Spaceflight

Rocket Formula:

$$v = s \ln \frac{M_{fuel} + M_{payload}}{M_{payload}}$$

v is the velocity of the spacecraft, which weighs (not including fuel) $M_{payload}$ after using the amount of fuel M_{fuel}. This implies that v/s cannot be very much larger than 1.

The exhaust velocity s is determined by energy content of fuel

$$s = \sqrt{2E_{fuel}/M_{fuel}}$$

Fuel	E_{fuel}/M_{fuel} kwh/kg	s km/s	
H+O	3.2	3	
U fission	2×10^7	8000	c/36
H fusion	2×10^8	25,000	c/12
matter-antimatter	3×10^{10}	300,000	c

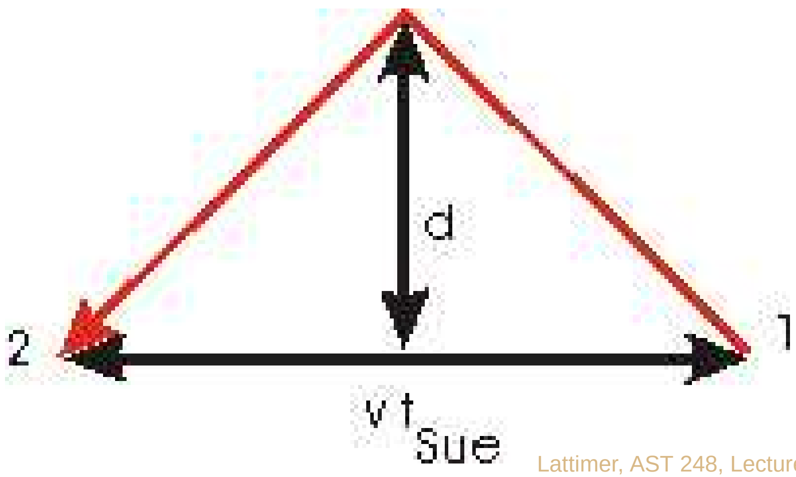
Time Dilation:

$$t_{ship} = t_{Earth}\sqrt{1 - (v/c)^2}$$

If $v/c = 0.99$, $\sqrt{1-(v/c)^2} = 1/7.1$.

Time Dilation

- A light is emitted from a source, reflected by a mirror, and detected by a detector. The mirror is a distance d from the light source.
- Observer Lou sees the light source, light detector and clock all located at exactly the same location. The time interval he notes between emission and detection is t_{Lou}.
- Observer Sue sees the light source, mirror and light detector all travelling to the left with a velocity v. The time interval she notes between emission and detection is t_{Sue}.
- According to Lou, the light must have travelled a distance of $2d$. At speed c, this takes a time $t_{Lou} = 2d/c$.
- According to Sue, who sees everything move a distance vt_{Sue} in between emission and detection, the light must have travelled a distance
  $ct_{Sue} = 2\sqrt{(vt_{Sue}/2)^2 + d^2}$
  so that $t_{Sue} = 2d\gamma/c$,
  where $\gamma = (1 - (v/c)^2)^{-1/2}$.
- $t_{Sue} = t_{Lou}\gamma$



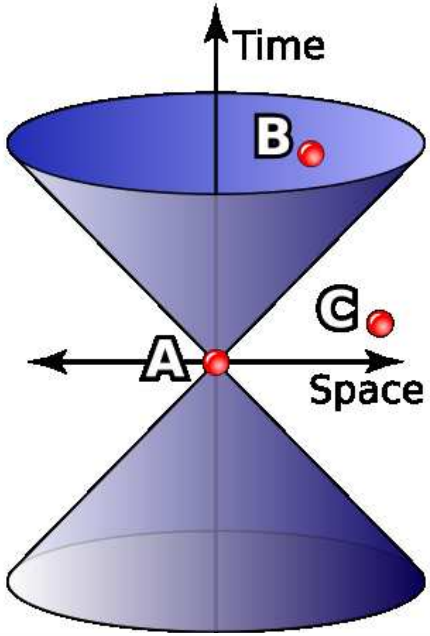
Relativistic Travel

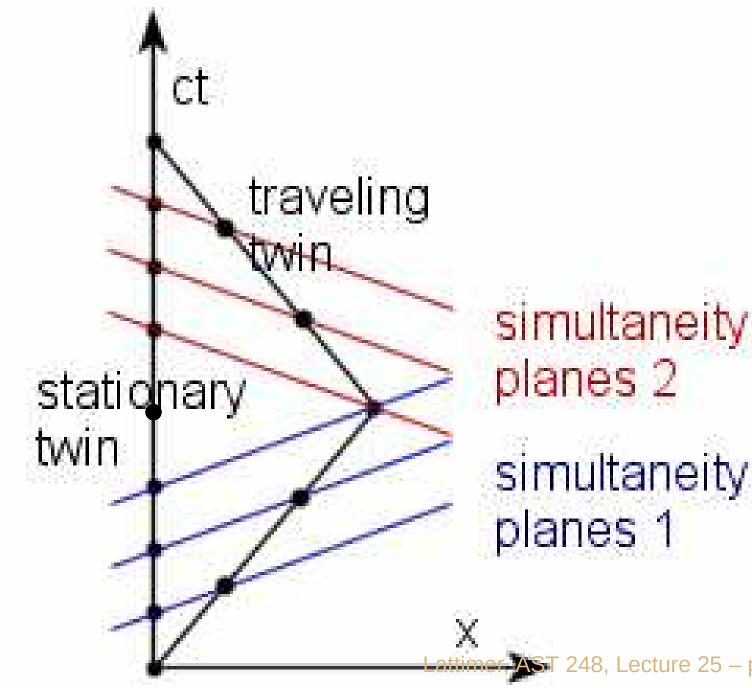
Time dilation The time lapse between two events is relative, *e.g.*, the twin paradox.

Relativity of simultaneity Two events happening in different locations that are simultaneous to one observer need not be simultaneous to another.

Lorentz contraction The dimensions of an object as measured by one observer may be different than measured by another observer, *e.g.*, the ladder paradox.

Twin Paradox Each twin sees the other as moving and having a slower clock. However, the traveling twin undergoes an acceleration to change direction which destroys the symmetry. He has fewer clock ticks than his twin.





