NIAC Fellows meeting

Atlanta March 7 2007

Phase I report

Practicality of a solar shield in space to counter global warming

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Pete Worden and Kevin Parkin	NASA Ames Research Center
Dave Miller	MIT

Planet Earth driver's test

1) You are zipping along happily, when you see warning lights ahead in the distance but visibility is not so great.

What should you do?

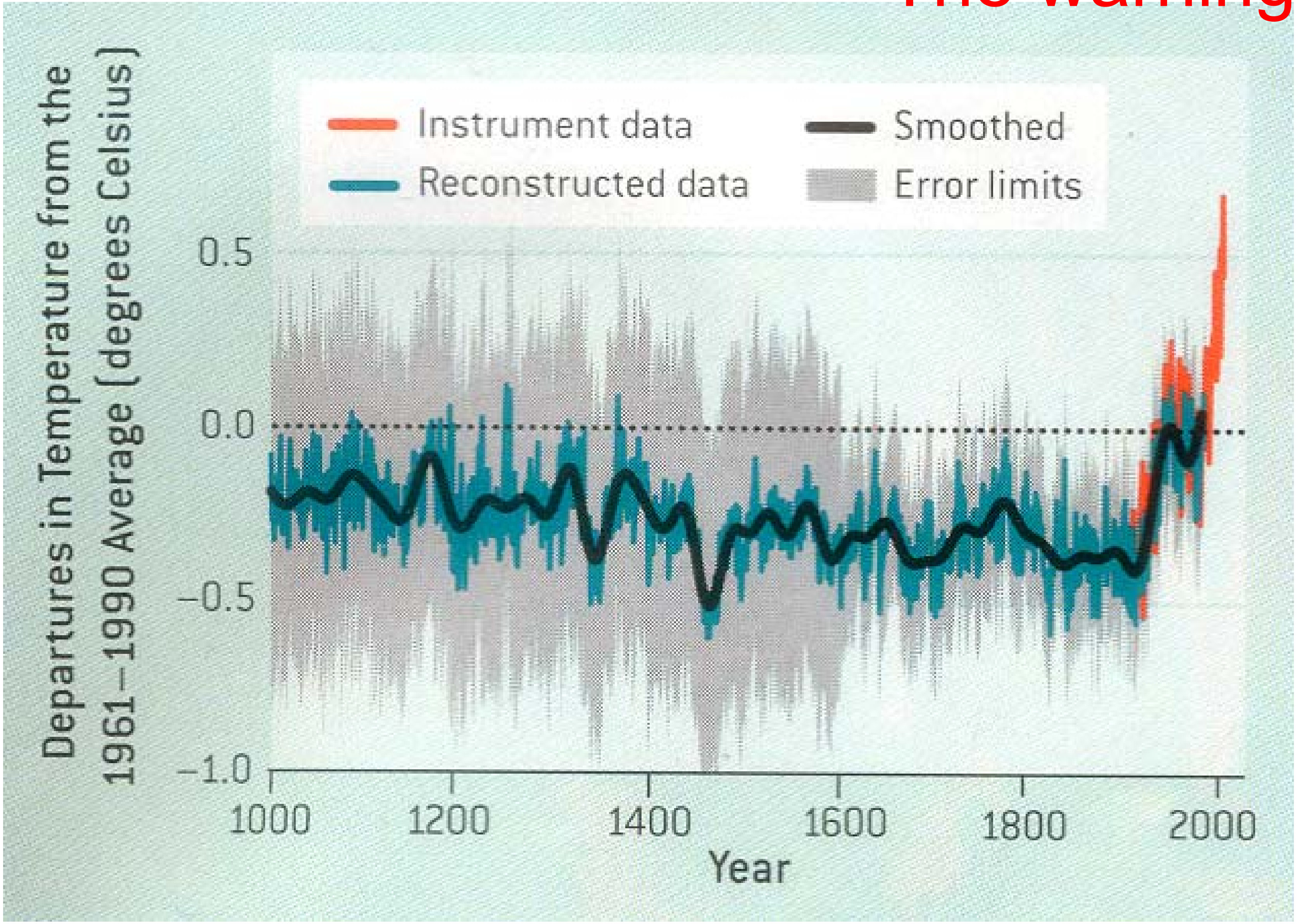
a) Just floor it

b) take you foot off the accelerator

c) apply the brakes

2) You find you have no brakes. What should you do now?

The warning



Instrument data
Smoothed
Reconstructed data
Error limits
Departures in Temperature from the 1961–1990 Average (degrees Celsius)
0.5
0.0
−0.5
−1.0
1000
1200
1400
1600
1800
2000
Year

CO_2 in atmosphere works just like water vapor

- Lets in warming sunlight in the day
- when humidity is high heat is trapped and nights stay warm
- when humidity is low heat escapes and nights are cold
- But unlike water vapor, CO_2 hangs around
  - added CO_2 in the atmosphere takes a century or two to dissipate

Geoengineering solutions could be really useful

- Needed if current CO_2 level already beyond "tipping point"
- Even extreme conservation may not be able to stop abrupt and disastrous changes e.g.
  - changes in ocean circulation
  - Greenland melts (20' permanent sea level rise)
- Many leading scientists seriously worried
- Probability of disaster 10% - 20%?
  - Geoengineering like taking out insurance against unlikely but catastrophic event)

Geoengineering has been taboo

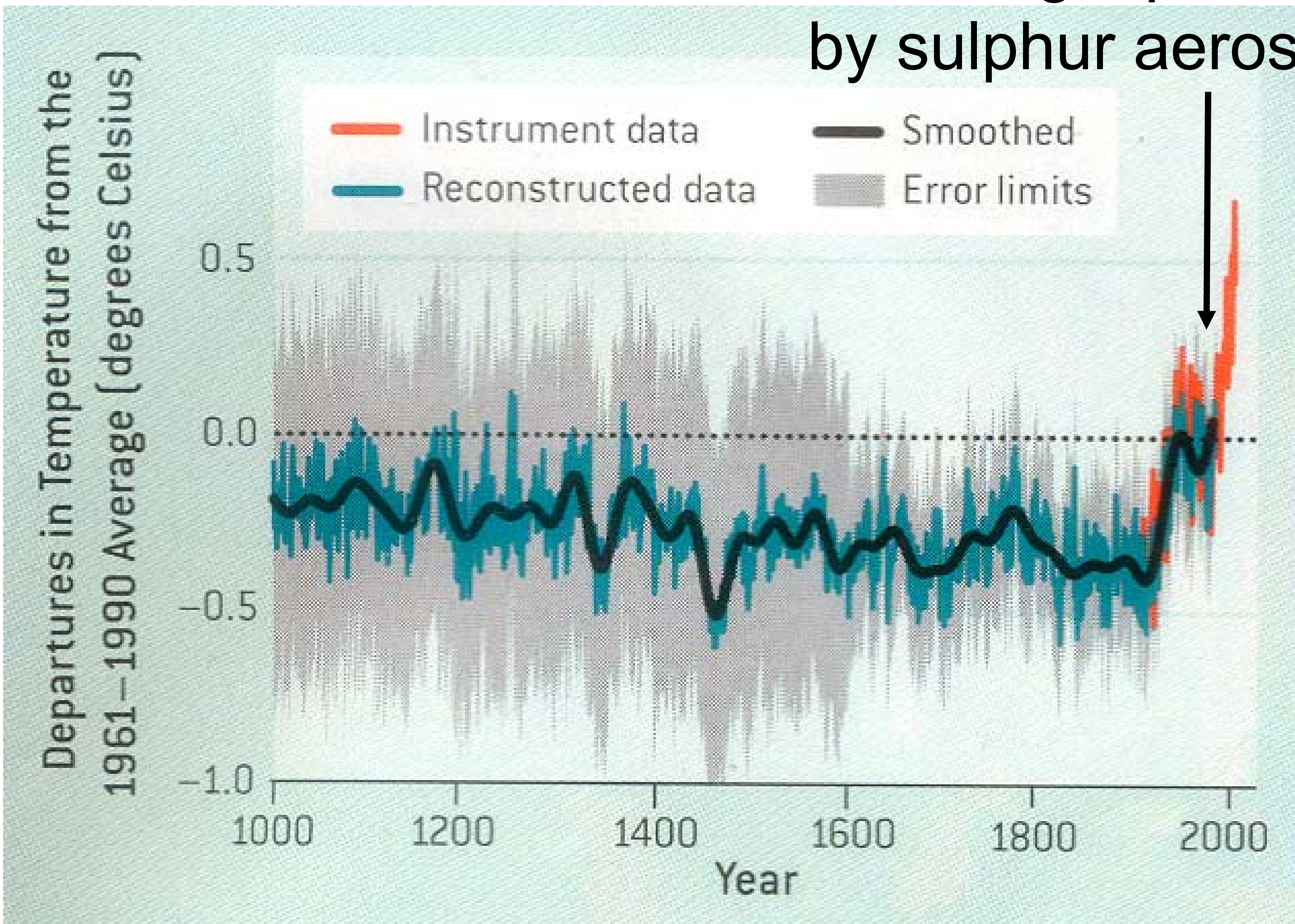
- People worry it will take off the pressure for permanent solution of not burning fossil fuel
  - Administration pointed to possibility of geoengineering and space mirrors just before recent IPCC report
- If used for an extended period, would lead to seriously unstable planet Earth, ever more hooked on carbon

- But if we don’t look at it, we have no insurance

Heating reversible by reducing solar flux

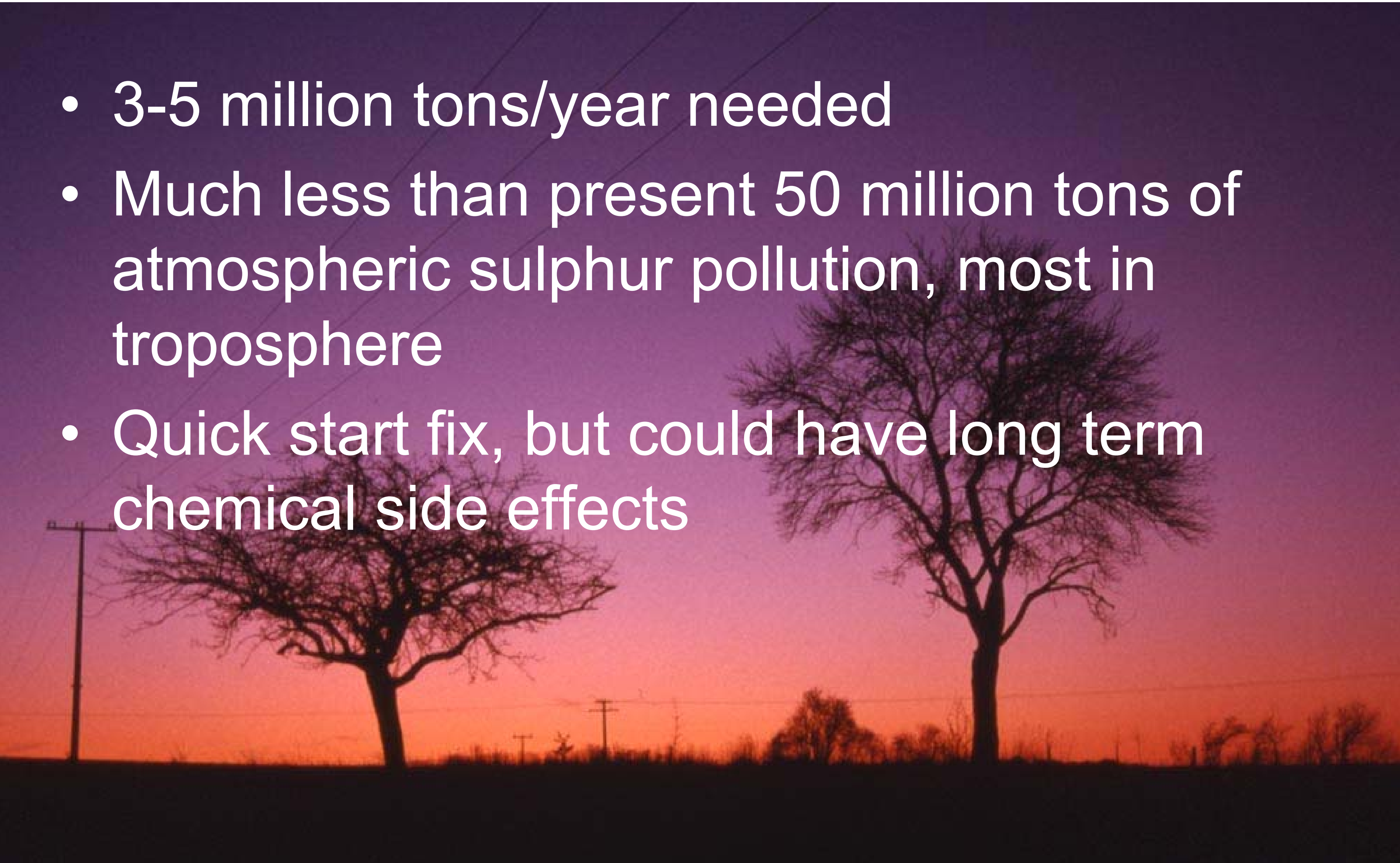
- Govindasamy, B. & Caldeira, K., (2000) Geophys. Res.Let. 27, 2141.
  - 1.8% reduction mitigates doubling of CO_2

