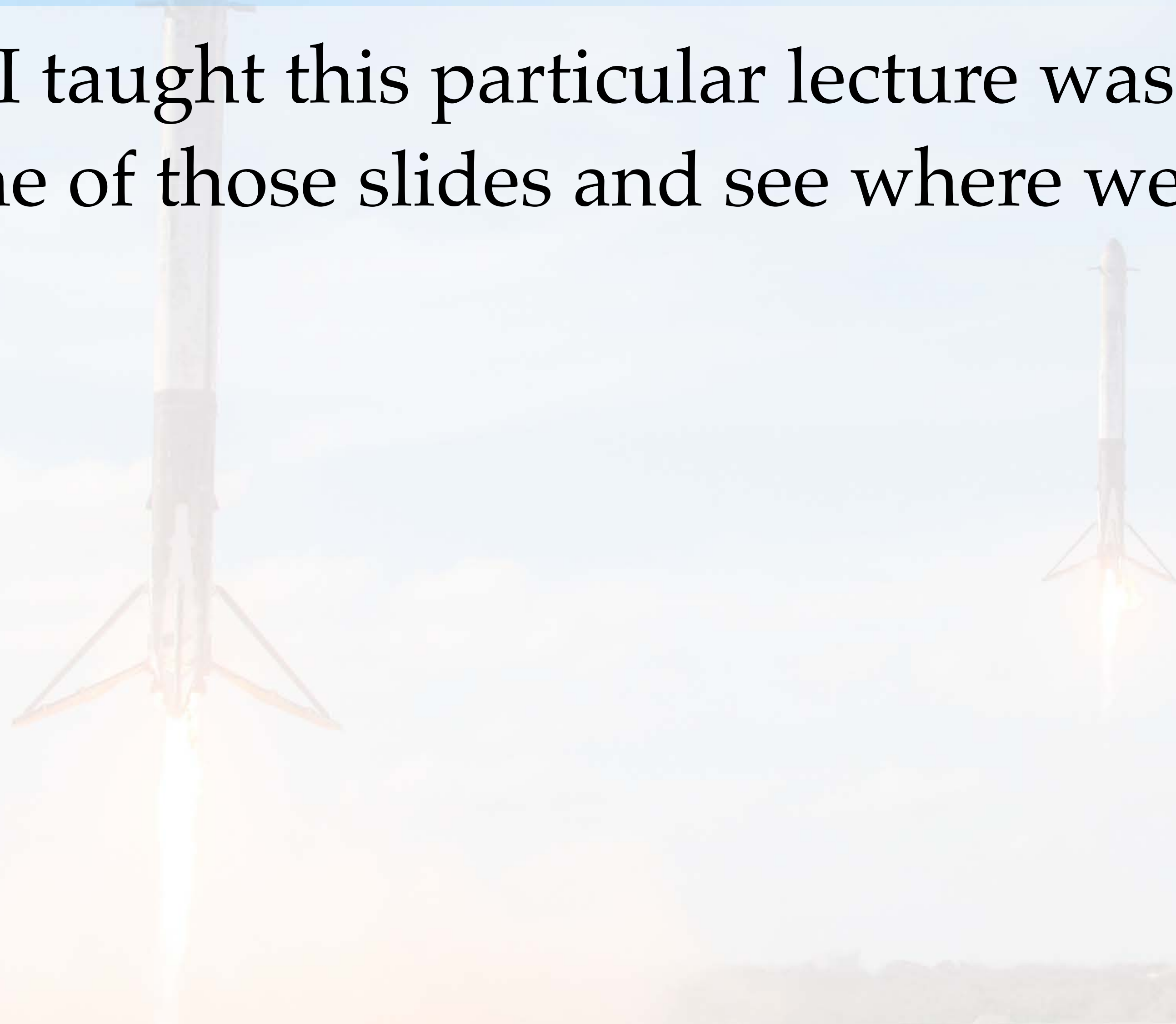
# The Vision

“Once you make it to low Earth orbit,  
you’re halfway to anywhere!”

- Robert A. Heinlein

# But First, Some Perspective...

- The first time I taught this particular lecture was in 2018. Let's start with some of those slides and see where we are today...



# Today's News (in 2018)



# 2018 ✓ Falcon Heavy First Flight



# ~~2019~~ - Virgin Galactic First Passengers

2021



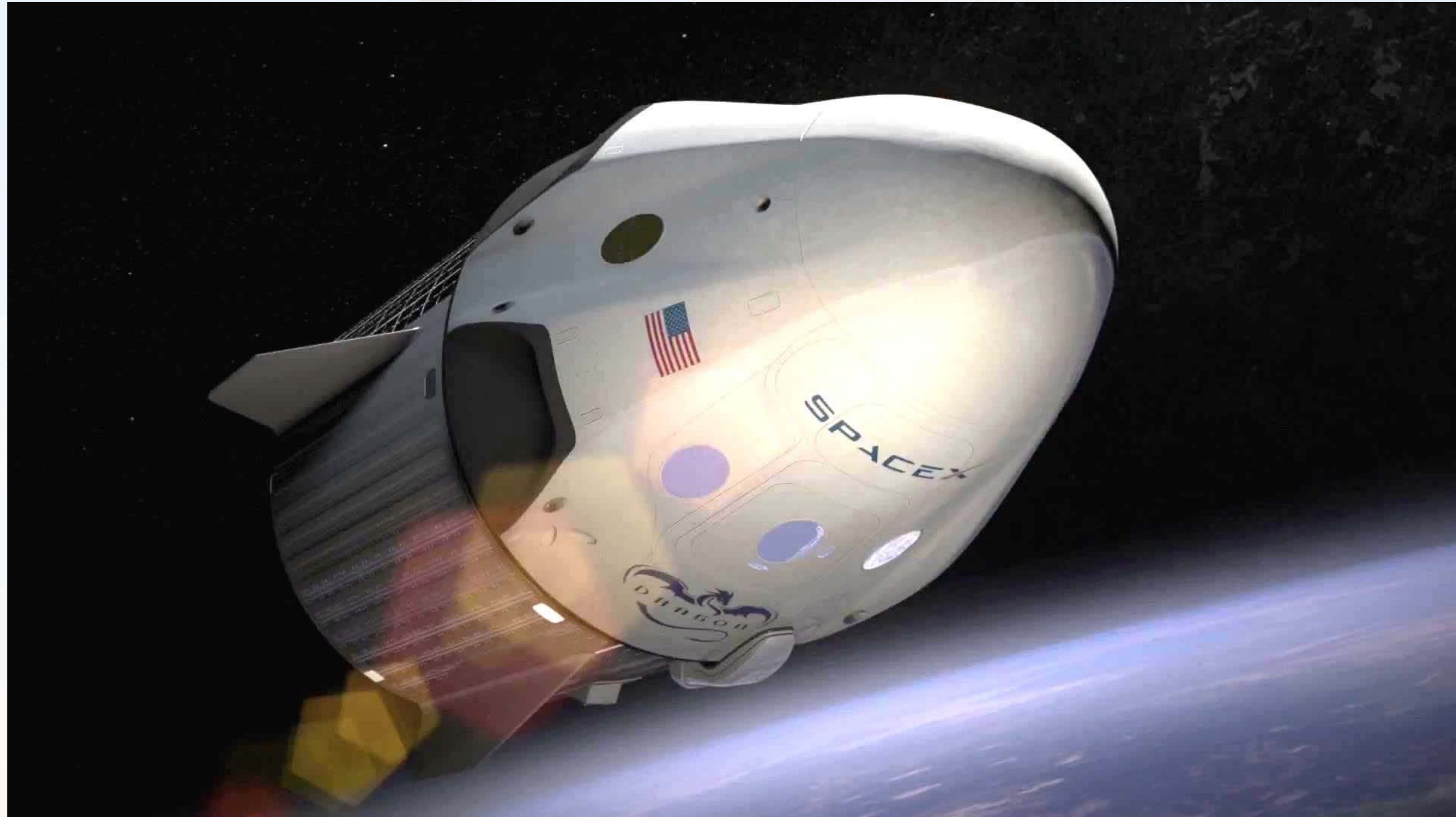
# ~~2018~~ - New Shepard First Passengers

2021



# ~~2019~~ - SpaceX Dragon 2 First Crew Flight

2020





# ~~2019~~ - Boeing CST-100 First Crew Flight

~~2023?~~

2024?



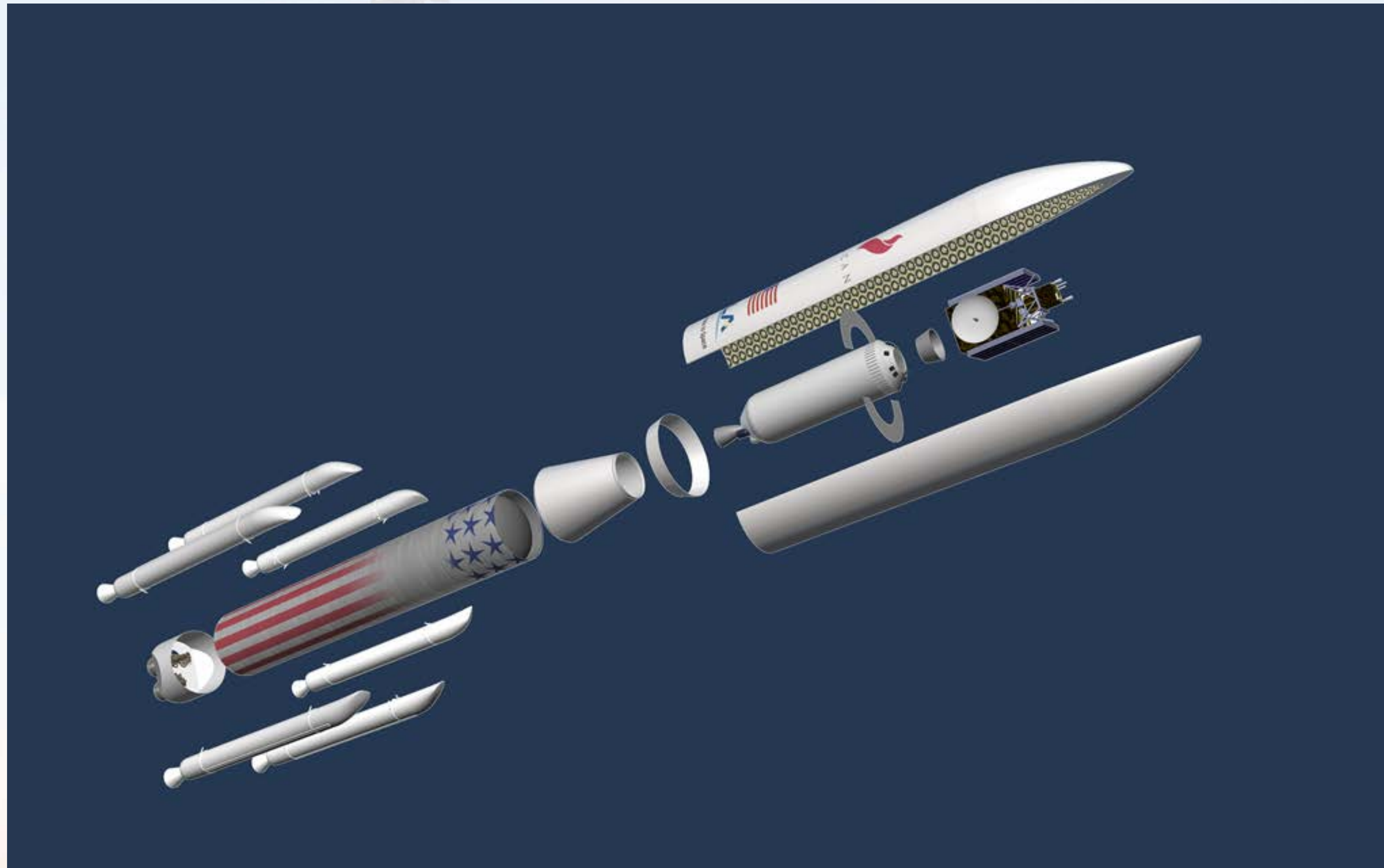
# ~~2020~~ - Space Launch System 1<sup>st</sup> Flight

2022



# ~~2021~~ - ULA Vulcan Launch Vehicle

2024



# ~~2021~~ - Blue Origin New Glenn Vehicle

2024?



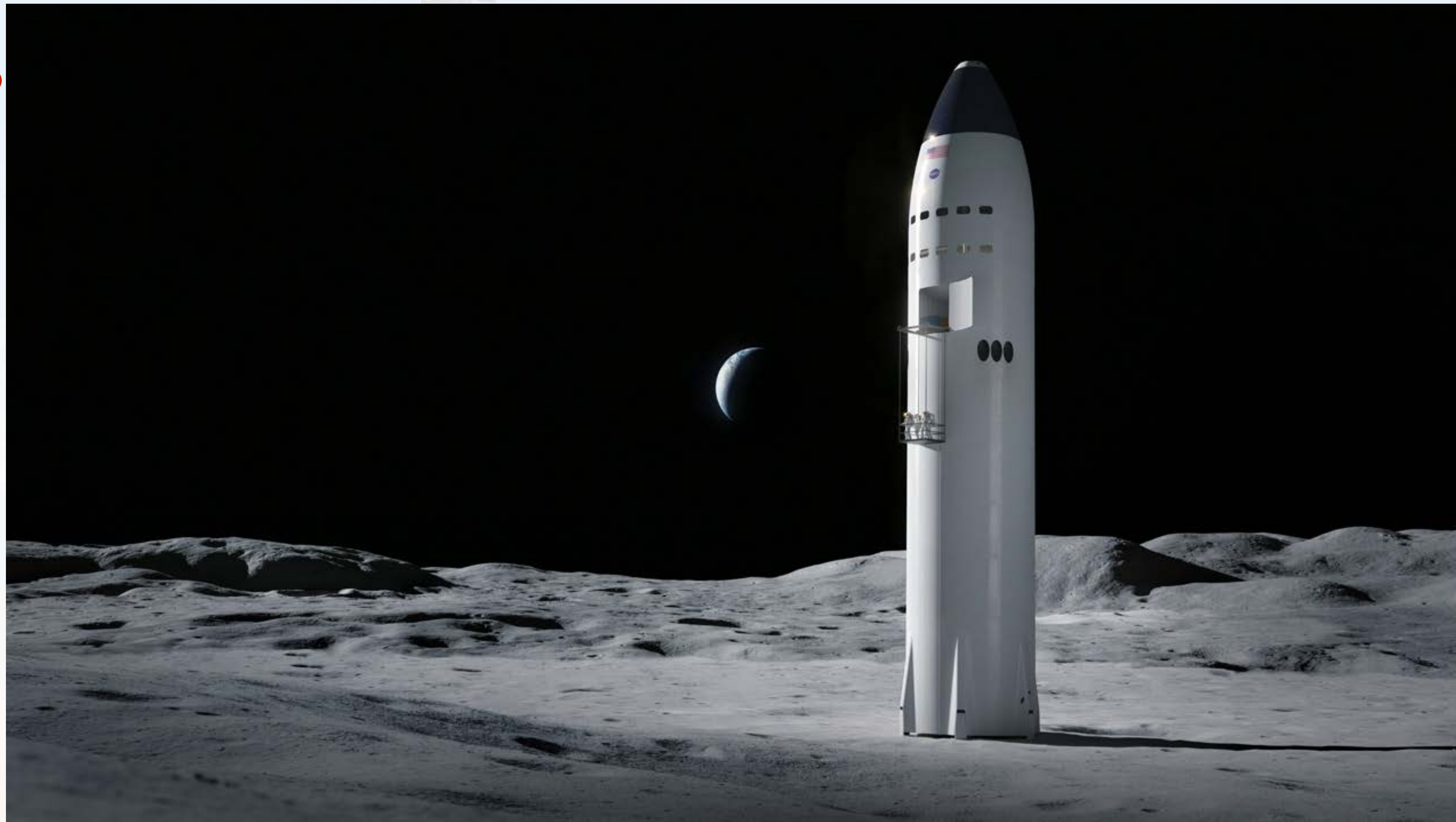
# ~~2023(?)~~ – Artemis 2 Mission

2025?