Round-Trip Voyages at 1g

Accelerate at $1g$ halfway to destination; decelerate at $1g$. Repeat to return to Earth.

τ	t	v/c	d	γ
Elapsed Time on Ship (yrs)	Elapsed Time on Earth (yrs)	Maximum Velocity	Maximum Distance Reached (lt.-yrs)	(Maximum)
1	1.01	.245	.063	1.03
2	2.08	.462	.255	1.13
3	3.29	.635	.59	1.29
4	4.70	.762	1.08	1.54
5	6.41	.848	1.77	1.89
10	24.2	.987	10.26	6.13
20	296.8	.9999	146.4	74.2
30	3613	1	1805	903
40	44,100	1	22,050	11,025
50	535,900	1	$2.68 \cdot 10^5$	$1.34 \cdot 10^5$
100	$1.44 \cdot 10^{11}$	1	$7.2 \cdot 10^{10}$	$3.6 \cdot 10^{10}$

Problems with Interstellar Space Travel

1. Vast Distances: Nearest star (α Cen) is 4.3 lt.yr. (1.4 pc) distant.

   With $v = 0.1c = 30,000$ km/s, need 43 years to reach it.

2. High Velocities require lots of fuel. For chemical fuel and $M_{payload} = 100$ tons:
   $M_{fuel}/M_{payload} \simeq e^{v/s} = e^{10,000} = 8.6 \times 10^{4340}$
   $M_{fuel} \simeq 8.6 \times 10^{4348}$ g $= 4.3 \times 10^{4315}$ $M_\odot \simeq 10^{4259} M_{Universe}$!!!

   For nuclear fuel
   $M_{fuel}/M_{payload} \approx e^{v/s} - 1 = e^{1.2} - 1 = 2.3$

   With matter-antimatter fuel, $s = c$, must use relativistic rocket formula:
   $\sqrt{\frac{c+v}{c-v}} = \frac{M_{fuel}+M_{payload}}{M_{payload}}$,
   $v = 0.1c$ requires $M_{fuel}/M_{payload} = 0.11$.
   Where do you get 11 tons of antimatter?

3. Total energy to accelerate Titanic ($m = 10^{11}$ g) to $v = 0.1c$ and slow down:
   $mv^2 = 10^{11}(3 \cdot 10^9)^2$ erg $= 10^{30}$ erg = $100\times$ Earth's annual energy usage.

4. Even moderate accelerations with high exhaust velocities require enormous power. Assume $M_{payload} = 100$ tons, acceleration is $1g$, exhaust velocity is $c/12$:
   $\mathrm{Power} = M_{payload} gc/24 = 12,250$ Gigawatts.
   This is equivalent to 2450 Hoover Dams, or to 40% the present world-wide energy consumption rate.

Alternate Proposals

Interstellar Ramjet (Bussard) H-fusion has $s = c/12$

Thrust $= M_{ship} \times$ acceleration = Fuel collection rate $\times s$

Fuel collection rate = collector area $\times v \times$ density (n)

Acceleration = $1g$; $v = 0.01c$ $M_{ship} = 10$ tons; $n = .1$ atom $\mathrm{H/cm^3} = 1.6 \cdot 10^{-25}$ g/cm^3

Collector area $= gM_{ship}/(svn) = 10^{16}$ cm^2 (a circle 300 km in radius).

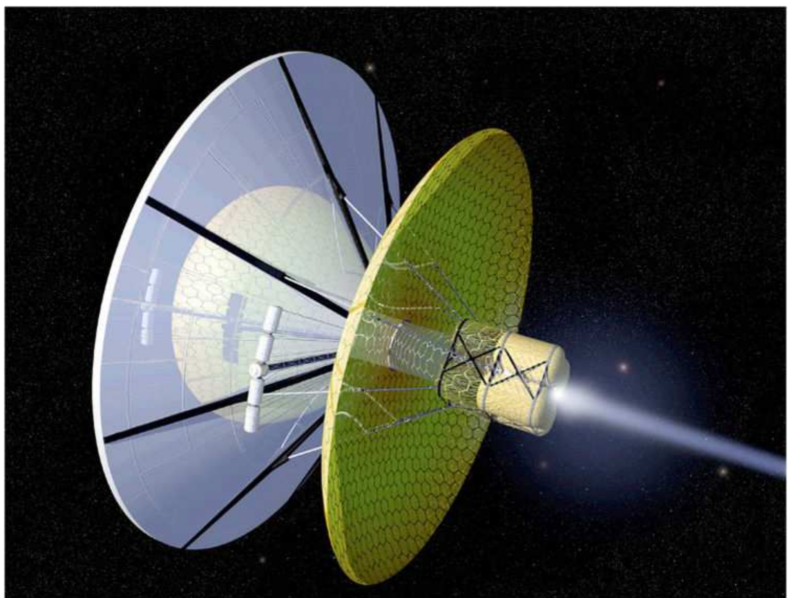
Solar Sails Usable power of sunlight is

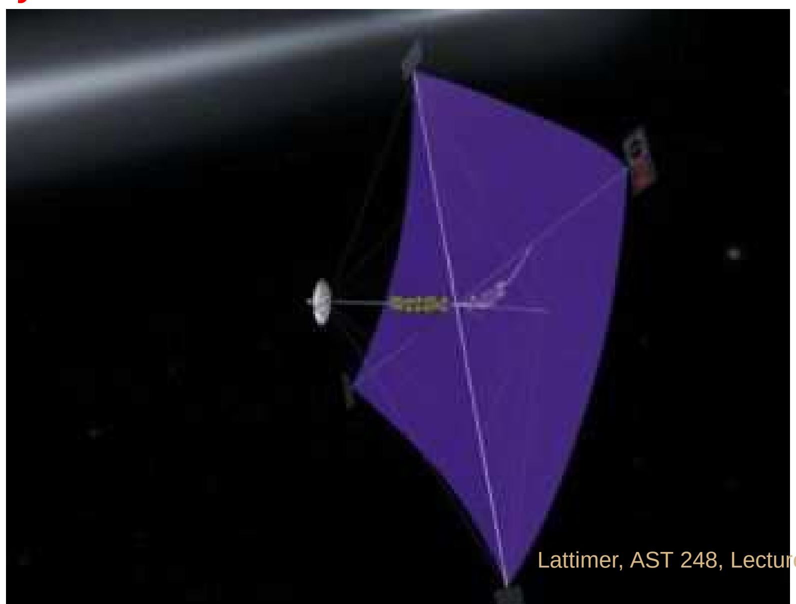
$$\mathrm{L}_\odot (R_{ship}/2d)^2 = 43,000 (\frac{R_{ship}}{100 \text{ km}})^2 (\frac{d}{1 \text{ AU}})^2 \text{ Gw} = 10^{-3} (\frac{R_{ship}}{100 \text{ km}})^2 (\frac{d}{1 \text{ pc}})^2 \text{ Mw}$$

