# Tethers for Affordable Earth to Orbit Transportation

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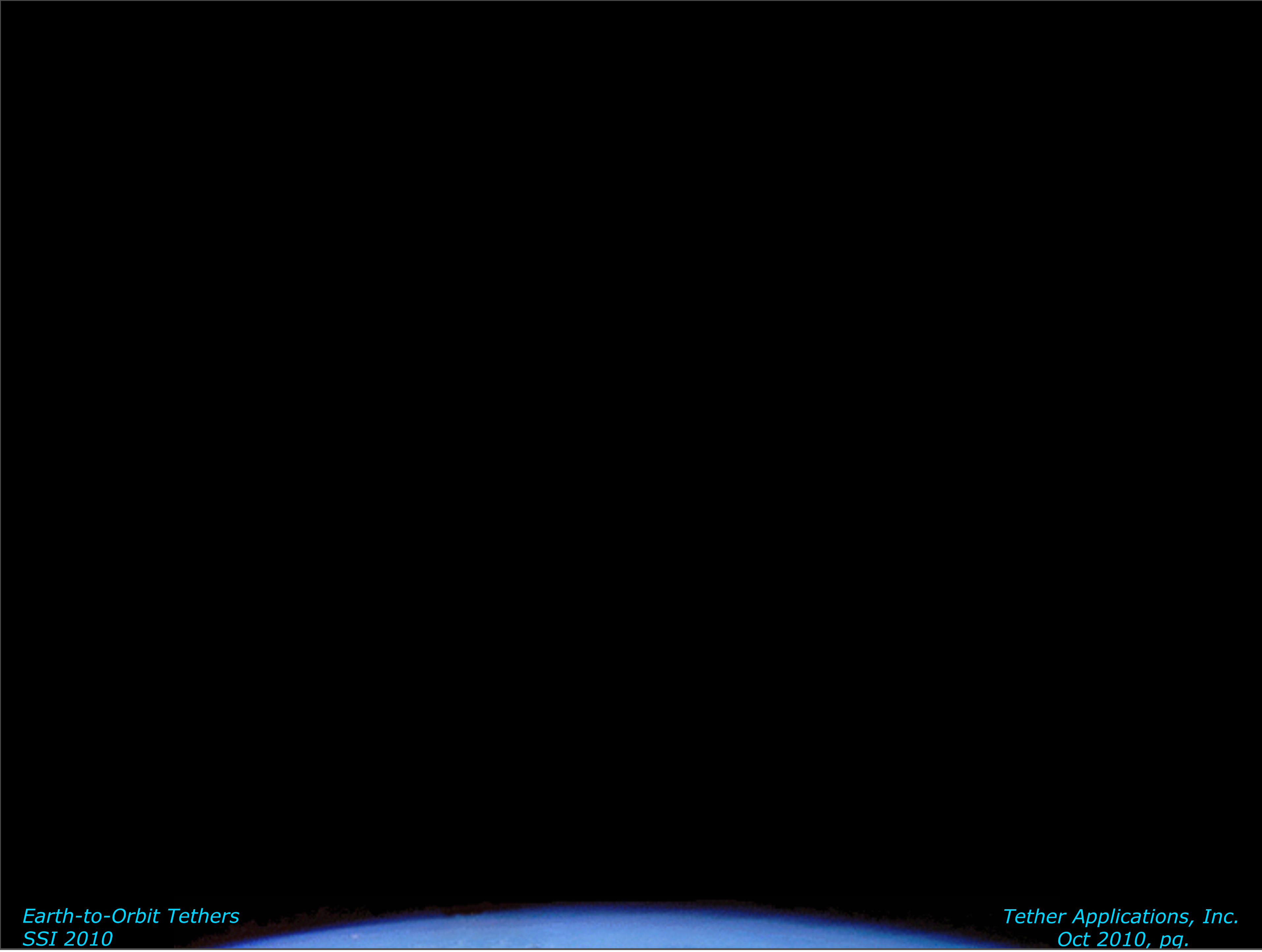
# Four "Wildcards" for ETO Transportation

1. Mid-air capture of multi-ton payloads
   - Allows downrange booster recovery & eases reuse
   - Allows payload recovery instead, after many aborts
2. Collecting and recycling aluminum alloys in space
   - EDDE vehicle can collect 2000 tons for recycling
   - Use as structure, shielding, ballast, fuel (liquid?)
3. High-DeltaV slings in LEO, to throw & catch payloads
   - Eases frequent transportation ***to selected destinations***
4. Manned Moon/Mars artificial-gravity research facility
   - The main early customer for sling operations in LEO?
   - A critical step in preparing for off-planet ***settlements***

# Wildcard #1:

## Mid-Air Capture of Multi-ton Payloads





Sunday, November 14, 2010

RP-75 Parachute Recovery Test
Date: 24 March 1998
Location: DeLand, FL
Test: #1
Video: #1 Scott Miller

Tether Applications Inc. NASA Performance Designs Inc.

RP-75 Parachute Recovery Test
Date: 27 March 1998
Location: DeLand, FL
Test: #2
Video: #2 John LeBlanc

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RP-75 Parachute Recovery Test
Date: 27 March 1998
Location: DeLand, FL
Test: #2
Video: #3 Jimmy Trainer

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# Why Consider Mid-Air Capture (Again)?

1. It allows downrange booster recovery without water impact or intrusion, and return to the launch site within hours. Downrange recovery allows higher payloads for a given booster & upper stage, or smaller boosters & upper stages.

2. It greatly reduces the booster's required glide performance, compared to glide-back and/or rocket-back RTLS designs.

3. After many aborts, the payload can be recovered instead of the booster, also without water impact or intrusion damage.

*But it does add new risks: failed capture & mid-air collision.*

# Is There Anything New Here?

1. Capture without chute damage allows chute release & recapture
   - This allows lots of practice in one flight, with one chute.
   - This allows more thorough training, and higher reliability.

2. Capture of large gliders allows "tow-back" as a return option
   - Like aerial re-fueling capture, but may be easier and safer
   - Airplanes can tow gliders; helicopters can tow gliding chutes
   - Capture adds risk, but towing allows go-arounds at landing

Plausible limits:

- Most of CH53's 36,000 lb rated external load w/soft capture
- Perhaps 100-200 kLb mass limit for glider tow-back.

# What Are the Implications?

1. If mid-air capture s***ubstantially*** improves cost-effectiveness, then boosters too heavy to capture may not make much sense.

2. If mid-air capture ***may*** seriously improve cost-effectiveness, then perhaps it is ***the*** critical technology to master first, so we can learn what booster sizes may make sense. (This assumes capture by existing aircraft, as a constraint on booster size.)

# Wildcard #2:

## Collecting and Recycling Aluminum in Space

# Why Consider Recycling in Space?

1. LEO orbital debris weighs >2100 metric tons, and probably >1000 tons is recoverable aluminum alloys. And most future stages left in LEO will use aluminum.

2. Controlled vapor and molten-spray deposition on balloon forms allows better properties than ingot metallurgy, and direct fabrication of arbitrarily large space structures.

3. Recycling "barely extraterrestrial" alloys is a natural first step in extraterrestrial material processing and use, and is part of living beyond earth in a more sustainable manner.