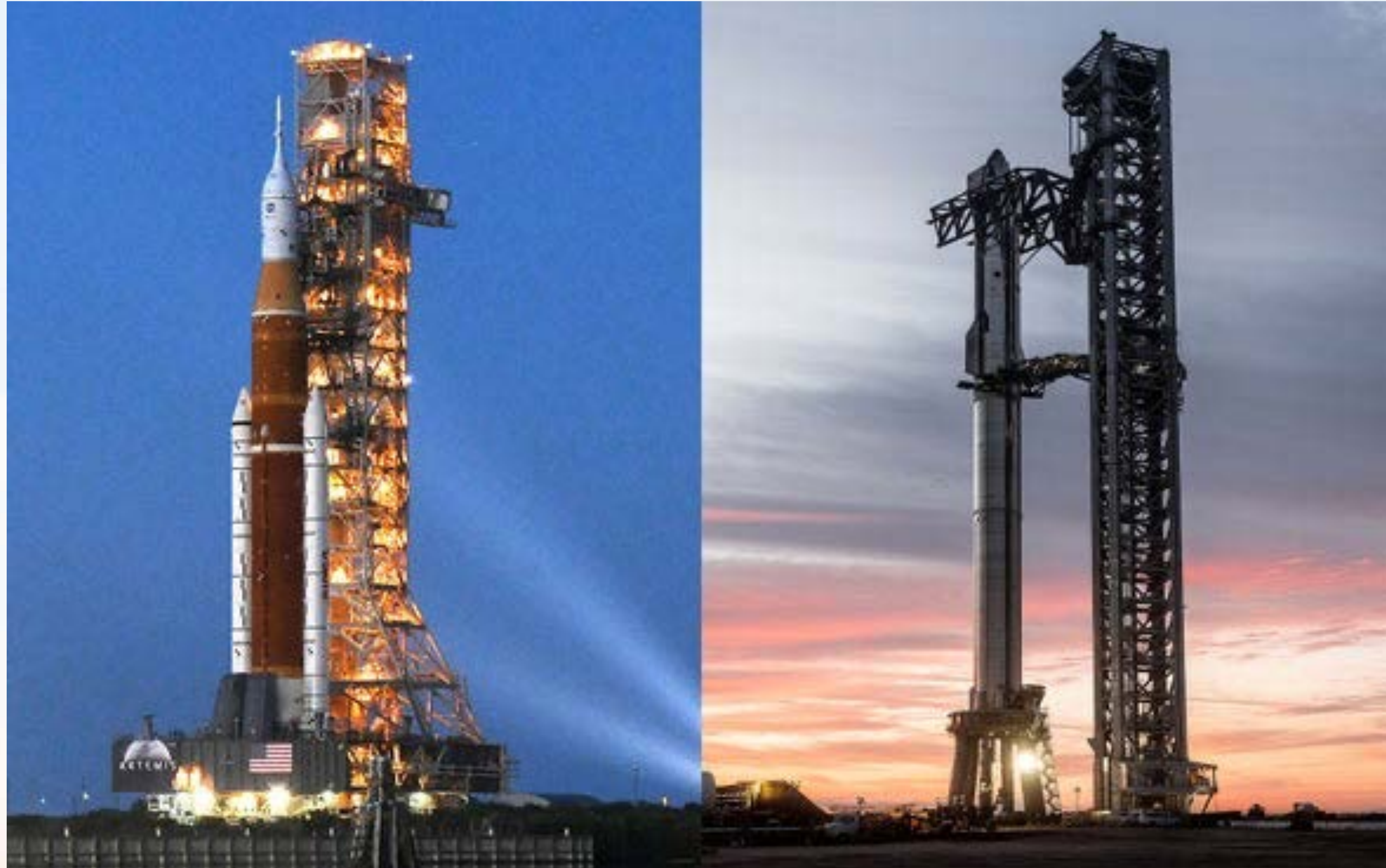


# ~~2024(?)~~ – Artemis 3 Mission

2027?



# The Race is On!!!



# Suborbital Starship Testing





# “The Flip”



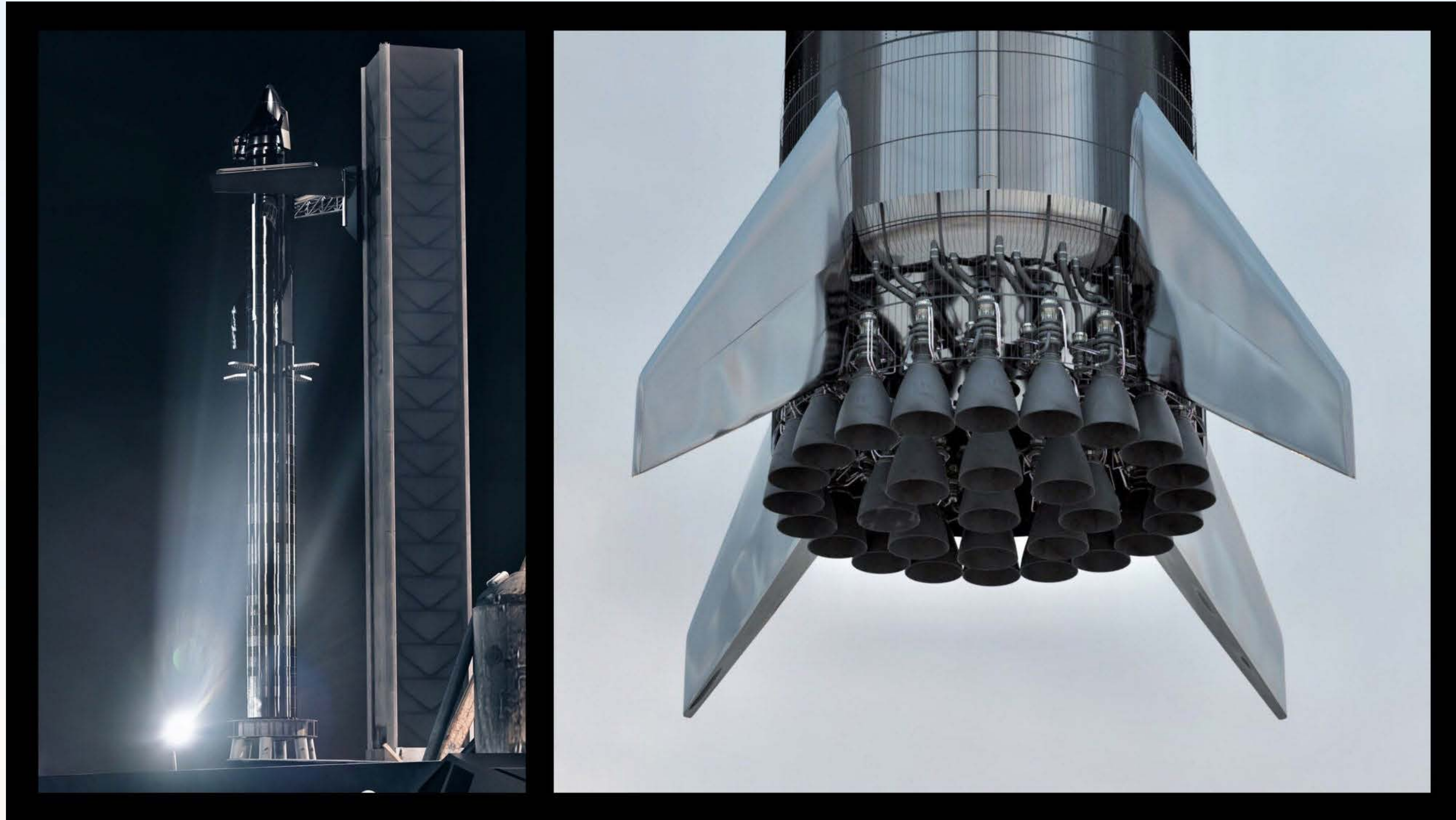
# Modern Launch Vehicle Engine Specifications

EVERYDAY  
ASTRONAUT



	Merlin	RD-180	F-1	Raptor	BE-4	RS-25
<b>Cycle</b>	Open	Closed (LOX rich)	Open	Closed (Full Flow)	Closed (LOX rich)	Closed (Fuel Rich)
<b>Fuel Type</b>	RP-1	RP-1	RP-1	Methane	Methane	Hydrogen
<b>Total Thrust</b>	0.84 MN	3.83 MN	<b>6.77 MN</b>	2.00 MN	~2.40 MN	1.86 MN
<b>Thrust : Weight</b>	<b>198 : 1</b>	78 : 1	94 : 1	107 : 1	~80 : 1	73 : 1
<b>Specific Impulse (ISP)</b>	282 sl 311 vac	311 sl 338 vac	263 sl 304 vac	330 sl ~350 vac	~310 sl ~340 vac	<b>366 sl</b> <b>452 vac</b>
<b>Chamber Pressure</b>	97 bar	257 bar	70 bar	<b>270 bar</b>	~135 bar	206 bar

# Super Heavy Engine Configuration



# Starship Integrated Flight Test 3



# Starship IFT 3 Entry



# Speculation on Interior Outfitting



# Starship as Human Landing System



# Launchers

Country

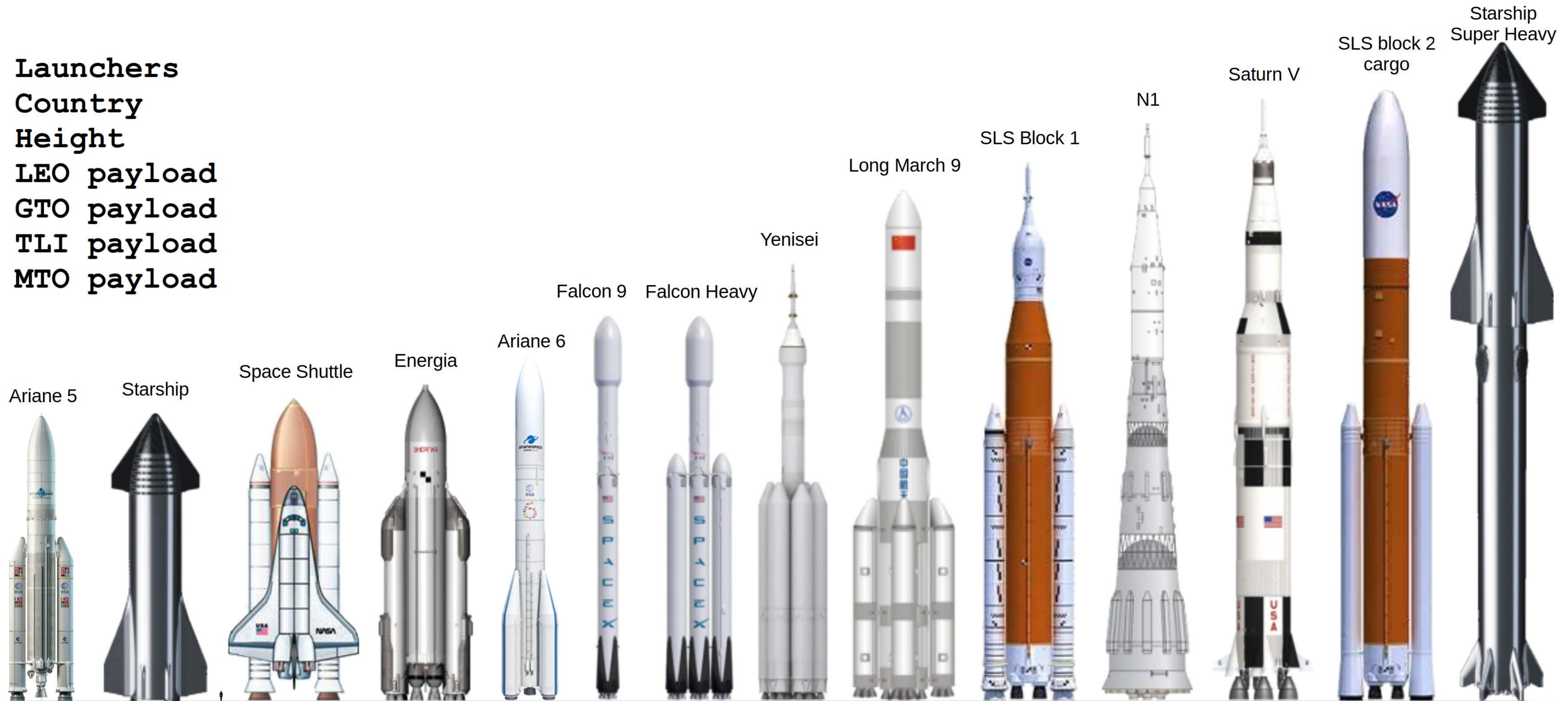
Height

LEO payload

GTO payload

TLI payload

MTO payload

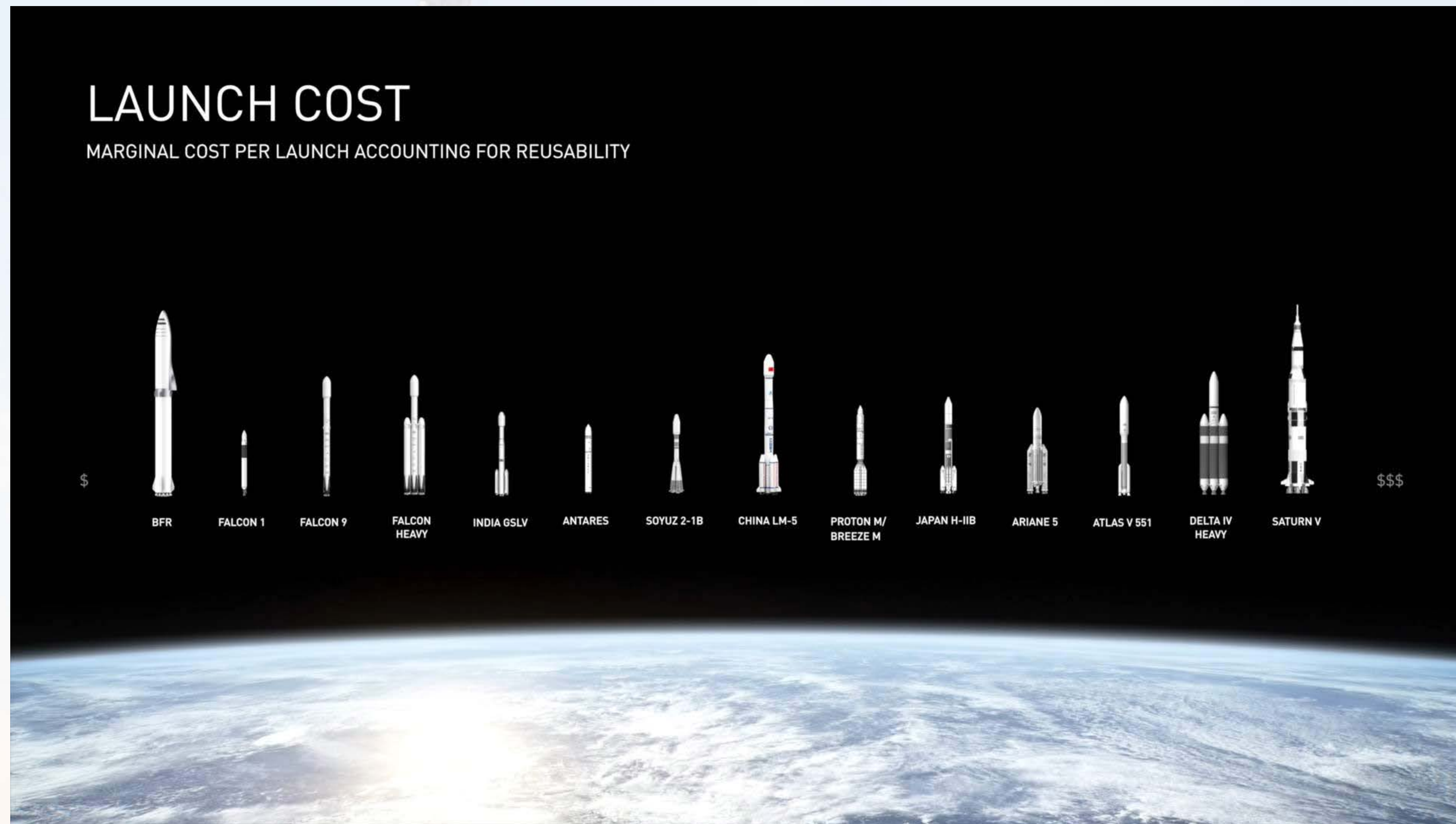


EU	USA	USA	USSR	EU	USA	USA	Russia	China	USA	USSR	USA	USA	USA
48 m	50 m	56.1 m	57.5 m	63 m	70 m	70 m	~80 m	93 m	98.1 m	105 m	110.6 m	111.3 m	120 m
20 t	?? t	27.5 t	100 t	21.7 t	22.8 t	63.8 t	103 t	140 t	95 t	95 t	140 t	130 t	150 t
10.6 t	?? t	10.9 t	38 t	11.5 t	8.3 t	26.7 t		56 t	55 t	28.1 t	57.8 t	55 t	
8.9 t		9.2 t	32 t	9.7 t	7.0 t	22.4 t		50 t	42 t	23.5 t	48.6 t	46 t	
					4.0 t	16.8 t		44 t					

