# How Space Elevators Work: Physics Concepts

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ISEC Webinar

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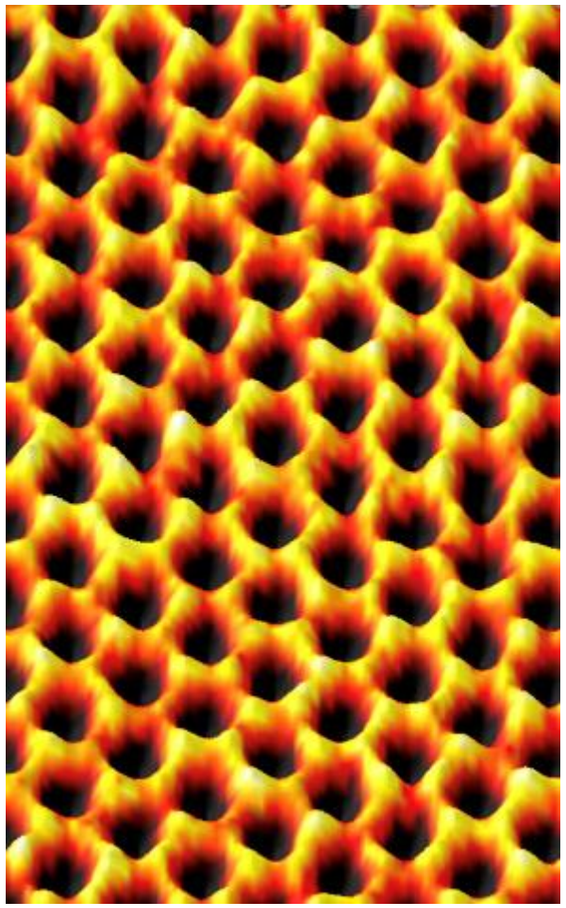
# Space Elevators: Where We Are Today

- SE physics has been around for a long time - some back to the 1890's
- Serious concepts from 1961 through 1999 NASA study and more
- Strong enough materials look to be on their way
- Time to start thinking about really building one (see Pete Swan's webinar: https://www.isec.org/recorded-webinars)

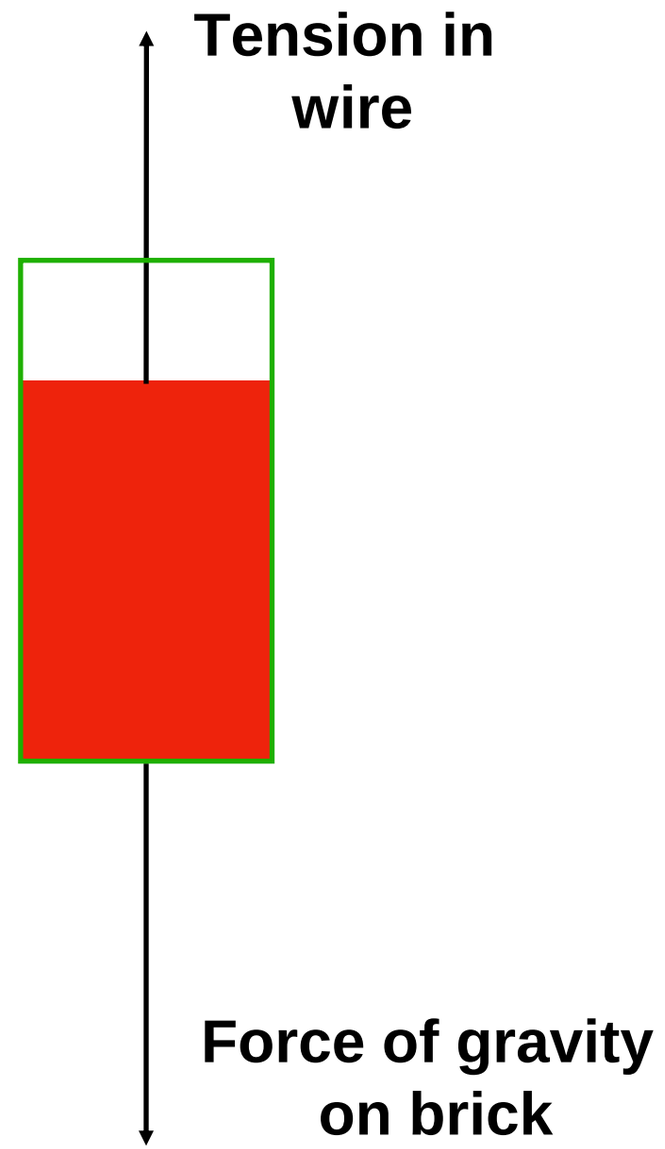


# How to Build a Space Elevator (from a physicist's point of view)

- Start with a Static Space Elevator
- Add Dynamics
- Add Climbers
- Place it in its Environment
- All the rest is details  ;^)