Warming dip caused by sulphur aerosol



Increase reflection with sulphur aerosol in stratosphere Crutzen (2006)

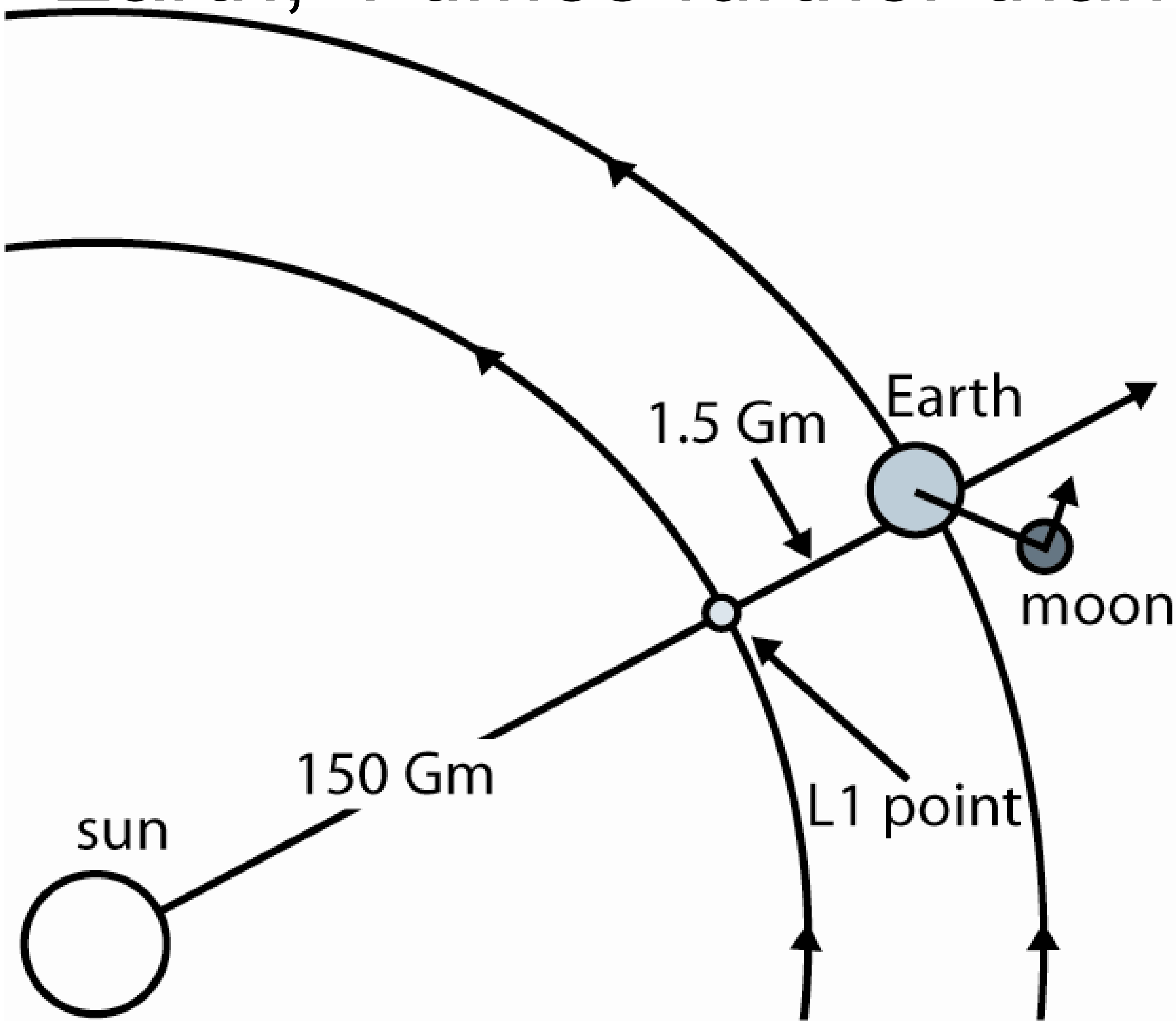
- 3-5 million tons/year needed
- Much less than present 50 million tons of atmospheric sulphur pollution, most in troposphere
- Quick start fix, but could have long term chemical side effects



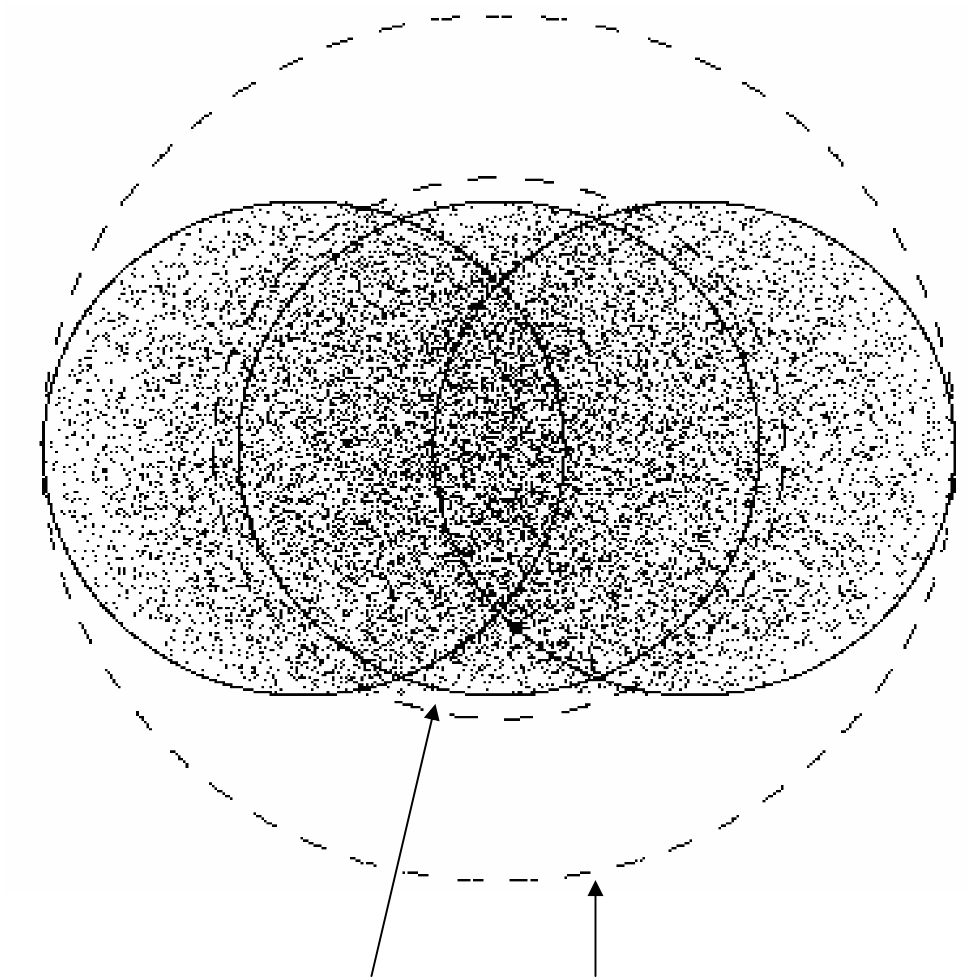
Space sunshade a possible alternative

- Changes only solar flux
- Potentially long life, doesn't need annual renewal
- Proposed by Early 1989:
- *"A thin glass shield built from lunar materials and located near the first Lagrange point of the Earth-sun system could offset the greenhouse effects caused by the CO_2 buildup in the Earth's atmosphere"*

L1 orbit is a million miles from Earth, 4 times further than moon



Penumbra and moon wobble



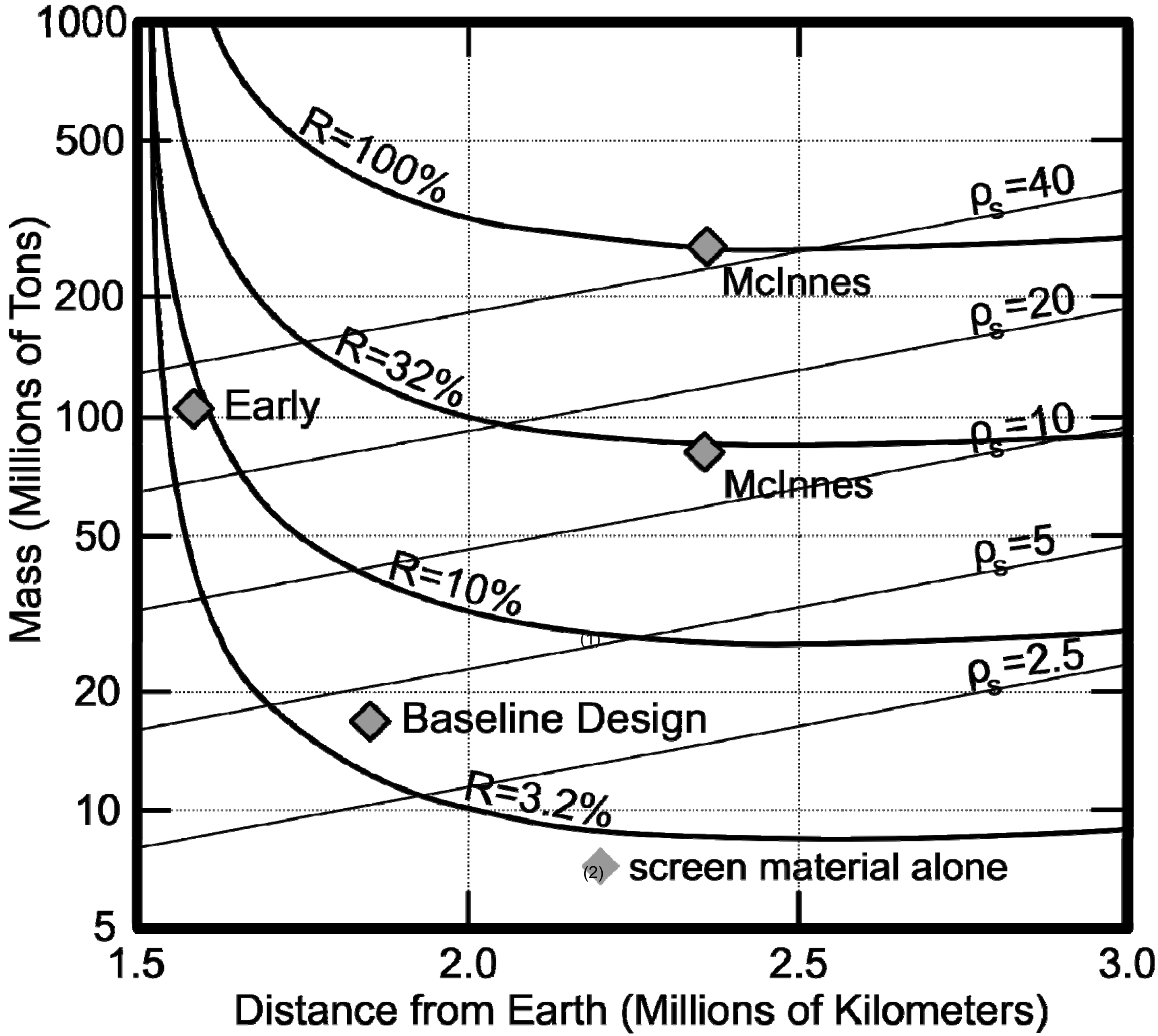
Penumbras from 1.5 and 2.4 Gm

(Earth and sun have same angular size seen from L1 – follows from same density)

