Advanced Solar- and Laser-pushed Lightsail Concepts

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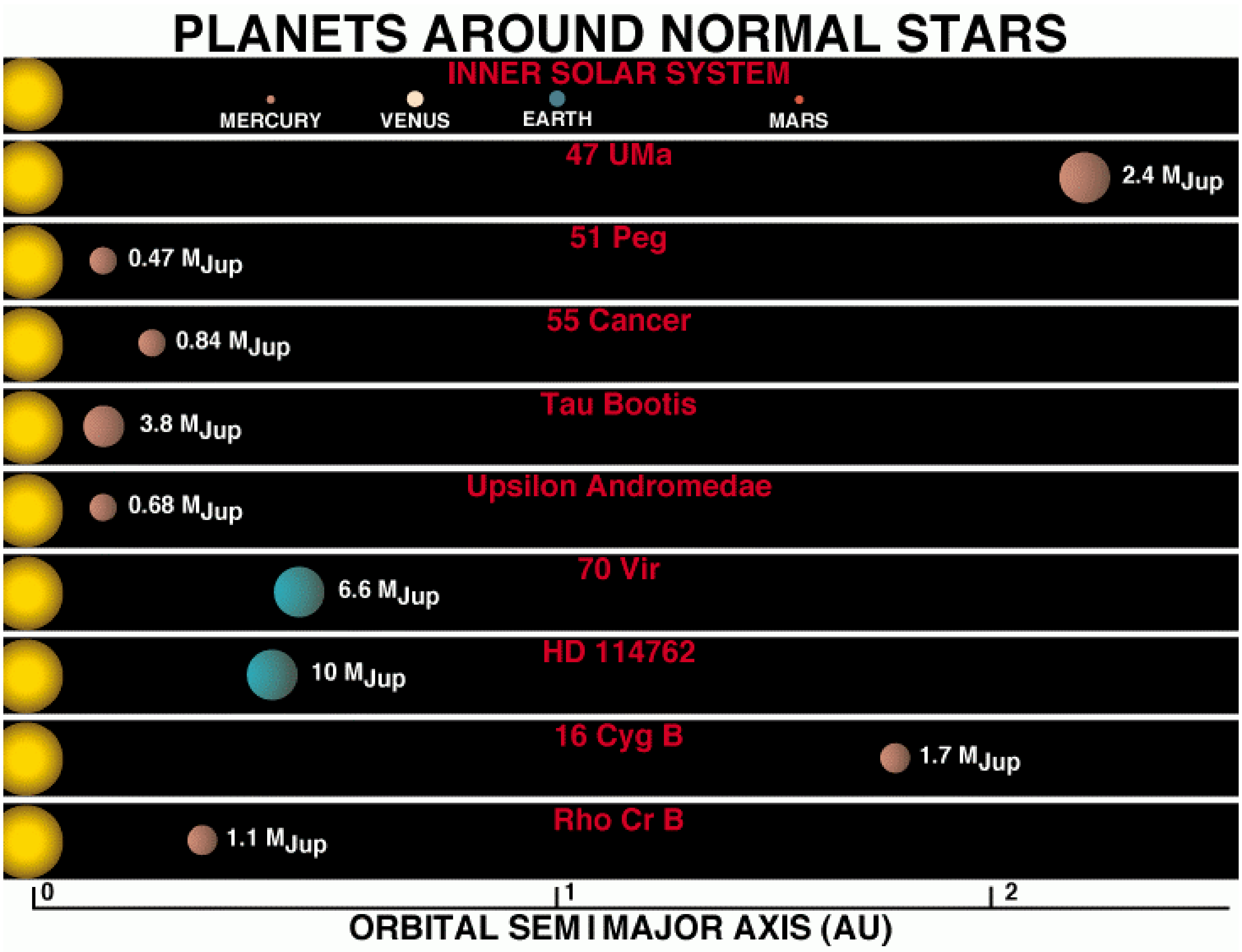