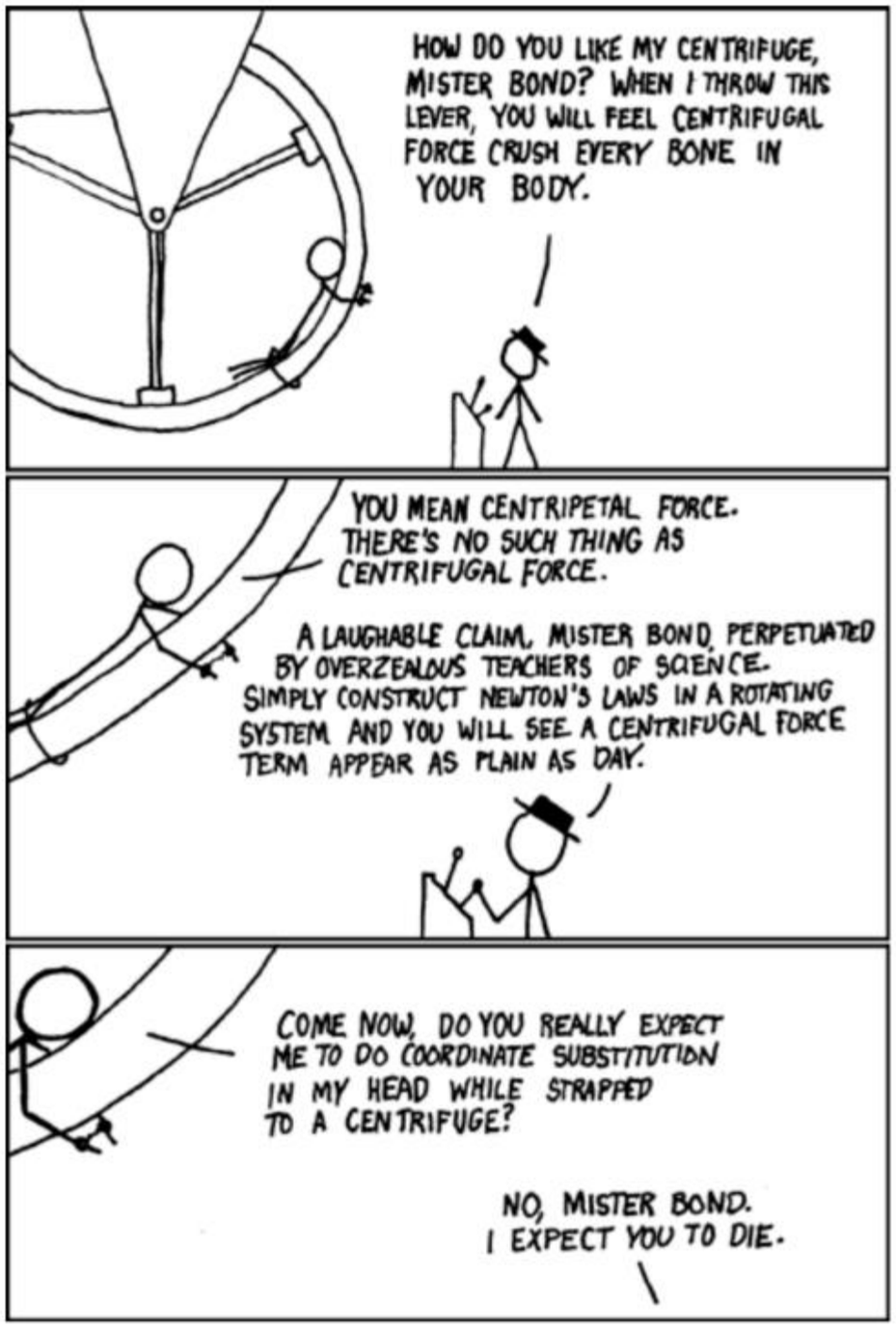
# Suspending a Brick: Physics 101

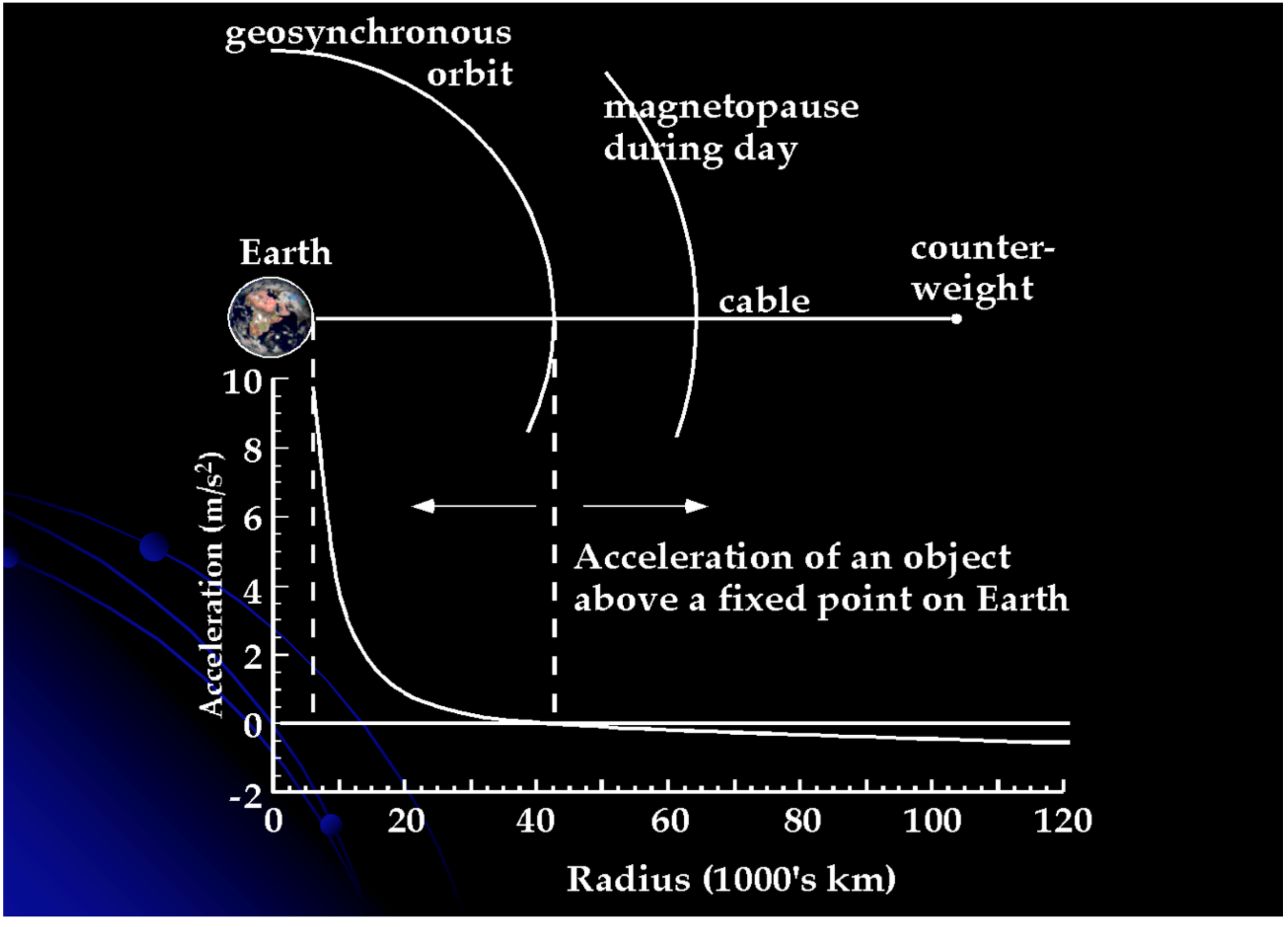
- Balance of forces
- Gravity pulls down, wire pulls up, brick stays in place
- Massless wire ?  Only in Physics 101 - must take mass into account —> exponential increase, big problem
- The inverse square law of gravity helps a lot, but not enough



# Centrifugal Force to the Rescue

- Because Earth is rotating, an outward force will eventually compensate gravity
- Yep, centrifugal, not centripetal. We're in a rotating reference system; dealing directly with centripetal force complicates things unnecessarily
- https://xkcd.com/123

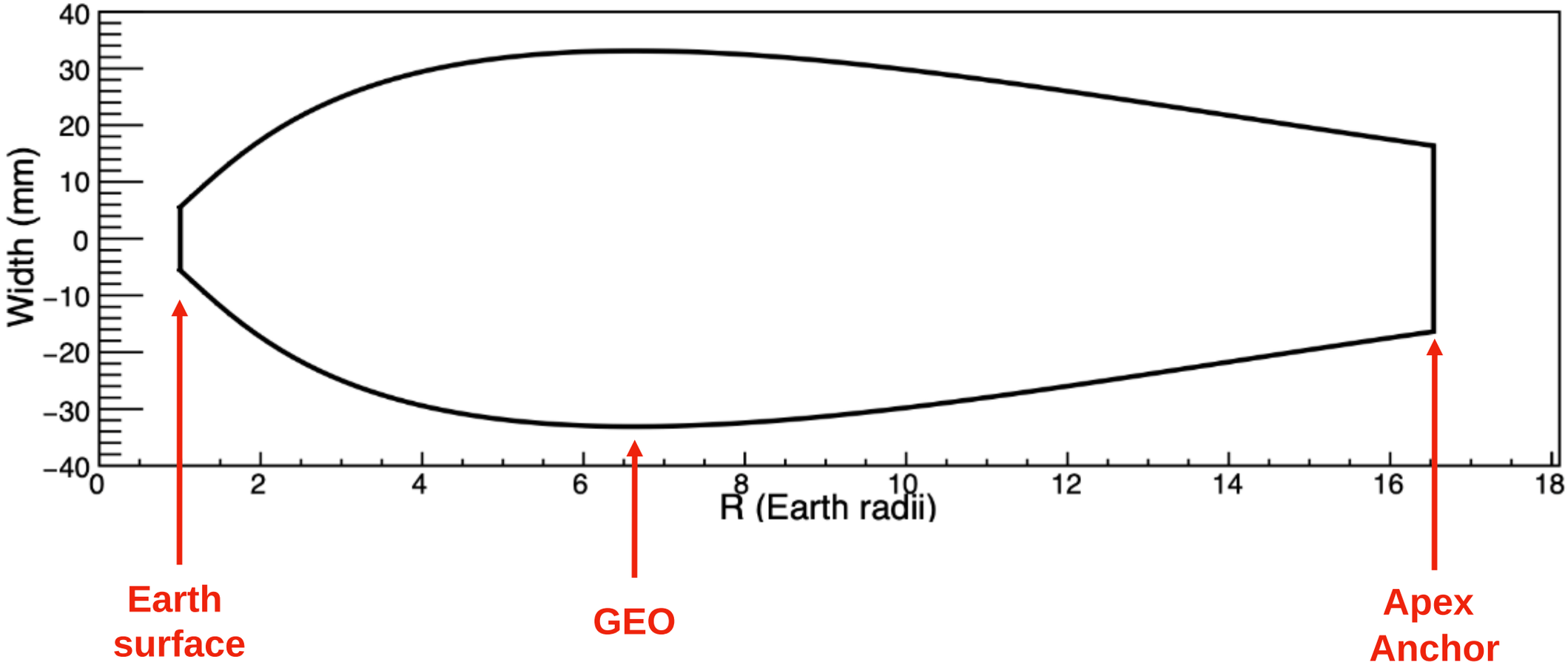



geosynchronous
orbit
magnetopause
during day
Earth
cable
counter-
weight
Acceleration (m/s²)
10
8
6
4
2
0
-2
0
20
40
60
80
100
120
Radius (1000's km)
Acceleration of an object
above a fixed point on Earth