Balance point from gravity and radiation pressure depends on effective reflectivity *R*

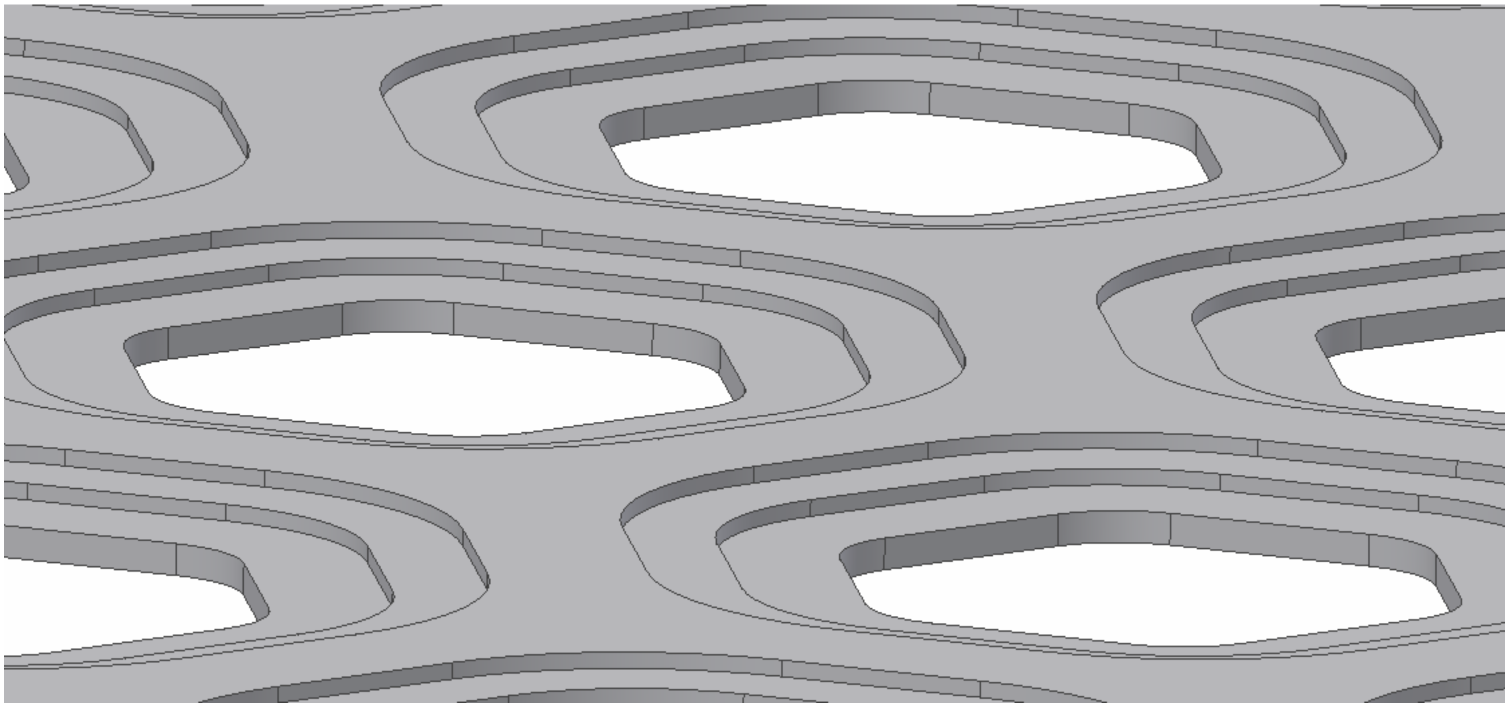
$$r\omega_E^{\ 2} = \frac{GM_s}{r^2} - \frac{GM_E}{(r_E - r)^2} - \frac{L_s}{2\pi r^2 c}\left(\frac{R}{\rho_s}\right)$$

Given any two of r_E-r, *Reflectivity*, ρ_s and $M_{sunshade}$, can solve for other two



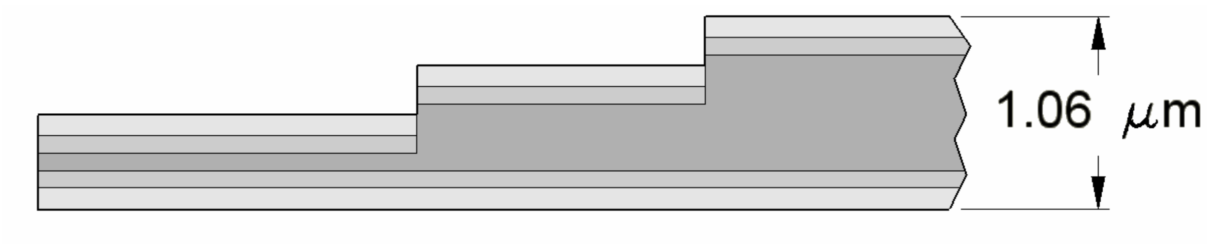
1000
500
200
100
50
20
10
5
Mass (Millions of Tons)
R=100%
R=32%
R=10%
R=3.2%
ρs=40
ρs=20
ρs=10
ρs=5
ρs=2.5
McInnes
McInnes
Early
Baseline Design
(1)
(2)
screen material alone
1.5
2.0
2.5
3.0
Distance from Earth (Millions of Kilometers)

transparent boron nitride screen optimized for lowest density and reflectivity



Holes are on 15 μm centers
maximum thickness 1.06 μm
Transmits 10% for full solar spectrum

Implementation with silicon nitride plus 2-level antireflection coating



R= 2.62%

average areal density ρ_s = 1.4 g/m^2.

adopted as the baseline design

Hexagonal boron nitride better, lower density, cool vapor deposition demonstrated on plastic

1 μm transparent layers

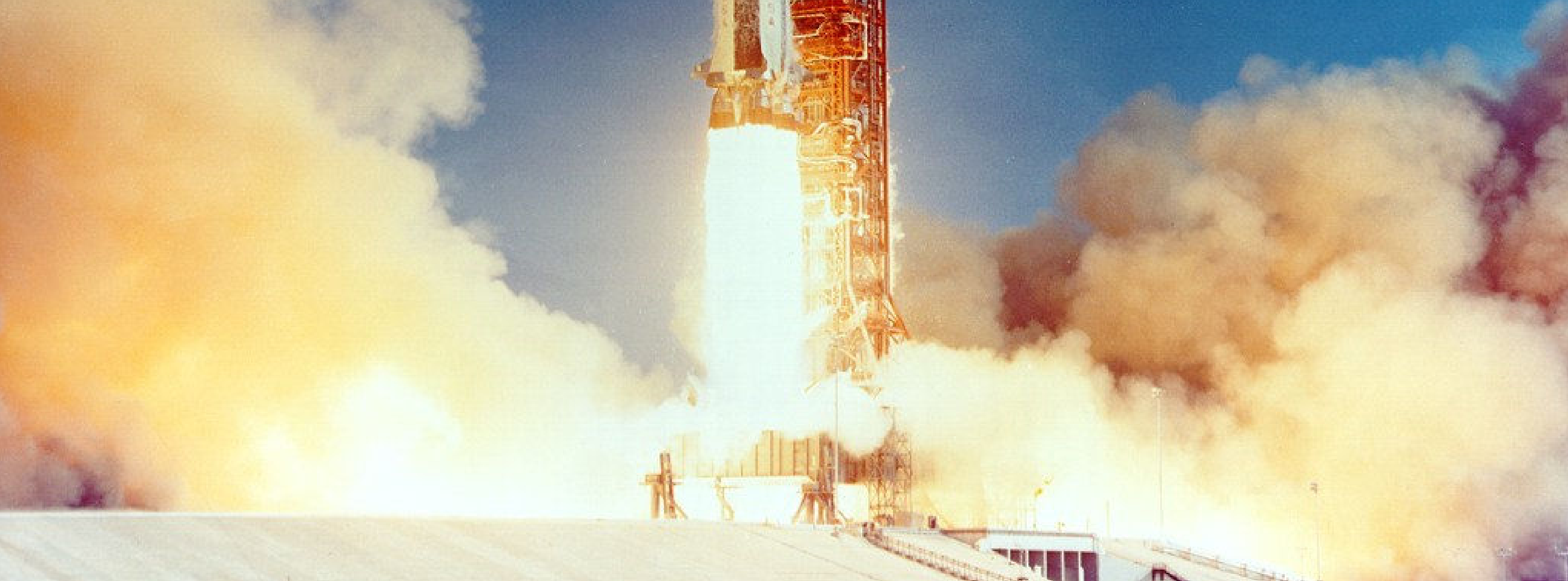
Victor Korolov’s plate

Real sunshade requires structural support, active position control system.

- Take full average areal density 3x higher, 4.2 g/m^2
- Reflectivity has to include radiation pressure sails
  - Up from 2.62 to 4.5±1%
- 1.85 million km out
- Total mass 20 million tons

Launching 20million tons?