For $1g$ acceleration, needs power of $gM_{ship}c/2 = 1.5 \cdot 10^6$ Mw

Effective L$_\odot$ could be enhanced by using giant solar collectors and reradiating power with lasers and/or lenses.

Nanotechnology SiC or C fibers, with mass of 10–100 g. A few Hoover Dams of power could accelerate this at more than 100 g's; velocities of 0.2 c are reached within a week, and nearest stars are reached in 20 years Earth-time.





Practical Proposals

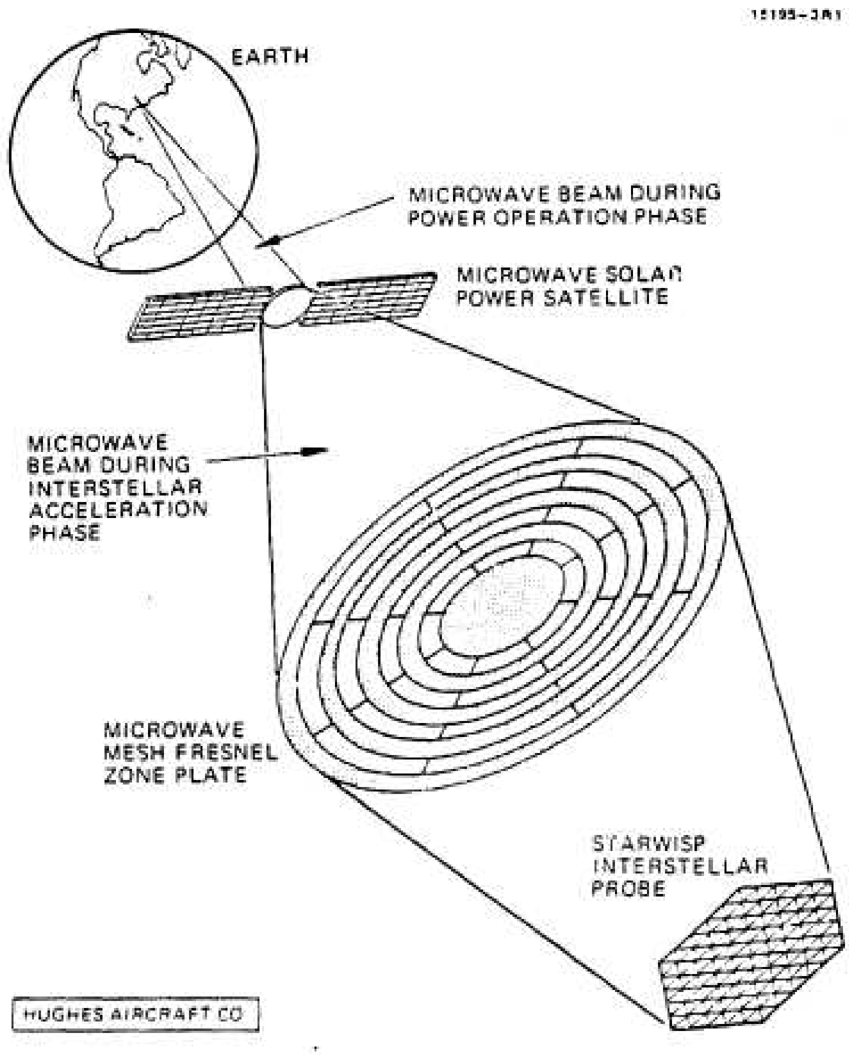


Figure A-1. Starwisp: A Maser-Pushed Interstellar Probe.