Soyuz-2	Atlas V	Titan IV	Proton-M	Vulcan Centaur	Delta IV Heavy
Russia/EU	USA	USA	Russia	USA	USA
46.3 m	58.3 m	62 m	58.2 m	61.6 m	72 m
8.2 t	20.5 t	21.7 t	23 t	27.2 t	28.8 t
3.3 t	8.9 t	5.7 t	6.9 t	14.4 t	14.2 t
				12.1 t	

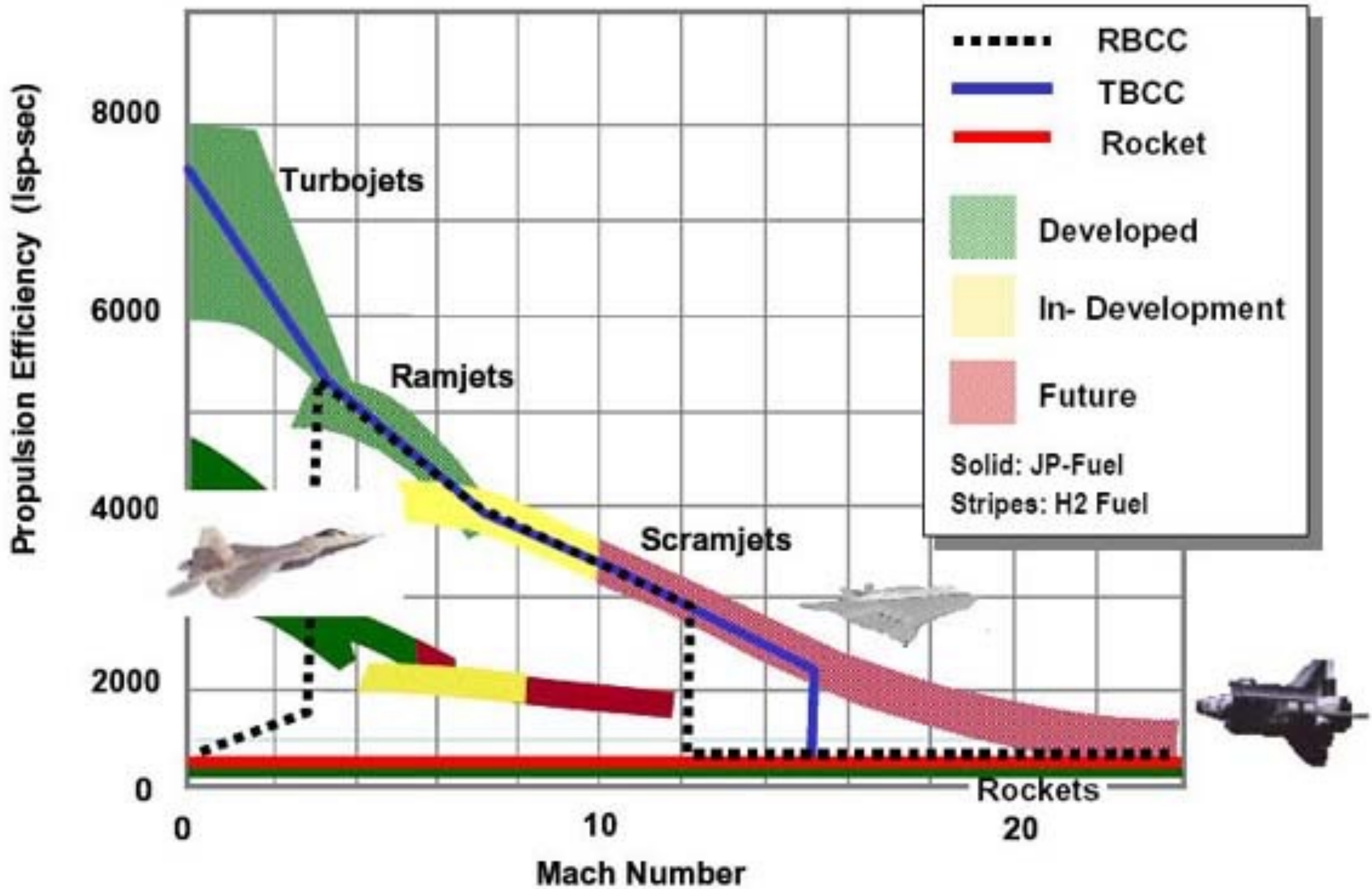


# BFR Costs (per Elon Musk)



# Sea Dragon (“For All Mankind”)





# Approaches to Air-Breathing Propulsion

Air-Augmented Rocket

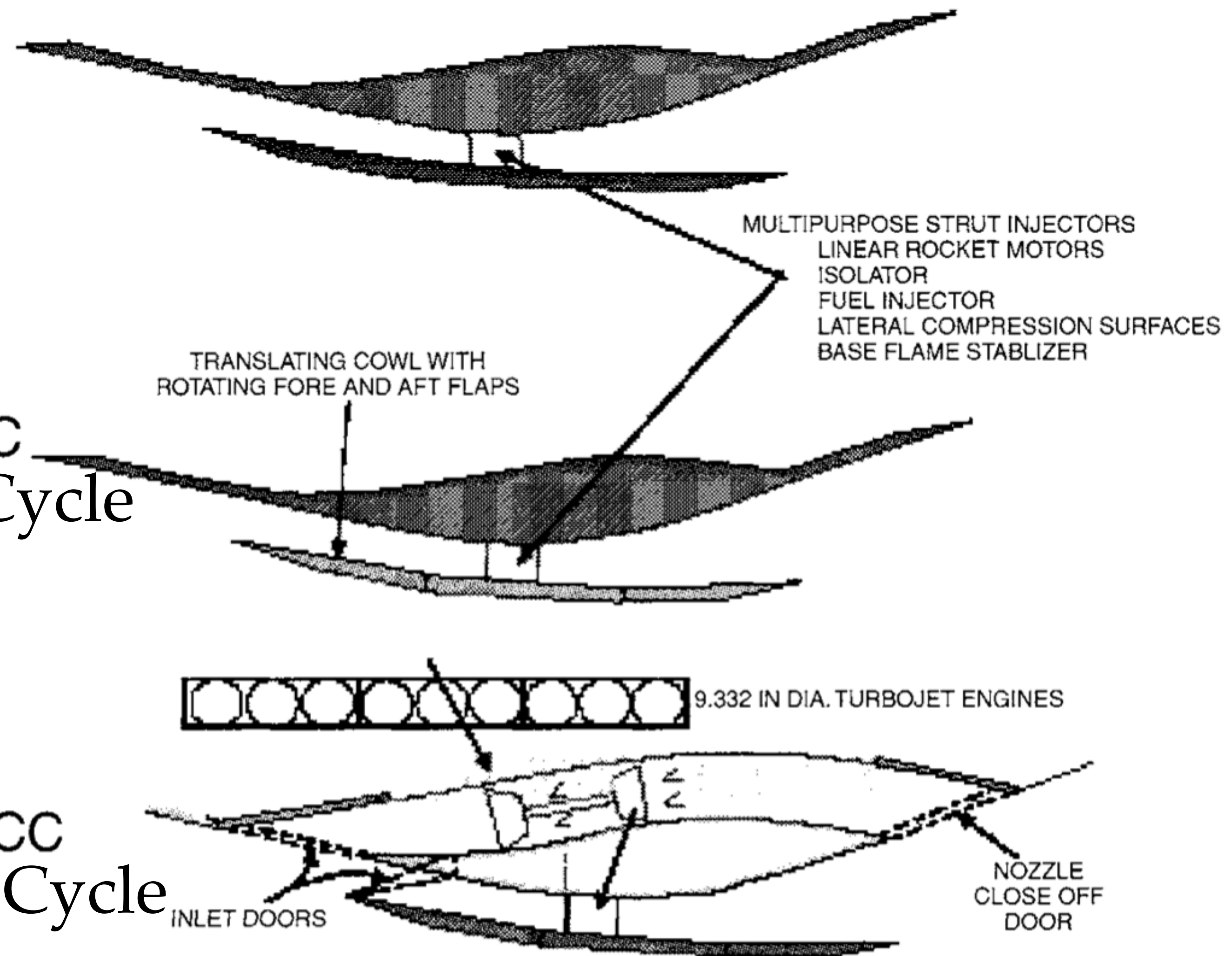
AAR

Rocket-Based Combined Cycle

RBCC

Turbine-Based Combined Cycle

TBCC





# Combined Cycle Launch Vehicles RBCC and TBCC



## Rocket Based Combined Cycle (RBCC)

*Rocket-ejector → Ramjet → Scramjet → Rocket*

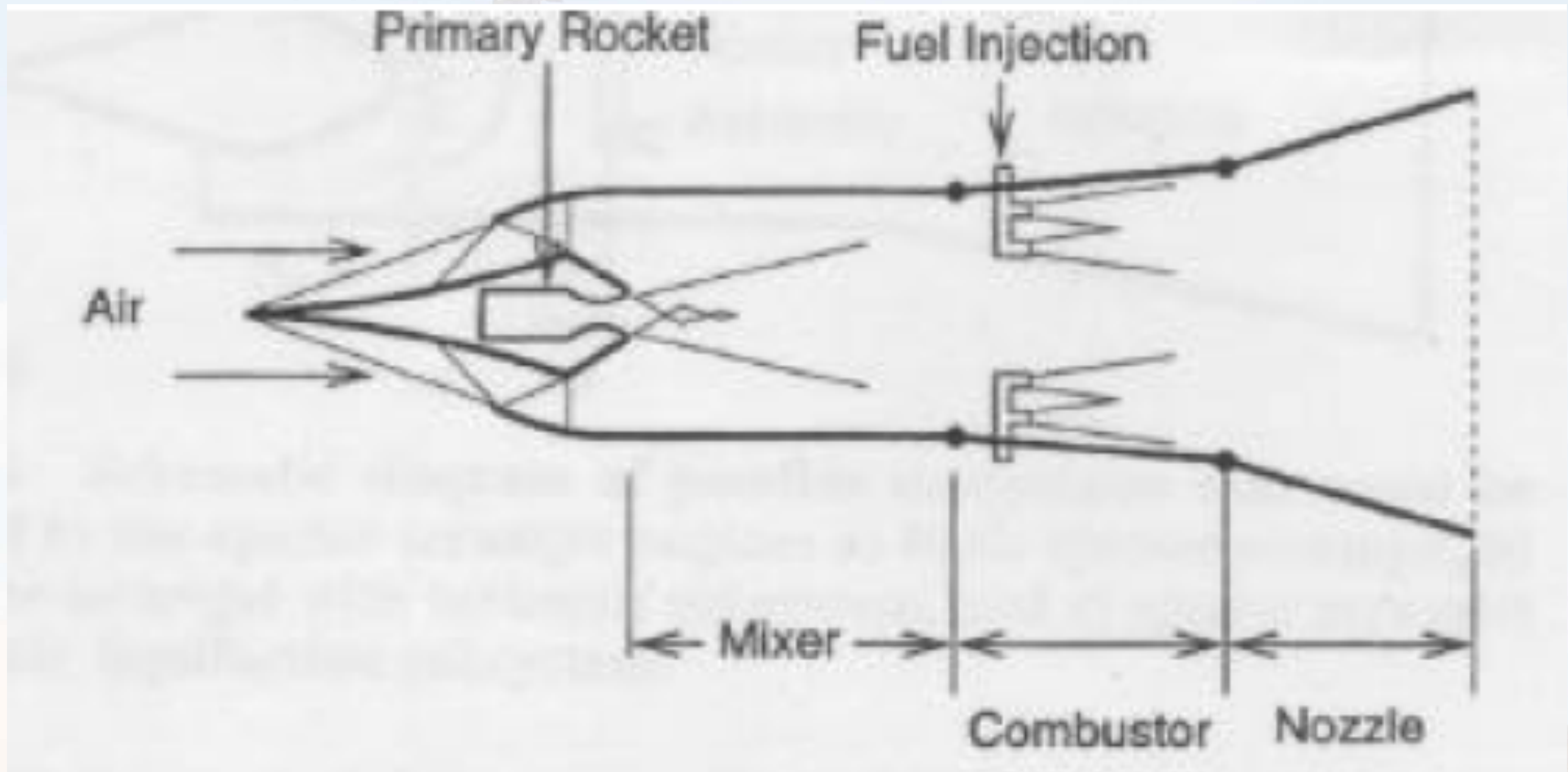
## Turbine Based Combined Cycle (TBCC)

*Turbojet → Ramjet → Scramjet → Rocket*

- Both technologies are under development at the component/initial integration stages.
- Basic demonstration of scramjets has been shown, but survivable, reusable vehicles have not.
- Development will probably require decades, but may yield a revolutionary launch technology.
- Could be viable for both launch scenarios