# What Would the Tether Be Like?

- Could make a simple, long, rectangular ribbon - same width at any distance
  - but material tensile strength would have to be higher than absolutely necessary
- Ideally, want shape that puts more mass where tension is greatest (GEO)
  - tapered shape as a function of altitude
  - stress is constant all along tether
- Pearson constant stress taper looks like best option

# Constant Stress Tether Shape



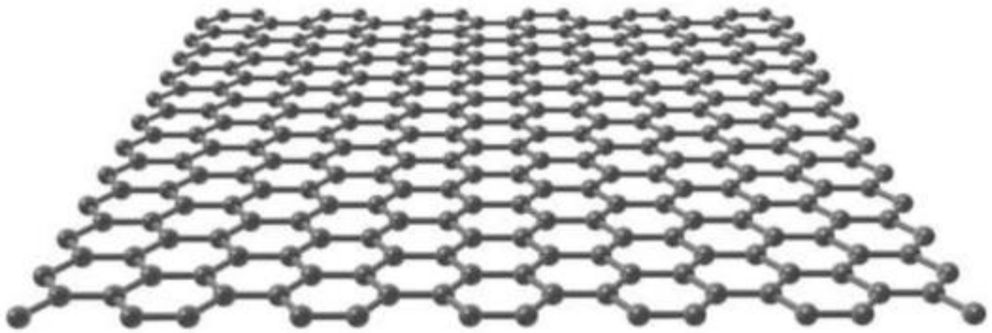

**Tensile strength = 49 GPa**

**Density = 1300 kg/m³**

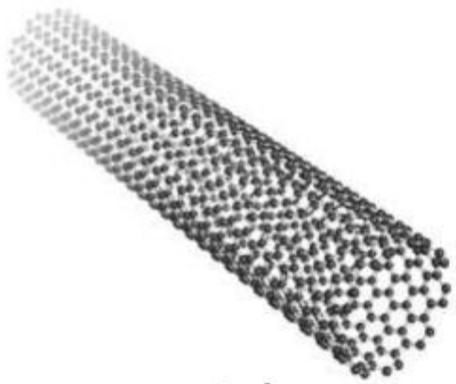
**Specific strength = TS/Dens = 38 MYuri**

# Strong Materials Are the Key

- Need a specific strength of 38 MYuris
  - somewhat more than needed, but allows for a safety factor
- What is this strong?
  - carbon nanotubes
  - single crystal graphene
  - boron-nitride
- See Adrian Nixon's webinar at http://www.isec.org/recorded-webinars



**Graphene and Boron Nitride 2D materials**



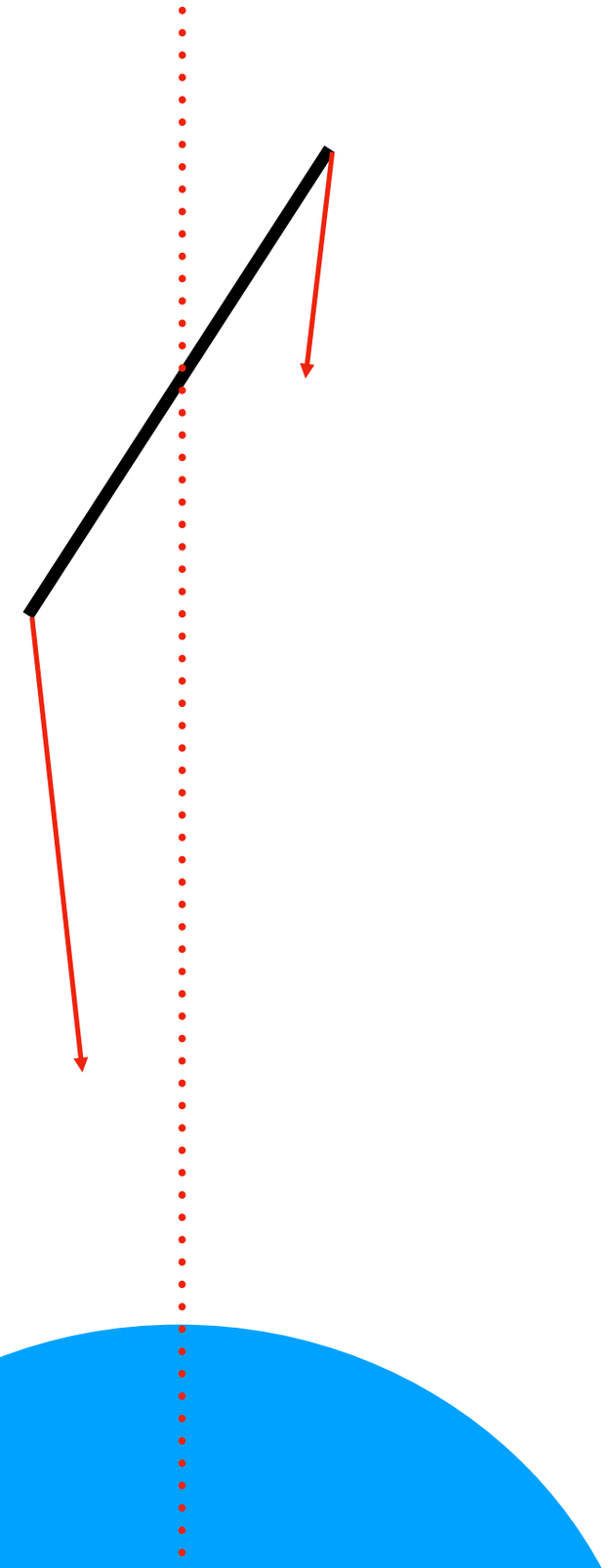
Carbon nanotubes: 1D material



# Adding Dynamics

# Gravity Gradient Stabilization

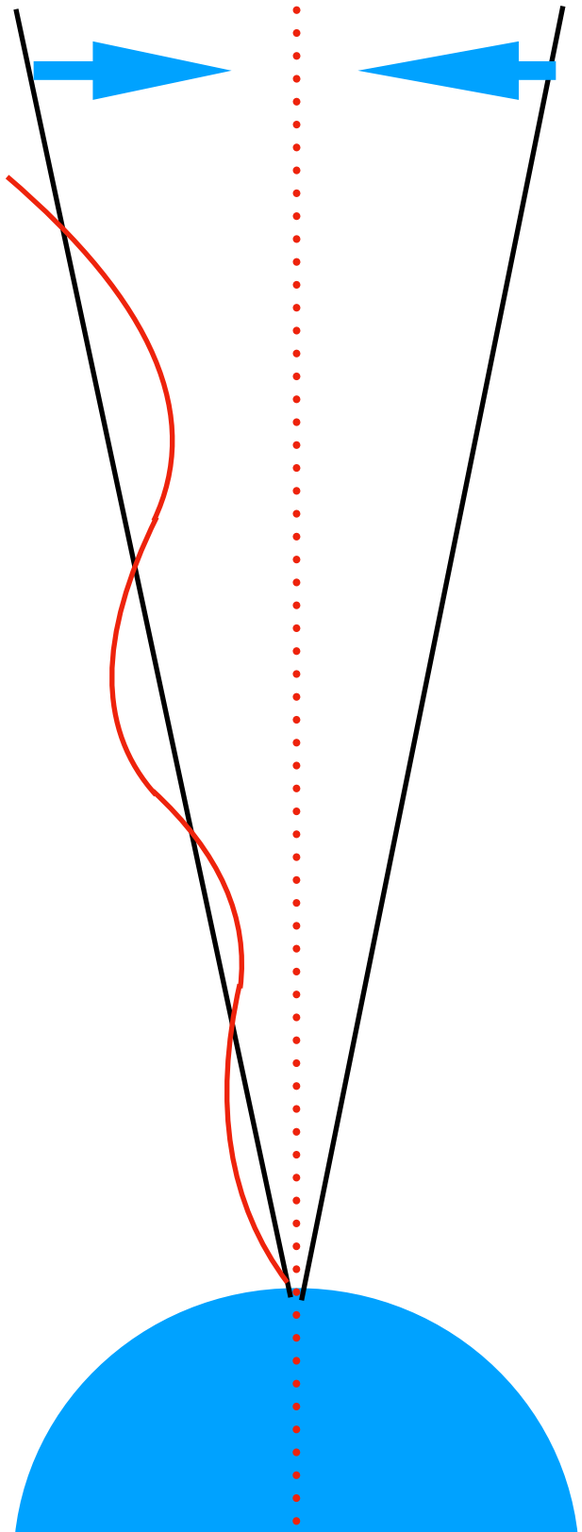
- Simple balance of forces says the SE will stay up
- But what if it is disturbed from its initial up-and-down state? (tidal forces, collision, etc.)
- Long objects in orbit want to be up and down
- If bumped, they go back to vertical