4. Mars ascent stages might use Al-Mg/$CO_2$ rockets, that burn recycled liquid metal in liquified Martian $CO_2$.

# Metal Combustion in Cold $CO_2$

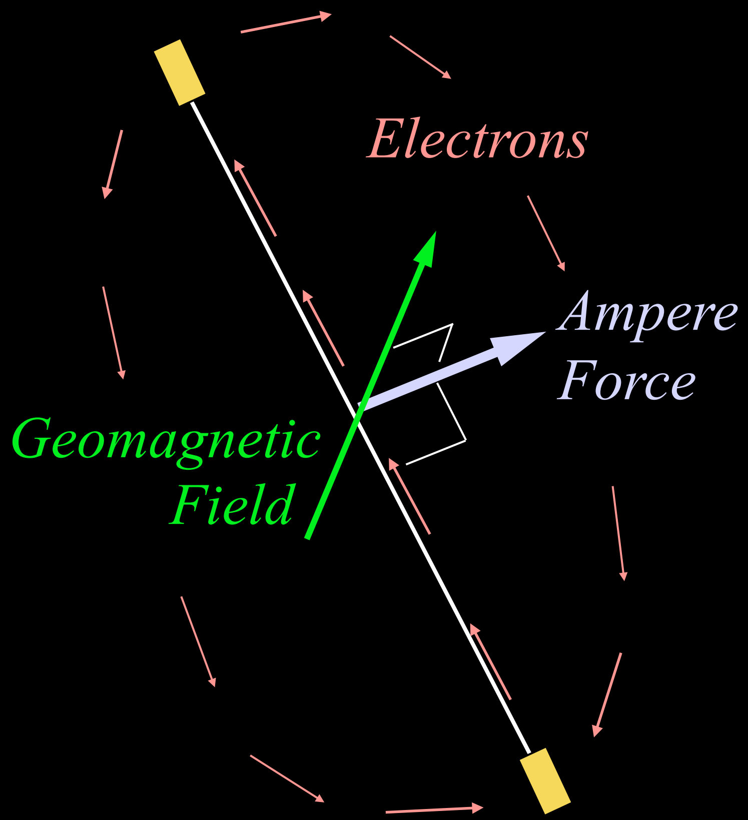
1. Magnesium burns energetically when surrounded by dry ice, enough to reduce some of the carbon to a black solid. Aluminum has a similar heat of combustion—and the space shuttle does burn more aluminum than hydrogen.

2. Zinc, lithium, and/or magnesium are used in many strong aluminum alloys, and greatly enhance aluminum burning.

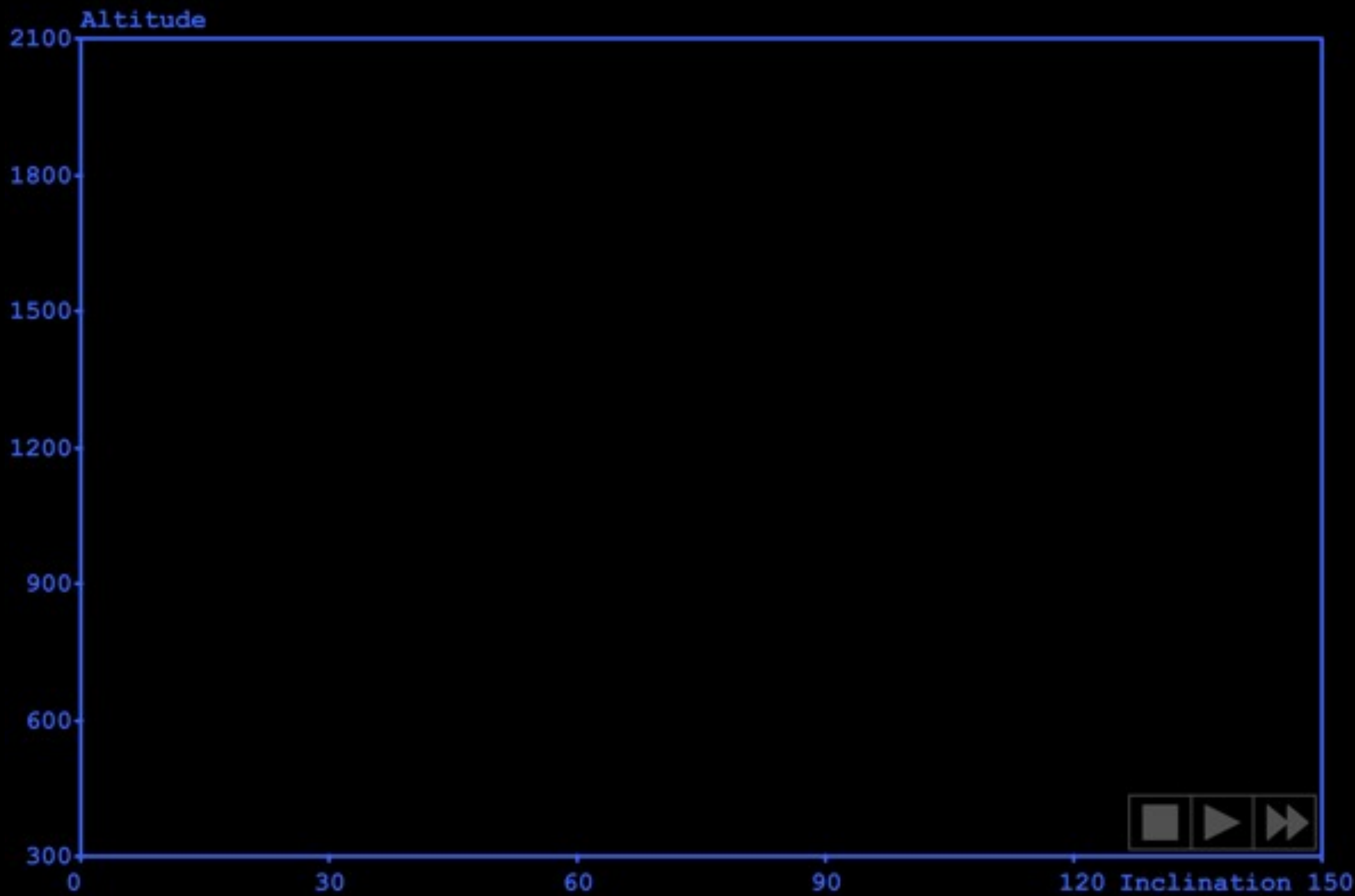
3. Key questions for ***liquid*** aluminum as a rocket fuel:
   - What mixture ratios and injector designs make sense?
   - How much Zn, Li, or Mg is needed in the aluminum?
   - Do liquid metal/$CO_2$ Mars ascent stages make sense?
   - What limits should be imposed in LEO (sandblasting)?