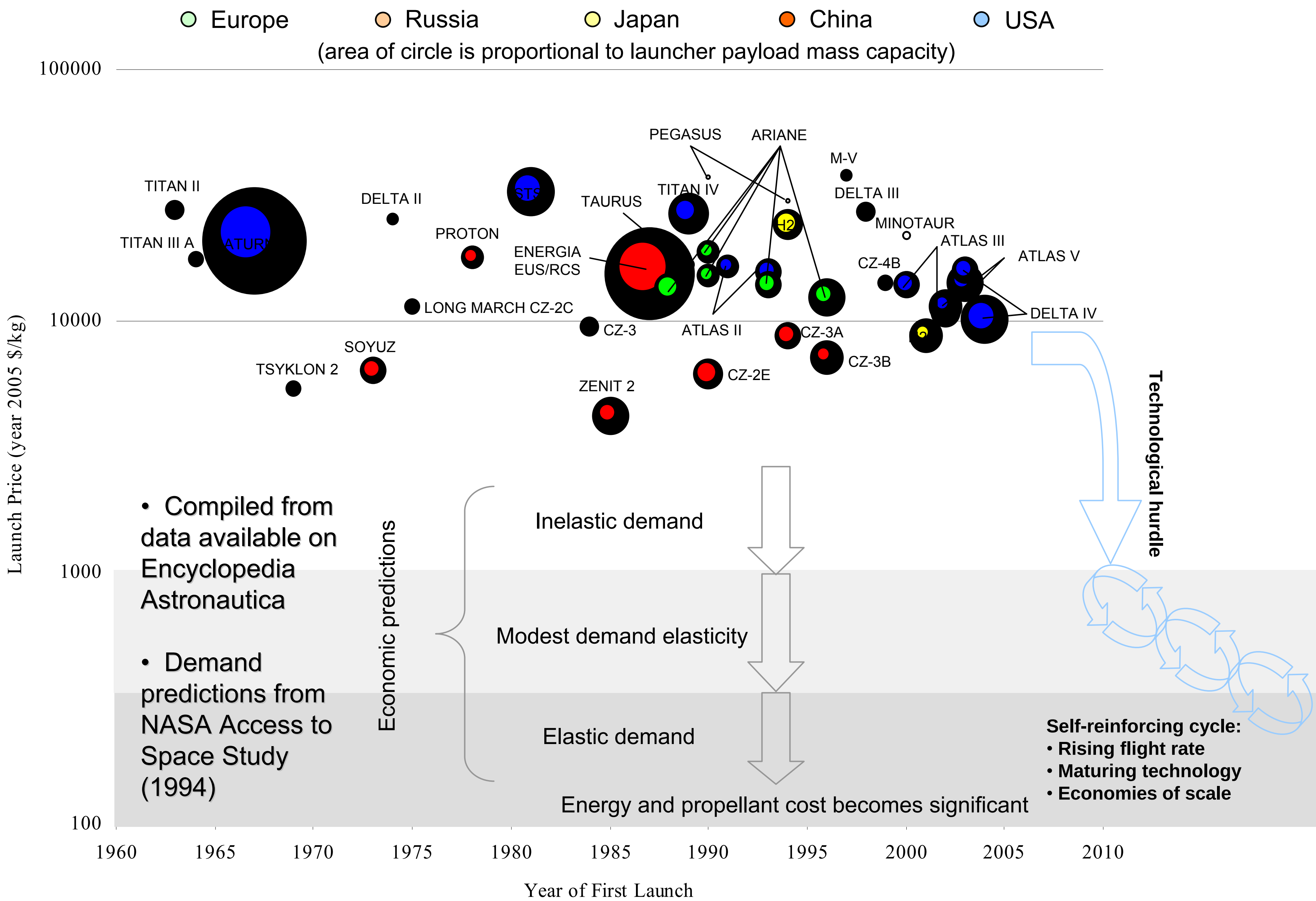
- Each Apollo shot sent 50 tons to the moon
- Would need 400,000 Saturn V launches
- Current cost $20,000 /kg => $400 trillion
- In huge volume might come down to $200/kg
- Total then still $4 trillion



Realistic to launch this much mass?

- Old concept
  - Build space infrastructure
  - Manufacture 100 million tons and transport to L1
  - For 10 year requires mining and processing of 30,000 tons/day
- Needs to be from Earth
- For budget $1 trillion, need $50/kg on-orbit
- Present rocket launch cost $20,000/kg
  - Fuel cost $100/kg floor $500/kg?
- Promising solution is electromagnetic launch to escape velocity, plus ion propulsion
  - Avoids rockets completely

THE LAUNCH PROBLEM, 1960 - 2005



ECONOMICS AND LOGISTICS (Parkin)

- Present space launch market is in metastable ***high cost, low demand*** regime - $10,000/kg of payload
- The solar sunshade represents a ***low cost, high demand*** need ~ $100/kg of payload or better

Example:

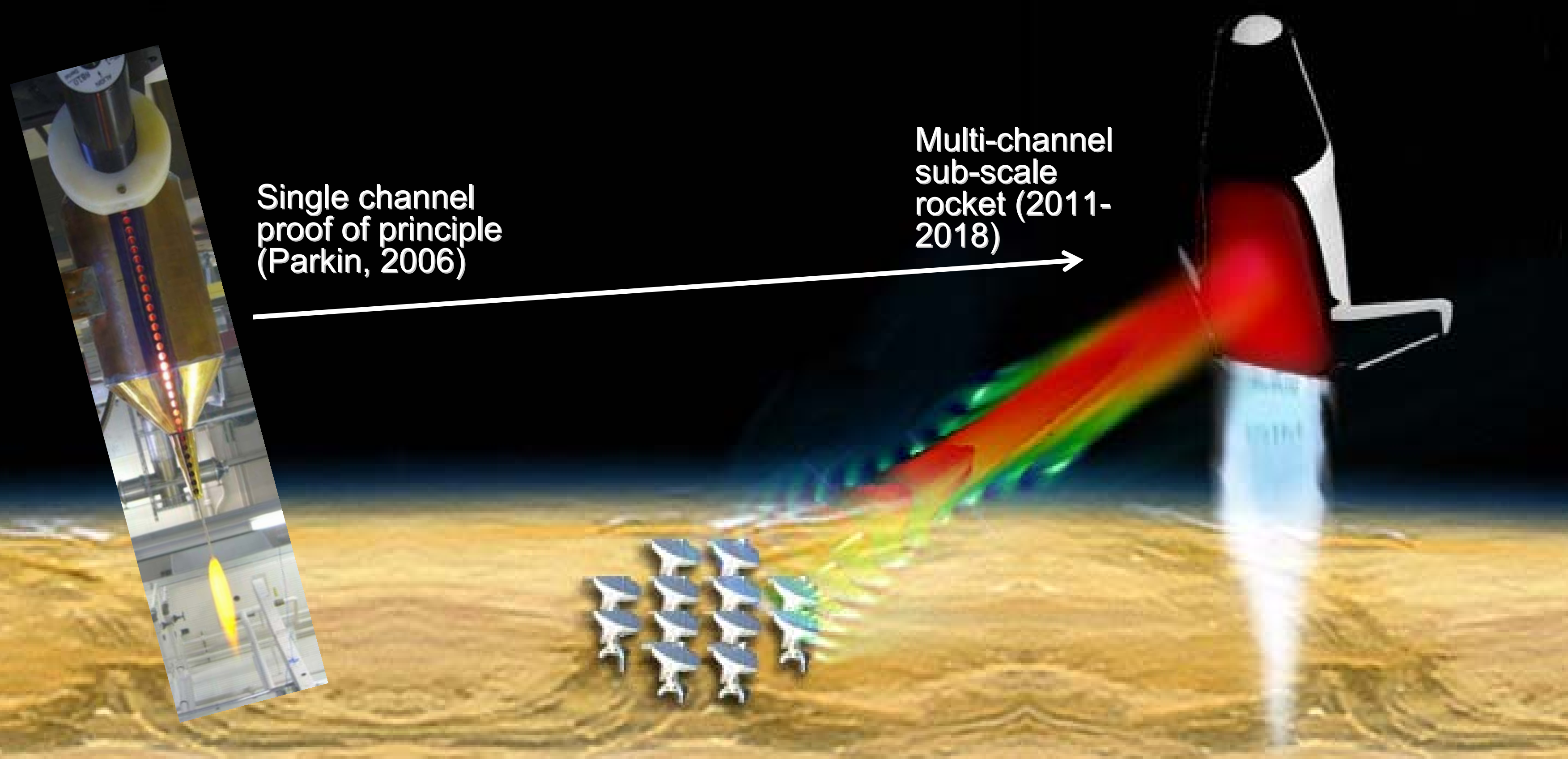
A sunshade mass of 20M tons launched over 20 years requires:

- 1 Mton/yr launch capacity = a 100 kg payload launch every 3 seconds
- Total launch cost is $100B/yr @ $100/kg = 0.2% of gross world product (GWP)

- At a payload fraction of <5%, conventional expendable waste an enormous quantity of engineered materials – need reusability or v. high payload fraction
- The reusability of conventional rockets is impeded by the v. low payload fraction – cheap reusability requires high structural margins
- Promising new options are:
    - Reusable microwave thermal rockets
    - Coil guns

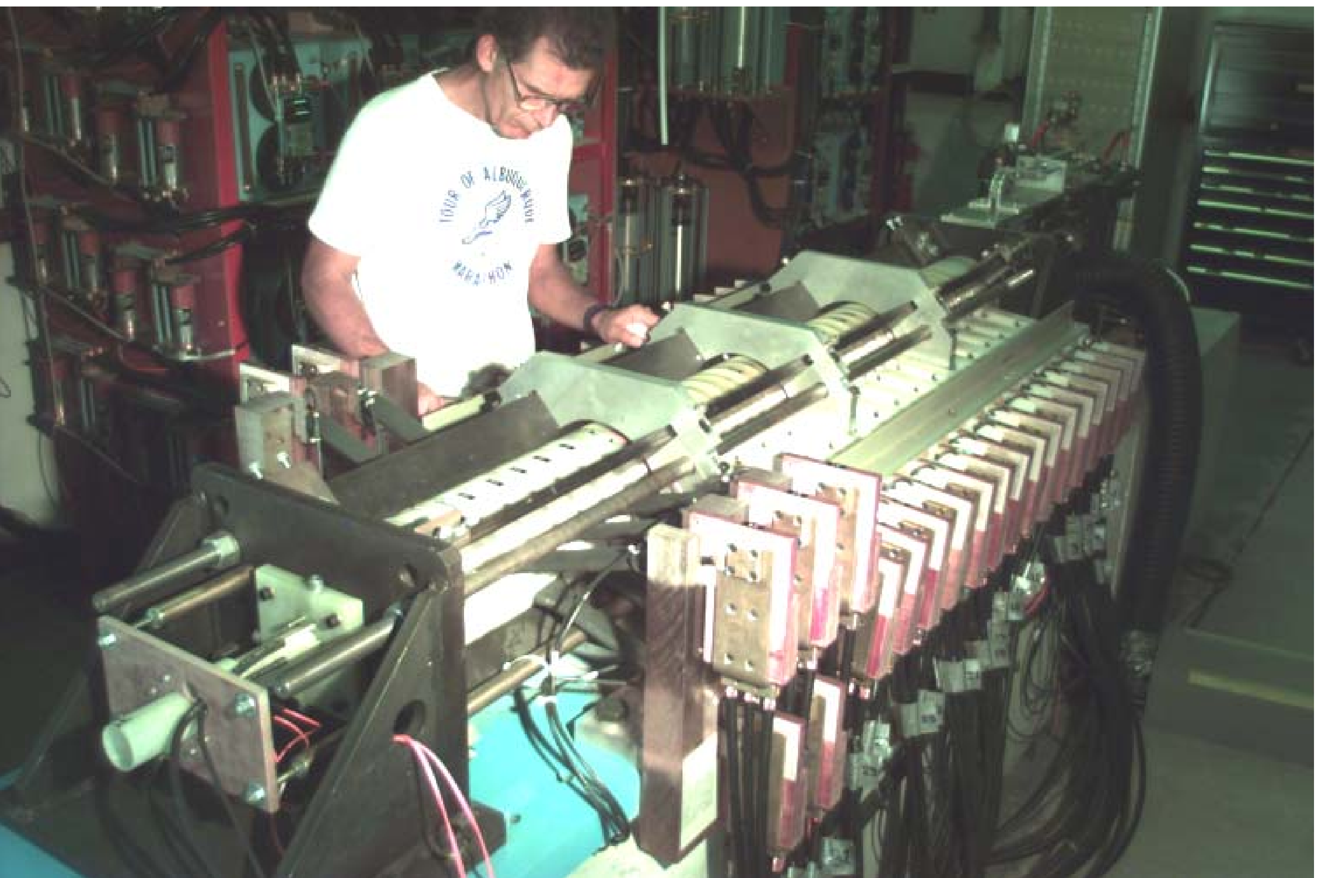
THE MICROWAVE THERMAL ROCKET

- Adaptation of nuclear thermal propulsion (heat exchangers) to use ground-based microwave source
- Single non-cryogenic propellant (e.g. methane) simplifies the rocket considerably
- Estimated 10-20% payload fraction as opposed to < 5% for conventional launch
- Estimated payload cost of mature reusable system is $100-500/kg
- Payload size for early systems will be ~ 100 kg