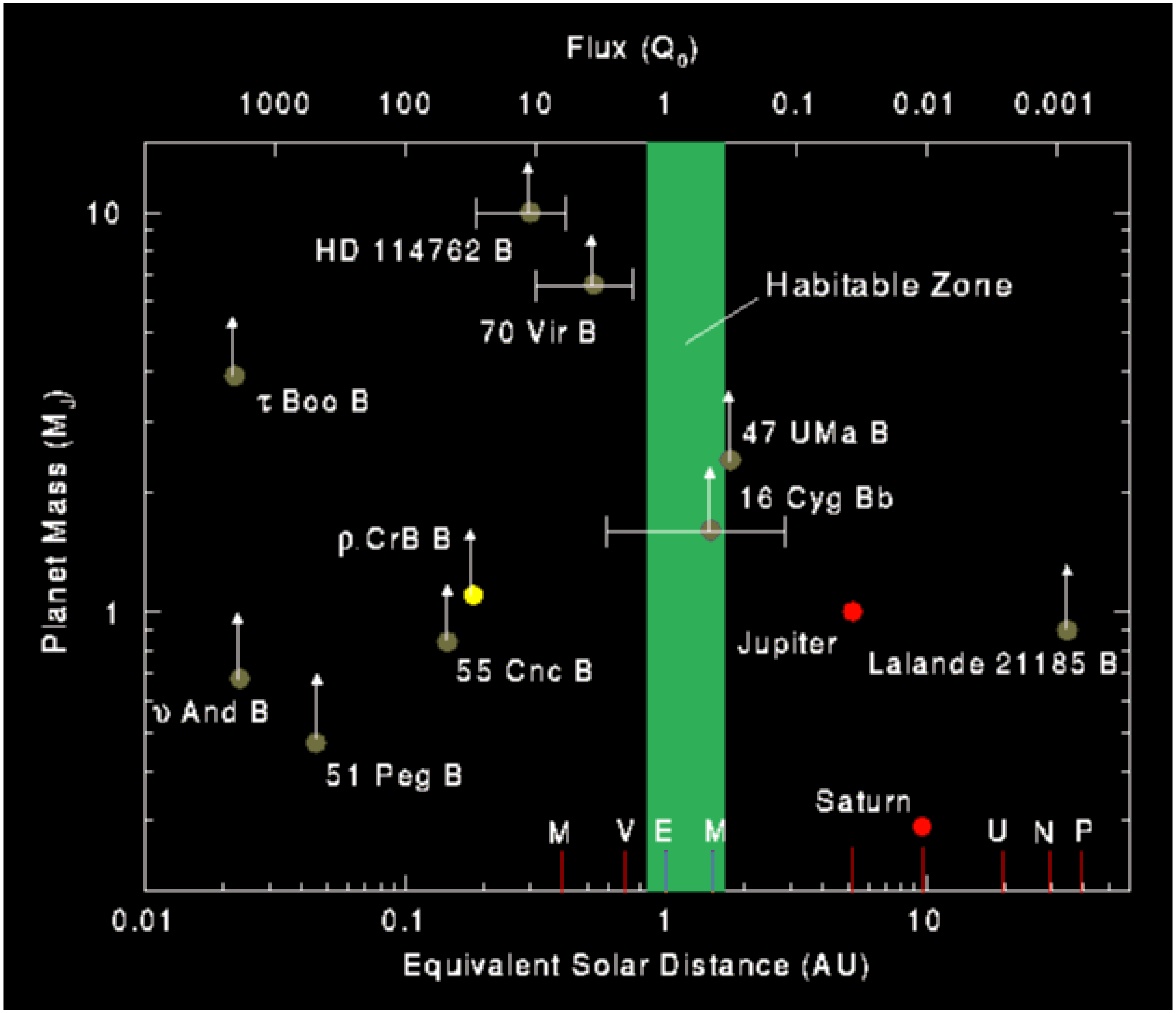
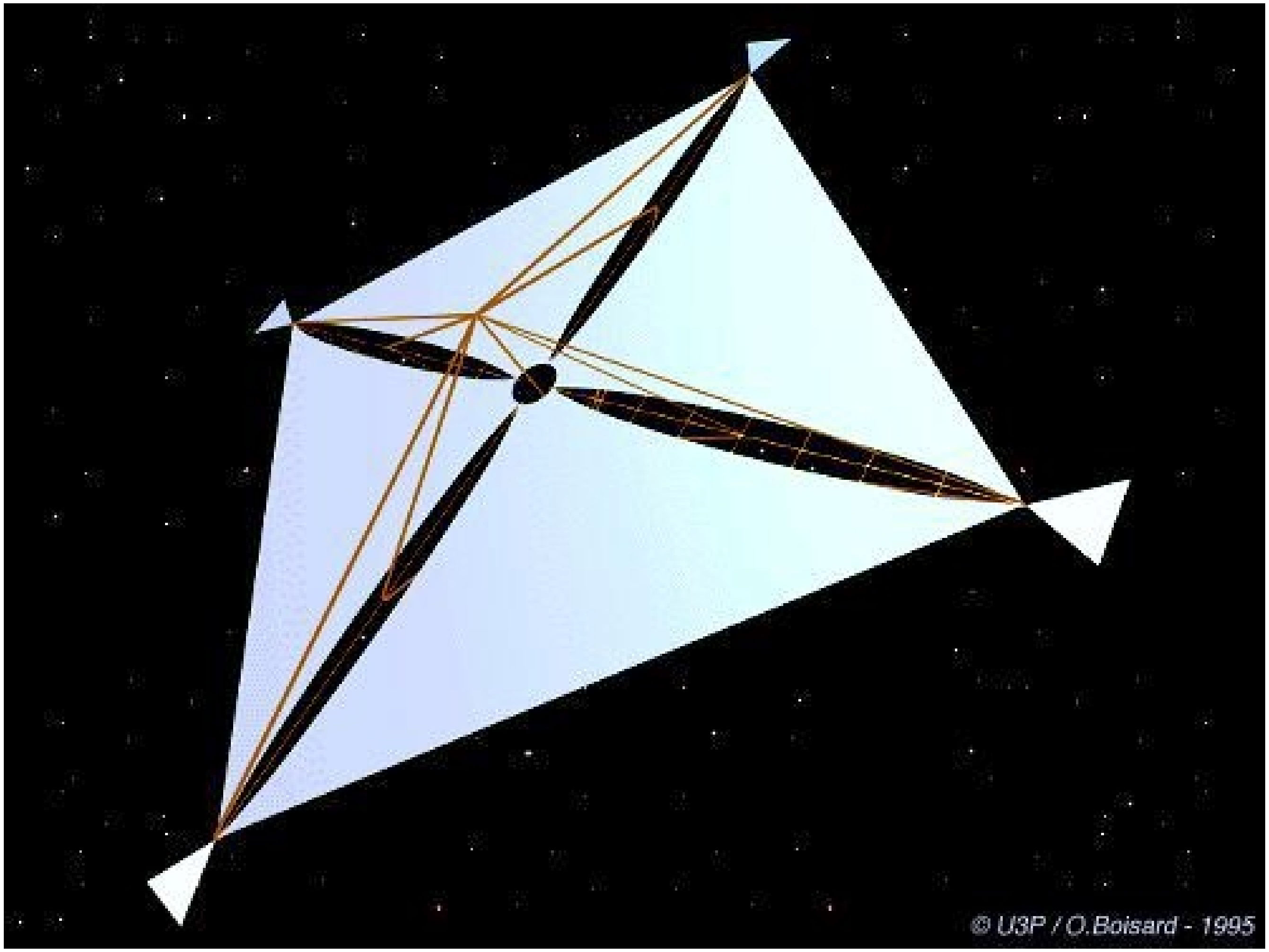
Discoveries of Extrasolar Planets mean that we may soon want to send probes to nearby stars:

Graphics from:
http://wwwusr.obspm.fr/planets/
http://cannon.sfsu.edu/~williams/planetsearch/planetsearch.html


PLANETS AROUND NORMAL STARS
INNER SOLAR SYSTEM
MERCURY
VENUS
EARTH
MARS
47 UMa
2.4 M_{Jup}
51 Peg
0.47 M_{Jup}
55 Cancer
0.84 M_{Jup}
Tau Bootis
3.8 M_{Jup}
Upsilon Andromedae
0.68 M_{Jup}
70 Vir
6.6 M_{Jup}
HD 114762
10 M_{Jup}
16 Cyg B
1.7 M_{Jup}
Rho Cr B
1.1 M_{Jup}
0
1
2
ORBITAL SEMIMAJOR AXIS (AU)



Flux (Q_0)
1000
100
10
1
0.1
0.01
0.001
Planet Mass (M_J)
10
1
HD 114762 B
70 Vir B
Habitable Zone
τ Boo B
47 UMa B
16 Cyg Bb
ρ CrB B
Jupiter
Lalande 21185 B
55 Cnc B
υ And B
51 Peg B
Saturn
M
V
E
M
U
N
P
0.01
0.1
1
10
Equivalent Solar Distance (AU)



Lightsails:

propulsion without propellant

A lightsail uses the momentum carried by a beam of light for propulsion
Lightsails include:

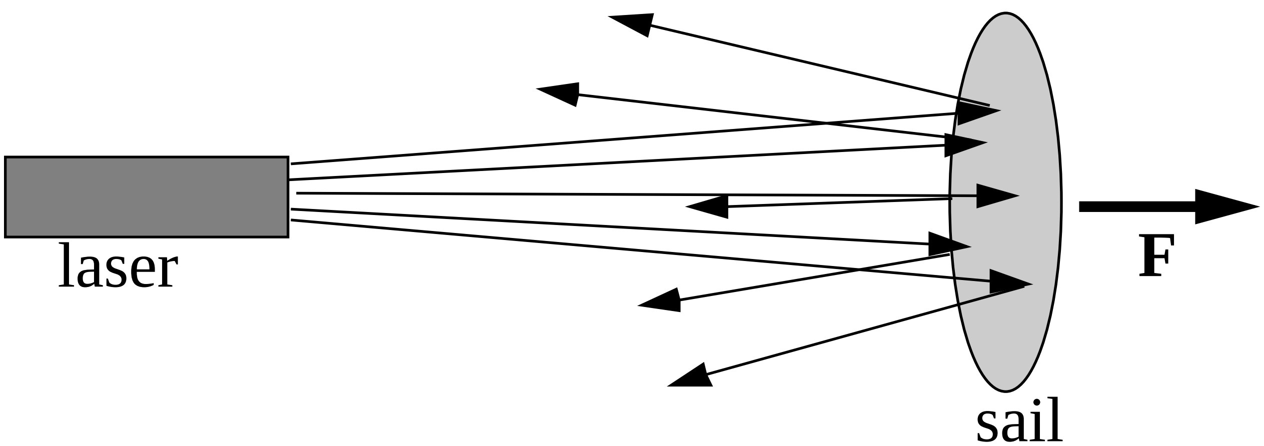
- solar sails
- laser-pushed sails
- microwave-pushed sails