# Rocket-Based Combined Cycle (RBCC)



# DUAL-MODE OPERATION

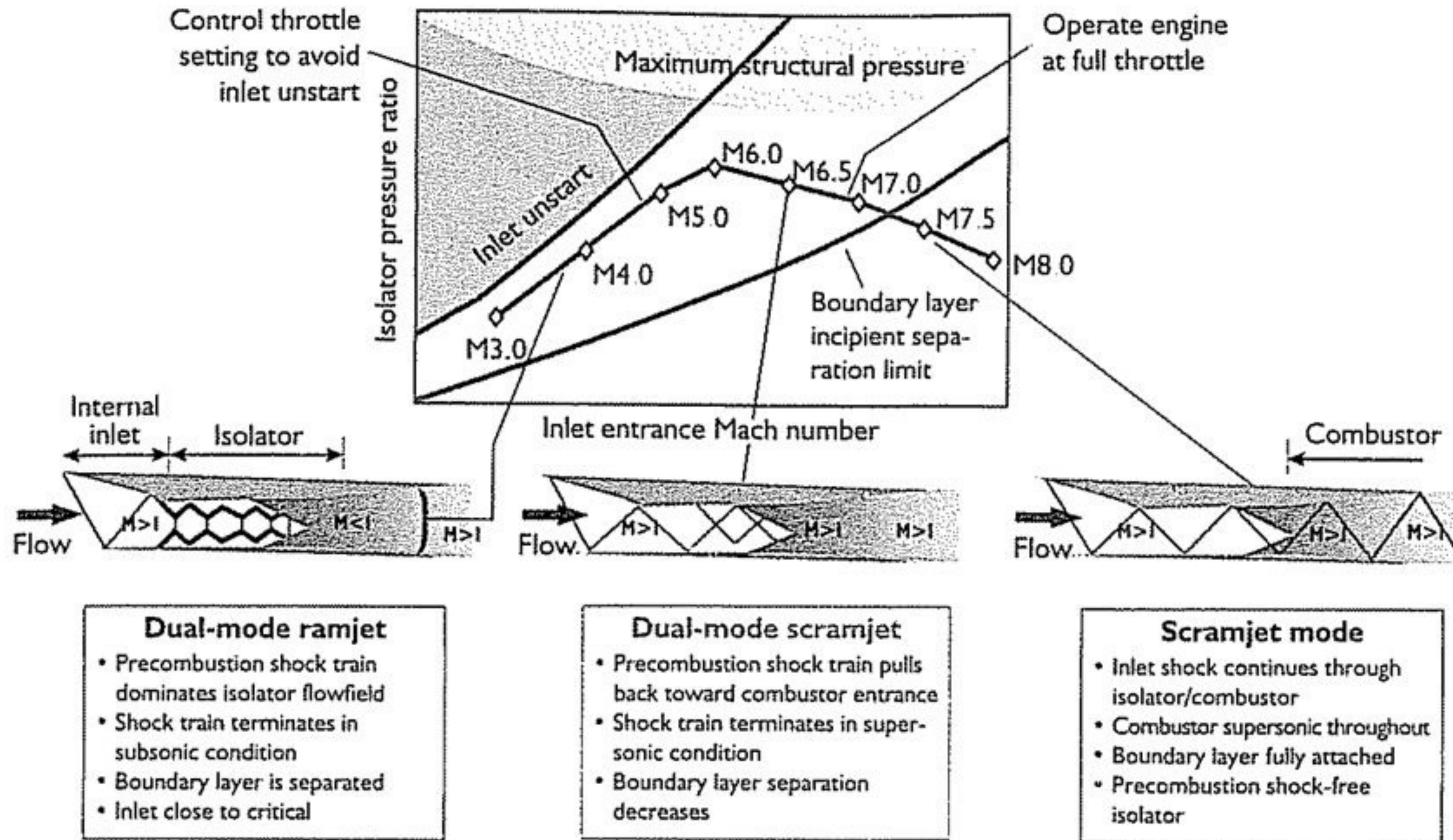
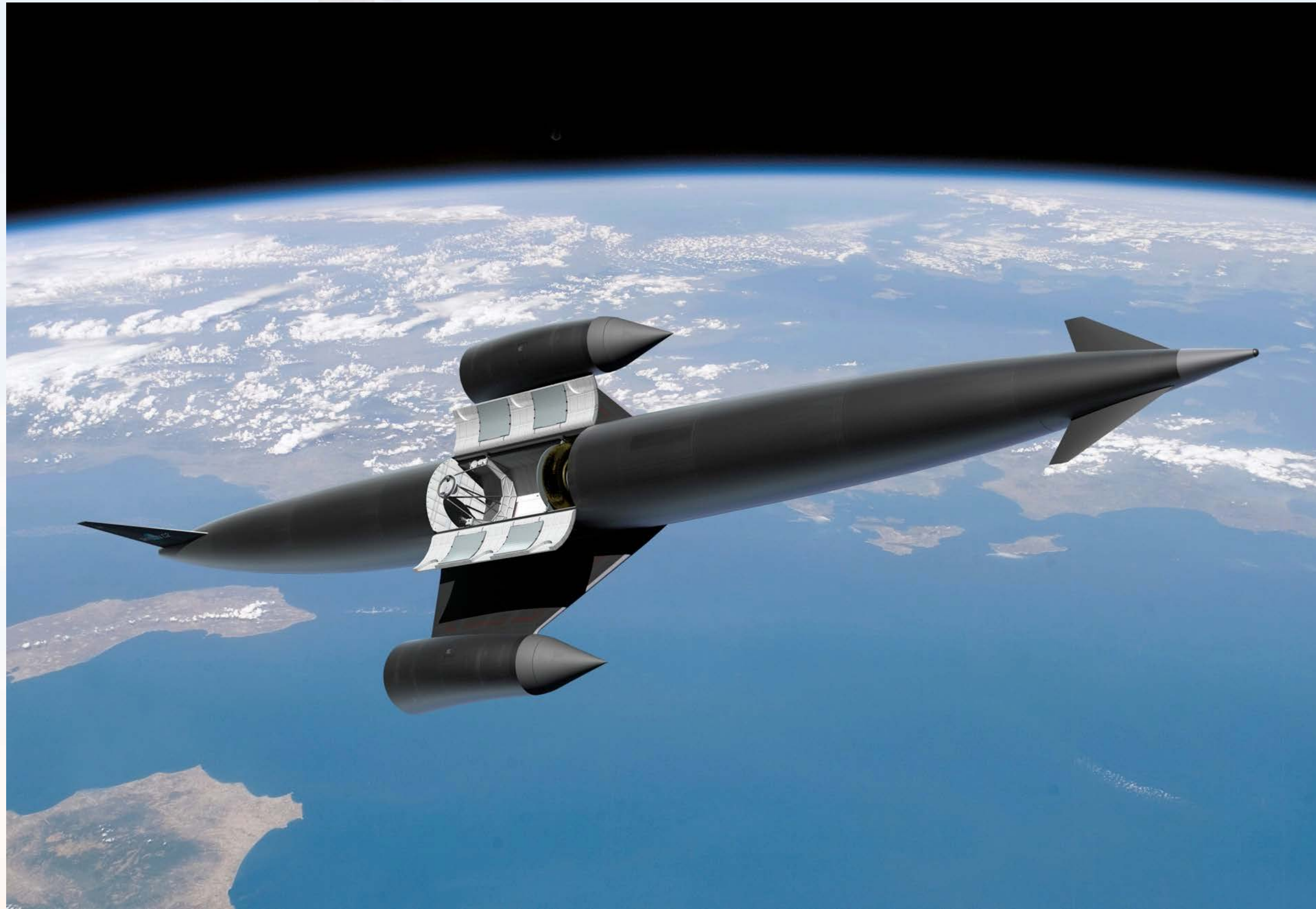


Figure 3. As the vehicle speed increases from Mach 3 to Mach 8, the isolator pressure ratio passes through a peak at Mach 6. As the shock train and boundary layer retreat, the modes change from dual-mode ramjet to dual-mode scramjet to pure scramjet mode.

# 20?? - Skylon







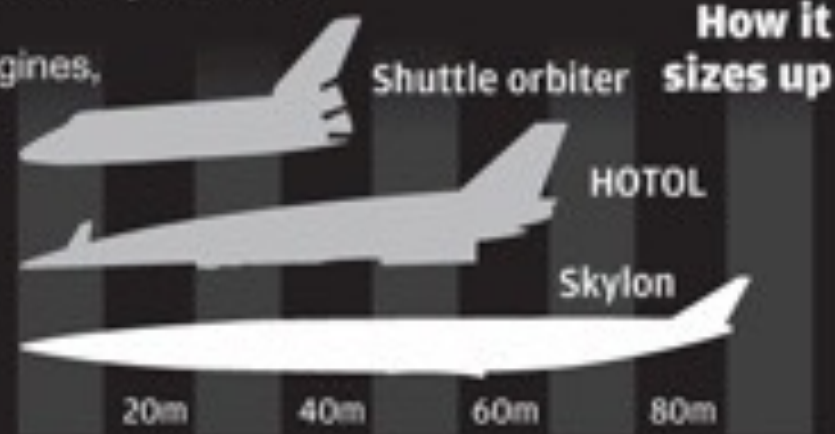
# SKYLON - THE FUTURE OF SPACE?



## Skylon

Skylon will be a fully-automated, pilotless space plane. Unlike the Space Shuttle, which is less than 30 per cent reusable, Skylon will be totally reusable

**Built by:** Reaction Engines, Oxfordshire, UK  
**Length:** 82m (269ft)  
**Fuselage width:** 6.25m (20ft)  
**Wingspan:** 25m (82ft)  
**Maximum payload:** 12,000kg



## Inside Skylon

Skylon's fuselage is made from carbon fibre reinforced plastic. Its aluminium fuel tanks are suspended within the frame and are free to move as the aircraft expands and contracts as it is subjected to heat and pressure fluctuations

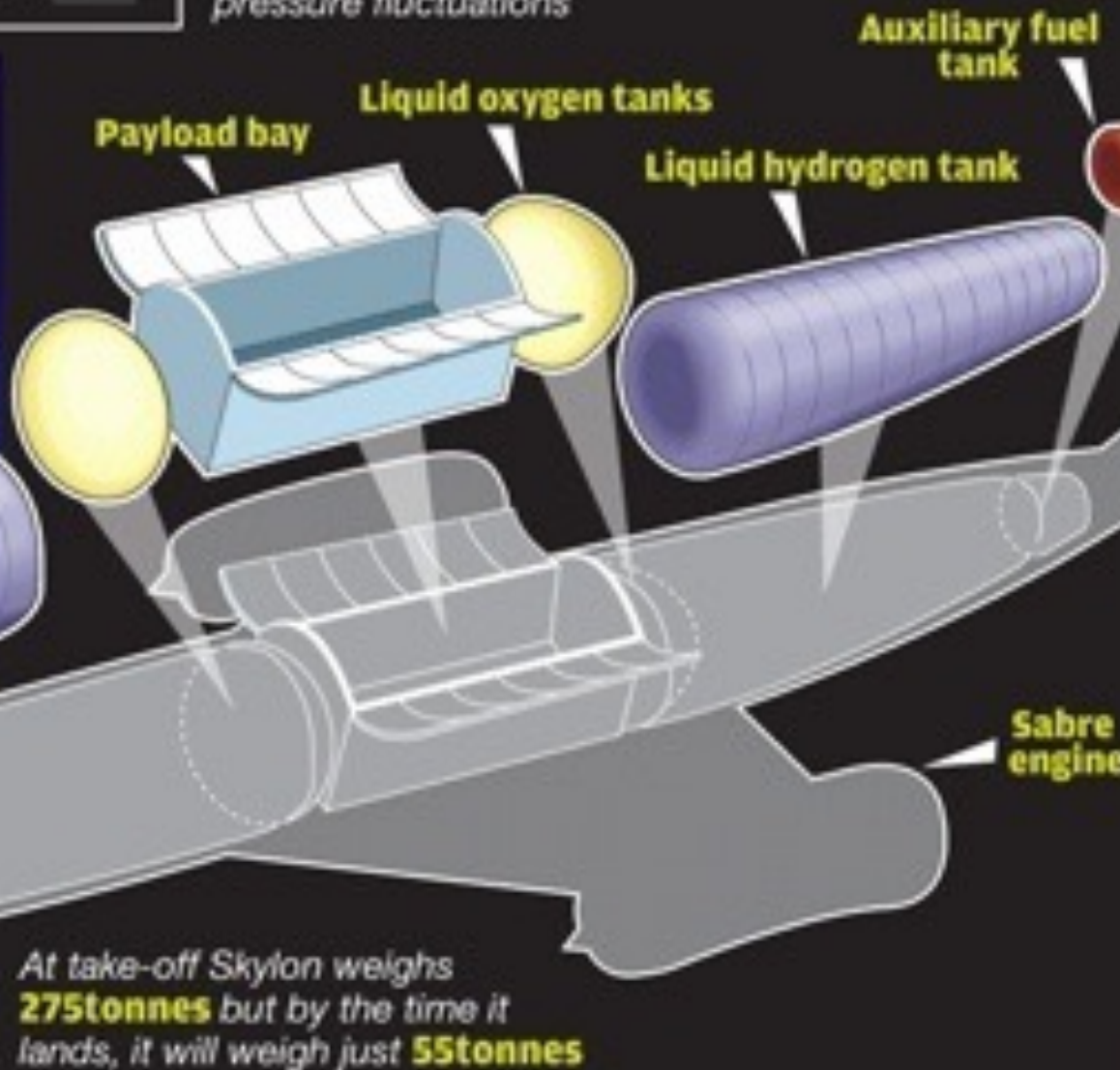
Skylon carries **150 tonnes** of liquid oxygen and **66 tonnes** of liquid hydrogen

(a litre of liquid oxygen weighs 1.14kg, but a litre of liquid hydrogen only weighs 70g, which is why the hydrogen tanks are much bigger despite the oxygen tanks carrying a far greater mass of gas)

Skylon's external shell is only 0.5mm thick and is made from fibre-reinforced ceramic. It is also free to move during thermal expansion, which is most extreme during atmospheric re-entry

**Liquid hydrogen tank**

**Foreplanes**  
(replace tailplanes for steering)



At take-off Skylon weighs **275 tonnes** but by the time it lands, it will weigh just **55 tonnes**

## The Sabre engine

To minimise the amount of fuel Skylon has to carry, during the first phase of flight, the Sabre engine gathers oxygen from the atmosphere as it flies

1. At speeds of more than **5,000kph** heat created by friction means that air gathered by the intake is a sizzling **1,000 C**
2. The hot air passes into a pre-cooler, which uses cold, high-pressure helium to chill the air down to **-140 C**. At -140 C, the air is just above the temperature at which it liquifies, which greatly reduces its volume and means the engine doesn't have to carry heavy compressors
3. This air then flows into the engines combustion chambers where it is mixed with hydrogen from Skylon's fuel tanks where it is ignited to produce thrust. When the engine shifts to 'rocket only' mode, the air intake closes and the engine uses liquid oxygen pumped from its internal tanks



## How Skylon gets into space

**1.** Skylon takes off in the same manner as a combat jet, but will require a runway about **5.6km** long

**2.** During the initial climb, Skylon's engines operate in air-breathing mode. During this time the engines collect oxygen from the atmosphere, which is used to fuel its ascent

If Skylon couldn't collect oxygen in this manner, it would need to carry an extra **250 tonnes** of liquid oxygen in its tanks  
**3.** It takes Skylon almost two hours to climb to **28km** and reach a speed of almost **5,400kph** (3,350mph)

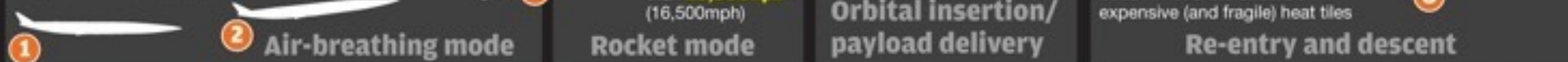
**4.** At an altitude of **28.5km**, the Sabre engine shifts to rocket mode – the air intakes close and it burns its internal fuel supplies. The rockets accelerate Skylon to more than **26,500kph** (16,500mph)

**5.** Skylon's rockets carry the craft to an altitude of **300km** at which point the main engines cut off and it uses smaller engines to manoeuvre into orbit