# Electrodynamic Propulsion

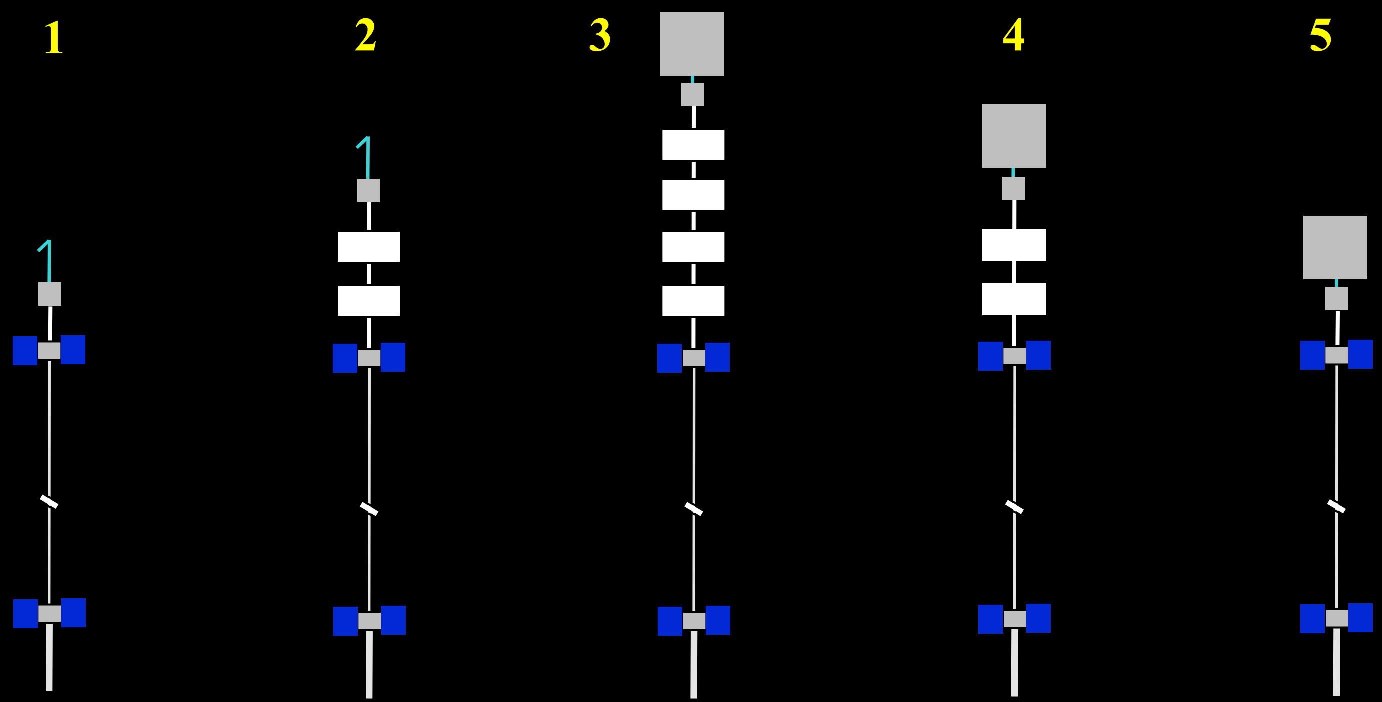
- Propellantless, solar powered
- Demonstrated in orbit by NASA JSC on the Plasma Motor Generator (PMG) flight



# LEO Debris Removal—*or* Collection



# A "Collect, Then Recycle" Scenario




1. Deploy "storage tethers" in 74° & 82° orbits at ~600 km
2. EDDEs capture and deliver stages at nodal co-incidence
3. Develop, launch and capture a large recycling device
4. Retrieve tether and process stored stages one at a time
5. Products ready for EDDE delivery to "marketplace orbits"

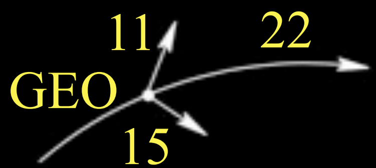
# Wildcard #3:

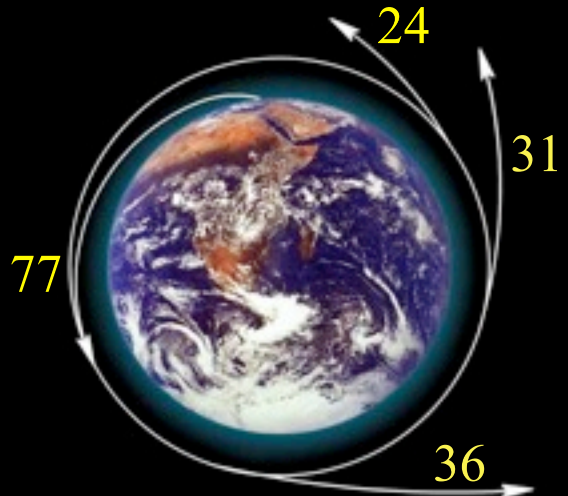
## High-DeltaV Slings in LEO

# Earth-LEO-GEO-Moon-Mars DeltaVs

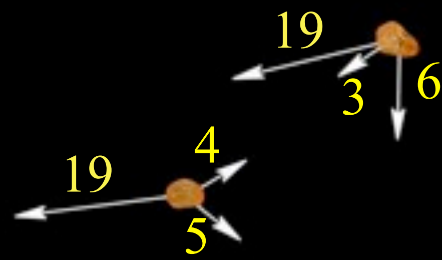

Hohmann deltaVs in units of 100 m/s, from 400 km circular equatorial orbits. Full deltaV is sum of start & finish #s.

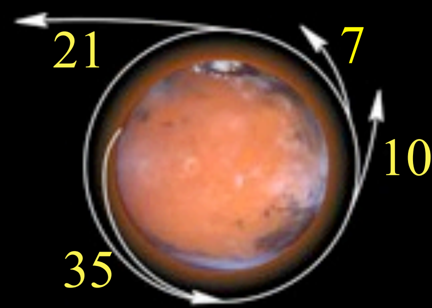
Orbiting slings with 1-3 km/s tip speeds can provide most or all of these deltaVs!




*Bodies like earth that keep enough air to evolve life are hard to leave!*



# First Things First: What Is a "Sling"?

- Any spinning tether that can throw (and catch?) payloads
- Includes McCarthy/Moravec slings, HASTOL, MXER, etc.
- Also surface-based slings (throw things into lunar orbit, etc.)
- ***Some*** of this applies to attached or orbiting vertical elevators

**Why consider slings?**

- Unlike rockets, slings allow reuse of the reaction mass
- Reaction mass is ~free on the ground, but **costly in orbit**
- Rocket reaction mass far outweighs rockets themselves
- So rockets are "slightly reusable;" slings can be **fully** reusable

# And What Is a "Trapeze"?

- Any capture or release interface that is not in free fall
    - Space elevator "ports" anywhere other than GEO
    - Any capture/release point not at CG of spinning facility

- Trapeze capture is undeniably unconventional and challenging
- But it does have compensating features:
    - Capture transient loads can be damped by simple reeling
    - It need not involve high bending loads (eg STS to ISS)
    - It need not even involve ***any*** rigid hardware at the interface
        - One easy-to-understand option is a hook and loop

# Rotating Slings vs Vertical Elevators

- Slings require capture & release; elevators **also** require climbers.

- Slings and ***orbiting*** vertical elevators can be done today,
  but attached elevators require ***serious*** advances in materials.

- Attached elevators use tilt + tension for momentum makeup;
  orbiting slings and elevators require ED or other reboost.

- Consider an elevator if the main market is people to/from LEO,
  but a rotating sling if a lot of payload will go beyond LEO.

# Ready for a Change from Ships to Railroads?

- Rockets are like ships, while slings are like railroads.

***Are we ready for a shift in focus, from ships to railroads?***

**<u>Some implications:</u>**

- Works best with modest payloads and ***frequent*** trips
- But the frequent service is ***only*** along fixed routes
- Encourages two-way traffic, not just one-way
- Creates a vested interest in really cleaning up LEO
- Slings and rockets serving them ***need*** each other
- Are slings + rockets a natural monopoly?