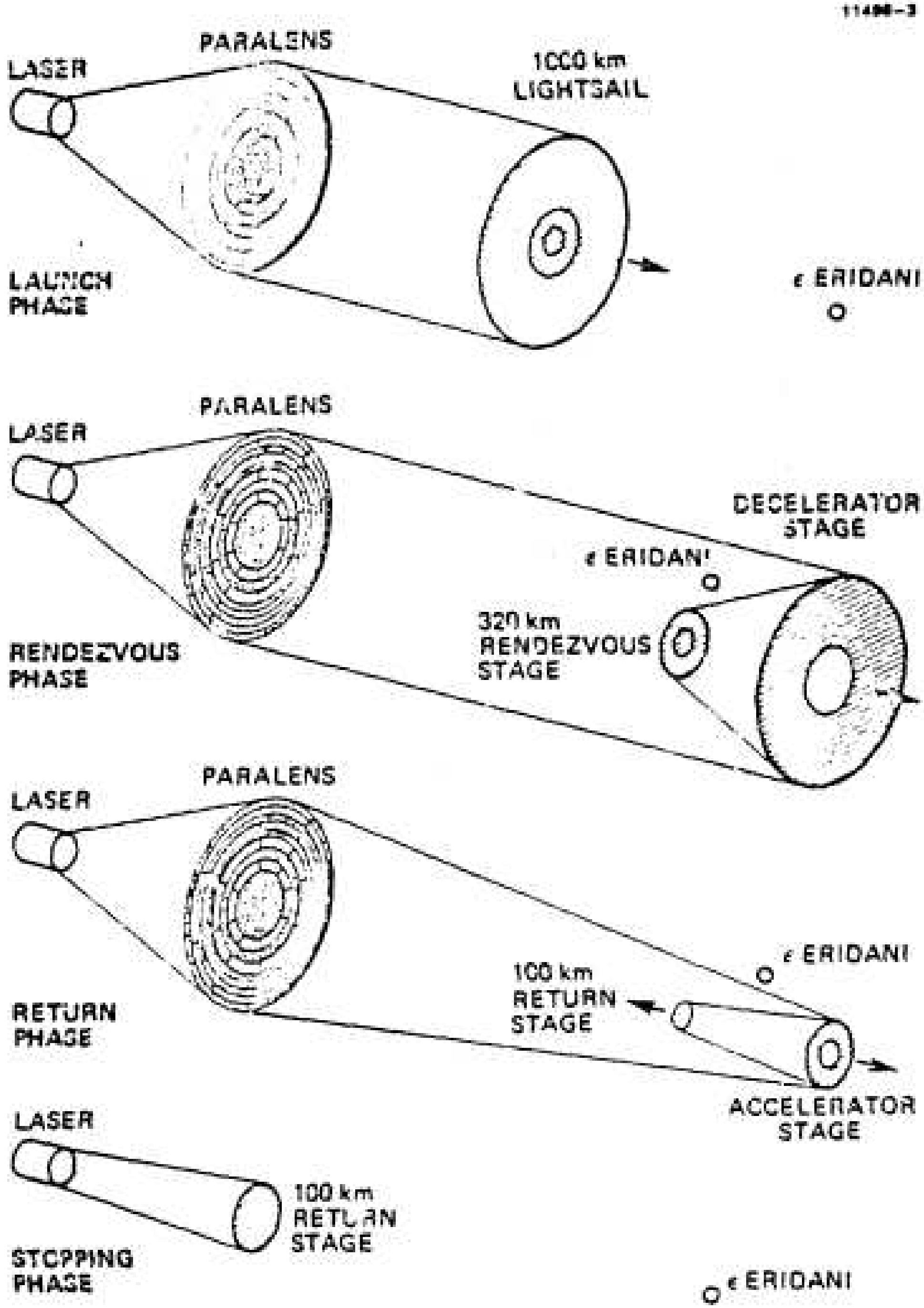


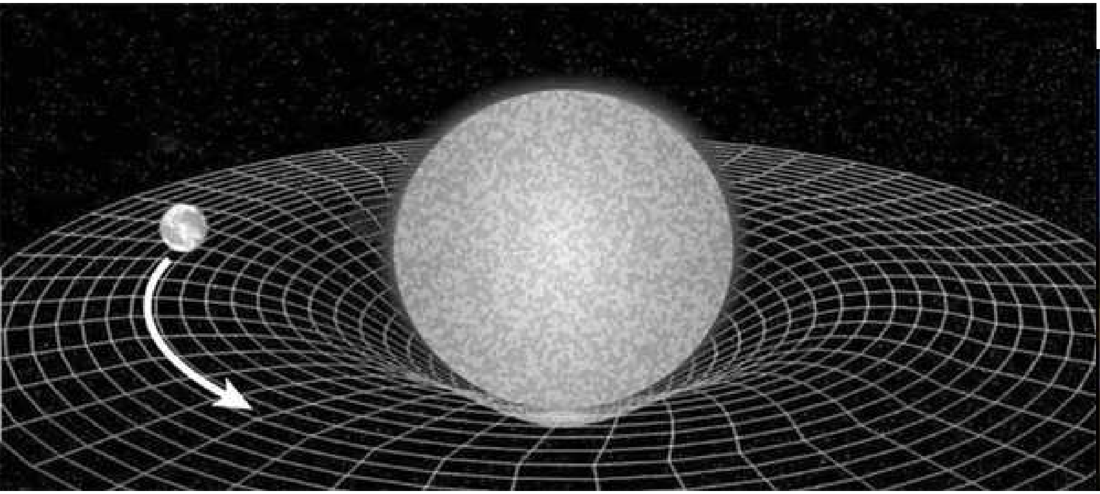
Figure A-2. Roundtrip Interstellar Travel Using Laser-Pushed Lightsails.

Robert L. Forward, AAAS Annual Meeting, May 1986

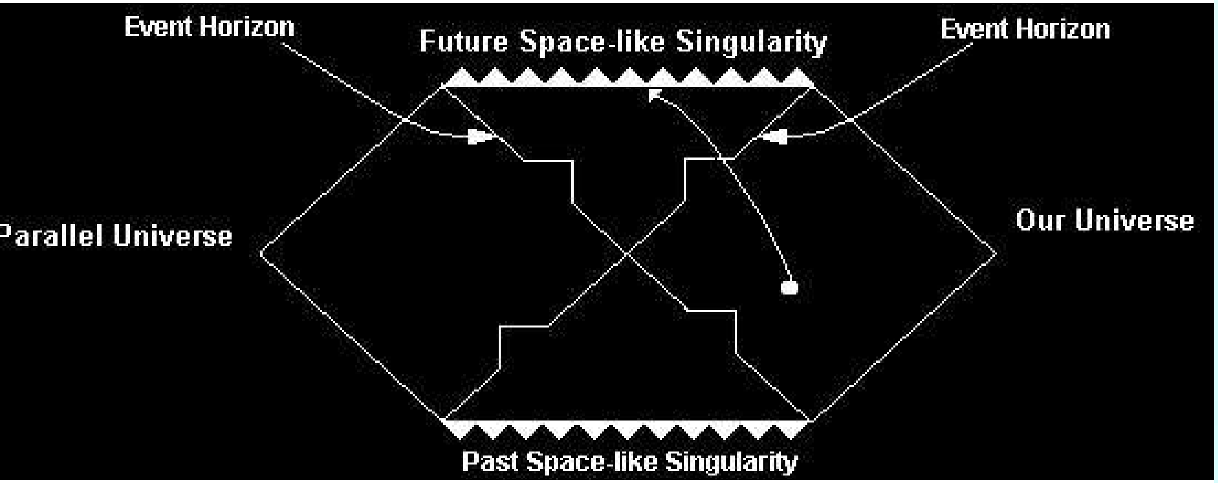
Spacetime Hypersurfing Requires exotic matter, which has negative energy density and repels normal matter. At present, exotic matter *virtually* exists under some conditions, and may have been the normal state of matter prior to the inflationary epoch in the Big Bang. Exotic matter could repel normal-matter spaceships to faster-than-light travel without violating causality and without permitting time travel. Such travelers would experience neither accelerations nor time dilation.