# Gravity Well Analogue Device

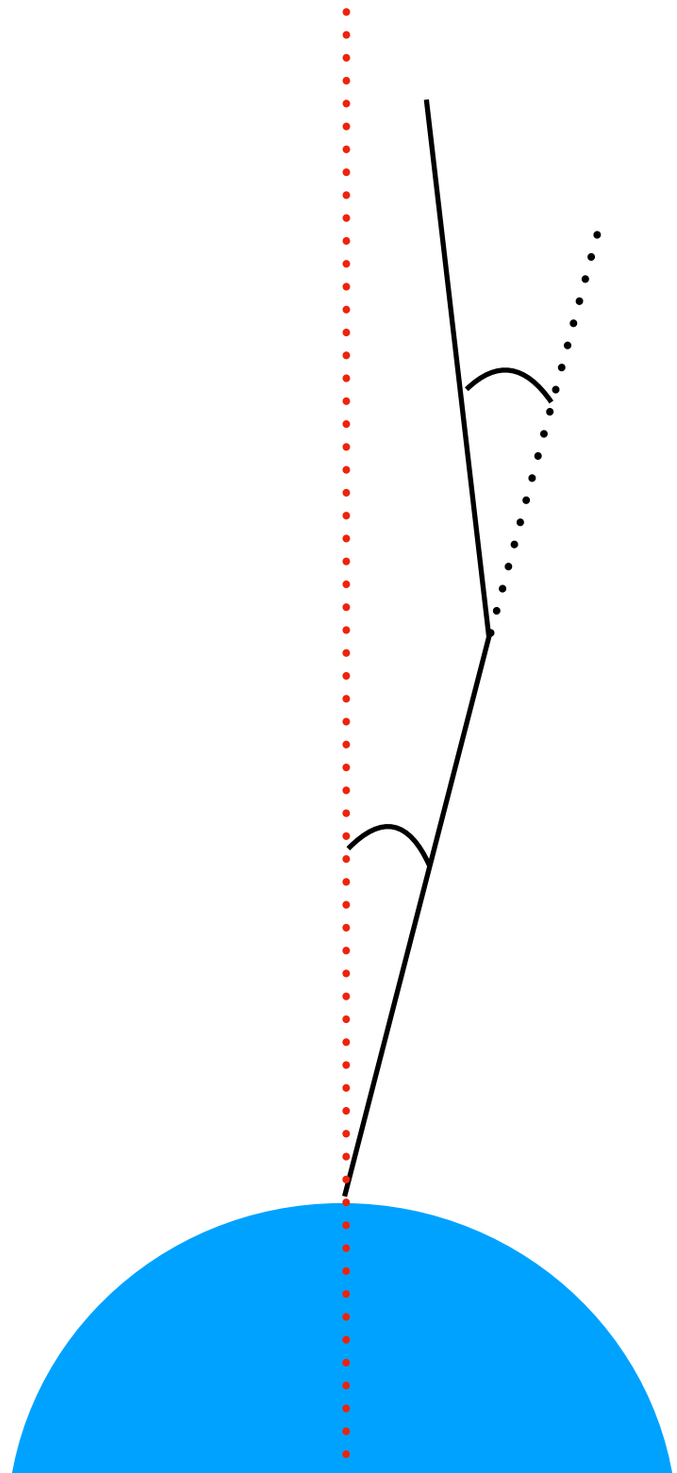
# Oscillations

- Object trying to get back to vertical will overshoot, then head back the other way -> oscillations
- Rigid body mode (libration):
  - arrangement of tether doesn't matter
  - oscillation calculated as if rigid
  - lowest frequency mode (5.8 days for 100,000 km SE)
- Try to avoid exciting oscillations



# Higher Modes of Oscillations (describing the wiggles)

- Double pendulum - represent SE as two connected rods
  - now two periods: libration mode (5.8 days) and first transverse mode (about 8 hours)
- Chaotic motion may be possible
- Higher modes - keep dividing into shorter and shorter rods
- Resonances - driven oscillations (Moon, Sun, …)



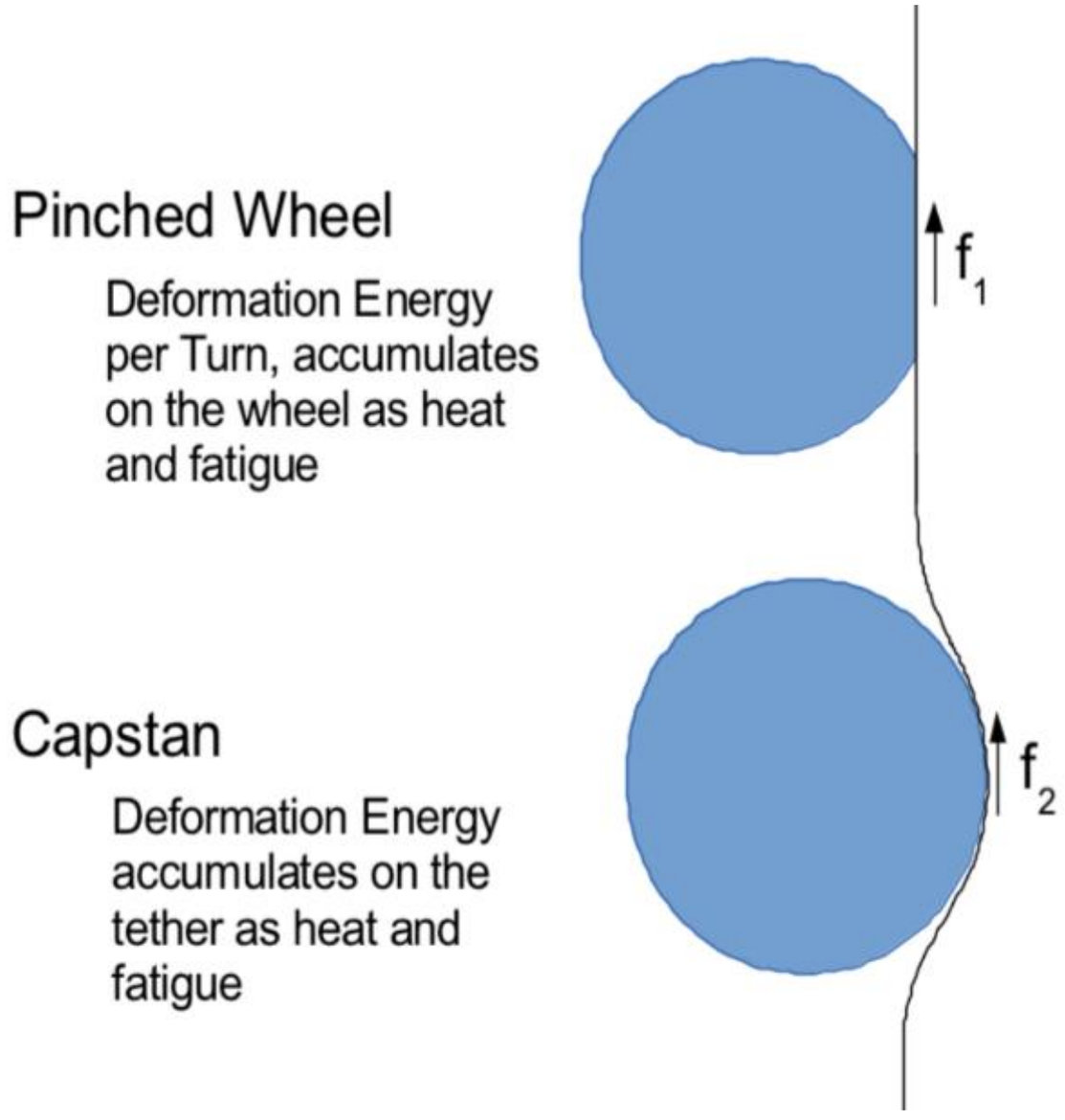
# Waves, Waves and More Waves

- Transverse waves (in equatorial plane and out) - vibrating string
- Torsion waves
- Compression (stretching) waves (3%) - speed of sound in tether (20 km/s in graphene)
- All couple together - this is where the math gets ugly