Electromagnetic launch has even lower cost potential

- Fuel is electricity
- Electric energy required is 10x launch energy
- At 5¢/kWh this is \$10/kg



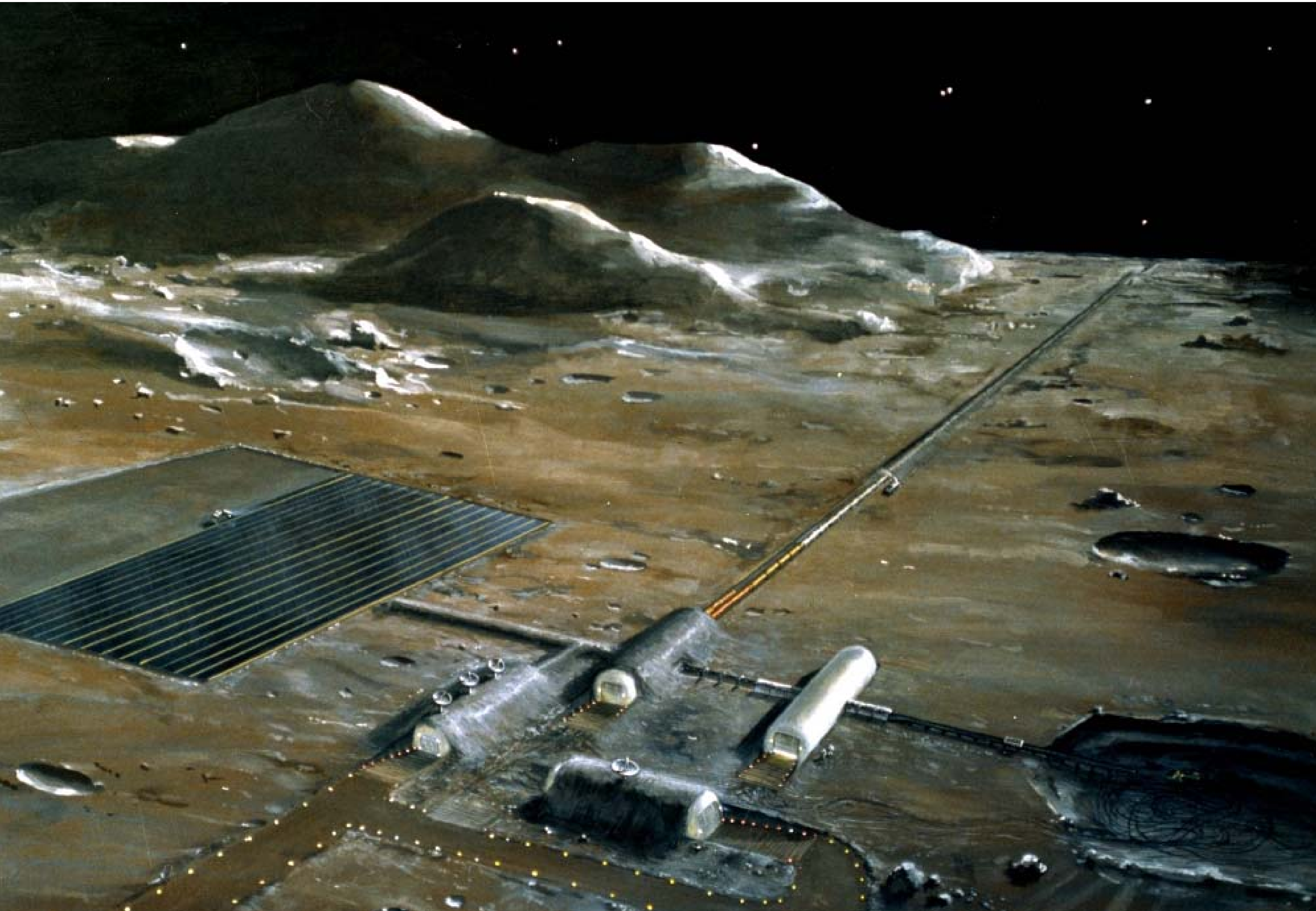
Small scale Prototype launcher at Sandia National Lab

launch pressure over 2 inch diameter higher than Saturn V engine!

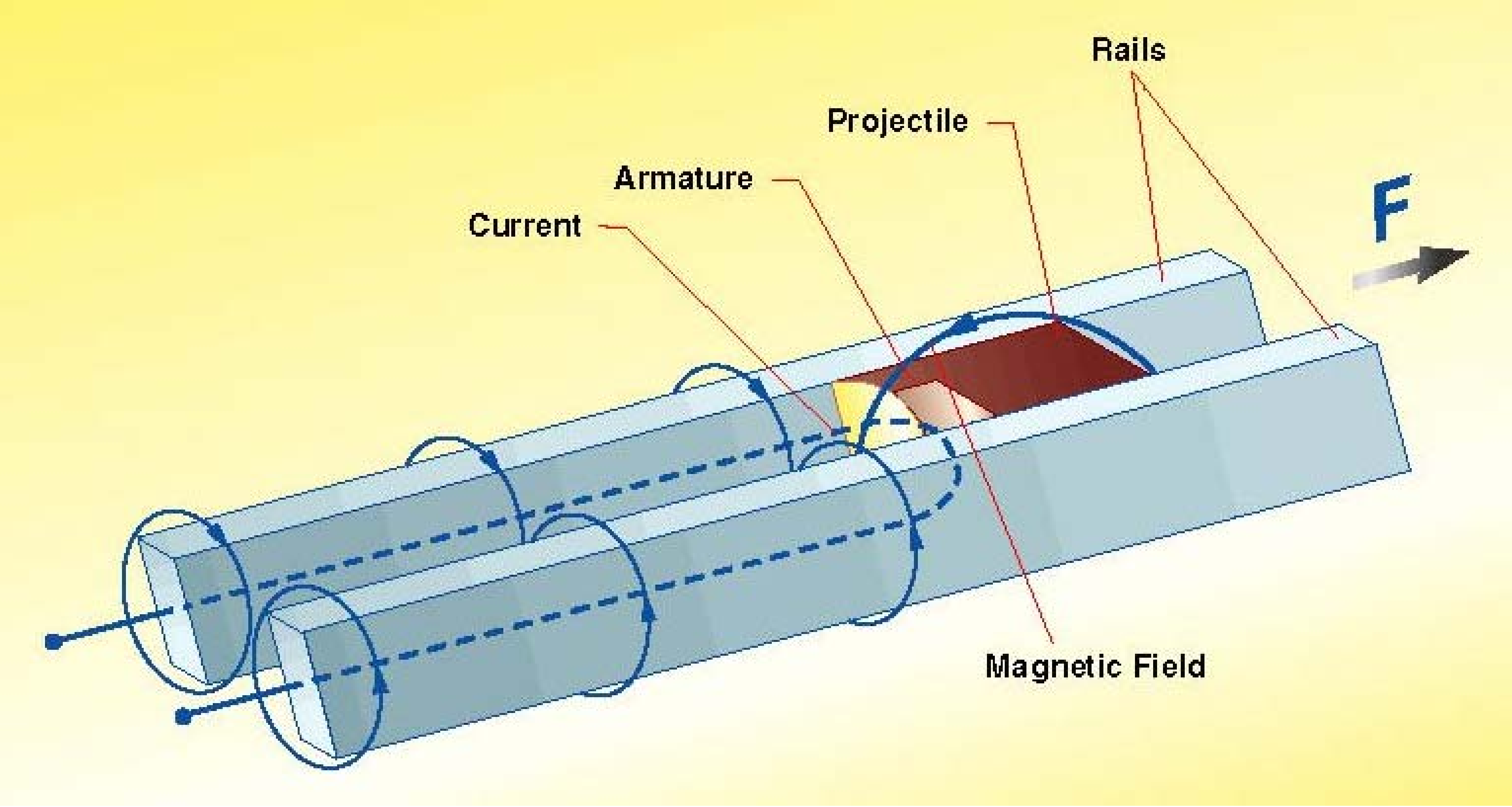
Cost floor for magnetic launch

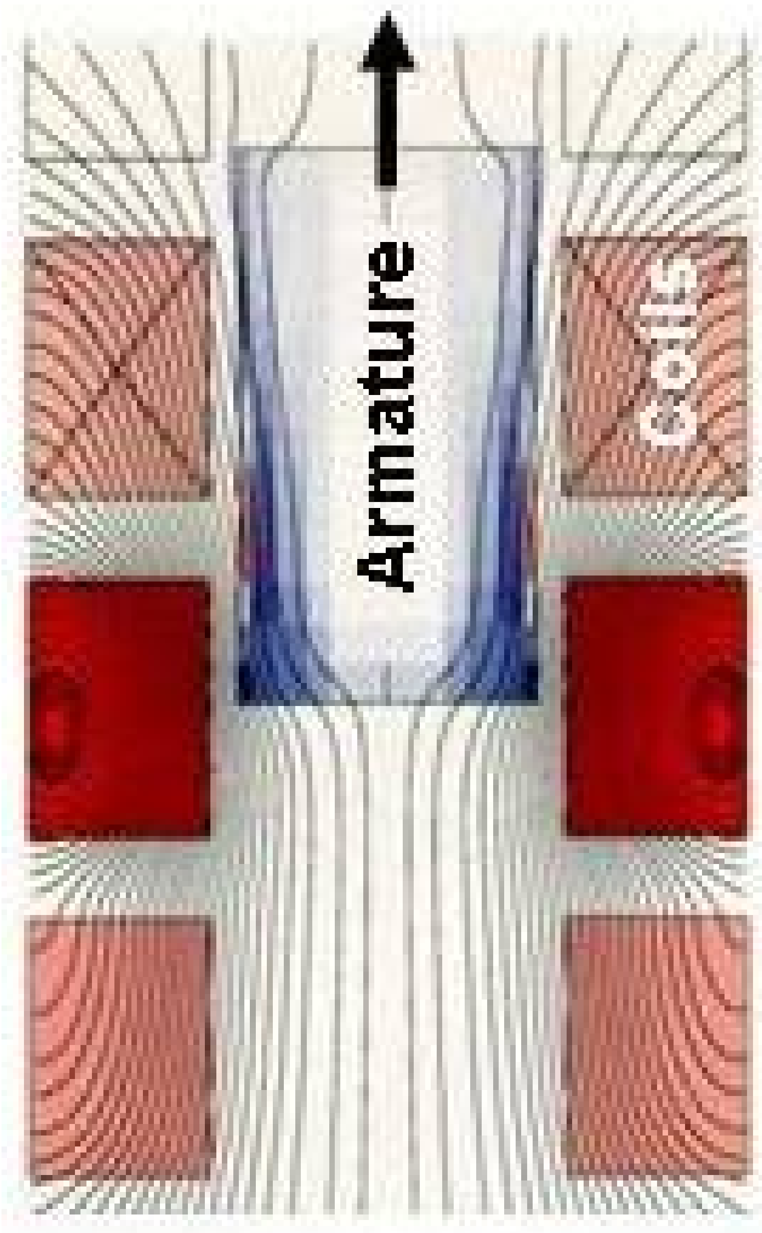
- Fuel is electricity
- Electric energy required is ~ 10x final payload KE
- At 5.3¢/kWh this is $9/kg

- Auto and air transportation
- Mature and in huge volume
- Come in at few times fuel cost



Rail guns (and gas guns) are simple but suffer from problems of low throughput and hypervelocity erosion