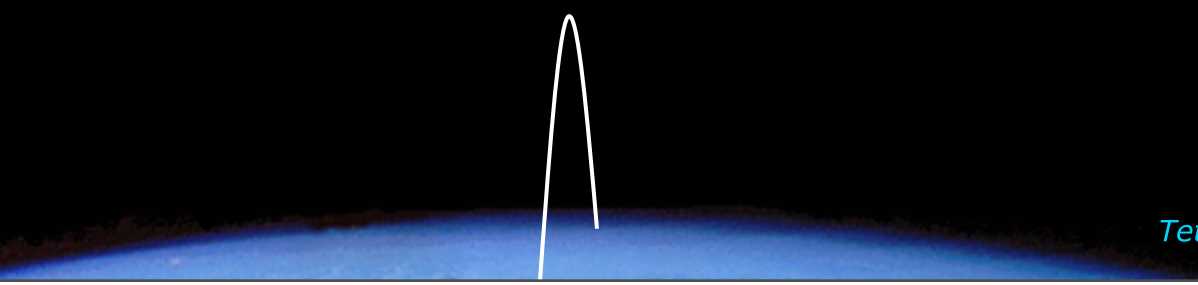
# Key Constraints on Suborbital Rockets + Slings

1. Going my way? (Sling orbit plane constrains options)
2. Sub-orbital reentry can have high peak gees and heating
3. Sub-orbital captures cause a large drop in sling altitude
4. Heavy electrodynamic reboost tends to reduce inclination
5. Reusable suborbital rockets need launch/land site ***pairs***
6. Plan on occasional missed captures and even sling breaks
7. Debris threats to slings: untracked bullets and sling pieces
8. Tethers are simple, but their system implications complex
9. Once rockets fly daily, can they recapture their market?

***(The next slides discuss the first 3 constraints in detail.)***

# 1. Going My Way?  (Orbit plane constrains ops)

- Spin plane is also constrained: near, or nearly normal to orbit
- Any other spin plane will wobble about the orbit plane
    - OOP spin provides less ΔV, and faces nadir less often
    - OOP spin seems likely to stimulate skip-rope modes
- Hence focus on nearly-in-plane spin, for max performance
- This means that a sling can serve only one inclination in LEO
- Sling CM altitude changes affect nodal regression rates
- So using $51.6^{o}$ inclination isn't enough to stay coplanar w/ISS



# Sling (and Orbiting Elevator) Inclination Trades

**51.6°:** - Easy abort and first-stage recovery, near east coast
- Can serve nearly all orbital launch sites world-wide
- Might capture some or most manned-space business

**28.5°:** - 7% higher EELV payload (~20% higher with RLVs)
- First-stage recovery may be expensive (far out in Atlantic)

**0.0°:** - 10% higher EELV payload (~30% higher with RLVs?)
- Allows launch on any pass; easy electrodynamic reboost
- Forget tourism, but great for GEO traffic & powersats:

**Tentative conclusions:**
- 51.6° may be hard to beat for market capture by the first sling
- GEO powersat launches may justify an equatorial sling later

# 2. Sub-orbital Reentry: High Gees & Heating

- Orbital entries "graze" the sensible atmosphere to limit peak loads
    - This limits both peak heating loads, and peak reentry gee-loads
- Sub-orbital reentries ***fall*** from apogee down to sensible atmosphere
    - Larger fall distances & velocity shortfalls increase peak loads
- Tether heating, drag, & dynamics are problems below 100-130 km
    - Hence high-ΔV slings should release payloads at 100-130 km
- Failed capture or successful "payload handoff" also cause reentries
    - Hence capture as well as release should be at 100-130 km

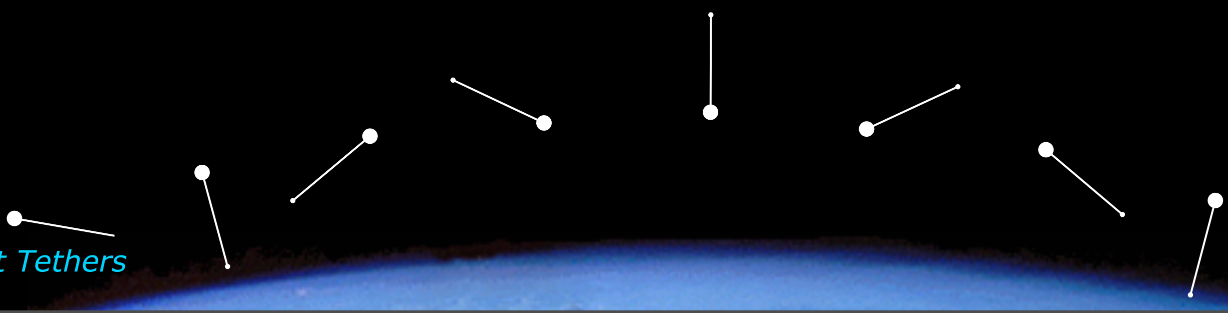
# 3. Slings Lose Altitude After Sub-orbital Capture

<u>Constraints imposed by altitude drop:</u>

- Don't let tether get lower than (or even as low as) capture altitude
- That requires elliptical sling orbit, or ~2:1 sling:orbit spin, or …?

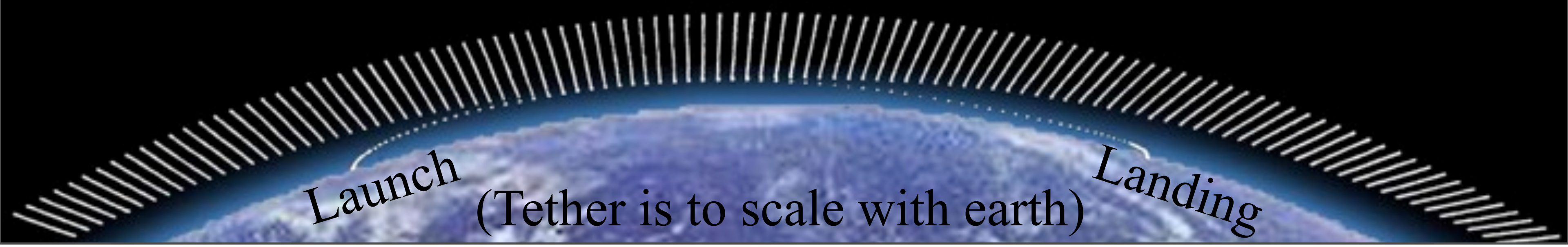
<u>Recovering the original sling orbit:</u>

- Reboost for 4 km/sec ΔV of 5 tons takes 5MW-days ion; 3 w/EDT
- To stay coplanar w/ISS, you must reboost quickly (don't "lap" ISS)



# Bottom Line: What Might a Sling Look Like?

- Some features of MXER, HASTOL, McCarthy/Moravec, etc.
- Sling is in $51.6^{o}$ orbit and stays co-planar with ISS
- To stay coplanar w/ISS, sling must not “lap” ISS after capture
- This requires a quick reboost capability, or paired operations
- A 395 km altitude allows passes over launch site every 3 days
- Use ~60 km ED tether plus ~240 km retractable sling tether
- Heavy end is manned (partial gravity—somewhat variable)
- Adjust spinrate for ~1.2-2 km/sec $\Delta V$ (above ***and*** below $V_{LEO}$)
- Sling tether is retractable after ED tether slows the spin enough
- Perhaps buy ~1000 tons of spent LEO stages as ballast mass

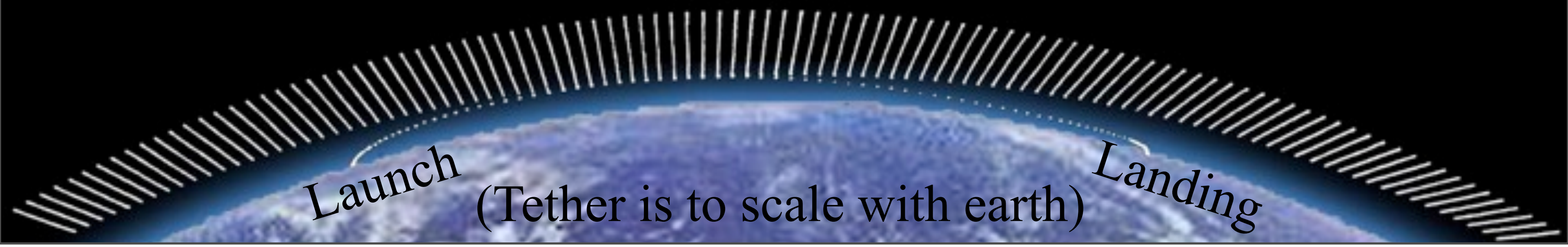


# Again: Are We Ready for a Railroad Era?

- Rockets are like ships, while slings are like railroads.
- Are we ready for a shift in focus, from ships to railroads?