# Adding Climbers

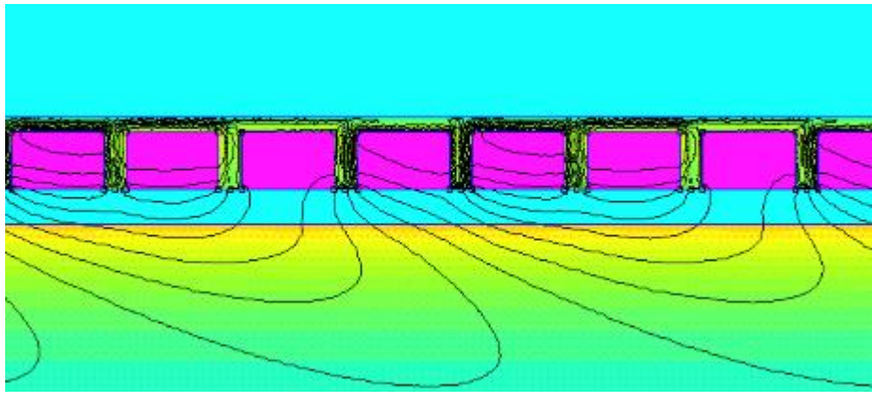
# How Does a Climber Climb?
# Friction

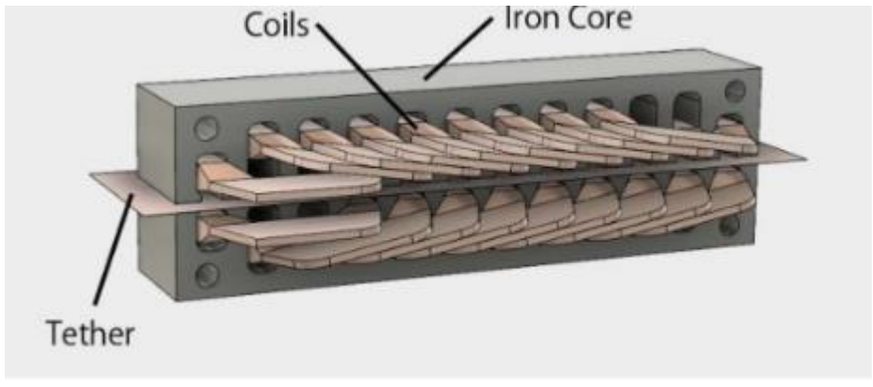
- Must grip tether in some way
  - climber wheels are deformed
  - tether is deformed
- Must deal with:
  - energy dissipation
  - material fatigue



# How Does a Climber Climb? Electromagnetically

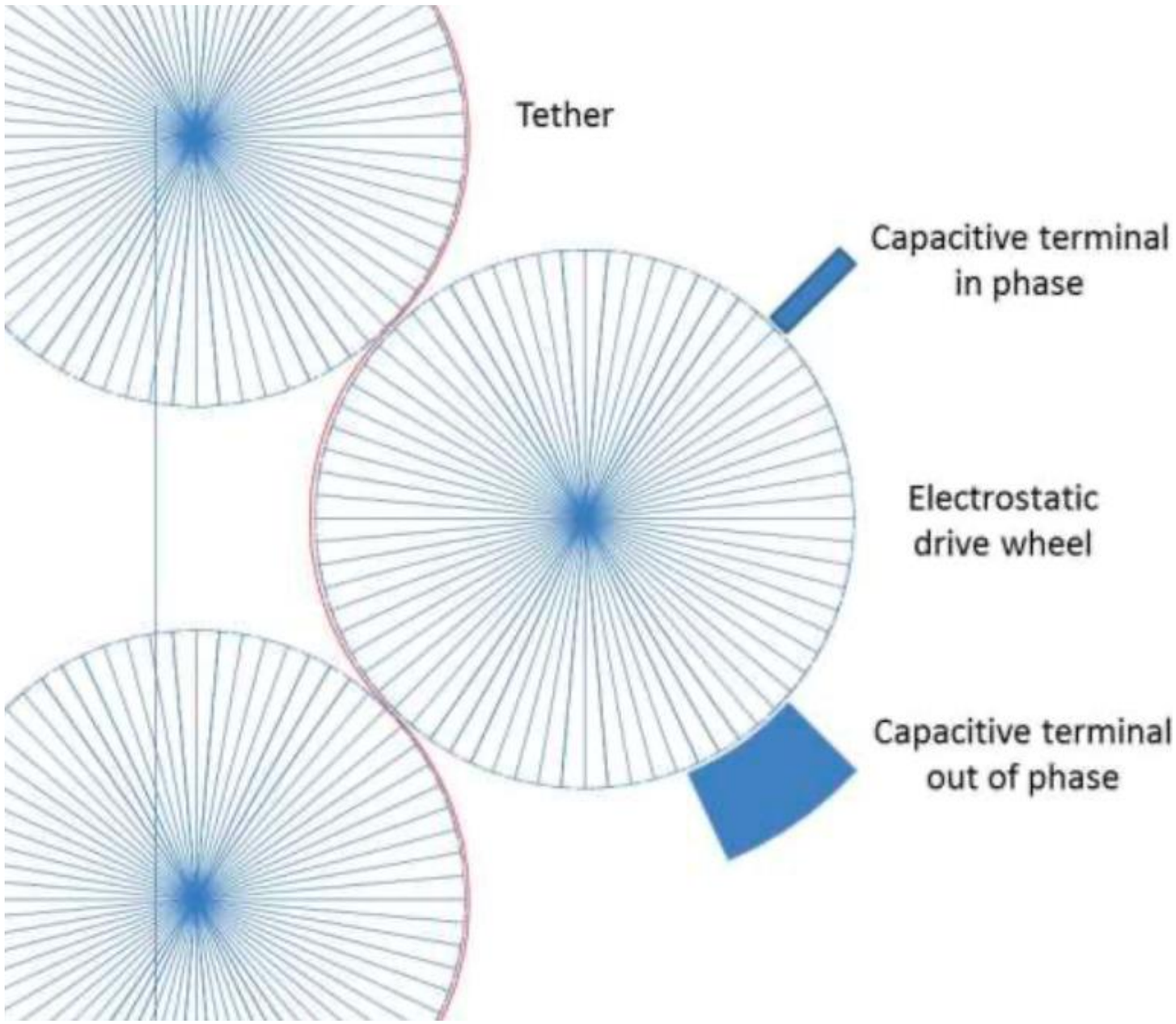
- Linear induction motor
  - probably the best climber option
  - many Earth-bound applications
  - climber prototypes already exist