How a Light-Sail works

Light has momentum. Therefore, a reflected beam of light exerts force proportional to its power:

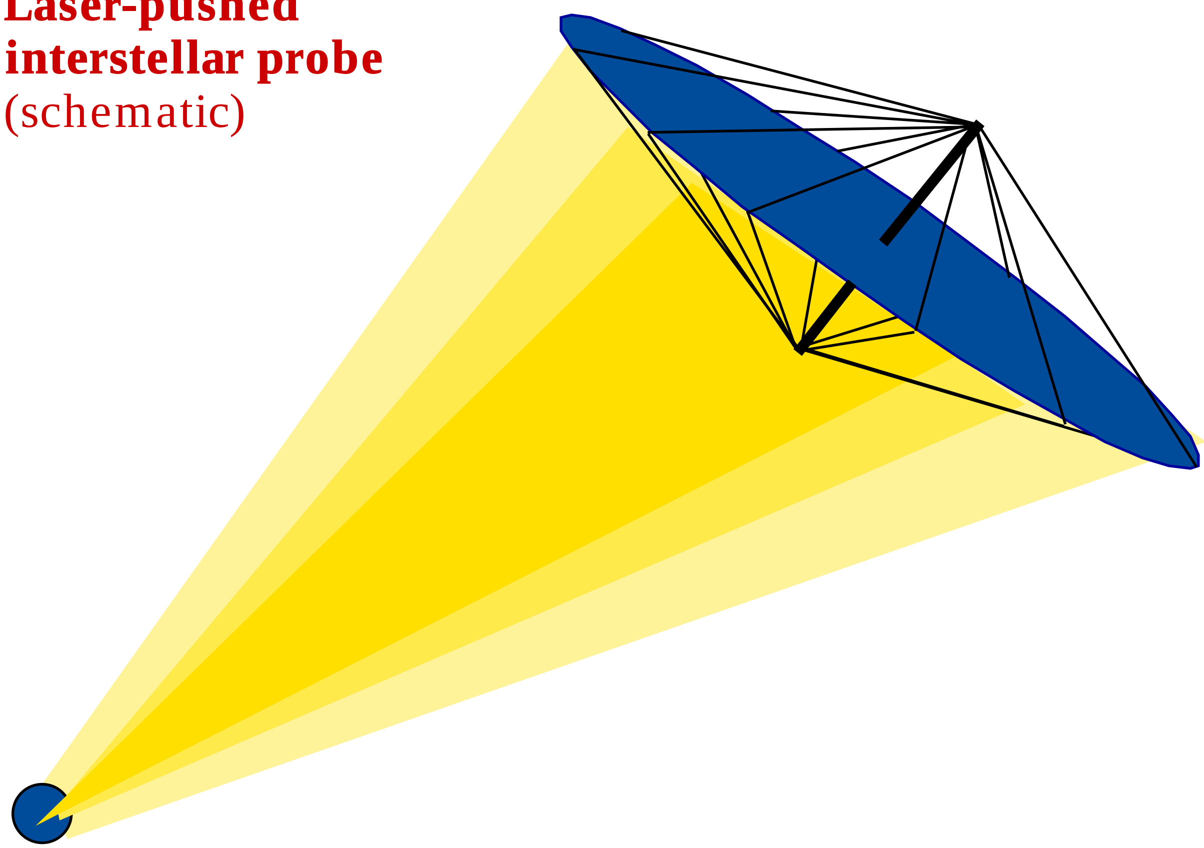
$$F=2P/c$$

where F is force in newtons
P is power in watts
and c is the speed of light in m/sec



In practical units: F=6.7 newtons/gigawatt

Laser-pushed interstellar probe
(schematic)



Solution:

Beamed energy propulsion

leave the energy source at home and send the energy to the spacecraft by a laser or microwave beam

--energy sources are heavy
--mass ratio for interstellar flight is high because you have to
carry the fuel-- carrying the fuel becomes exponentially difficult as the mission -V increases
--leaving the fuel on the ground makes interstellar probe practical