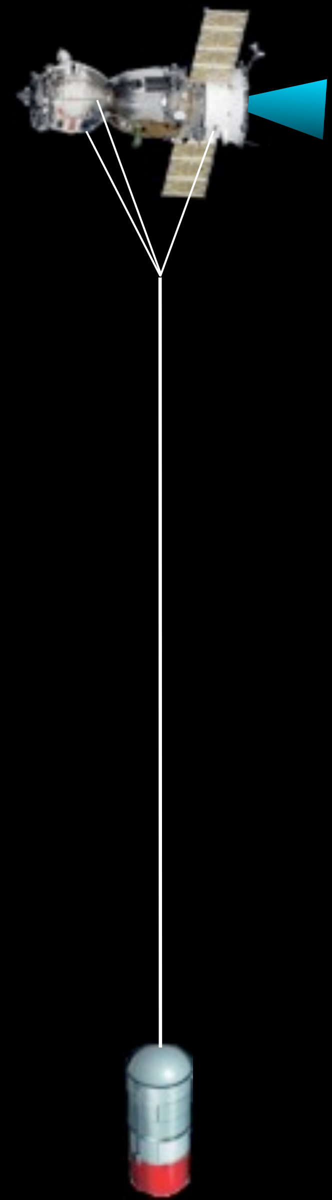
**<u>Some implications:</u>**

- Works better w/smaller payloads (like railcars vs ships)
- Eases frequent service, but ***only*** along fixed routes ($51.6^{o}$?)
- Encourages two-way traffic, not just one-way
- Creates a vested interest in cleaning LEO (for ballast, etc.)
- Slings & rockets designed for them ***depend on*** each other
- A $0.0^{o}$ sling could ***radically*** cut GEO powersat launch cost

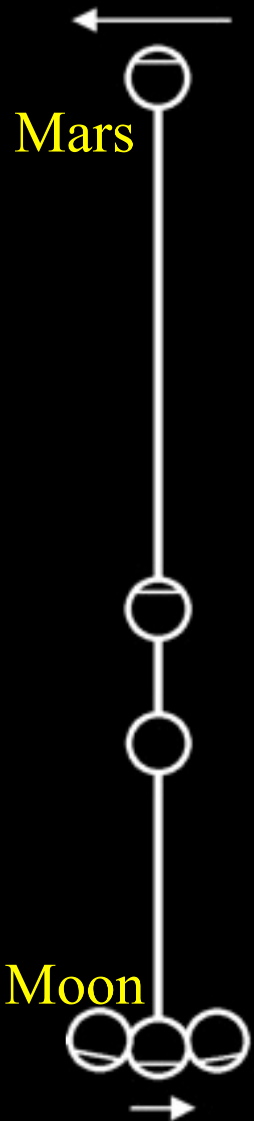


# Wildcard #4:

## A Manned Artificial Gravity Research Facility in LEO



# Possible Goals for Artificial Gravity Facility



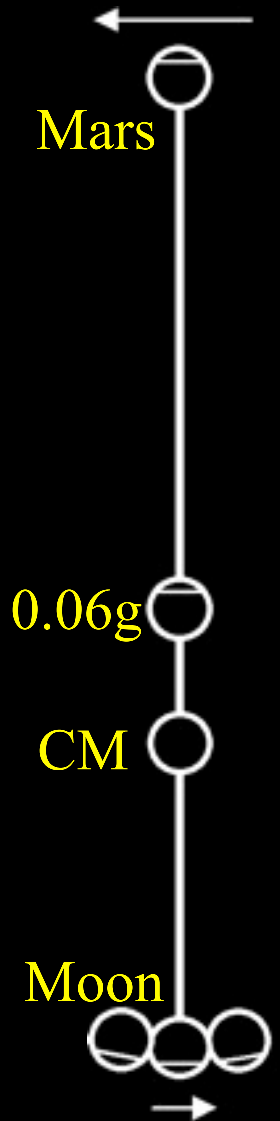

- Focus on the overall effects of long-term hypogravity
- Allow ***realistic*** planning for Moon & Mars settlements
- Address critical long-term questions like:

1. Can people stay healthy for years—and years later?
2. Can mice and monkeys (and man) reproduce normally?
3. Can monkeys raised in low gravity adapt to earth?
4. What plants are useful for food on the moon and Mars?
5. Does hypogravity allow advances in basic biology?

- Facility can also resolve nearer-term issues like:

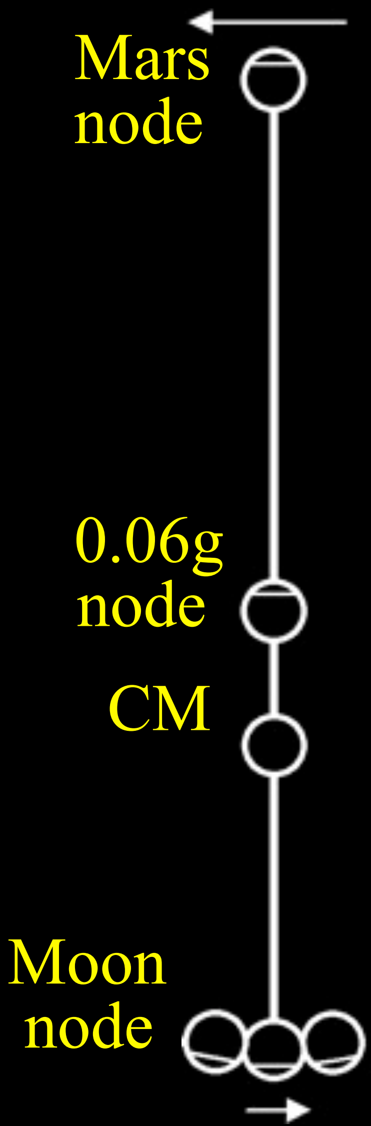
6. How much gravity to use in cruise to and from

# Why 0.06 Gee, and not Just Moon and Mars?




1. It's the next ~1/e step, after Earth—Mars—Moon
   - This makes it a useful step for fundamental bio studies
   - Nobody knows what levels trigger gravity responses
2. It may be the lowest level allowing intuitive behavior
   - Sitting, using a desk, hygiene, even rolling over in bed
   - It may not require days of accommodation—or may aid it
   - It may be popular with tourists, or for unique exercises
3. It's also good if you want some gravity, but not much
   - Plant growth tests; satellite assembly, etc.
4. Finally, it's very easy to add: same hardware, etc.