Magnetic launch principle

coils switched in sequence

field acts on current induced in armature

Coil gun is high throughput, *non-contact* solution for high volume space launch

- Coil gun can be visualized as sequence of solenoid stages
- As projectile velocity increases, discharge time of electromagnet stage decreases
- Muzzle velocity of 12 km/sec requires pulsed power sources – solid state and pulse compression techniques offer the desired sub-microsecond pulse control
- Effect of atmospheric transit on ablative nosecones is understood, and projectiles may be launched through the atmosphere at greater than 14 km/sec, if needed
- Coil gun design codes (such as Sandia Slingshot code) now exist and can be used to design working coil gun

Aerodynamic drag

- Loss of momentum is equivalent to picking up stationary mass equal to air column mass x drag coefficient
- For 18,000’ (half seal level pressure) and drag coefficient, effective mass is 500 kg/m^2
- Set target $\Delta v/v$ = 1/8
- Vehicle mass density must be ~ 4 tons/m^2
- Escape velocity = 11.2 km/sec
- Launch velocity must be 12.8 km/sec (1/8 higher)

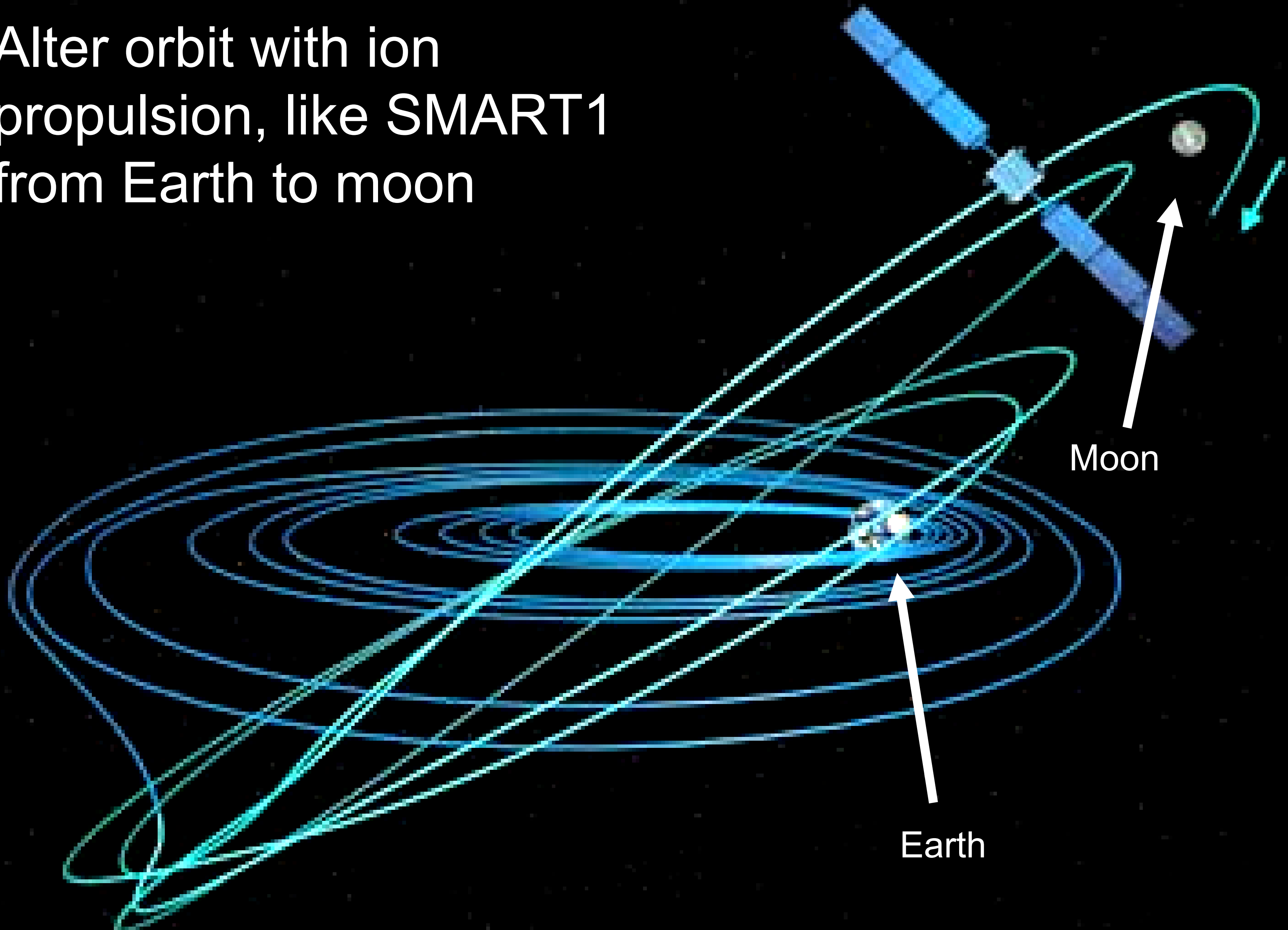
Launcher issues

- Heating of armature by eddy current
  - Field penetration during launch sets current density
- Energy storage cost
- Very high voltage
  - For top end coils, rise time = 1m/13 km/sec = 70 μsec
  - $E=d\Phi/dt$ = 30T x 1m^2 / 7e^{-5} = 430 kV/turn
- High acceleration, 4000g
  - 0 to 29,000 mph in 0.3 sec

Scenario for rocket-free delivery – Magnetic induction launch to escape velocity + ion engine to L1

- Launch vehicle consists mainly of aluminum armature and glass shield material
- Vertical launch and acute conical aeroshell to minimize ablation
  - Equatorial launch not required, launch any time
- Launch directly out of Earth's potential well to ~ 1.5 M km
  - Few months travel time
- Ion engines then used to get trajectory to L1
  - $\Delta v \leq 2$ km/sec
  - Force of 0.1 N/ton over 100 days
  - Proven technology (Smart 1 to moon)

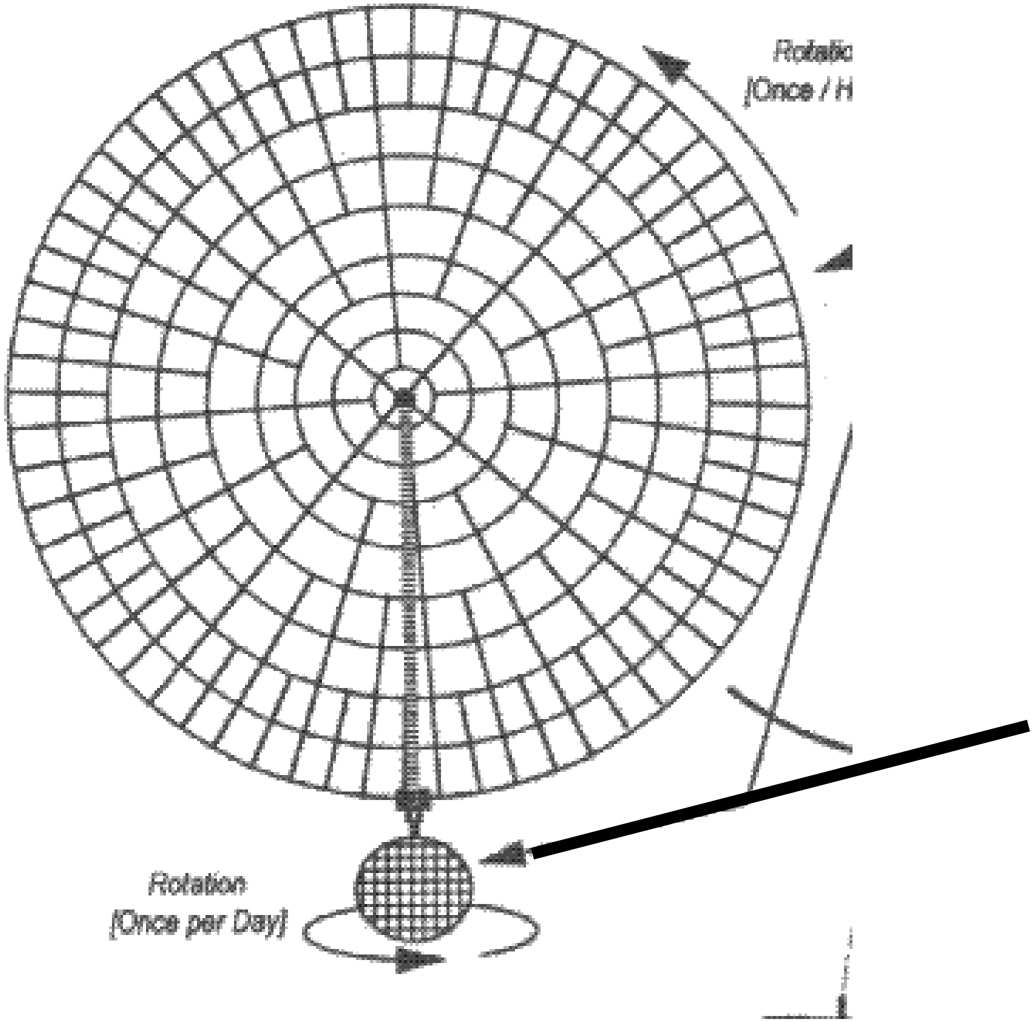
Alter orbit with ion propulsion, like SMART1 from Earth to moon



Why low-cost launch might get developed by the private sector

Space solar energy

- annual sales of electricity in 2050 projected to be $2 trillion worldwide
- Space solar could provide maybe ¼ of this, complementing ground solar, hydro and wind and last of coal



Single 30 km^2 5 GW geosynchronous power satellite

"bicycle fork" configuration

Collector 6 km diameter

photovoltaics generate10 GW

power transmitted as microwaves by 1 km phased array

5 GW power for distribution on earth

View from 40000 km above 0°N 35°W

View from solar power station in geostationary orbit 24,000 miles above Atlantic

- transmit solar power down via microwaves

600 x 30 km^2 spacecraft yield 3000 power stations

continuous 24 hours

NASA/NRC 2000 cost study

- Six 5 GW satellites over 30 years
- 1 ground receiver per satellite
- Lifetime = 40 years
- 25% mass refurbished every 20 years

- Costs
  - Launch cost $400/kg
  - Commercial cost-to-first-power - $30-40B
  - Constellation Installation Cost - $150B (-$5/W)
  - Average power cost – 2 cents/kW-hr