Laser-pushed sail different than solar sail

■ Solar sail is a thin reflective (metal) layer on a plastic film

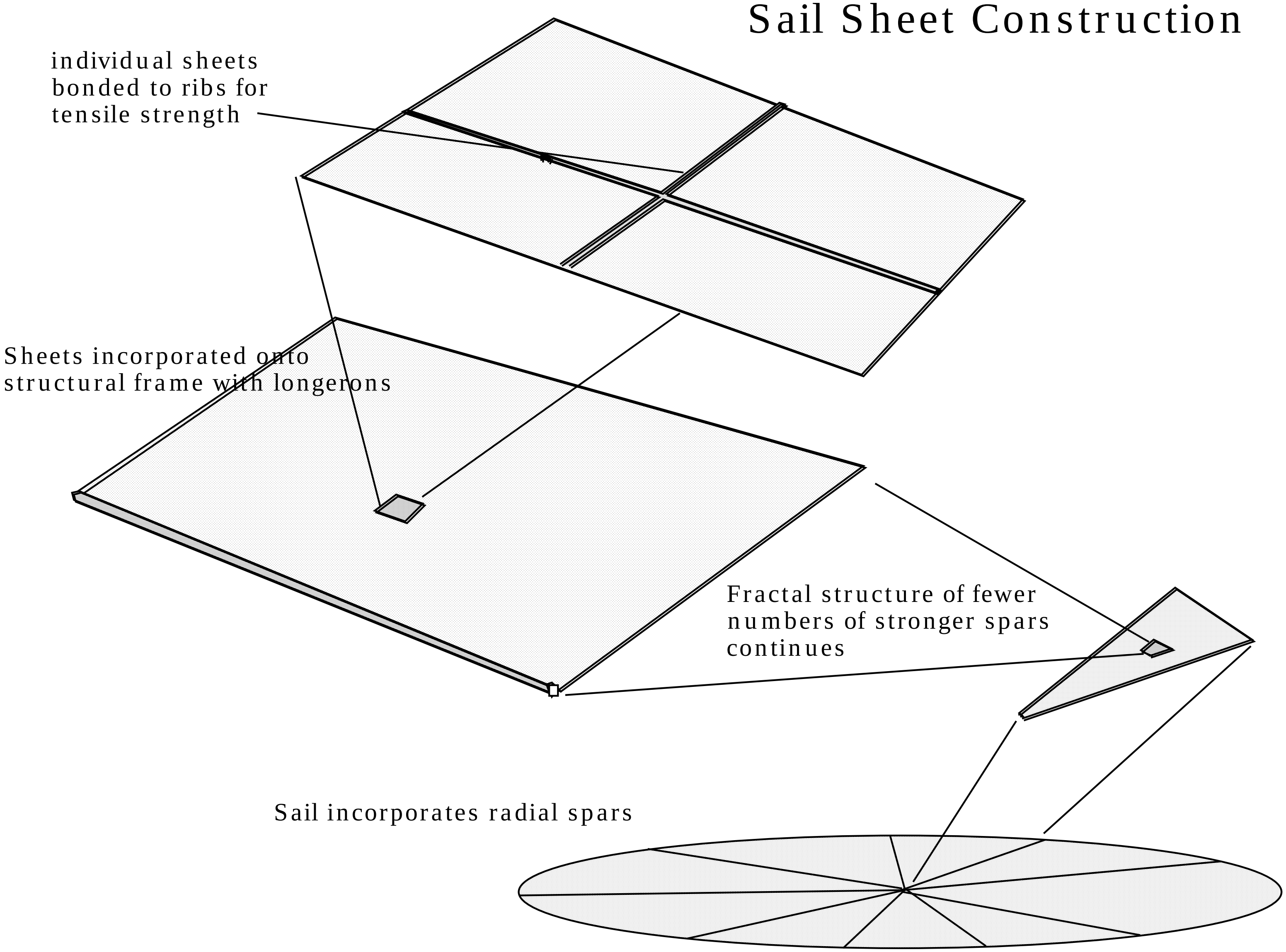
❒ Laser sail leaves the plastic film behind

- plastic is the major mass component
- plastic limits operating temperature
- plastic unnecessary; metal film is self supporting

❒ Only the reflective layer is used

- metal film has higher temperature capability
- film thickness can be 20 nm or so (200 atoms thick)
- film deposition on removable substrate (has been demonstrated)
- needs secondary structure, typically a fractal mesh
- must be as thin as possible to minimize mass
- <u>cannot be rolled up and deployed</u>-- must be assembled in space

Sail Sheet Construction



Problem:

☆The sail and focusing lens required for interstellar fly-by mission with aluminum film sail is **enormous**

☆ The power required is huge

☆ **NOT** a “micro” mission

❐ Solution:Need Higher Acceleration

- want sail to reaches cruise velocity closer to the laser
- closer to the laser there is less beam divergence-- smaller lens and sail are possible
- minimum diameter of lens or sail reduces proportional to acceleration
- minimum laser power reduces directly proportional to acceleration
- but acceleration is thermally limited-- **can’t** go faster with an Al sail

Need a better sail material

- Metal films have low emissivity; and thus get hot in beam
- Material with higher melting temperature is needed
- **Need a high- emissivity refractory material**

Advantages of dielectric films

1. refractory operating temperatures
2. Very high emissivity and low absorptivity

absorptivity should be <<1%
emissivity will depend on thickness, but
α/ε ratio should be <0.1
(compare α/ε 13% / 6% for Al film)

thermally limited acceleration scales with α/ε ratio

Dielectric Film Reflectors

Thin dielectric films are reflective due to interference
Maximum reflection for a fingle film comes with single layer dielectric of quarter-wave thickness
extra layers add more to mass than the increase in reflectivity

$$R = \left[\frac{(n^2-1)}{(n^2+1)}\right]^2$$

Physical Properties of Some Refractory Dielectric Materials.