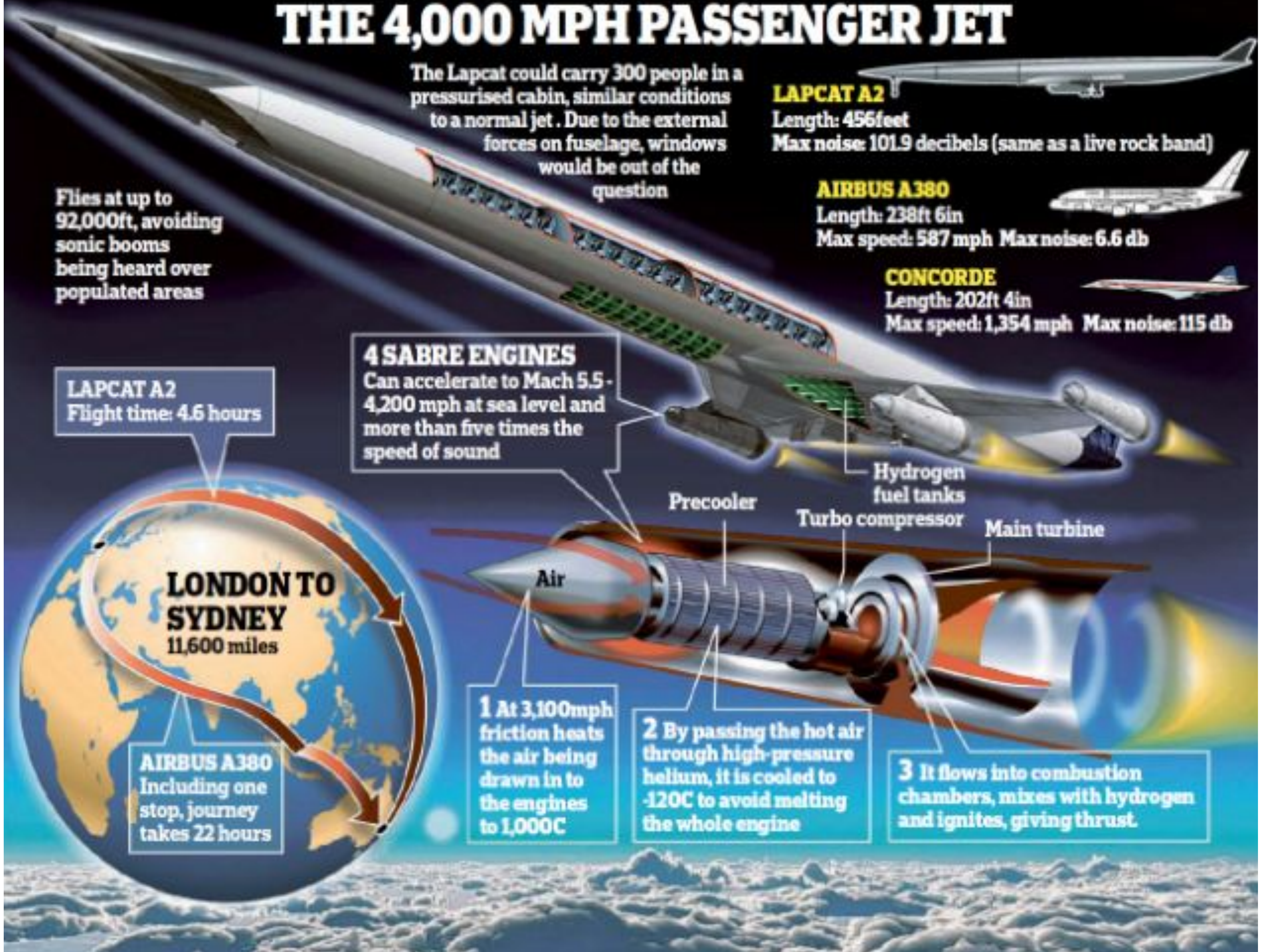
**6.** The craft deploys its payload

**7.** Skylon re-enters the Earth's atmosphere. Being much lighter than the Space Shuttle, Skylon can re-enter at a much lower speed – meaning it doesn't need the Shuttle's expensive (and fragile) heat tiles

**8.** Skylon's landing speed is about **240kph** (150mph) – compared to the Shuttle which lands at up to **650kph** (400mph)



# THE 4,000 MPH PASSENGER JET



The Lapcat could carry 300 people in a pressurised cabin, similar conditions to a normal jet. Due to the external forces on fuselage, windows would be out of the question

Flies at up to 92,000ft, avoiding sonic booms being heard over populated areas

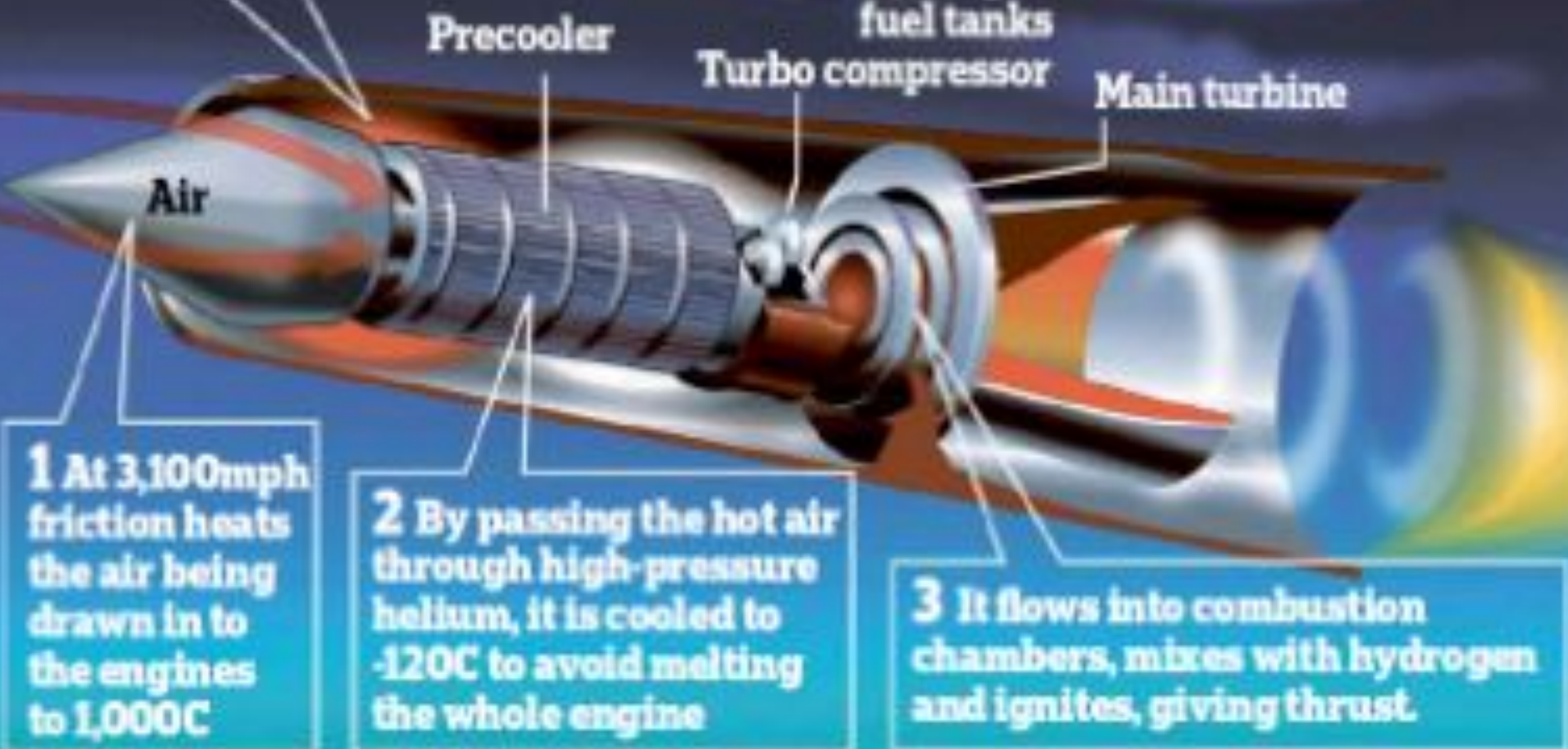
**LAPCAT A2**  
Length: 456feet  
Max noise: 101.9 decibels (same as a live rock band)

**AIRBUS A380**  
Length: 238ft 6in  
Max speed: 587 mph Max noise: 6.6 db

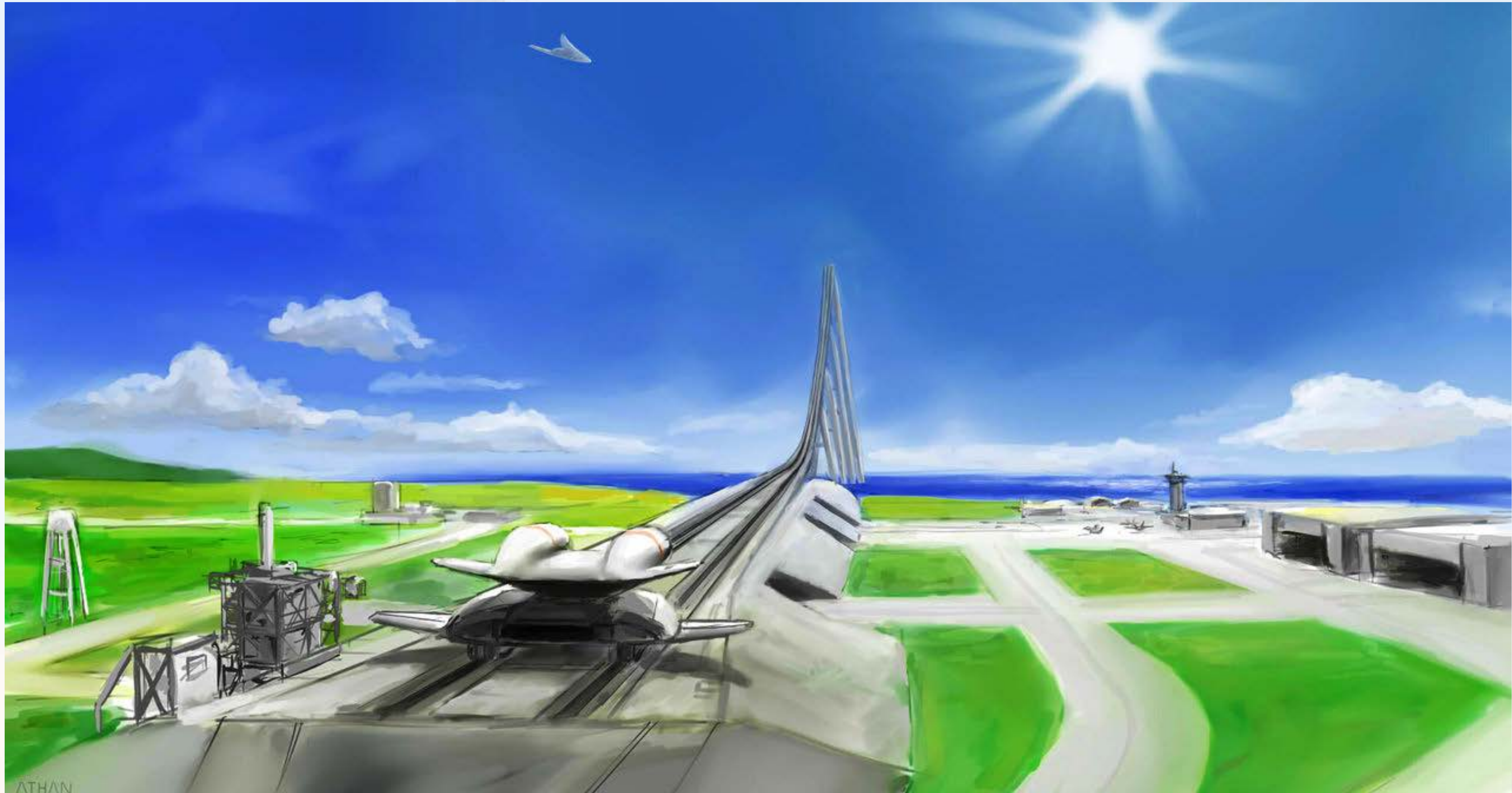
**CONCORDE**  
Length: 202ft 4in  
Max speed: 1,354 mph Max noise: 115 db

**LAPCAT A2**  
Flight time: 4.6 hours

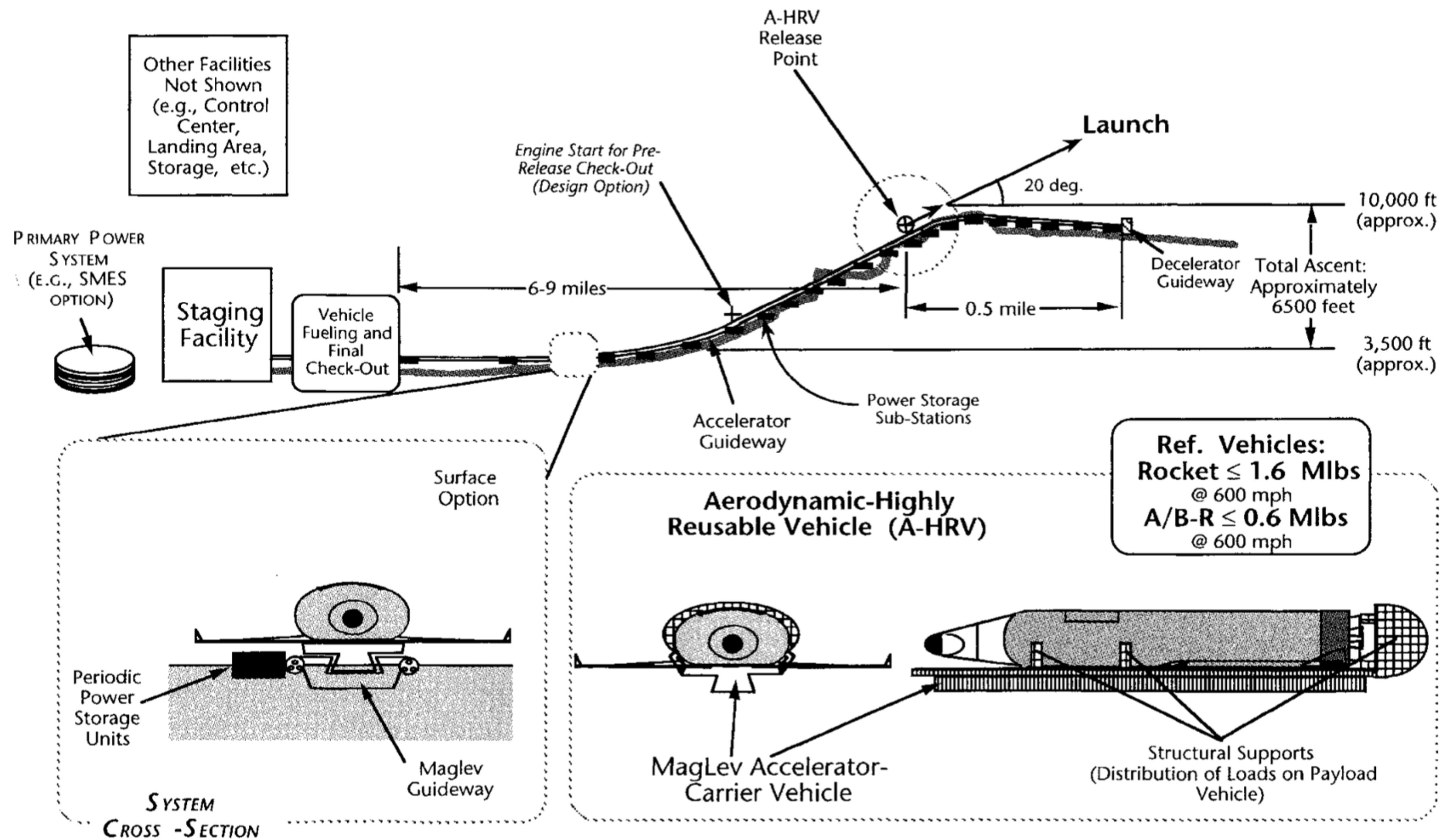
**4 SABRE ENGINES**  
Can accelerate to Mach 5.5 - 4,200 mph at sea level and more than five times the speed of sound