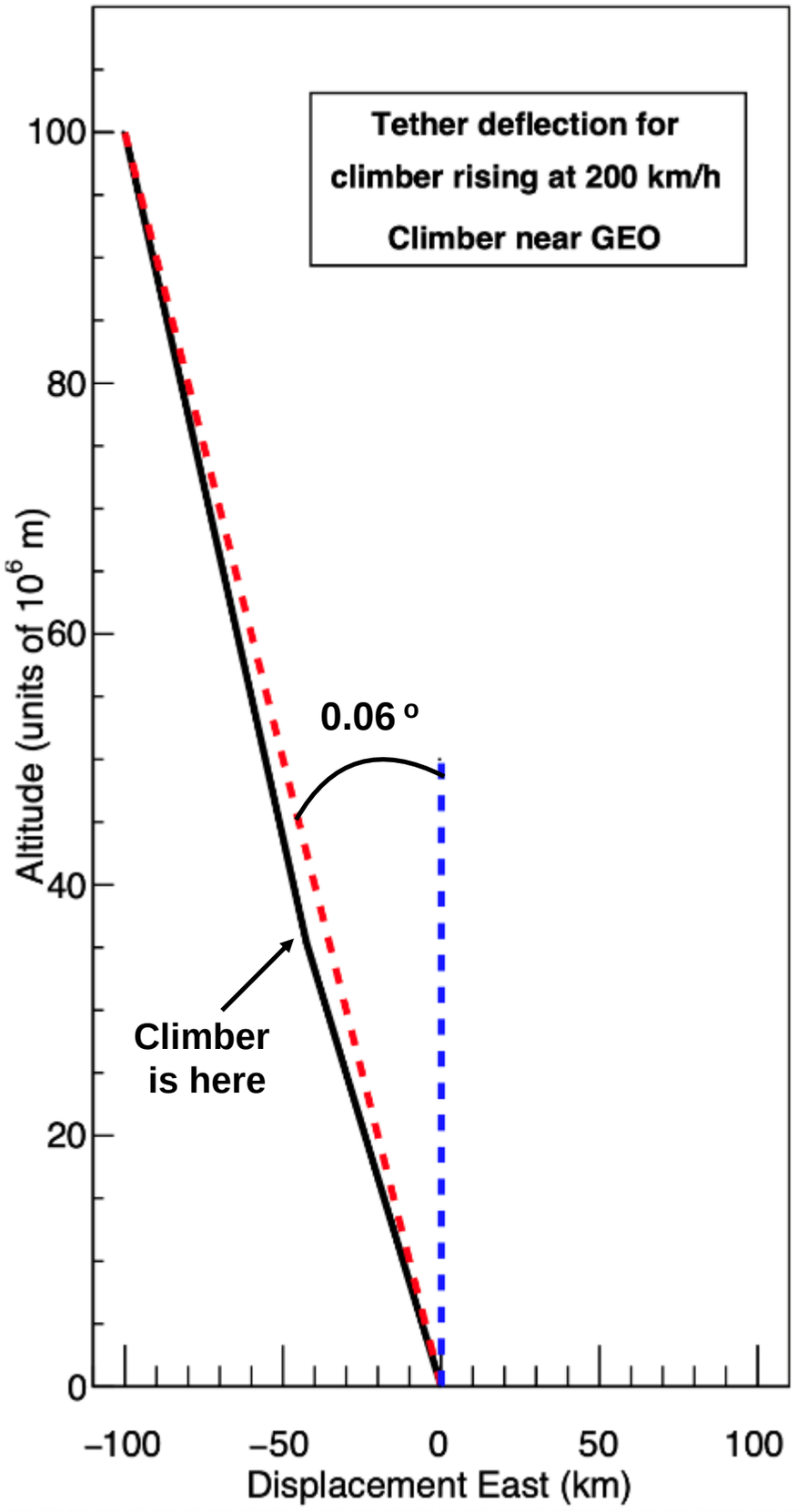

# Another Option: Electrostatic Wheel

- Design by John Knapman
- Put a 10 MV potential across gap between wheel plate and tether
- Force between two angled plates of a capacitor has an upward component
- Can lift 20 ton climber with five wheels

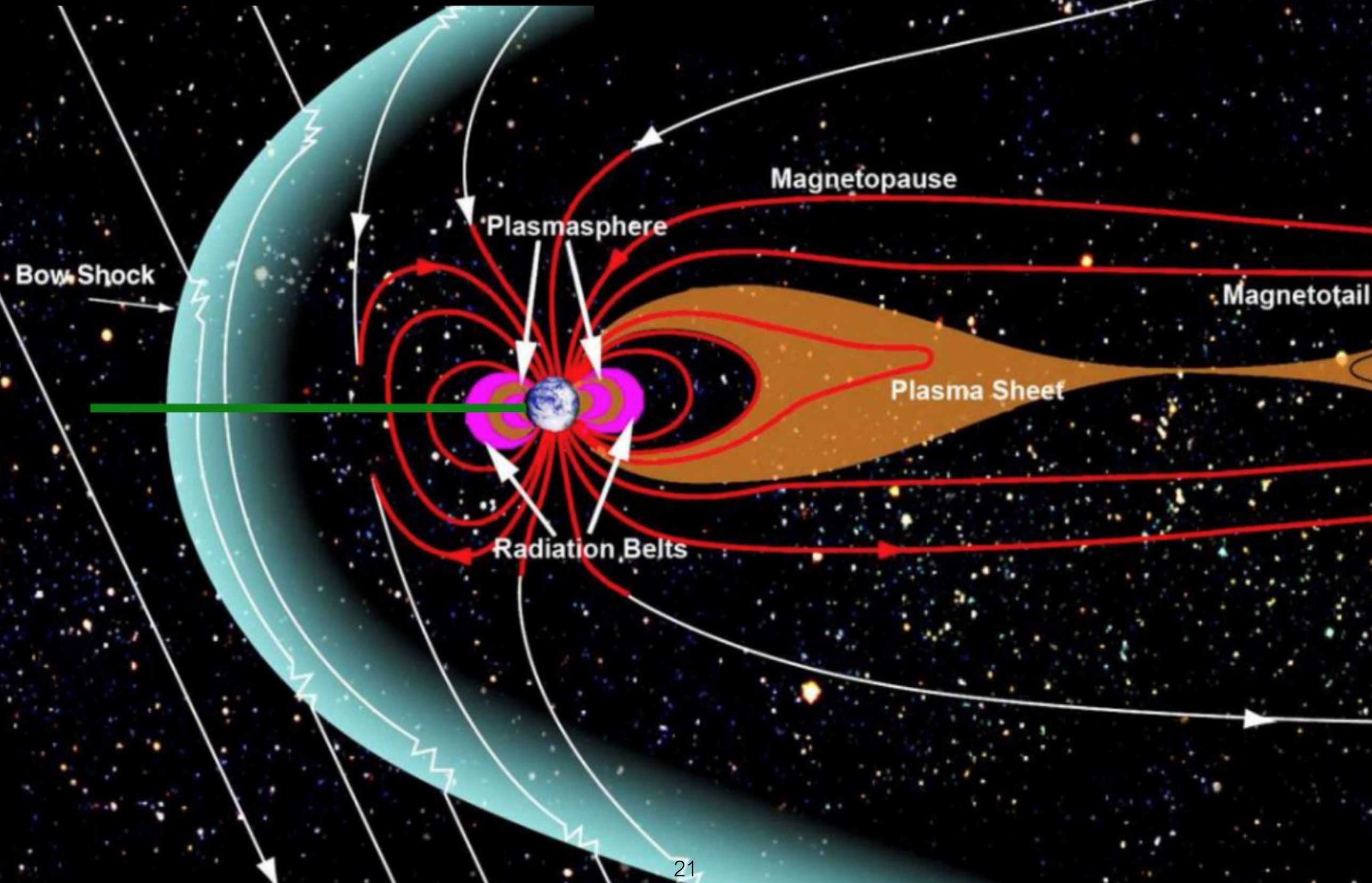


# Effect of Climbers

- Moving climber pulls on the tether
  - pressure waves
  - torsion waves
  - transverse waves
- Coriolis forces cause deflection
  - couple with libration mode