Material	Max Temp (°C)	Density (gr/cm3)	
Zirconium dioxide	2715	5.5	
Aluminum trioxide	2072	3.96	
Silicon Carbide	2000.*	3.17	(*sublimes)
Tantalum Pentoxide	1870	8.75	
Diamond	1800.†	3.5	(†graphite conversion)
Silicon dioxide	1600	2.7	
Lithium fluoride	820	2.6	

Example Calculation:

Al_2O_3 (sapphire) sail; 400 nm wavelength laser light , quarter wave thickness (n= 1.765)
t= 57 nm

mass: 57 nm at ρ = 3960 kg/m^3 = **226 kg/km^2**

acceleration per unit power is: **0.03 m/sec^2 per (GW/km^2)**

assume maximum operating temperature is 2/3 T_m (1563 K)

for α/ε = 0.01, incident power at T_m is 34 MW/m^2 =
34,000 GW/km^2
so, thermally limited acceleration is 1000 m/sec^2

ONE HUNDRED G

compares to Forward thermally-limited aluminum lightsail acceleration of 0.036 G
2800 times better acceleration

Minimum sail has 28002 times smaller area-- laser power required is 335 times lower

200 MW (not 65 GW)

(accounts for the difference in thickness, density, reflectivity, and wavelength)

Next Step:

Move beam-pushed sail from paper to laboratory demonstration

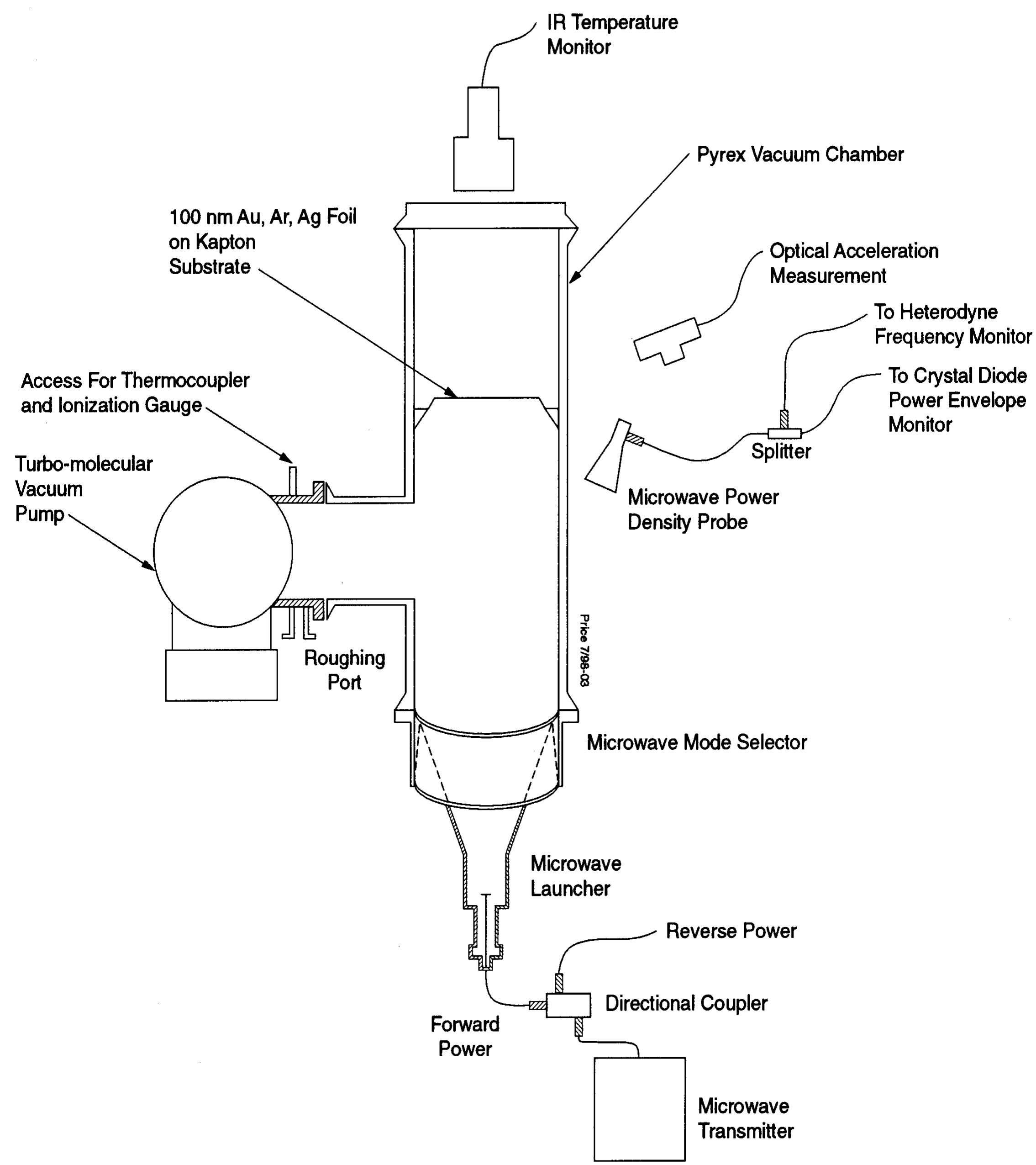
Demonstration of Microwave–Driven Propulsion