# Basic Moon/Mars Dumbbell Concept



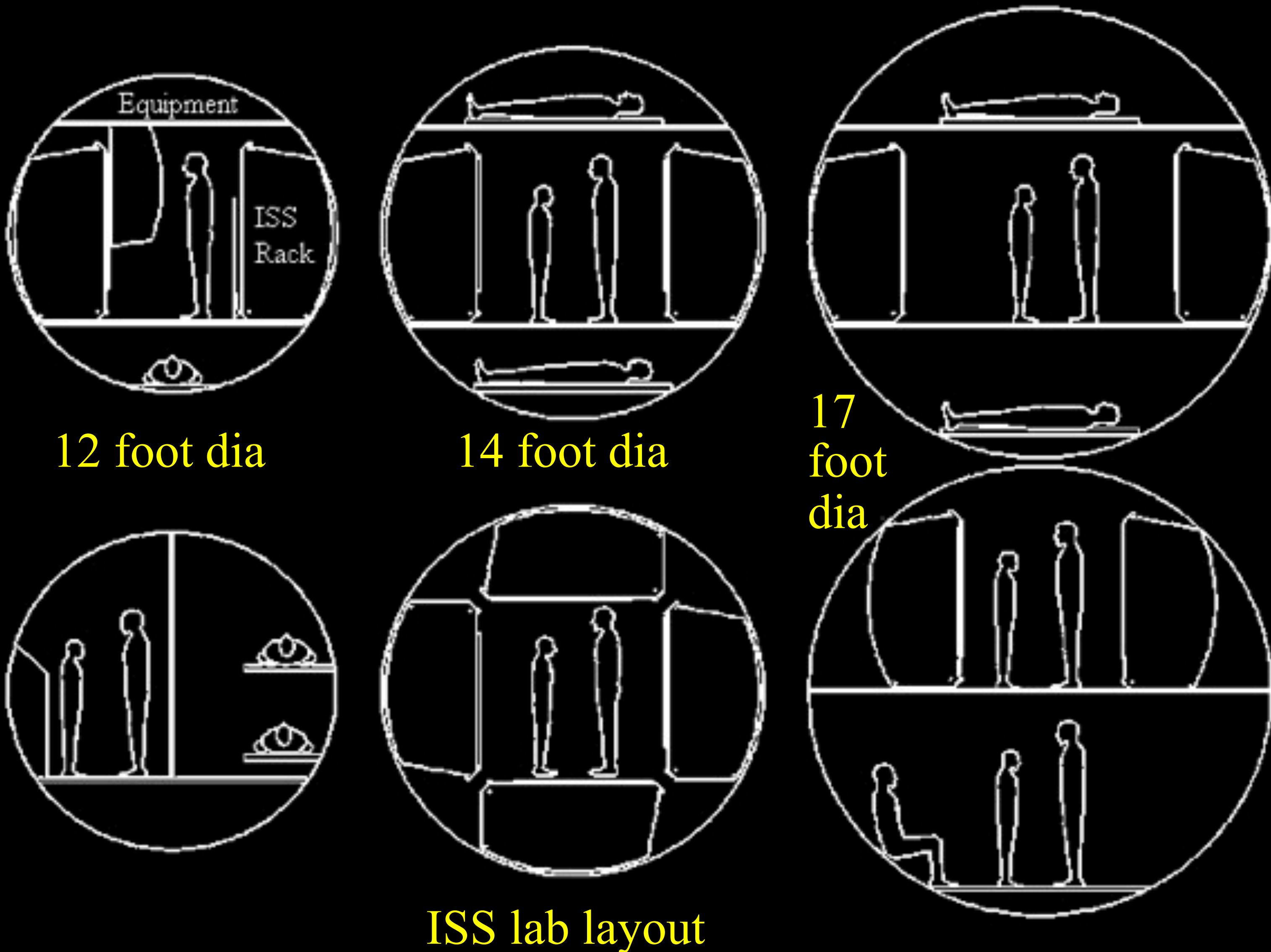

## A Key Challenge:

We really don't know what rotation rates are reasonable, since ground-based rotating rooms have ***very*** different effects. We need better tests of rotation & Coriolis susceptibility for these facilities. Until then, we should consider a variety of lengths ***and designs***:

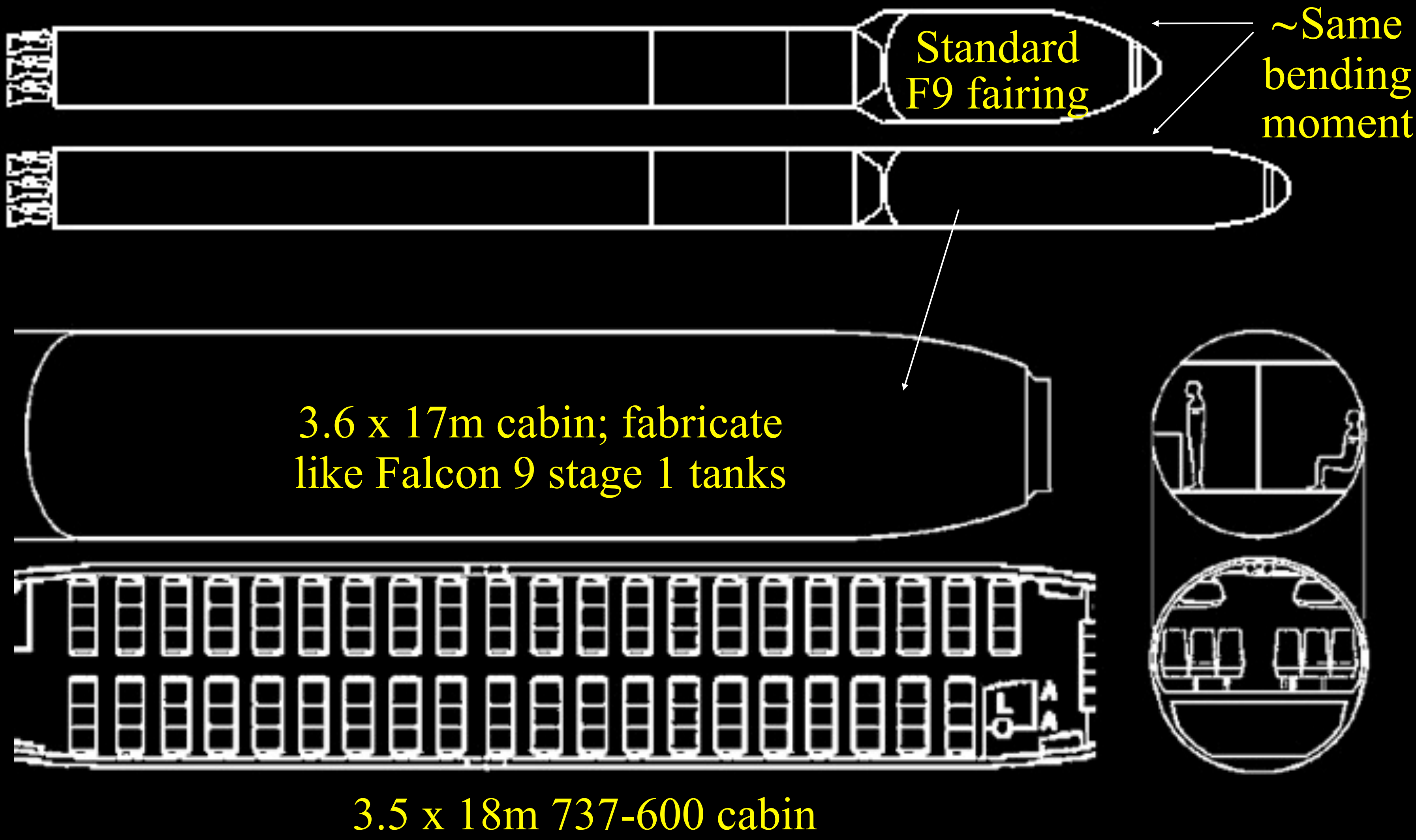
## 4 Options for Radial Structure:

| Spin rate | Length | Radial structure | Key length-limiters: |
|---|---|---|---|
| >2.0 rpm | <120m | Rigid modules | Mass of radial modules |
| >0.8 rpm | <760m | Airbeam tunnels | Tunnel area, impact risk |
| >0.55 rpm | <1.6km | Tunnels+cables | Area; post-cut perigees |
| >0.25 rpm | <8 km | Cables | Cable mass; node " |