Quantum Entanglement Otherwise known as "Action at a Distance". Some recent experiments seem to show that mass can influence other mass, no matter how distant it might be, virtually instantaneously. Perhaps this quantum mechanical effect could be utilized for "faster-than-light" travel. Very speculative.

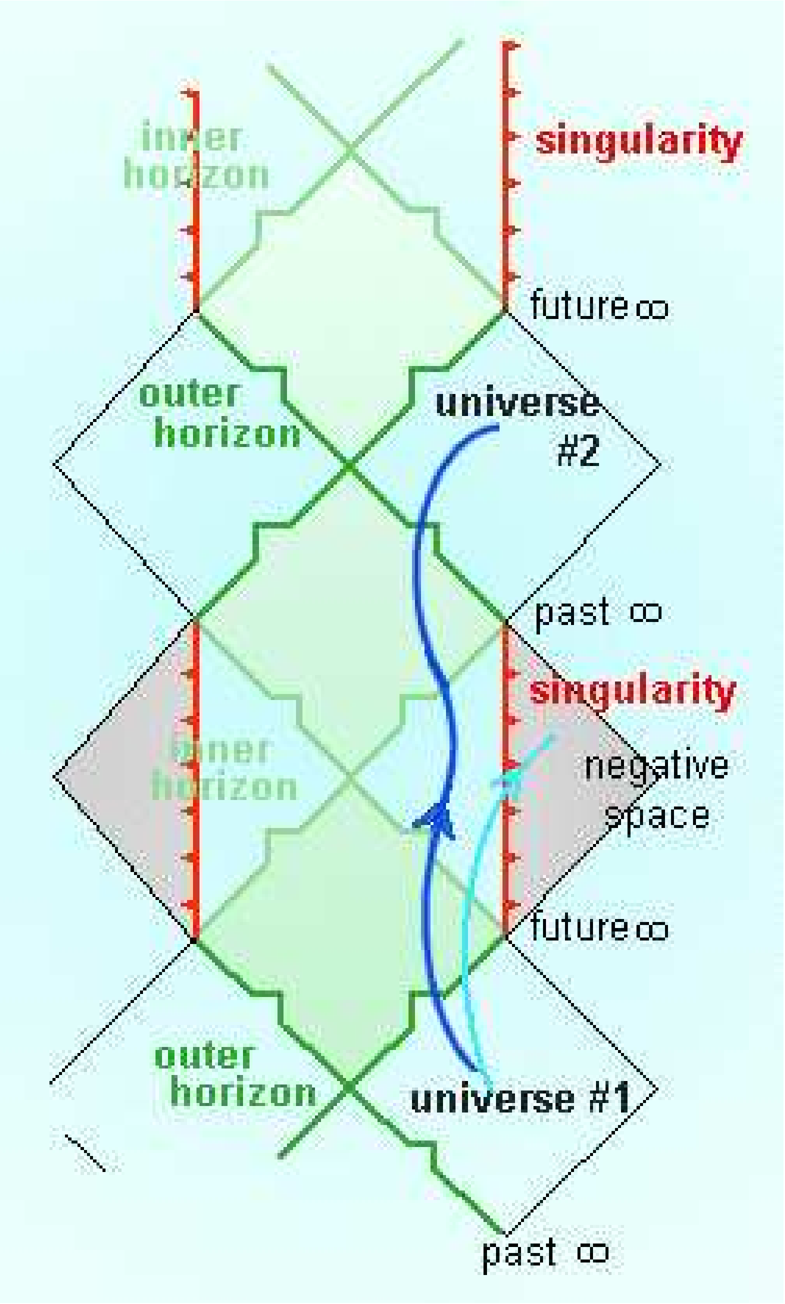
Burkhard Heim's unified field theory A German theoretical physicist developed an idea for a propulsion device that could travel faster than light using extra dimensions contained in his theory. The theory has made a number of interesting, correct predictions about subatomic particles, but otherwise has not been verified. Few people really understand it and it remains speculative and controversial.



Using Black Holes



Schwarzschile (non-rotating) black hole



Kerr (rapidly rotating) black hole

The Fermi Paradox

The apparent contradiction between high estimates of the probability of the existence of extraterrestrial civilizations and the lack of evidence for, or contact with, such civilizations.

- Drake equation arguments support the idea that the Earth is not special and that large numbers of ET civilizations exist.
- Intelligent life will explore space and tend to colonize new habitats.
- The timescale for exploration is not prohibitively large. Spacecraft velocities of $0.01c$ could be achieved through gravitational slingshots coupled with solar sail propulsion.
- Robot probes would be much more efficient than manned probes. If the robot probes (von Neumann probes) could make copies of themselves when they arrive at each stellar system, and send their offspring to further explore, a wave of exploration will propagate (the coral model). $t_b \approx 100$ years would be an estimate of time needed to build new probes from raw materials of a stellar system. Probes could even carry genetic information needed to populate habitable systems.
- Propagation speed is $\frac{D_* v_s}{D_* + t_b v_s} \simeq 0.0075c$, where $D_* \approx 3$ lt. yr., $v_s \approx 0.01c$, and $t_b \approx 100$ years.
- To explore a sphere of 100,000 lt. yr. diameter would then take 13 Myr if done most efficiently. This is much less than the Galaxy's age.
- Even with $t_b = 5000$ yr, it would take 170 Myr to colonize the Galaxy.
- Alternatively, a civilization could construct communication probes (Bracewell probes) and flood the Galaxy with them.