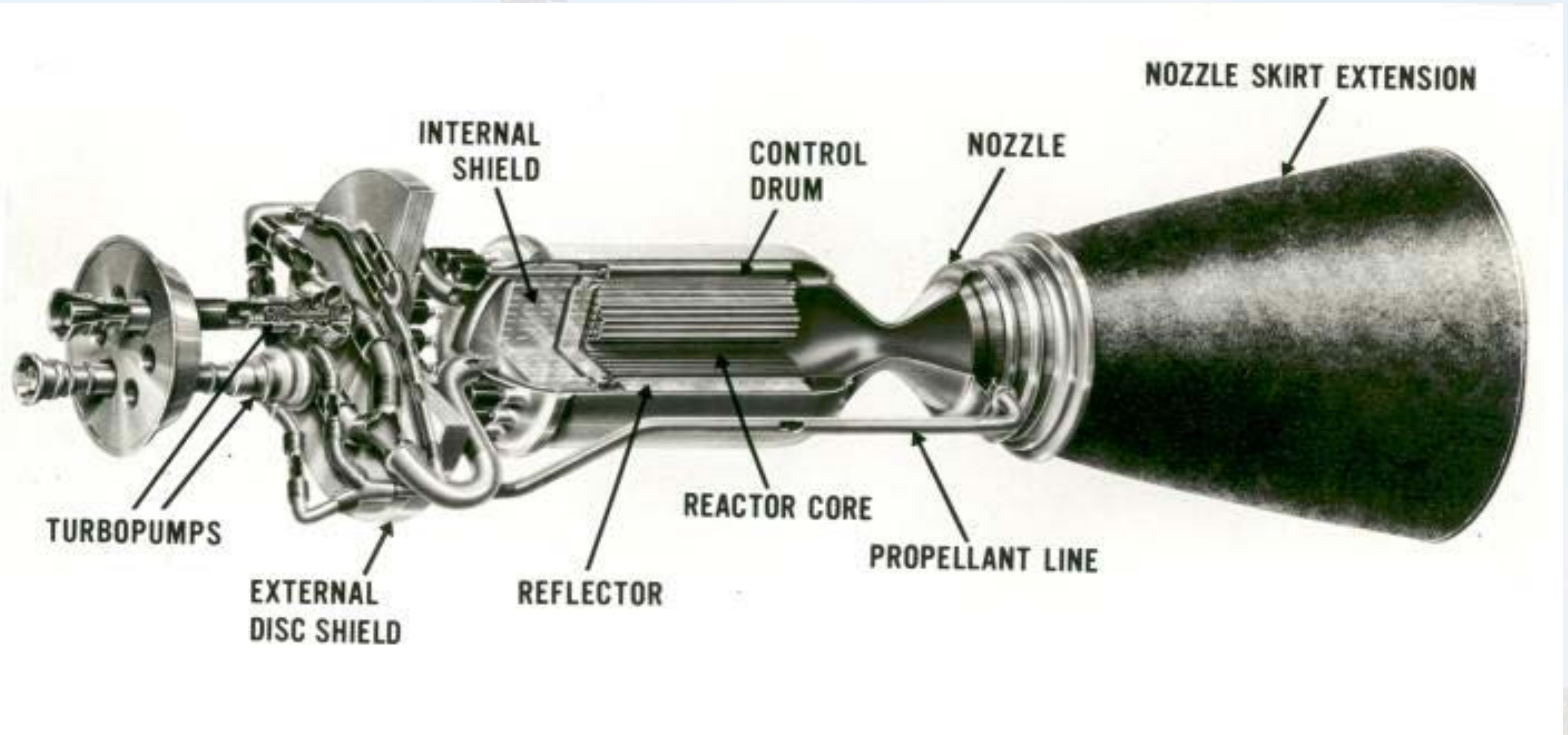
# Catapult/Tracked Launch System



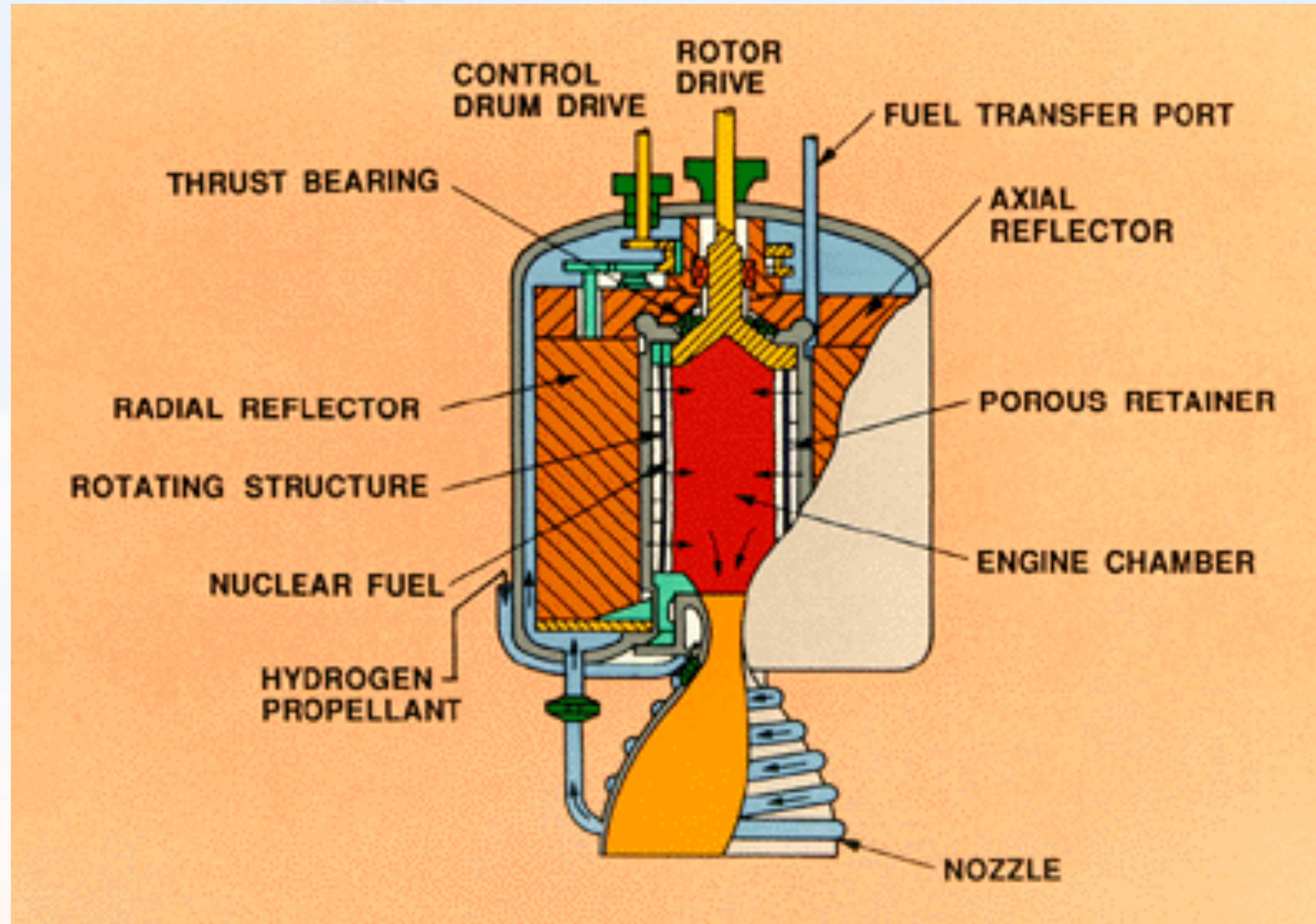
# MagLifter Tracked Launch



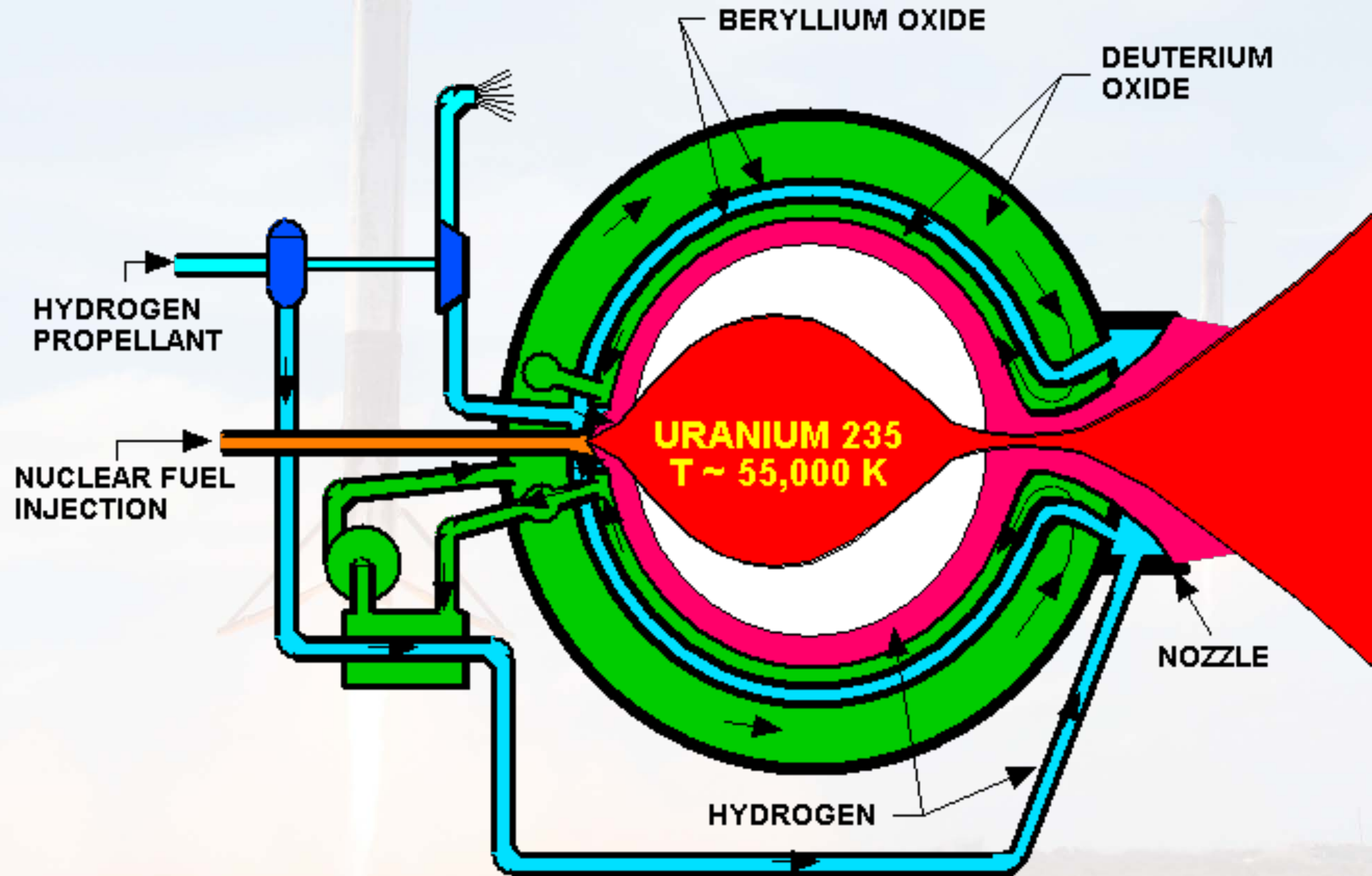
# NERVA Nuclear Thermal Engine



# Liquid Core Nuclear Rocket

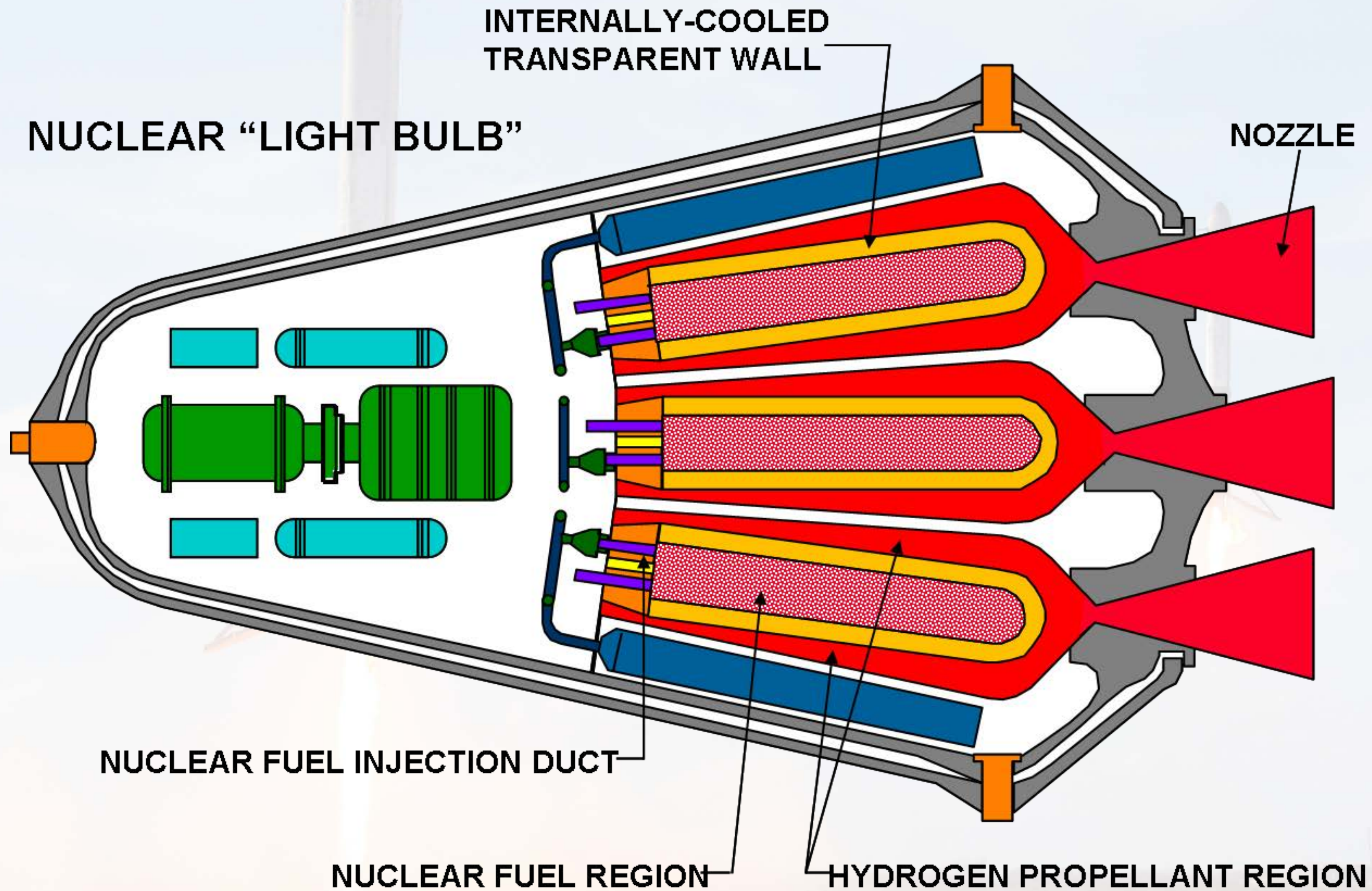


# Gas-Core Nuclear Rocket Engine

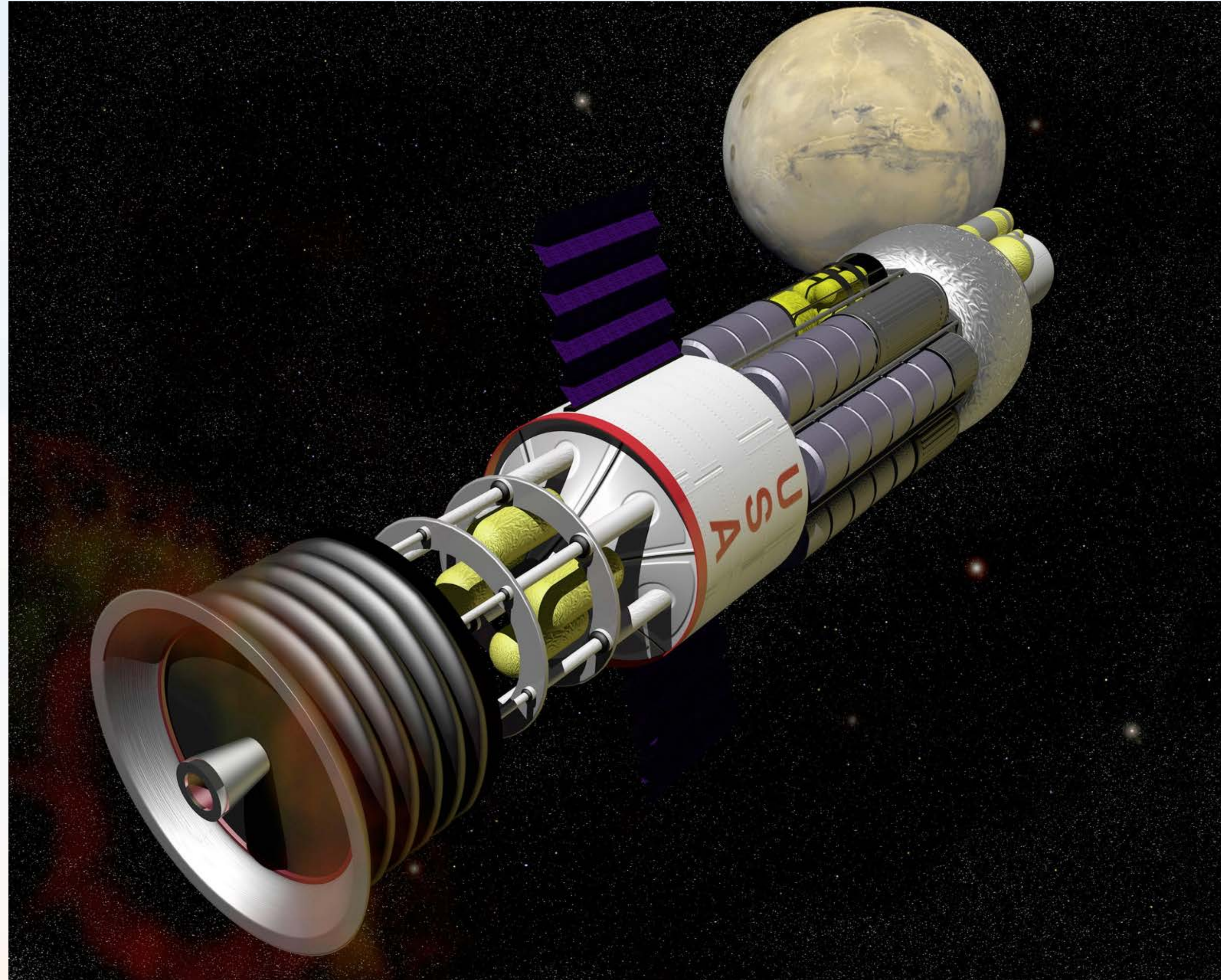




# Gas-Core Nuclear Rocket



# Project Orion



# Nuclear Fusion Engine Approaches



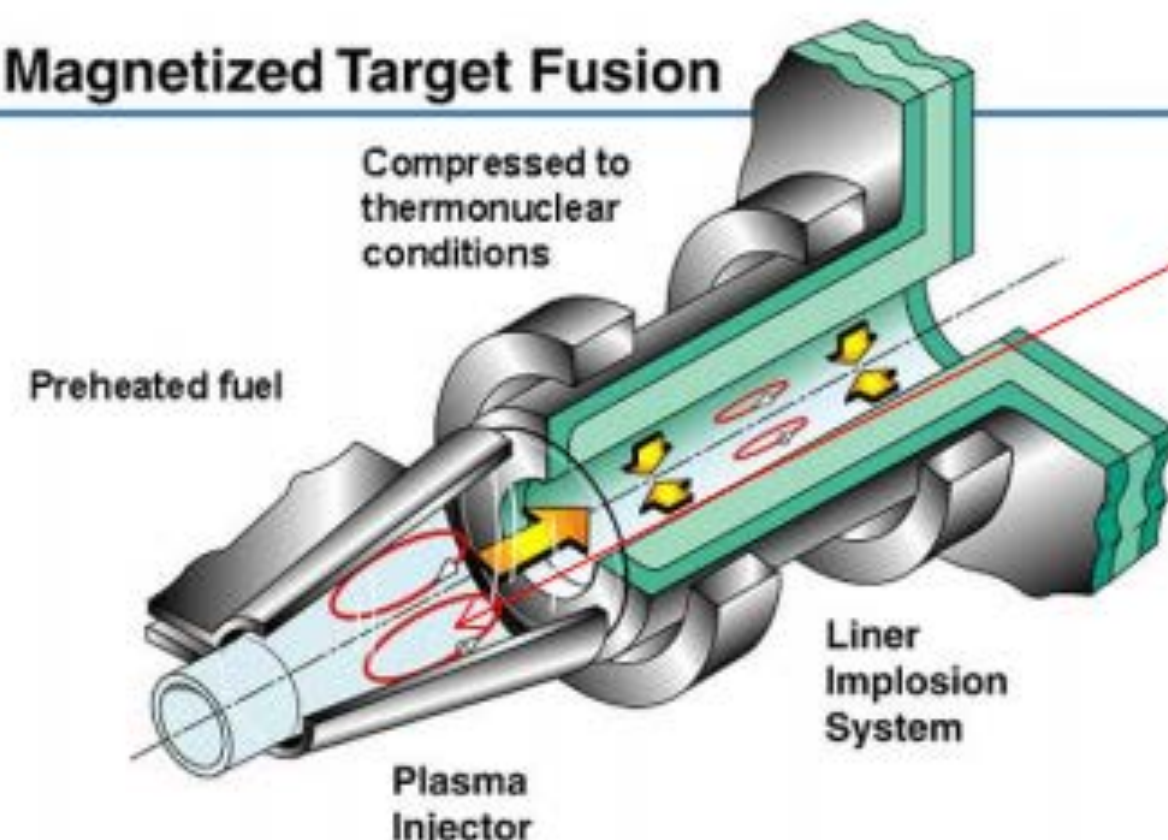
## Magneto-Inertial Fusion Two Approaches



Shell (liner) implosion driven by  $B_0$  from large axial currents in shell.

Liner implosion from  $j \times B$  force between external coil and induced liner currents

### Magnetized Target Fusion

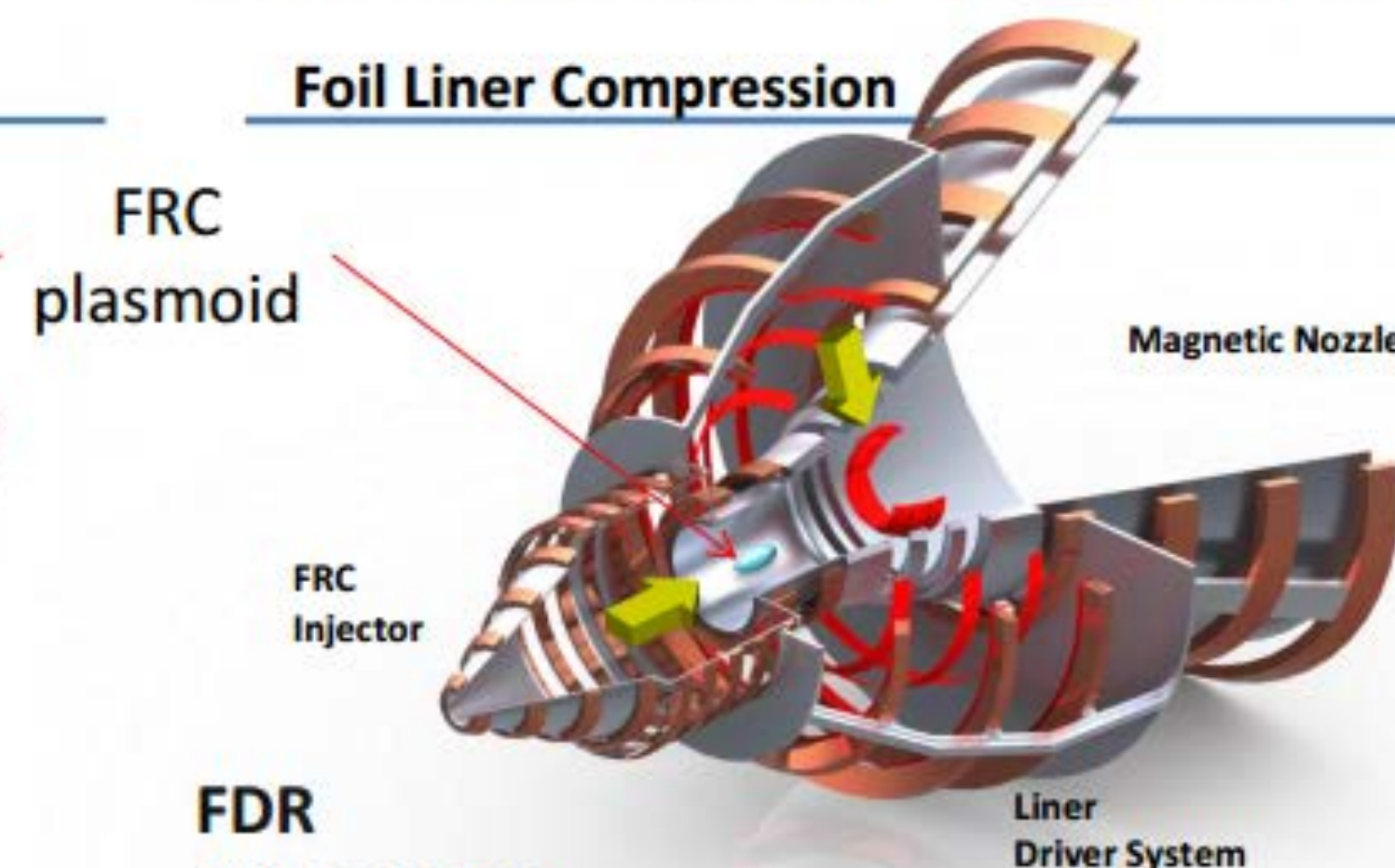