# Some Cabin Layout Options



# Falcon 9 Cabin Compared to 737-600



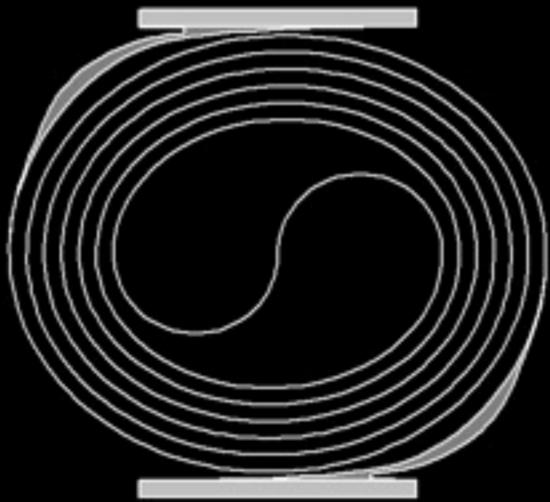
# Airbeam Tunnels for Radial Structure

**Inflatable airbeams**

- Vectran fiber in flexible matrix
- Damage tolerant; easy to customize
- Two people can carry beam at left

**Tunnel stowage**

- Fold deflated beam in half & roll up
- Keeps rigid end fixtures on outside:





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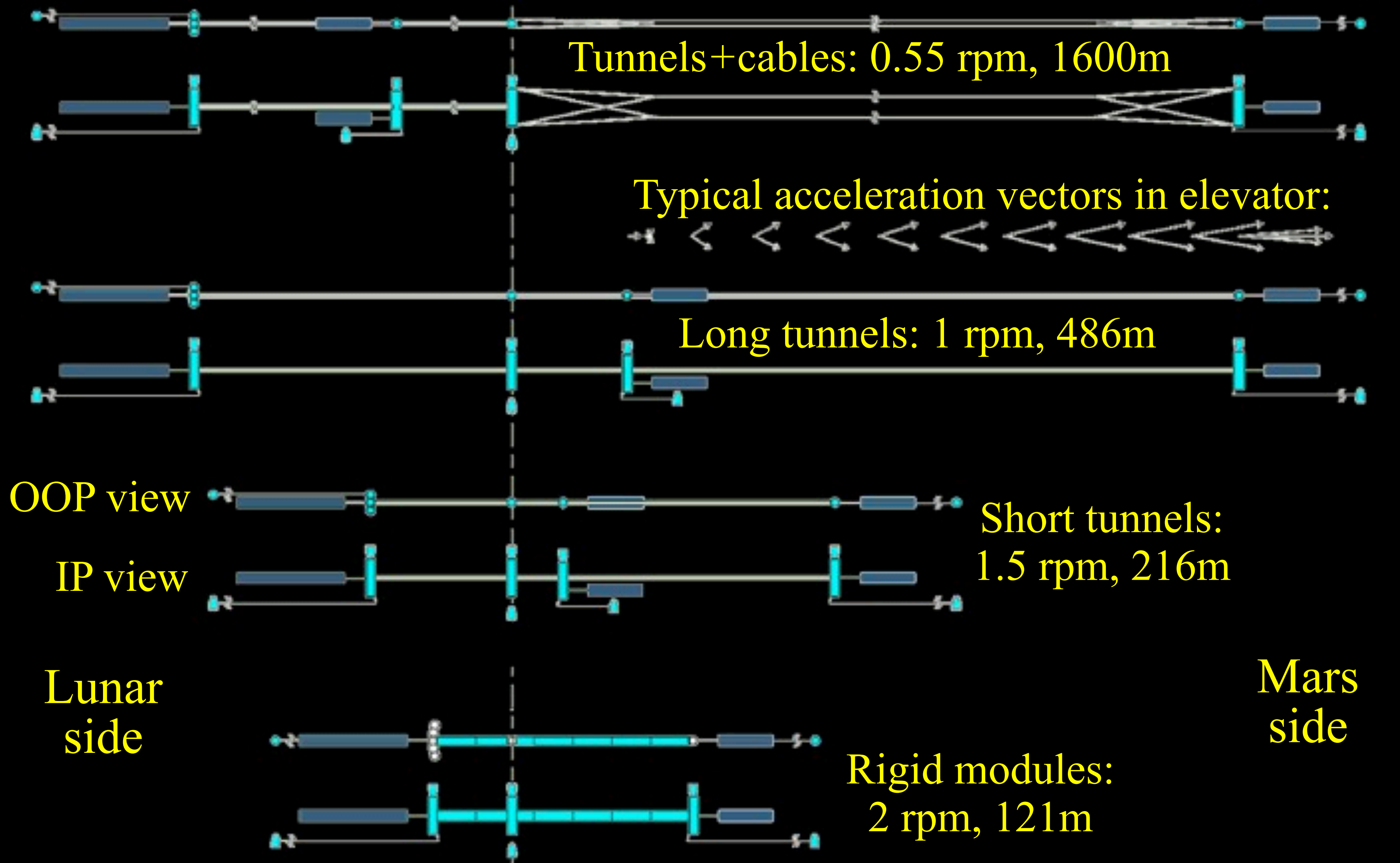
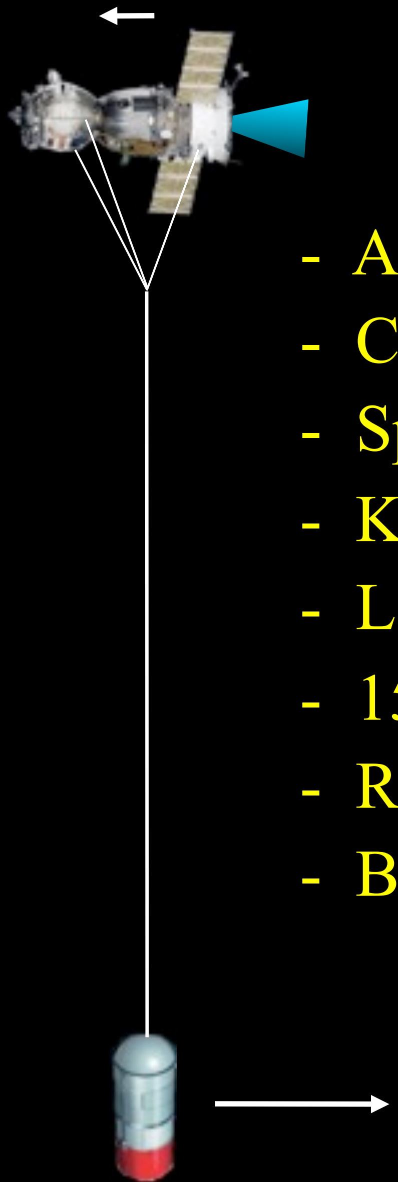
# Radial Structure Options vs Length