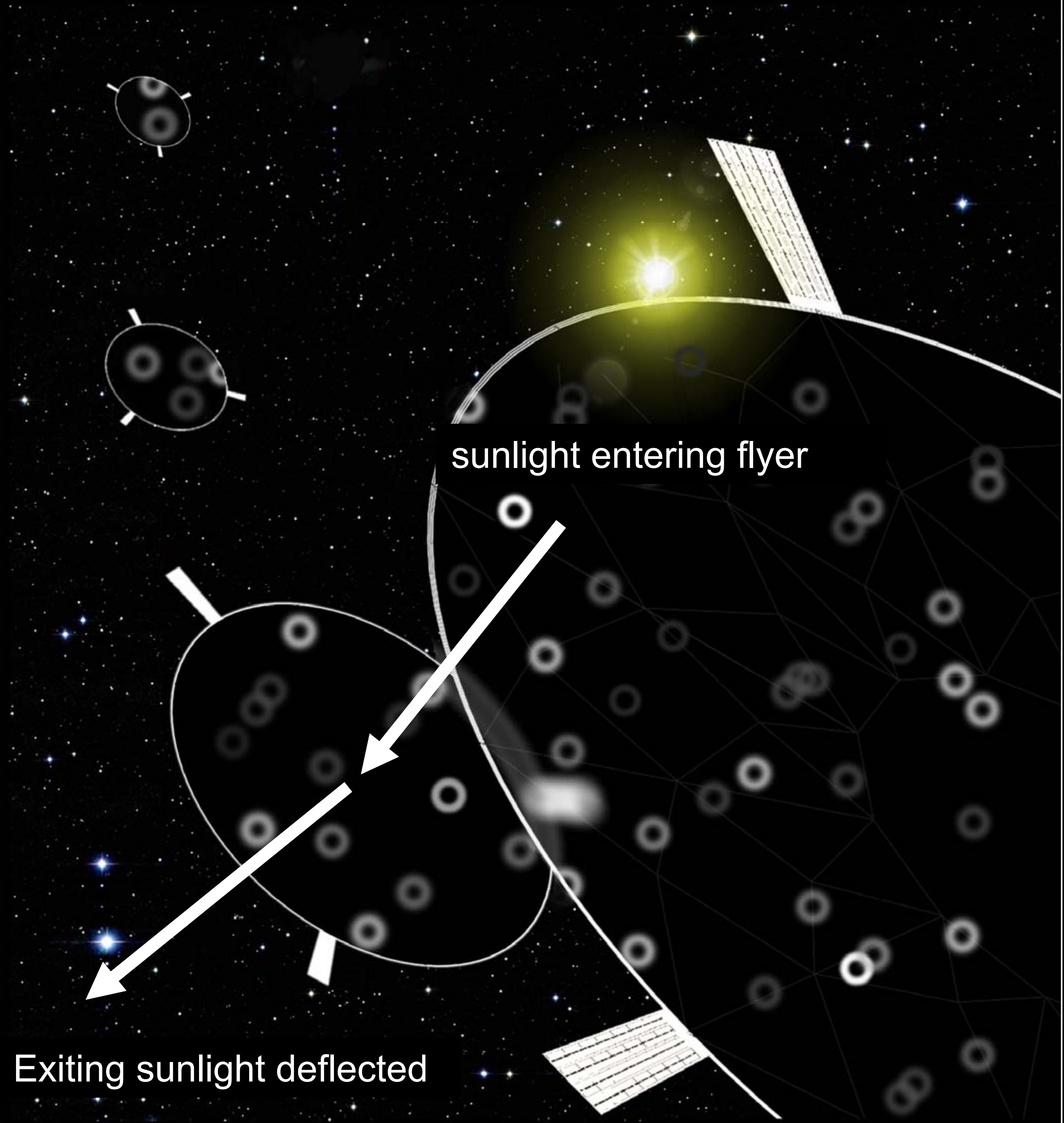
- Challenges
  - Launch cost
  - In-space construction

Sunshade design

How to assemble?

- Don’t assemble at all, difficult in space
- Leave as a bunch of free flyers

- What size flyer?
- NIAC proposal was for kilometer size assembled in space and flown in close formation
- Better ~ 1 m^2, then the flyers can be fully assembled and stacked for launch
- Make it big, so flyers can be randomly positioned and not shadow each other much
- But not so big that the the shadows form the cloud edges miss the Earth

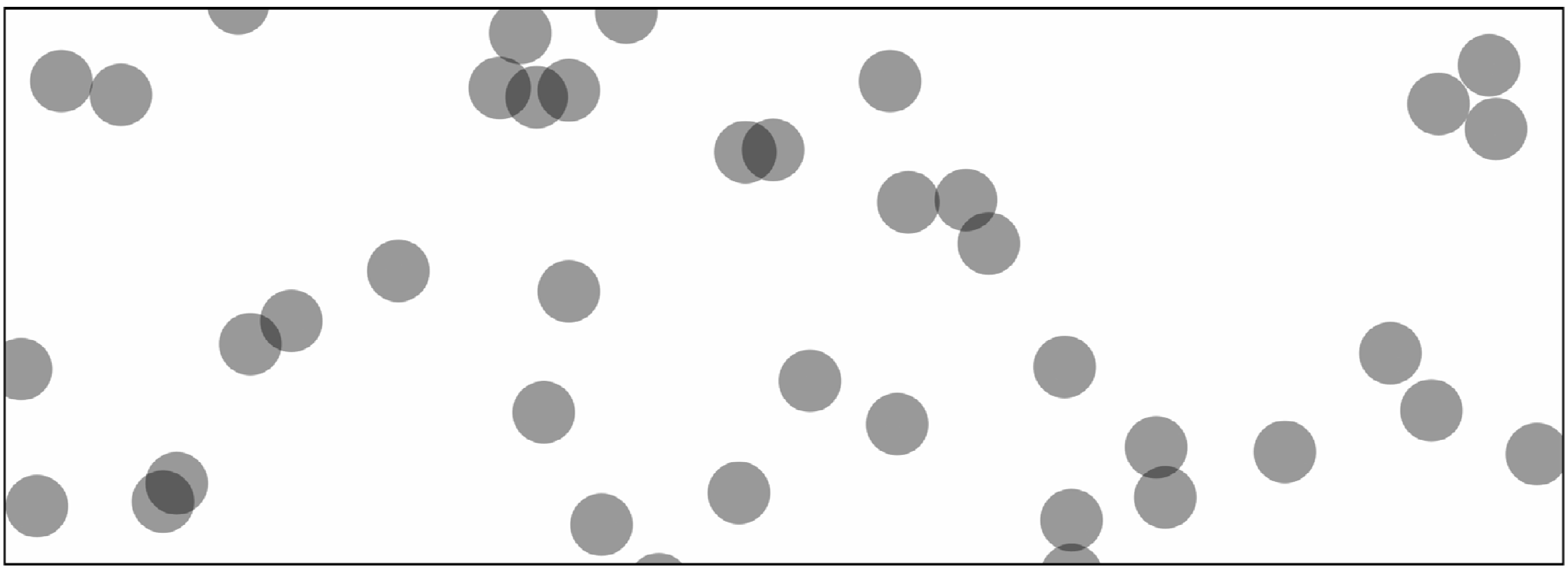


flyer cloud seen from the side

sunlight deflected to miss Earth

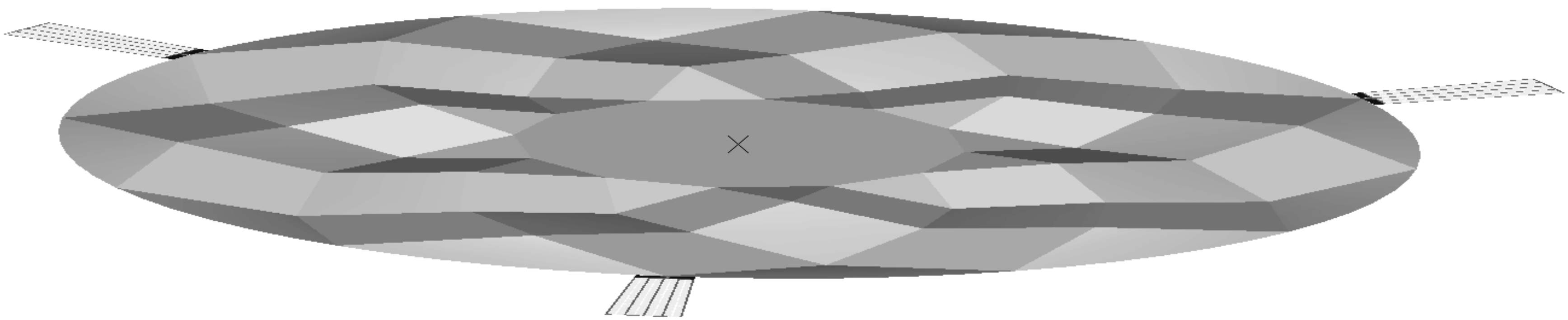
starlight passing through flyers is also deflected, into donut rings

cloud against sun, tiny detail



6% self-shadowing and 6% efficiency loss from being spread-out

Flyer design



- Screen 0.6 m diameter
- Ears stick out 0.1 m
  - Mems mirrors for radiation pressure control
  - Small cameras, solar cells and computers
- Thickness 5 μm screen, 100 μm ears
- Mass 1.2 g each, 16 trillion required
- Launched in stacks of 800,000 weighing 1 ton, 4 m high
- Each vehicle has its own destacker robot

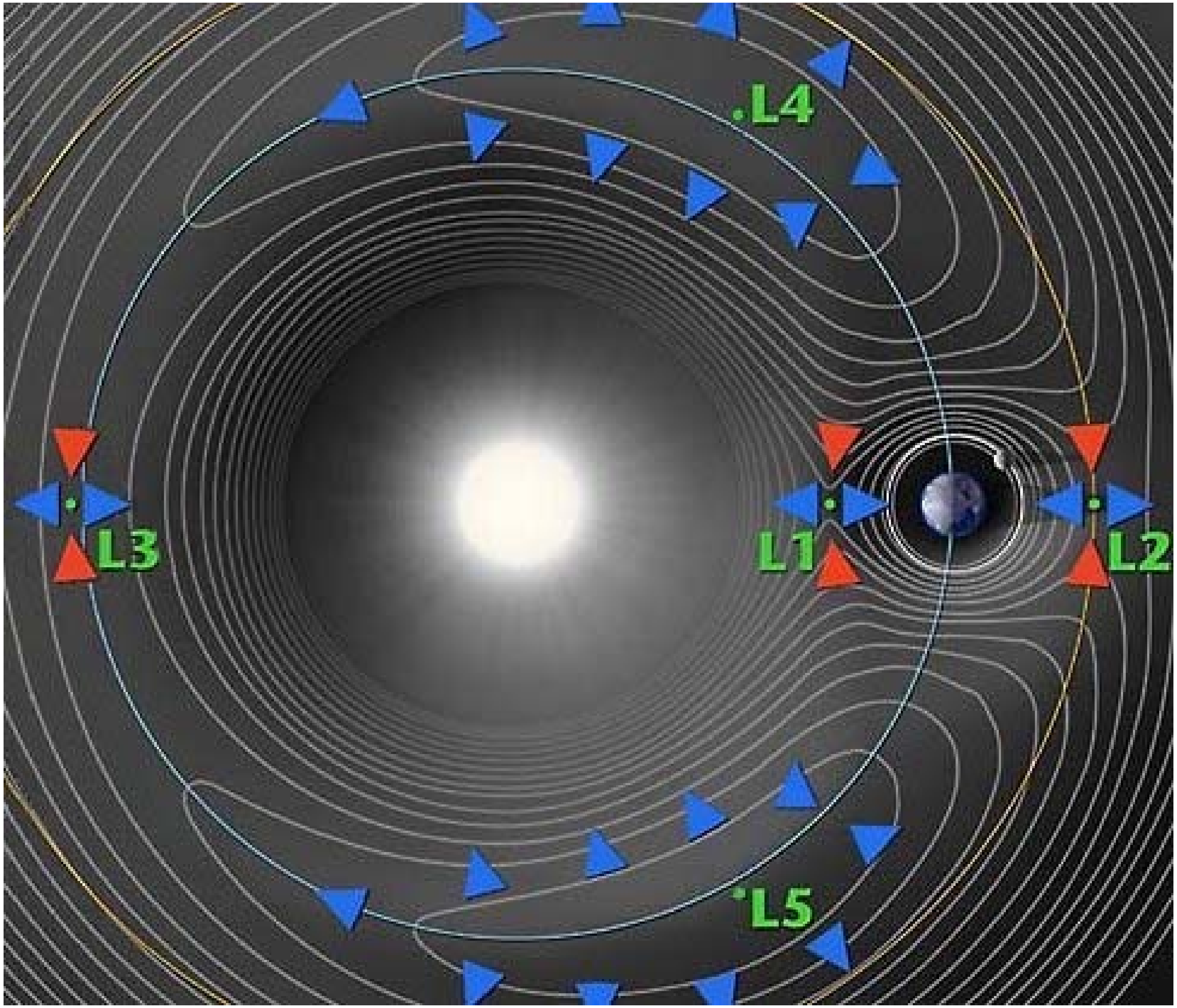
Formation Flight Strategy- Miller (1)