#### MTF

##### Issues:

- Extremely low inductance load difficult to drive (massively parallel HV caps and switches)
- Close proximity and electrical contact  $\Rightarrow$  major collateral damage with each pulse
- Small FRC must be formed close to implosion  $\Rightarrow$  marginal B for ignition w injector destruction
- Only inefficient 2D compression possible  $\Rightarrow$  requires much larger driver energy

### Foil Liner Compression



#### FDR

##### Advantages:

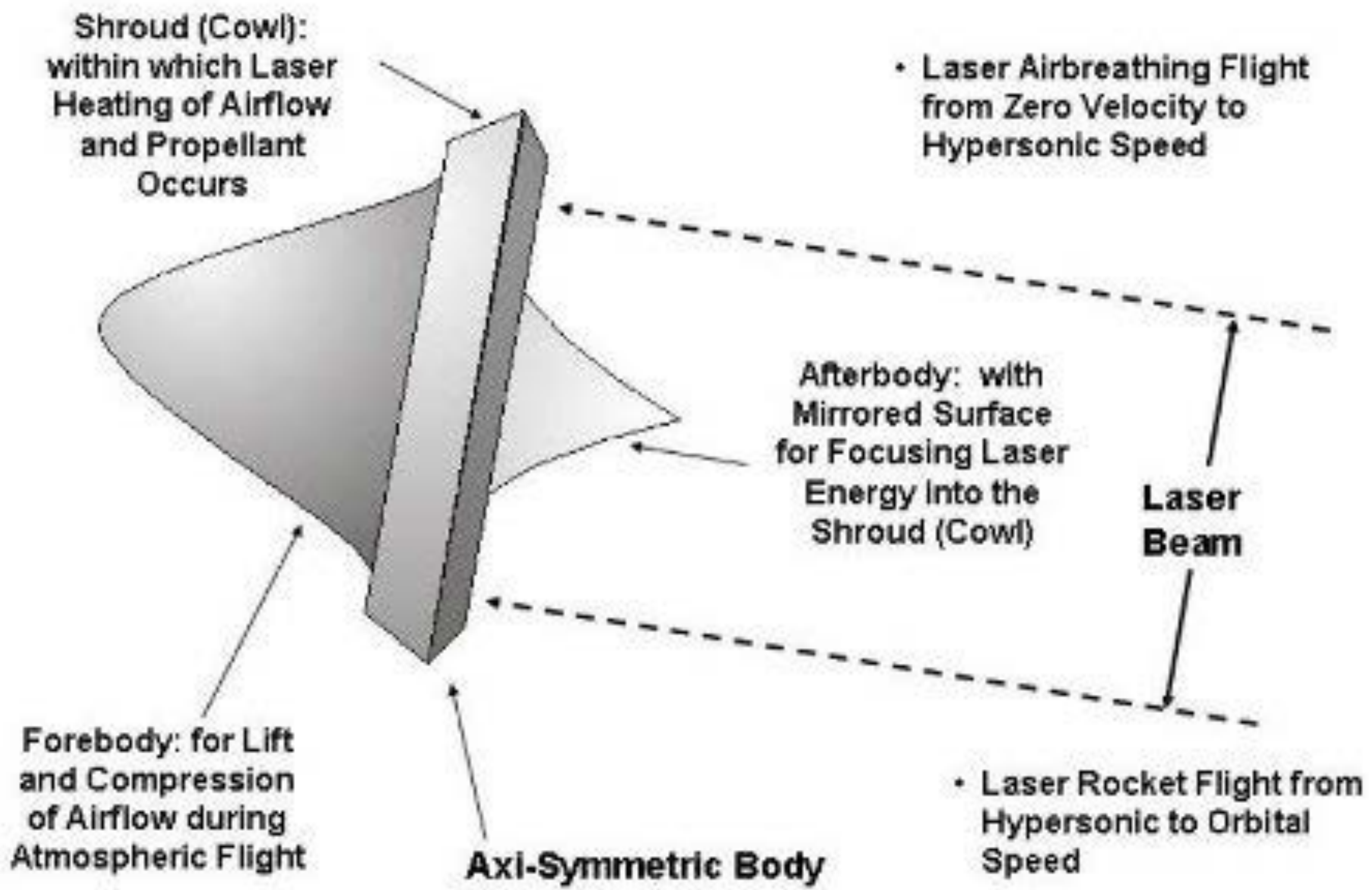
- Large driver coil easy to power with ample standoff
- Driver electrically isolated from liner and magnetically from fusion process
- Large FRC can be formed external to implosion with abundant B for ignition
- Full 3D compression can be realized for efficient compression and translation