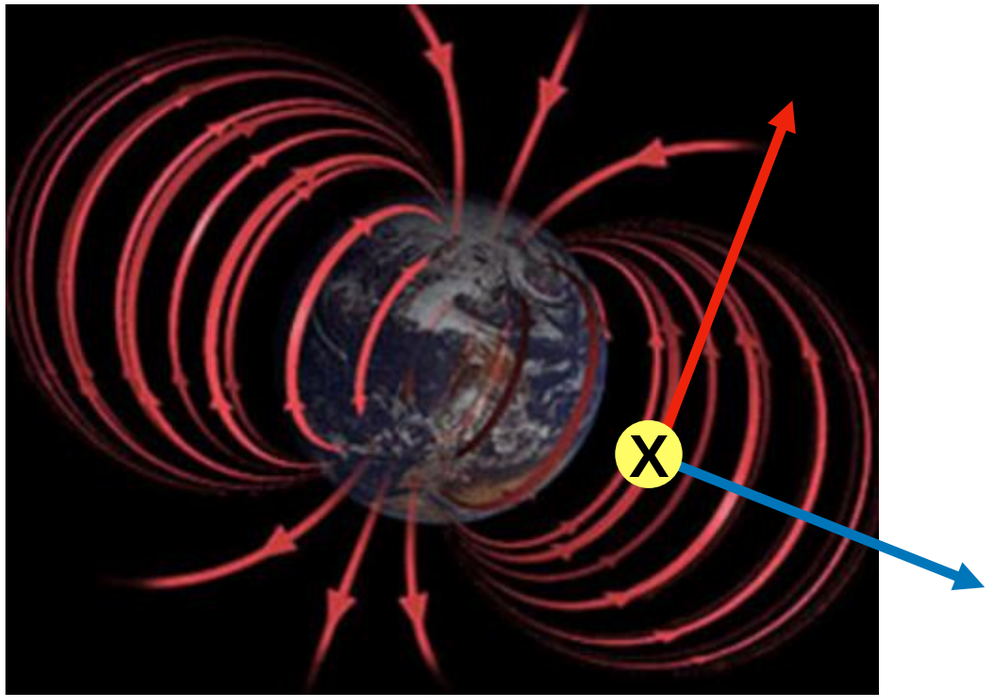


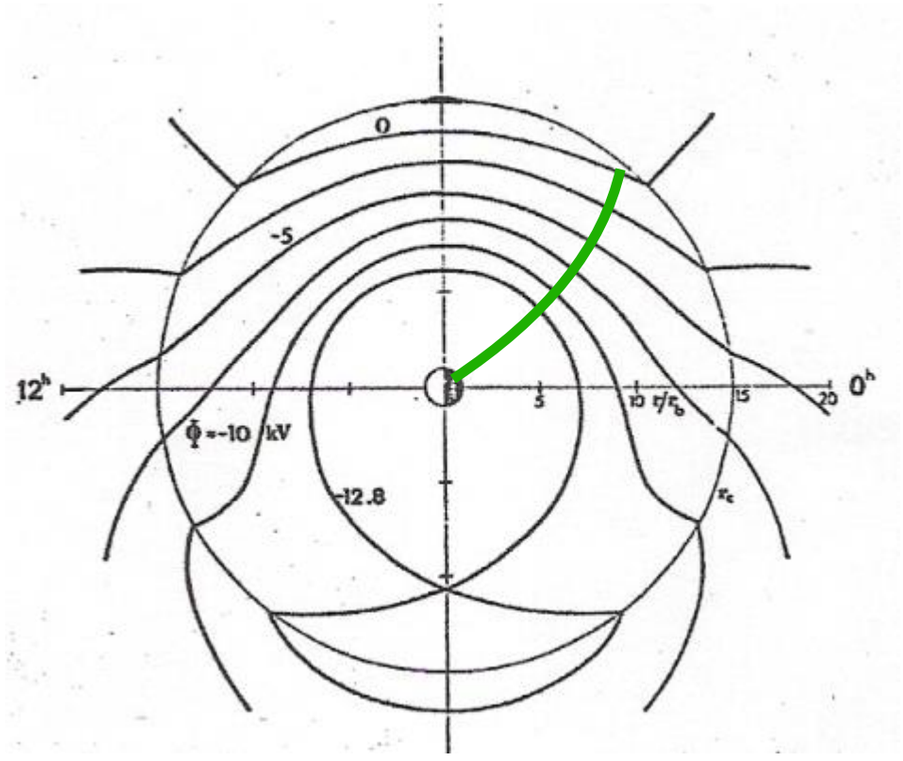
# Space Elevator Environment



# Electrodynamics

- Lorentz force: sum of electric and magnetic forces on charges
  - B force: perpendicular to both velocity and magnetic field
  - E force: along electric field lines
- EM fields provide enough force to move the tether
  - Magnetic field not so much
  - Electric field - yes. Co-rotational electric field produced by solar wind interacting with magnetosphere



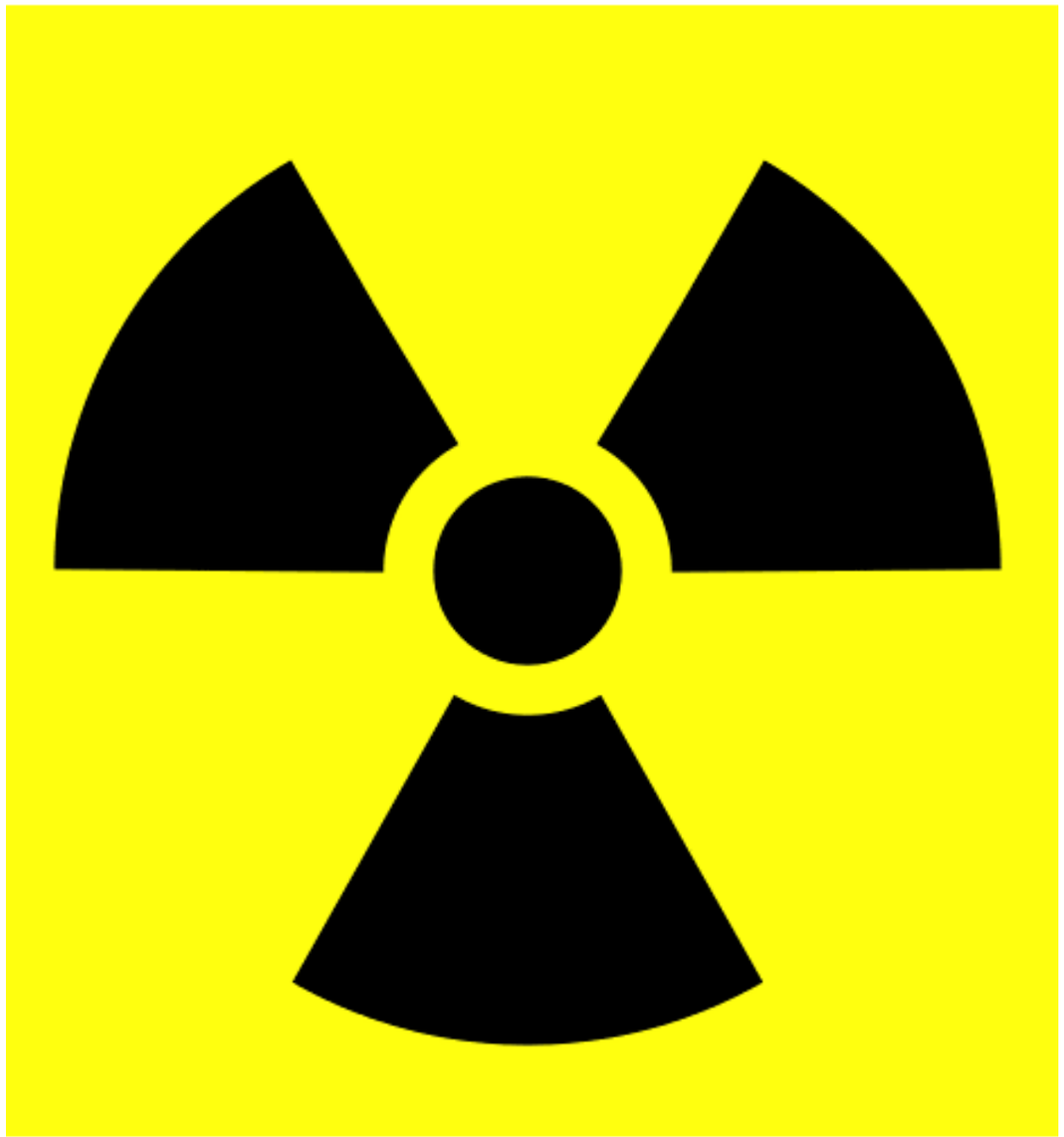



# The Electromagnetic Environment is Dynamic

- Earth's dipole field is not at all symmetric
  - Nor even completely dipole
  - Day-side and night-side quite different
  - Many time-dependent "wobbles"
- Bow shock will cause magnetosphere to compress or expand depending on solar activity
- Electrostatic charging a serious and well-known effect
- Many instabilities
  - X-class solar storms may move apex anchor as much a s 6000 km
  - Power generation may be possible but instabilities must first be well-understood

# Radiation

- SE extends through three different radiation regimes
  - Galactic cosmic rays
  - Van Allen belts
  - Solar wind
- How do you deal with this?
  - Shielding
  - Time
  - Distance