Goals and Key Features

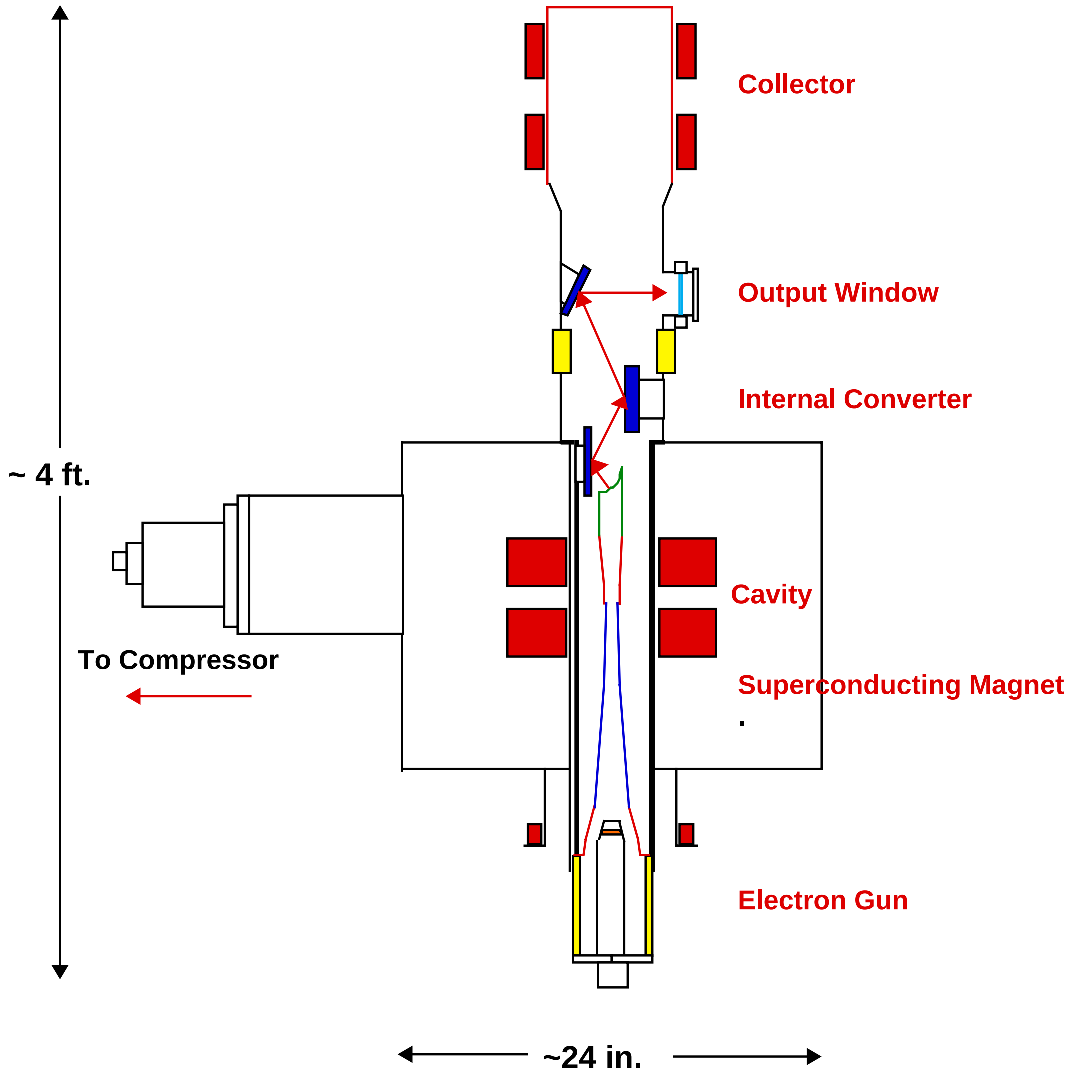
- Fly a Sail at high accelerations over meters of flightpath
- Conduct flight in vacuum at 1 gee, flying vertically
- Thoroughly diagnose the major phenomena–sail speed, sail heating
- Test analytical/computational models of sail performance
- Provide testbed for further experiments on
  - –sail stabilization schemes
  - –flight of sails with payloads
  - –special sail materials

MOVE ‘PHOTON-PUSHED’ SAILS FROM PAPER CONCEPT TO LABORATORY REALITY

Layout of Demonstration Experiment


IR Temperature
Monitor
Pyrex Vacuum Chamber
100 nm Au, Ar, Ag Foil
on Kapton
Substrate
Optical Acceleration
Measurement
To Heterodyne
Frequency Monitor
To Crystal Diode
Power Envelope
Monitor
Access For Thermocoupler
and Ionization Gauge
Splitter
Turbo-molecular
Vacuum
Pump
Microwave Power
Density Probe
Price 7/98-03
Roughing
Port
Microwave Mode Selector
Microwave
Launcher
Reverse Power
Directional Coupler
Forward
Power
Microwave
Transmitter