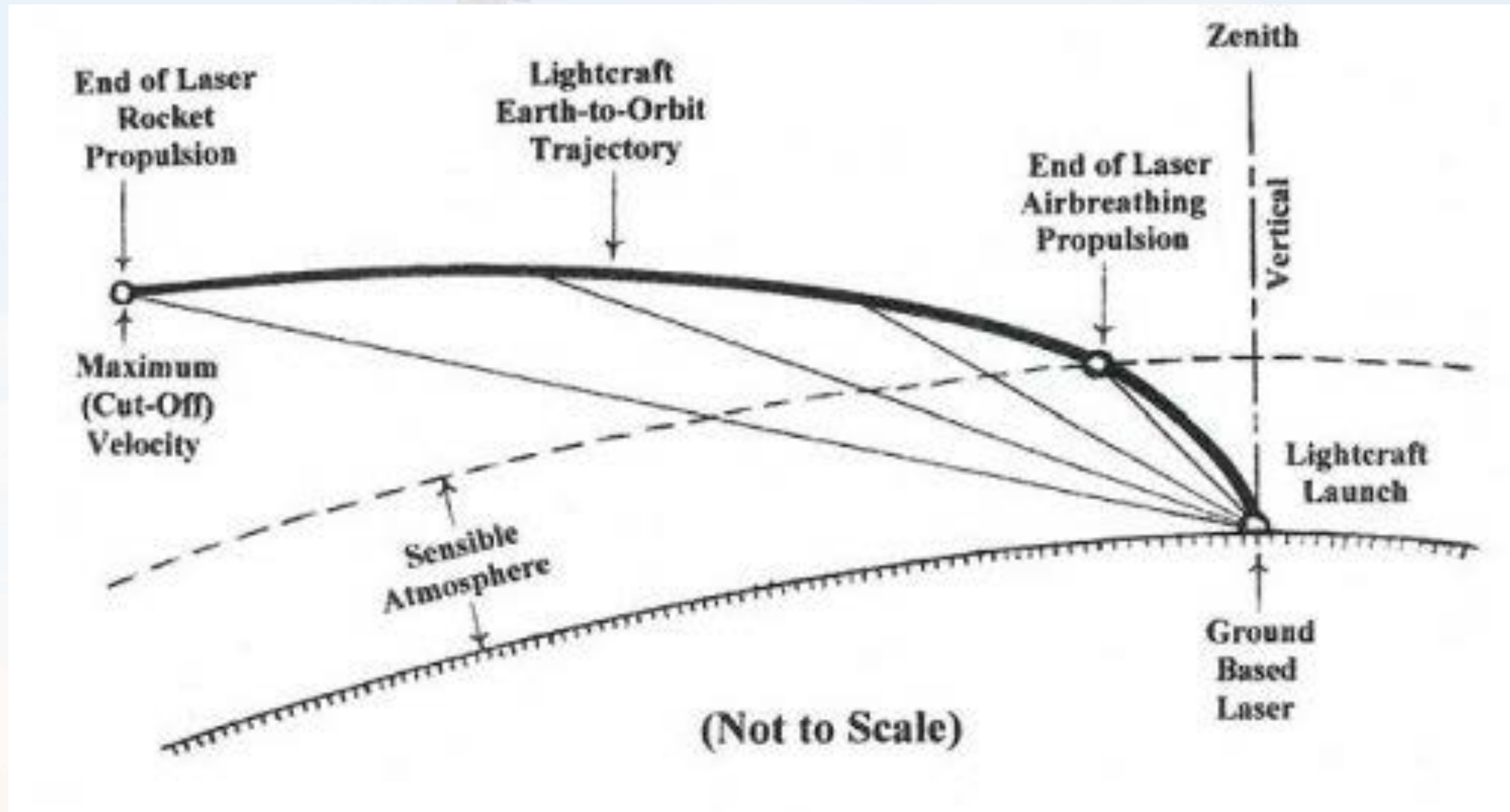
# Lightcraft Laser Launch System



# Lightcraft Operating Concept



# Lightcraft Trajectory



# Lunar Surface Mass Driver

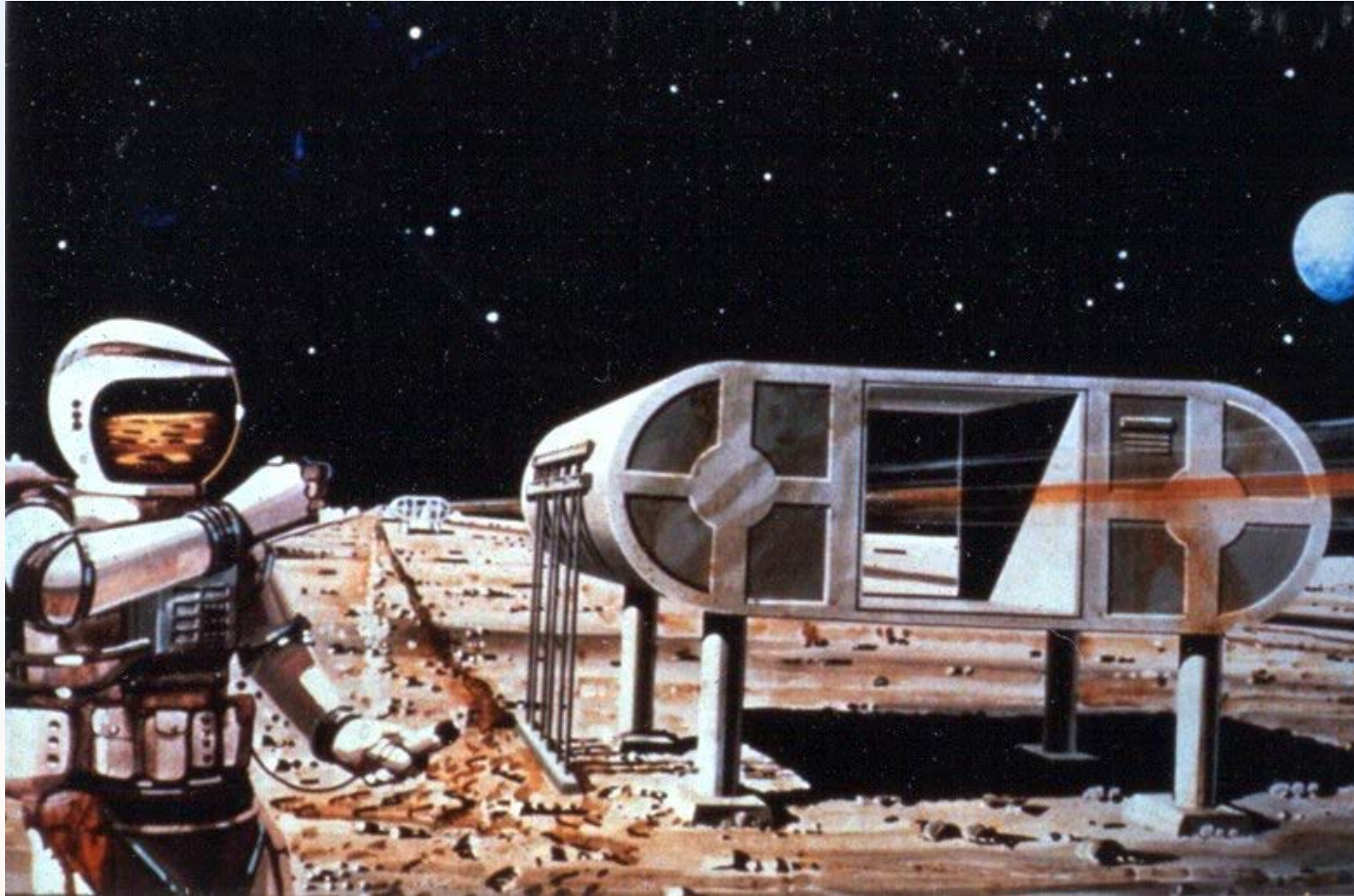


# MIT Massdriver Prototype





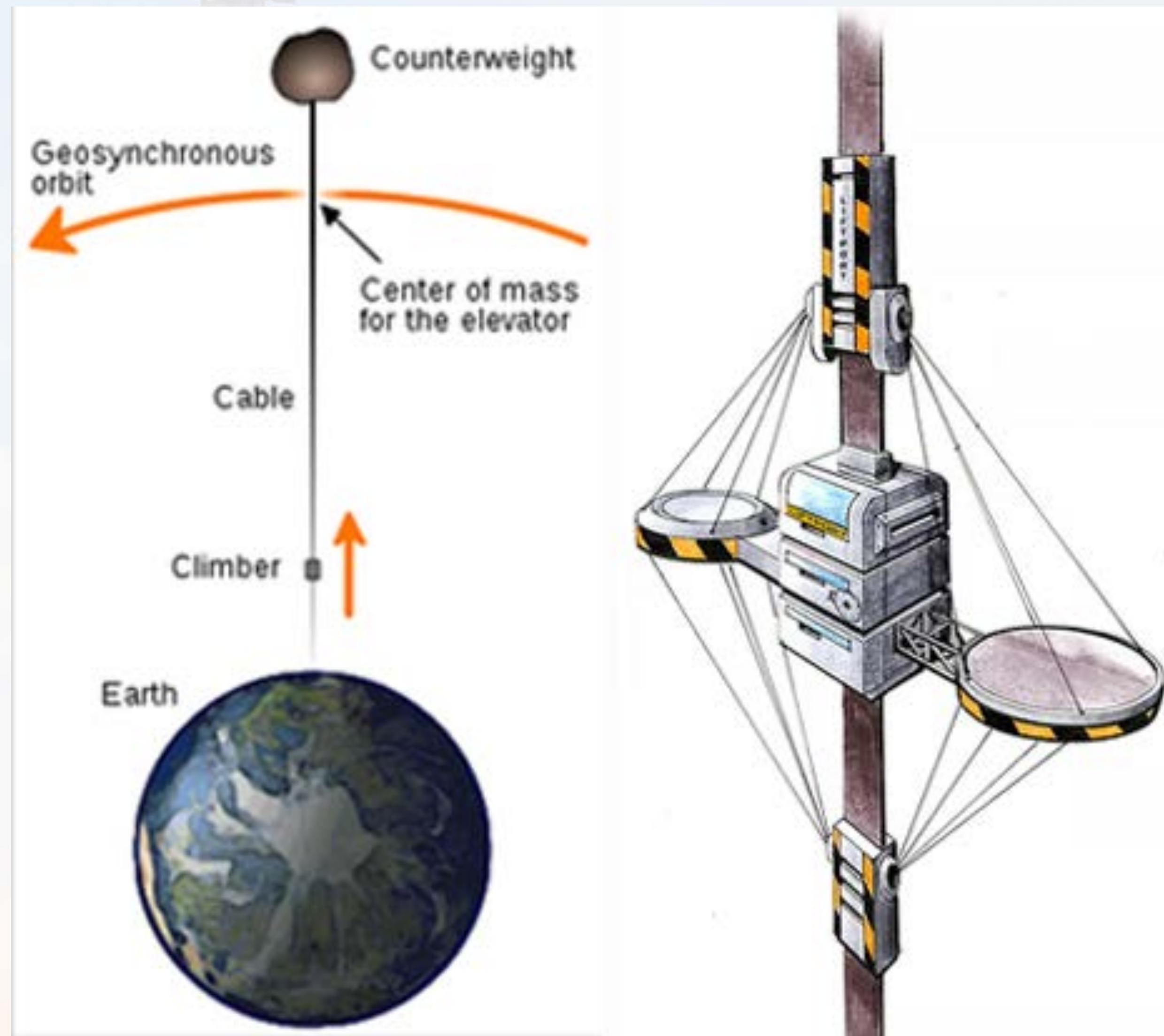
# Mass Driver Trajectory Adjustment



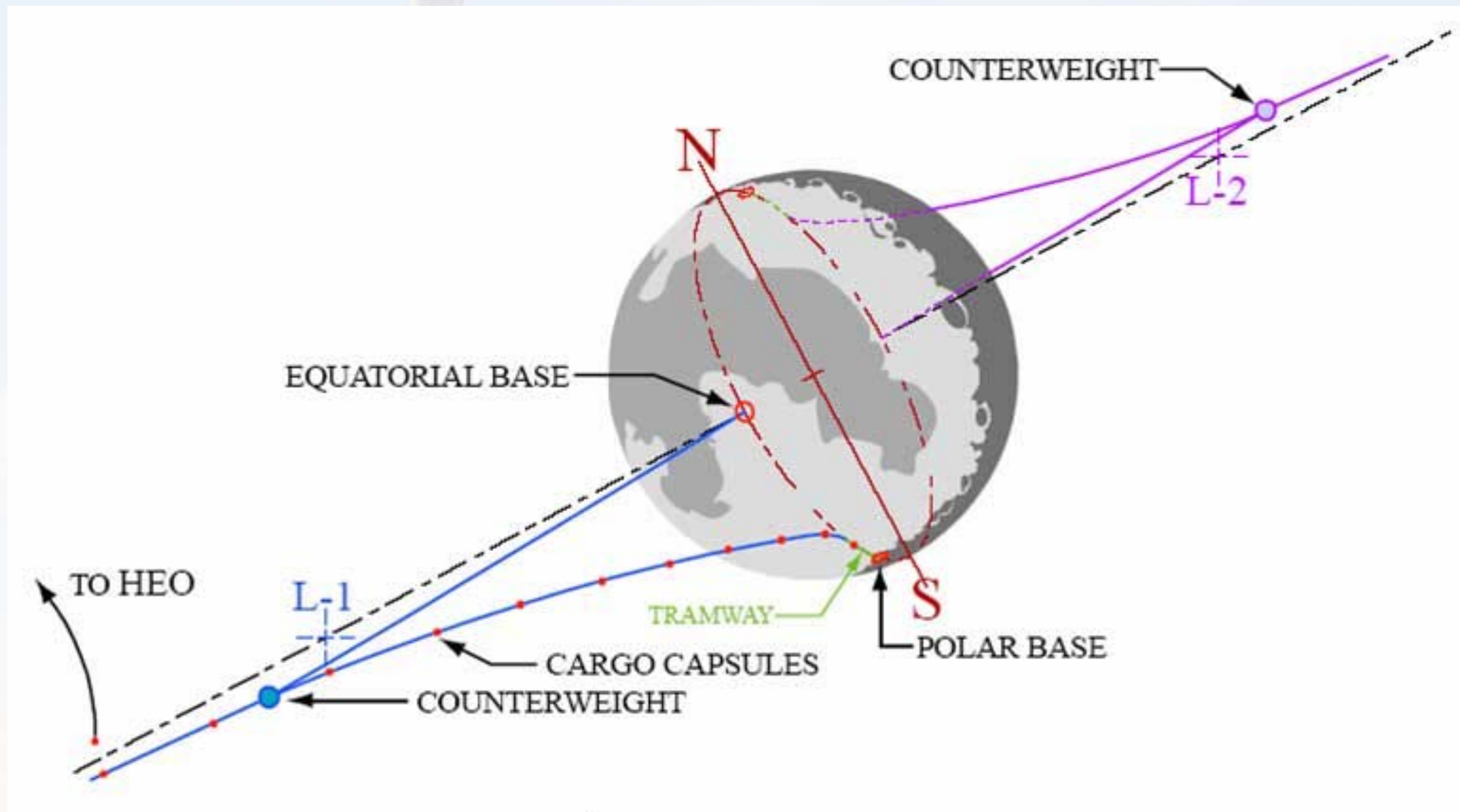
# Space Elevator



# Space Elevator Schematic



# Lunar Space Elevator



# Theoretical Cost to Orbit

- Convert to usual energy units

$$\frac{\text{Total Energy}}{\text{kg in orbit}} = 32 \times 10^6 \frac{J}{kg} = 8.9 \frac{kWhrs}{kg}$$

- Domestic energy costs are ~\$0.09 / kWhr

▶▶ Theoretical cost to orbit \$0.99 / kg

# Arthur C. Clarke's Three Laws

1. When a distinguished but elderly scientist states that something is possible, they are almost certainly right. When they state that something is impossible, they are very probably wrong
2. The only way of discoing the limits of the possible is to venture a little way past them into the impossible
3. Any sufficiently advanced technology is indistinguishable from magic