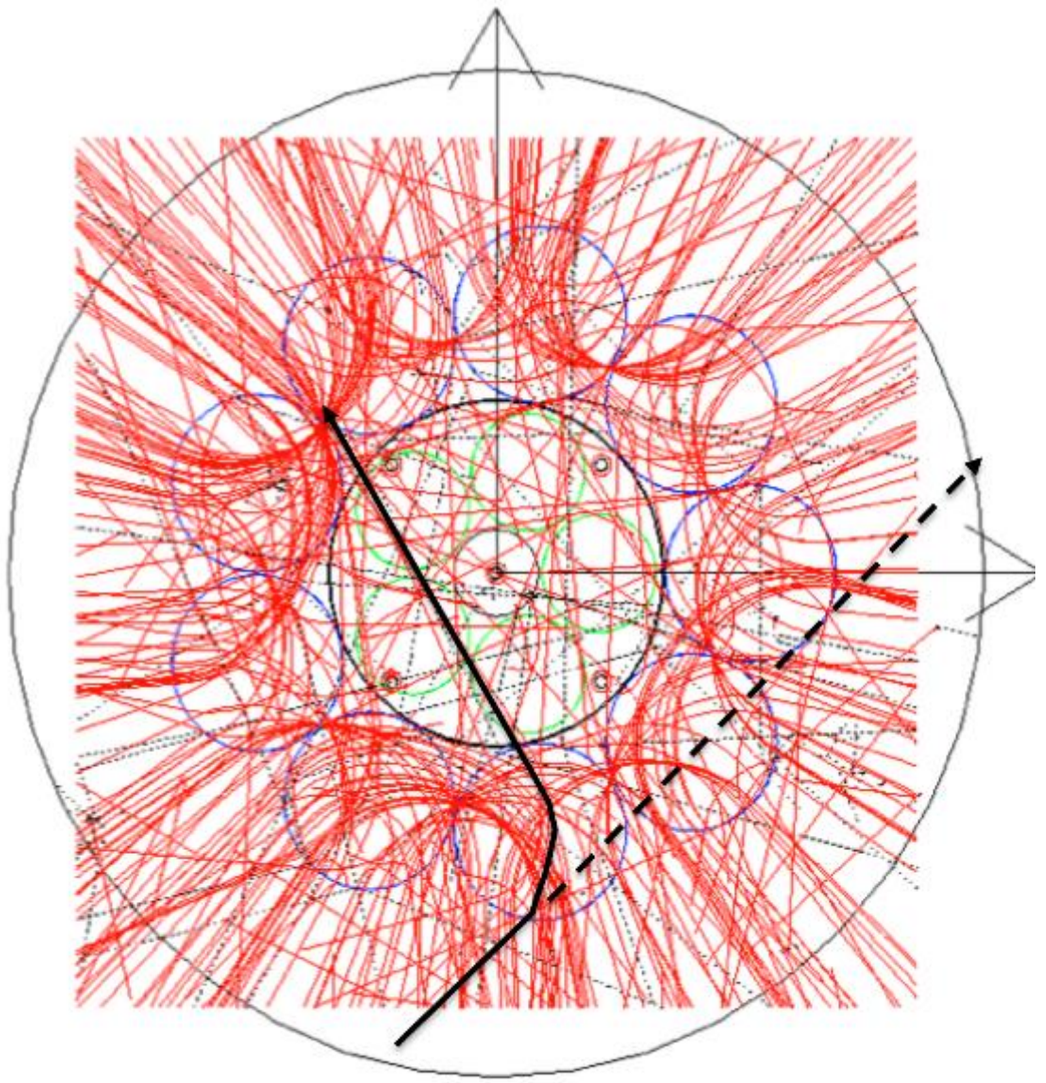


# Radiation Shielding

- Low energy particles
  - lead shielding -> heavy
- Medium energy particles
  - tricky -> need lead - borated hydrocarbon sandwich
  - boron nitride to absorb neutrons?
- High energy particles
  - don’t bother

# Active Shielding

- Passive shielding will be heavy
- Try magnetic shielding
  - Superconducting coils can generate large magnetic fields
  - Fields can deflect some cosmic rays
  - Also adds weight - but if graphene is a superconductor?
- First space elevator -> no shielding -> freight elevator



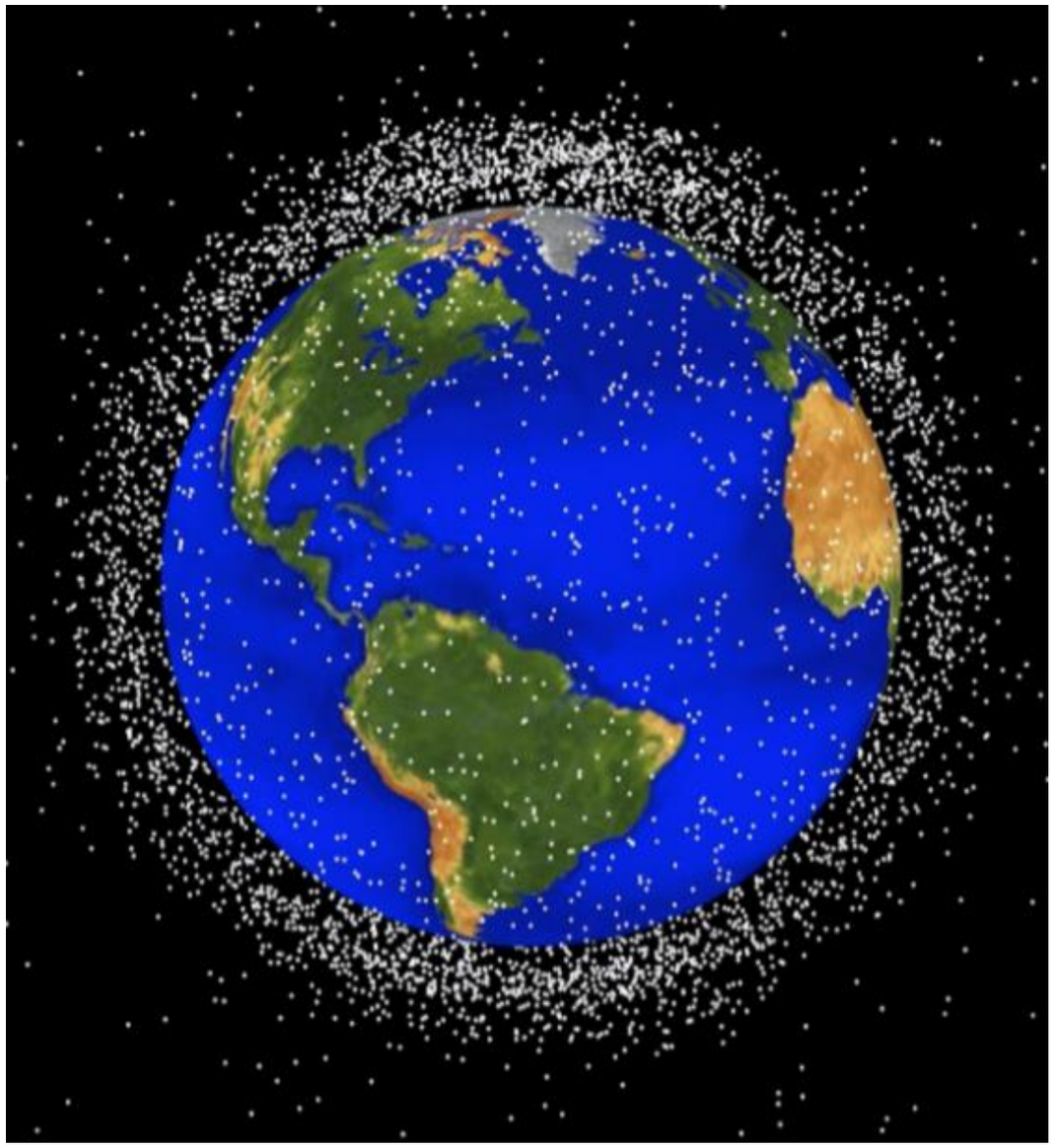
Analysis by R. Battiston, W. Burger

# Atmosphere

- Weather effects below 40 km
  - High winds (loading on tether, driven oscillations, etc.)
  - Lightning
  - Rain (corrosion, electrical)
- Chemical effects
  - Monatomic O (LEO)
  - $O_3$ (ozone) between 17 and 23 km altitude
  - Both O and $O_3$ could attack tether

# Space Debris

- 2010, 2020 ISEC studies
  - Threat is manageable by both active and passive measures
- But what happens when a severance does occur?
  - at LEO: best outcome - most of tether drifts slowly upward - time for recovery
  - at Apex anchor: worst outcome - all the tether comes down - may want to destroy it as soon as possible



# Summary

- Static space elevator is stable
- Dynamic space elevator
  - Much more complicated
  - It looks stable in most normal circumstances, but more study needed
- Climber technology is crucial
  - Will traction be electromagnetic or friction?
- Environment of SE is dynamic and intense
  - First SE will likely be a freight elevator due to radiation and slow transit time
  - Space debris is a manageable problem