Resolutions

- No other civilizations exist
  - No other civilizations have been born yet (Rare Earth hypothesis)
  - Intelligent life destroys itself before exploration ensues (doomsday argument) from nuclear or biological war, contamination, nanotechnological catastrophe, disastrous physics experiments, Malthusian overpopulation
  - Intelligent life destroys others; to be successful, an alien species will be a superpredator
- They do exist but we see no evidence
  - Communication is impossible due to vast distances and timing
  - It is too expensive to perform the von Neumann or Bracewell search strategies
  - Humans have not been searching long enough
- Communication is impossible for technical reasons
  - Humans are not listening properly
  - Civilizations may only broadcast for a brief time period
  - Civilizations experience a technological singularity and attain a posthuman character that is uninterested in communication.
  - Robot probes lose their programming or radiation effects alter or destroy them.
- Aliens choose not to interact with us
  - Earth is purposely isolated (the zoo and/or sentinel hypotheses)
  - They are too alien or non-technological (or posthuman)
- They are here unobserved (zoo hypothesis again)

Space Settlements

Motivations:

- Solar power: An array 100 km on a side can collect Earth's entire power consumption, worth $3 billion per hour.
  Energy beamed as microwaves to rectennae which absorb microwaves and convert them to electricity.
- Pharmacology, molecular nanotechnology (diamonoid mechanosynthesis)
- Orbital towers or space elevators possible, would permit low-cost orbital transportation.
- Could serve as base for space mining.
- Not practical for reduction of population: world-wide population growth is $N(b-d) \simeq 270,000$ persons per day.

Advantages over planetary colonization:

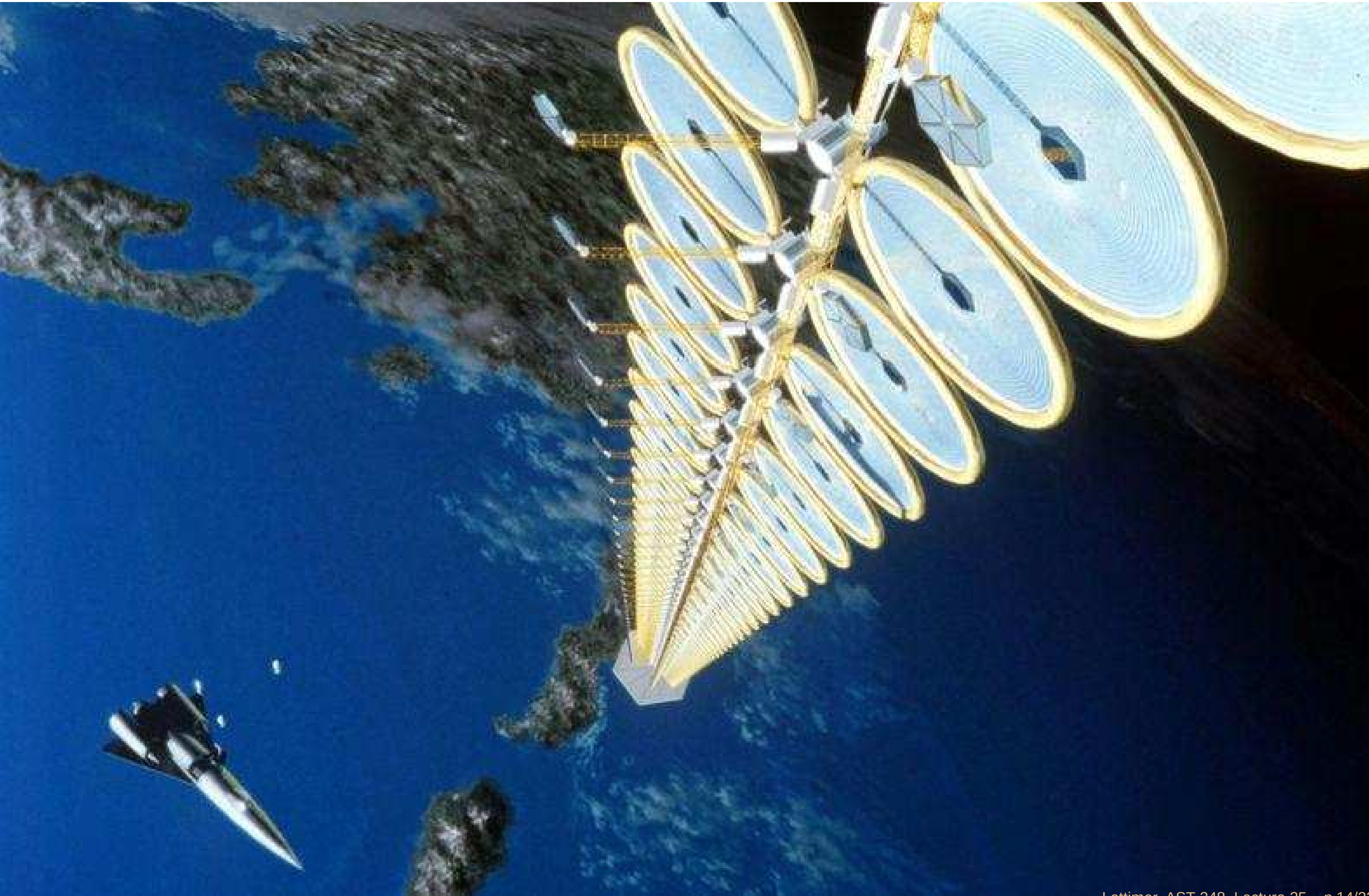
- Access to perpetual solar energy
- Access to zero gravity
- Long-term expansion of land area available to human race.
- Control of environment
- Location at top of Earth's gravity well
- First step to interstellar colonization

Solar Power Satellites

Design Parameters

- Geostationary orbit: 22,300 miles
- Circular satellite antennae at least 1 km diameter to avoid losses due to diffraction and sidelobes
- Elliptical ground antennae (rectennae) about 10×14 km, composed of many short dipole antennae connected via diodes. Crops and animals could be raised underneath them, since antennae are thin enough to permit sunlight to penetrate.
- Desired microwave intensity is 23 mW/cm^2, so each antenna transfers between 5 and 10 Gigawatts of power.
- Optimum microwave frequency is about 2.45 GHz.
- With monocrystalline silicon solar cells (14% efficiency), the satellite would need 50 - 100 km^2 collector area; 2/3 less if triple junction gallium arsenide solar cells are used.
- Major cost is that of space launches. Will be reduced by economies of scale. Mass-to-power ratio would be about 1 kg/kW, or 10^4 tons for each antenna. At present, the launch cost is as high as the energy returns over a 10-year timespan.
- Using materials from the moon or asteroids could ultimately reduce costs.
- Another strategy for reducing launch costs involves using space elevators.