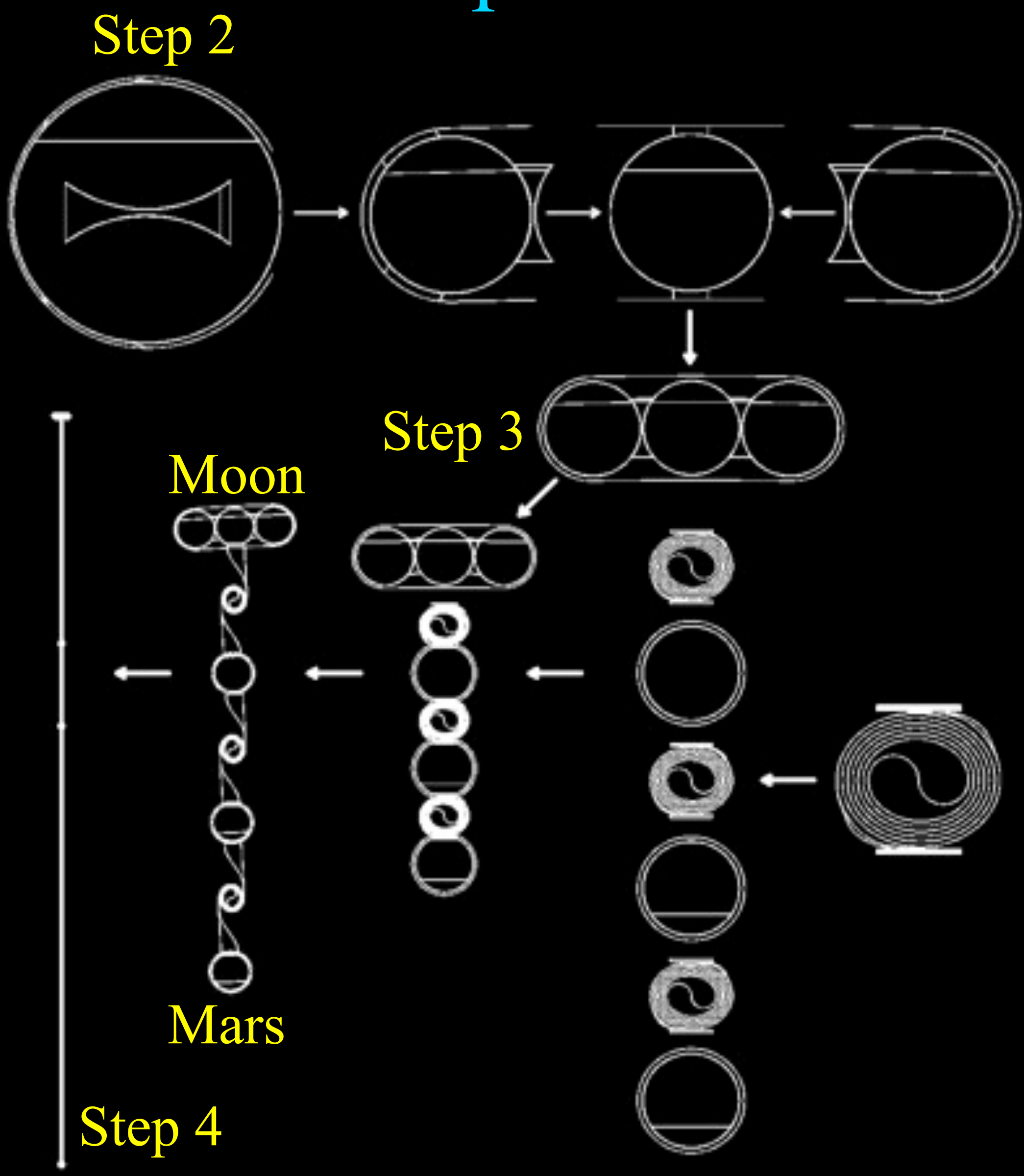


# The First Step:  Gemini-like Tether Tests



- After MECO, deploy 20 kg 600m tether from booster
- Can be done during phasing, on any flight(s) to ISS
- Spin up w/pulsed posigrade burns during phasing
- Kite bridle on manned end can stabilize its attitude
- Like Gemini XI test, but longer tether & faster spin
- 150m from CM, 0.6-1 rpm gives 0.06-0.16 gee
- Release spent booster when it is moving backward
- Boost in south & release in north, to deorbit booster

# Steps 2-4: Full Development




## Step 2: 1 cabin

- 1 cabin + spent booster
- Can test trapeze capture

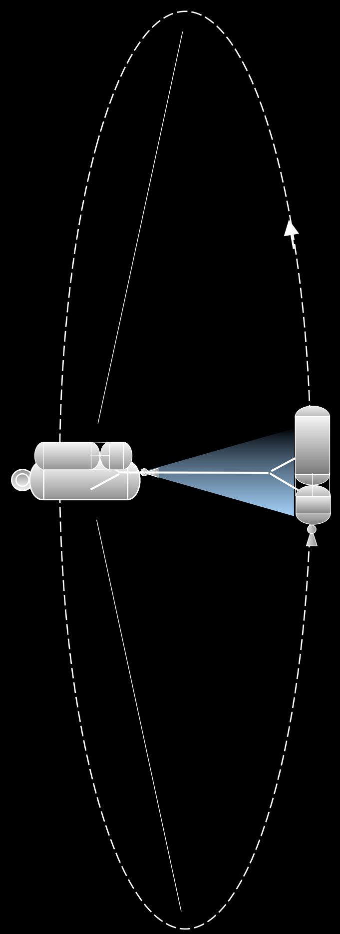
## Step 3: 3 cabins

- Attach 2 more cabins

## Step 4: full assembly

- Launch 3 cabins + tunnels
- Join 6 cabins w/tunnels
- Deploy tunnels 1 by 1
- Inflate slightly to deploy
- Spin up from Mars end

# Two Operational Derivatives

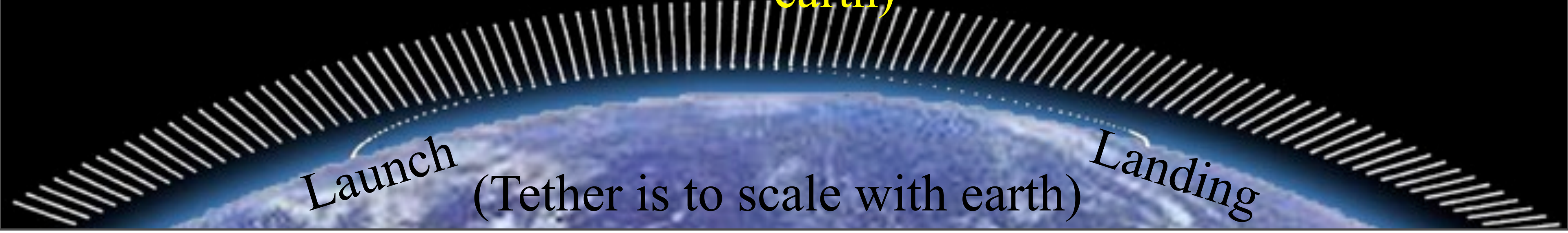


**Spinning exploration cruise stage:**

- Uses spent departure stage as ballast
- Can retain stage through maneuvers
- Tether cut: lose gravity, not mission

**High-deltaV spinning LEO slings:**

- 1.2-3.4 km/sec above ***and*** below $V_{LEO}$
- Similar trapeze accelerations (0.5-1g)
- Low capture altitude, for soft reentry
- Shown: 1.2 km/s $\Delta V$; 290 km tether (to scale with earth)



# Conclusions for Wildcard #4

1. Man has been going into orbit for almost 50 years, but we seem stuck. Maybe it's time to take human physiology seriously, ***before*** planning long missions.

2. A manned artificial gravity facility in LEO lets us learn more about our future and any limits on that future, ***and*** lets us test ways around those limits.

3. We can start with tethered capsule tests, as done on Gemini XI. Evaluating spin effects on crew will let us settle on the facility length ***and*** design.

# Recap of the 4 Wildcards

1. Mid-air capture of multi-ton payloads
   - Allows booster and payload recovery/reuse at low cost
   - If useful, it may be the key technology to master ***first***

2. Collecting and recycling aluminum alloys in space
   - Start with old stages (debris); continue with new ones

3. High-DeltaV slings in LEO, to throw & catch payloads
   - Eases frequent transportation ***to selected destinations***

4. Manned Moon/Mars artificial-gravity research facility
   - The main early customer for sling operations in LEO?
   - A critical step in preparing for off-planet ***settlements***