- Through solar sailing, maintain separation between thousands of membrane structures at the unstable Earth-Sun L1 point (ESL1).
  - Understand ESL1 orbital dynamics
  - Develop trajectories in vicinity of ESL1 to avoid collision and occultation
  - Address stability of ESL1
  - Derive strategy for controlling perturbations

Formation Flight Strategy (2)

- Ensure that failed vehicles do not impact the Earth orbit environment.
  - This includes intentional disposal of aging vehicles as well as a fail-safe mode for failed and uncontrollable vehicles.
- Requirements
  - Several million membranes distributed across several 1,000 kilometers dia. X 100,000 km long
  - Baseline Design:
    - Diameter of 1m and mass of ~1 gram
  - Solar flux reduction by a fraction of 0.018

ESL1 Orbital Environment



ESL1 Orbital Environment

- Three body problem reveals that ESL1 is:
  - Stable in orbital velocity direction
  - Stable normal to the orbital plane
  - Unstable along Earth-Sun line.
  - Time constant of unstable direction is roughly 22 days (e-folding)
- Orbit location on Sun side of ESL1 to balance solar pressure and gravitational acceleration

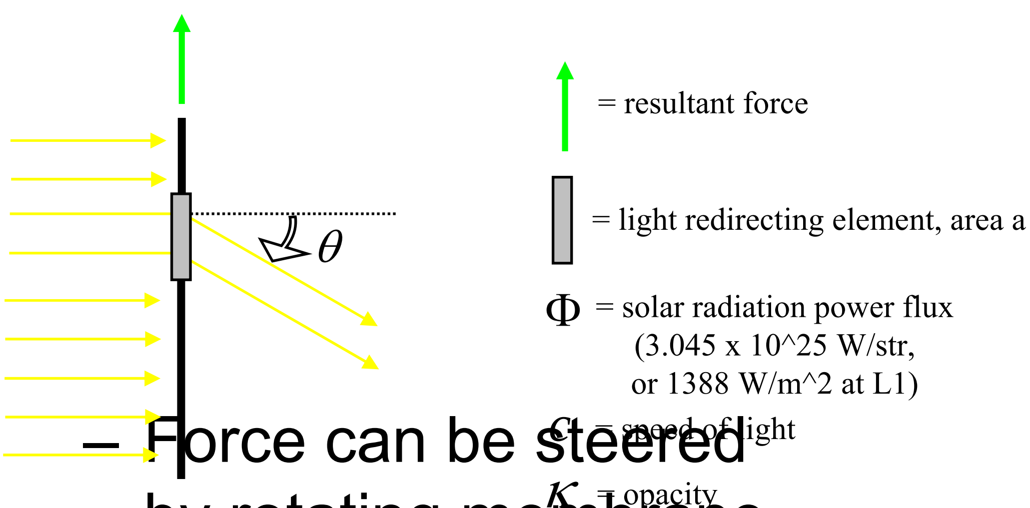
Maintaining Formation Geometry

- **Several possibilities exist for keeping membranes separated across several 1000 km without need for propellant**
  – Random initial velocity vector
  – Halo trajectories around L1
  – Offsets in Earth-Sun direction
- **Random initial velocity vector**
  – Timing, direction, and magnitude chosen to minimize collisions

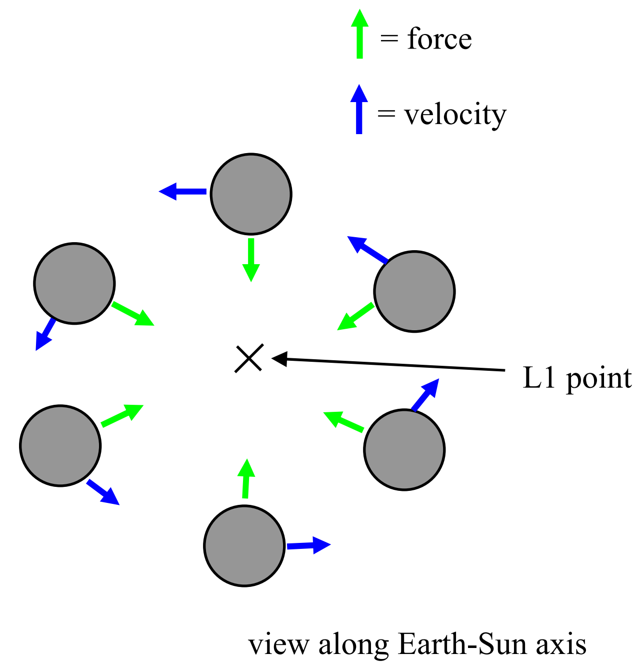
- **Halo trajectories around L1**
  - Membranes follow circular trajectories around the Earth-Sun line and perpendicular to it (like SOHO)
- **Offsets in Earth-Sun direction**
  - Use different sized (or opacity) membranes establishing pressure-acceleration balances at different ESL1 offset distances, causing the membranes to orbit in a Halo trajectory in front of L1

Perturbation Control

- Since membrane induces change in photon propagation direction
  - A transverse force is created
  - Force can be steered by rotating membrane



- Changing opacity alters force in Earth-Sun direction
  - Use electro-chromics to change opacity

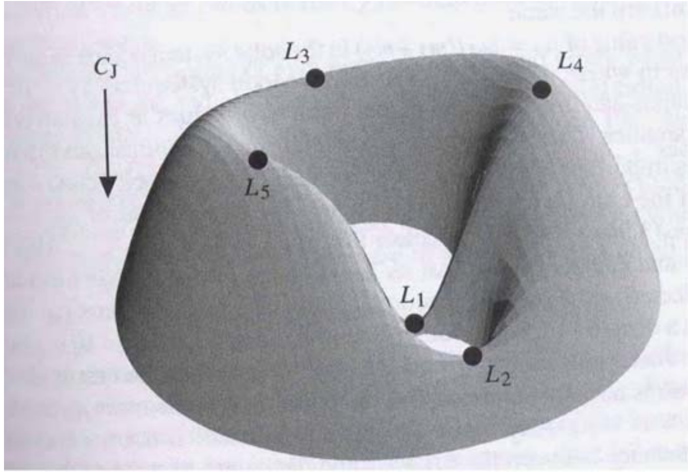


Sensing

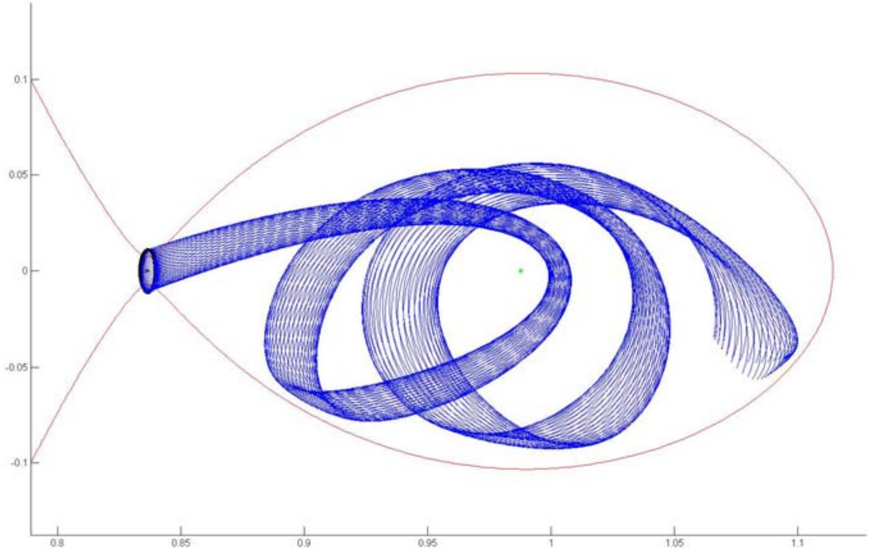
- Need to sense position of each element
- Distributed GPS
  - GPS sensors on each element
  - L1 GPS system needed
- Optical
  - each element has several reflectors
  - camera located at L1 images elements
  - 3 images are needed to calculate position
  - several cameras will likely be needed
- Relative
  - each element has only a short-range relative sensor (radio based)
  - separation is the responsibility of each vehicle

Membrane Disposal (1)

- Membranes will fail due to
  - Aging and wear-out of electronics
  - Collision with another membrane
  - Can result in thousands per year
- Need to ensure that failed membranes do not damage Earth-orbiting satellites
  - GEO is of particular concern



Source: *Solar System Dynamics*, C.D. Murray and S.F. Dermott, CUP 1999



Perturbed orbit closest passages to Earth: 110 000km

Acknowledgement: J.D. Mireles James

Membrane Disposal (2)

- If fails on Sun side of ESL1
  - Likely that solar pressure is reduced
  - Membrane stays in solar orbit within C2 contour in figure
- If fails on Earth side of ESL1
  - Membrane needs 17.1m/s ΔV perturbation to reach GEO
  - Will eventually be kicked out of Earth orbit for single small perturbation pushing it toward Earth

FF Summary (1)

- Formation geometry can be maintained with no propellant
  - Only deployment may require some modest propellant
- All degrees-of-freedom are controllable using photon pressure
  - Unstable orbital dynamics are stabilizable
  - Collision and occultation can be avoided

FF Summary (2)

- Membrane disposal is fail-safe by either being
  - Trapped in Sun’s gravitational well
  - Trapped in high altitude Earth orbit and eventually ejected

- Formation control is feasible

Sunshade discussion

- Lifetime
  - GEO communications 20 yr (cosmic ray damage to solar cells)
  - Estimate 50 yr for flyers
- Sunshade debris a problem?
  - Needs to be less than natural background
    - 1 million 1-g hits (flyer size)
    - 100 1-ton hits (armature-size)
- Launch environmental impact
  - Worst case, coal generated electricity
    - 1 kg sunshade on orbit uses 30 kg of carbon for electric launch
    - But each 1 kg mitigates 30 tons of atmospheric carbon
  - Rocket launch would have similar carbon impact, but cost more because kerosene costs more than coal.

Sunshade Cost

- Energy storage cost
  - Needs to be ≤ 2¢/J with 10^6 shot lifetime to equal power cost
  - Possible with capacitors like at NIF (currently 7¢/J for 0.3 GJ
  - Flywheels (3 GJ at JET torus)
  - Batteries with 0.3 sec discharge?
- Single launcher cost
  - Storage 640 GJ @ 2¢/J = $13 billion
  - 2 km launch structure $10 billion (450 m Sears tower $0.15 billion, 1973)
  - Estimate for 1 launcher = $30 billion
- Total cost for deployment in 10 years
  - 20 launchers, total transportation $1T
  - Flyers @ $50/kg $1T (laptops $100/kg)
  - Total ~ $5T
- Cost amortized over 50 year lifetime = $100 billion/yr

Sunshade conclusion

- space sunshade only valuable if dangerous abrupt climate change found to be imminent or in progress.
- short term fix, makes no sense as a way to counter more use of fossil fuel
  - The same massive level of technology innovation applied to renewable energy would yield better and permanent solutions.

Advances under NIAC Phase A

- Paper in PNAS
  - Angel
- Prototype screen optics
  - Peng, Korolov
- Low cost launch concept development
  - Parkin, Angel
- Magnetic launch model
  - Stock, Angel
- On-orbit configuration and control
  - Miller Angel

Where next?

- NIAC Phase B?
- TV scientist reality show? ($150K)
- NASA?
  - Email last month from Mike Griffin, NASA administrator:
  - "Roger- Thanks. I do not foresee this being something we will be sponsoring at NASA. Mike -----"
- Space solar as route to cheap launch
- Which space megaproject would you rather have NASA be working on?
  - Men to Mars
  - Space solar energy
  - Space sunshade