Solar Power Satellite



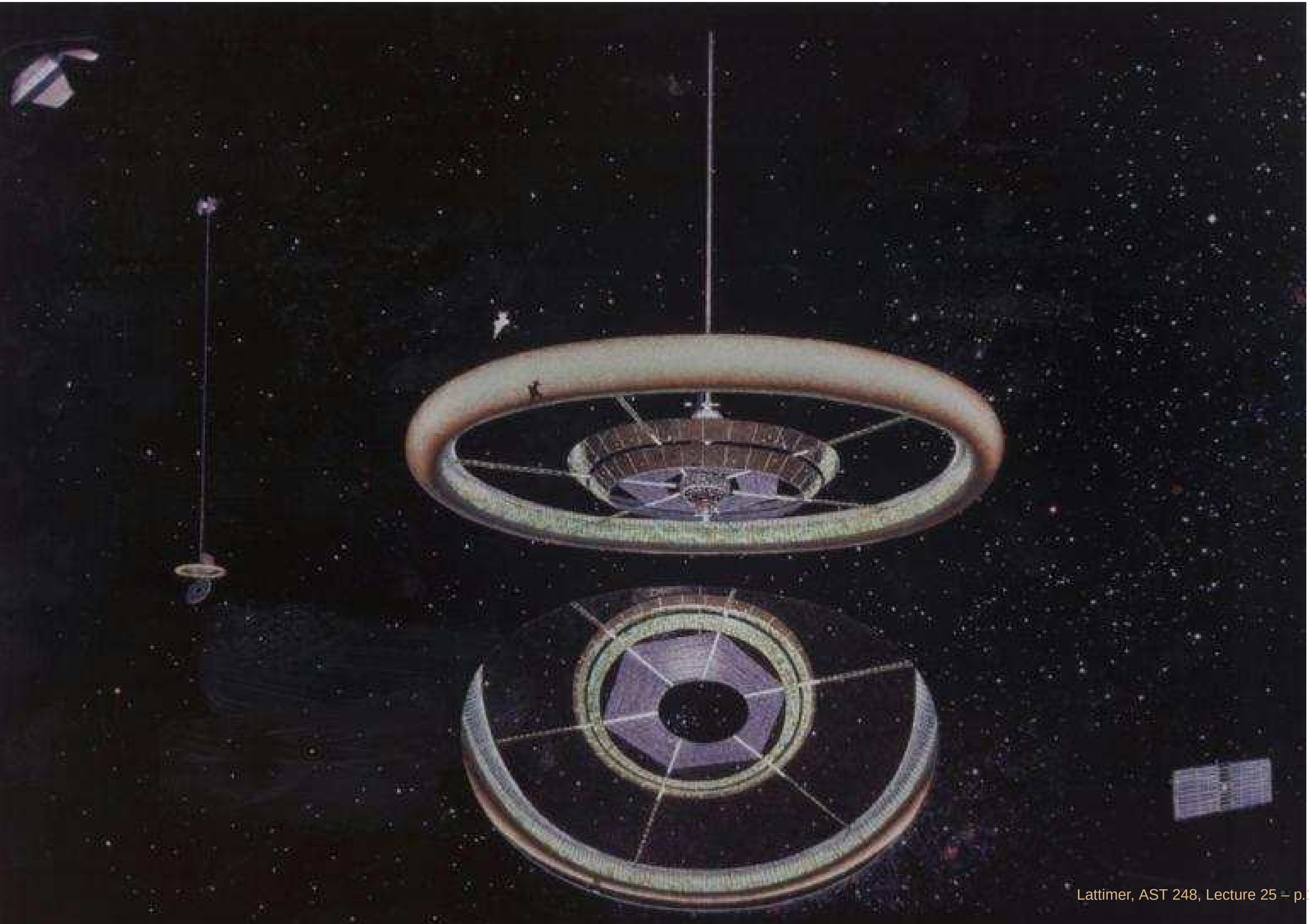
Constraints for Space Habitats:

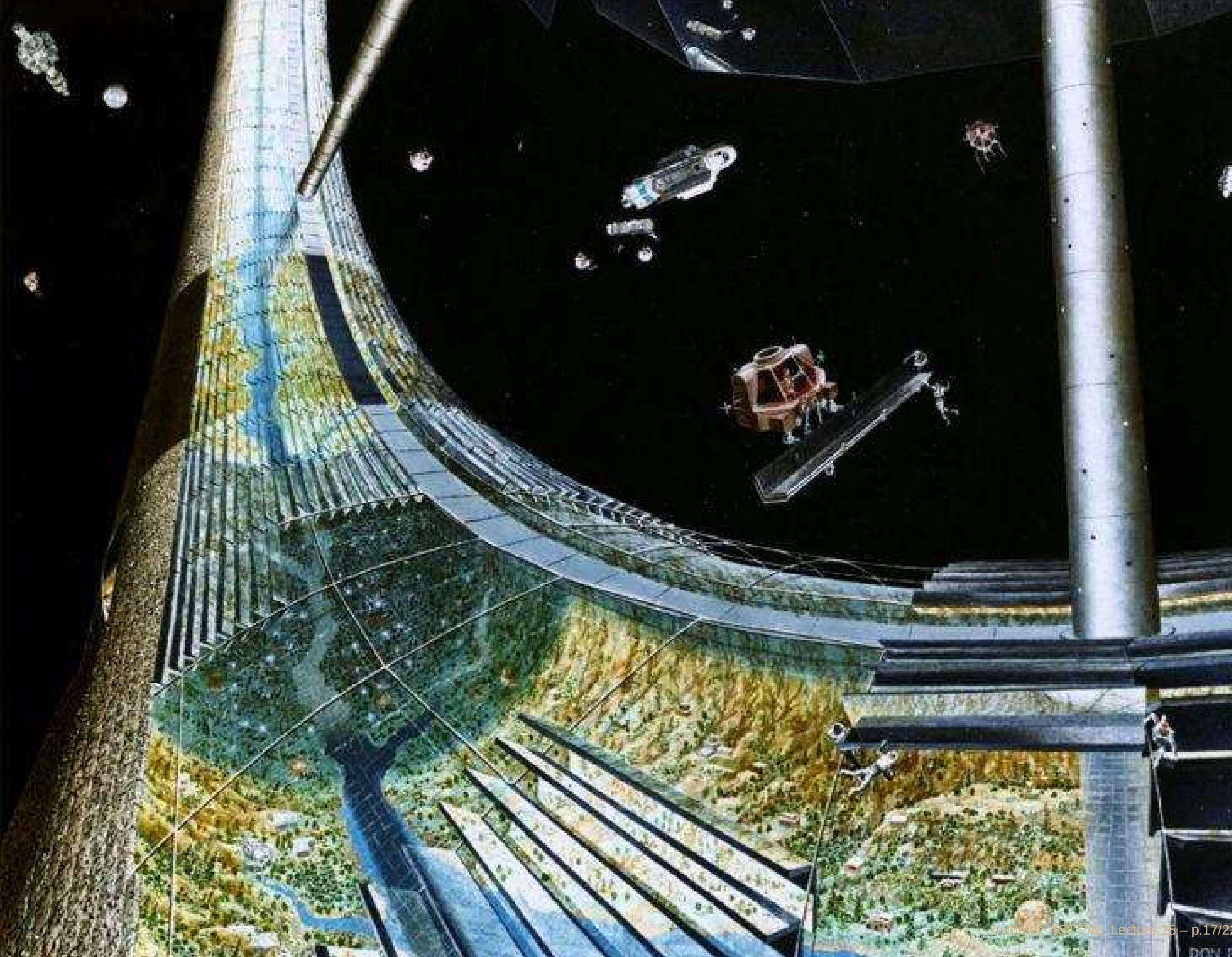
- Most material should originate from Moon, or possibly asteroids or comets. Use electromagnetic mass drivers to inject material from lunar surface into Earth orbit.
- Earth-normal gravity required in living and most working quarters. Axial area is zero-gee. Diameter must be greater than about 1.8 km to keep rotation rate low.

$$D = 2gP^2/(2\pi)^2 = 1.8(P/1\ \mathrm{min})^2\ \mathrm{km}.$$

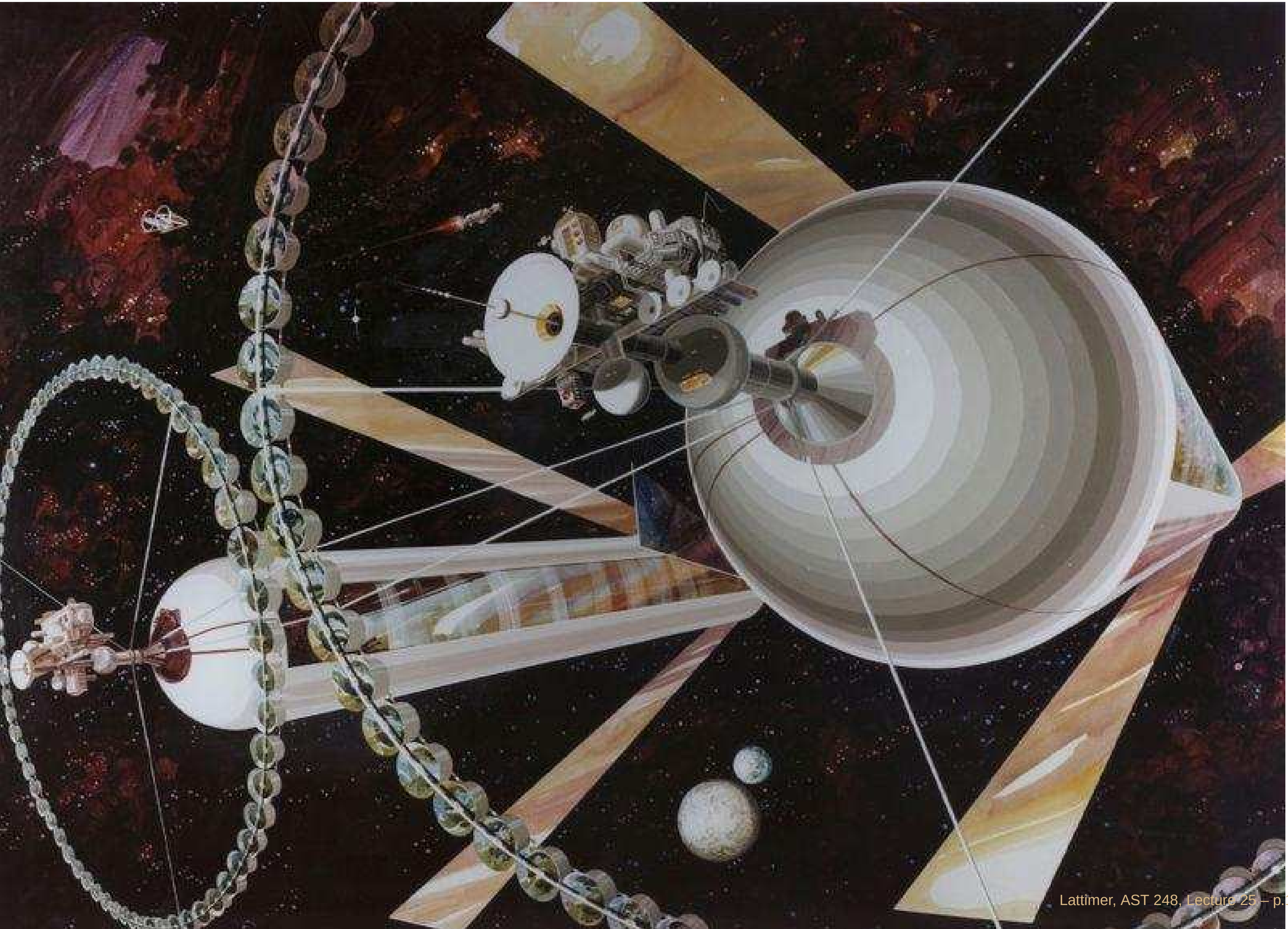
- To protect against cosmic rays and solar radiation, shielding of several tons per square foot of exterior surface, which corresponds to about 2–3 feet thickness, is needed. Less could be more harmful than none at all.
- System of mirrors and louvers needed to permit solar lighting and heating.
- Torus (Stanford), sphere (Bernal), or cylinder (O'Neill) geometry favored because of longer sightlines, lessens claustrophobia, permits weather.

Stanford Torus





O’Neill Cylinder



Bernal Sphere