100 kW CW, 95 GHz Microwave Source (Gyrotron)

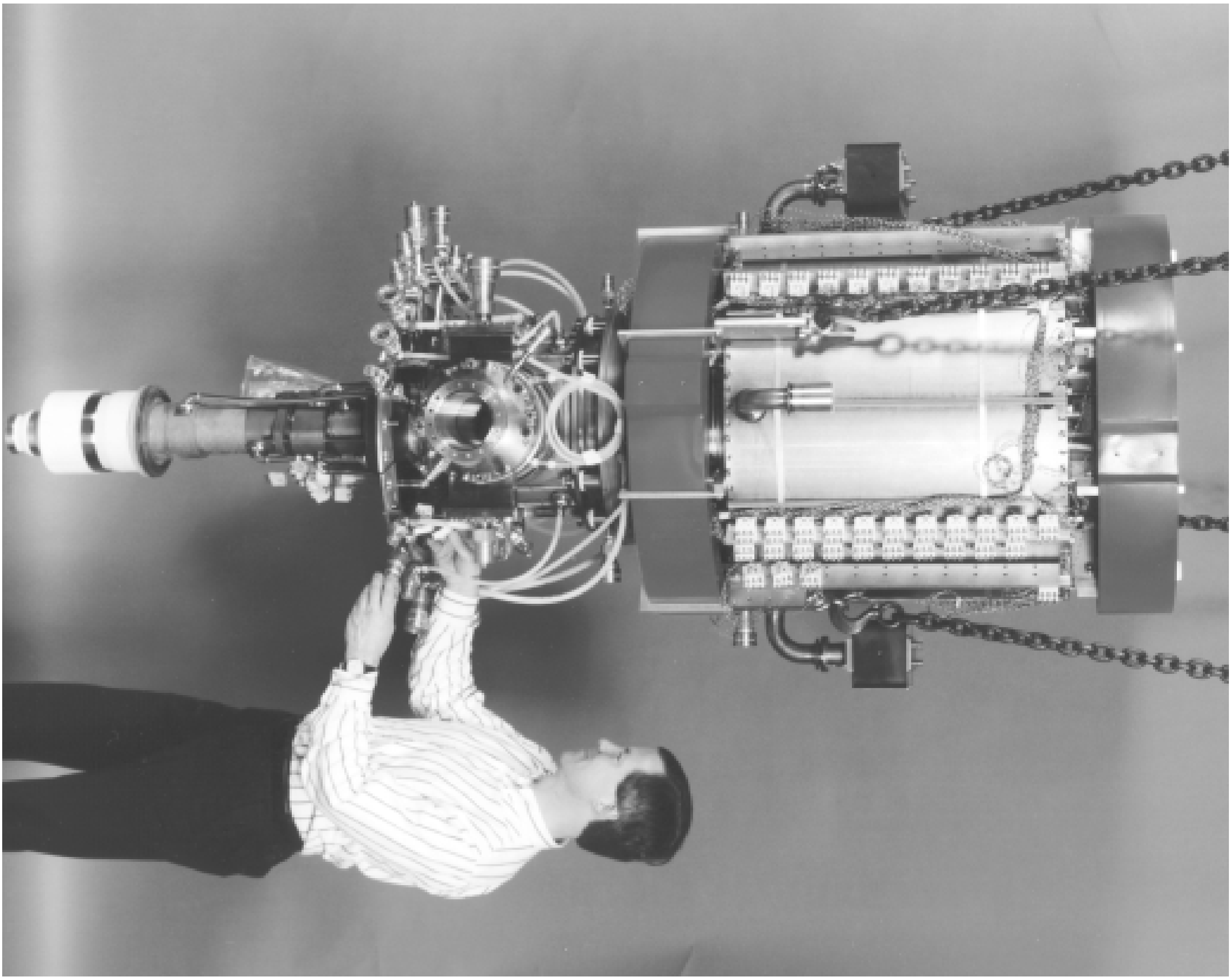


Approx. Tube Weight: 300 lbs.
Approx. Magnet Weight: 300 lbs + Compressor

- Power extracted at 43 kW/cm^2, then expanded to desired area in Gaussian mode

- The technology will be scaled to 2 MW in ~ 3 years at 95 GHz. This will allow experiments at 20 X accelerations or 20 X sail areas.

1 MW, 1110 GHz Gyrotron



• **In use for several years in fusion research**

microwave sciences

Point Design for Demonstration

• **Length of Flight: 8 meters**

• **Acceleration: 2 gees from microwaves, 1 gee net**

• **Sail material and dimensions: Carbon, 1 micrometer thick, 9.7 cm diameter.**

• **Power density on Sail: 1,350 W/cm^2**

• **Sail final velocity: 3 m/sec**

• **Sail Temperature: 3,300°K (C sublimates at 3,925°K)**

• **Other sail materials to be used: Screens and foils of Al, Au, Ag, on Kapton substrate, etc….**

Experimental Measurements

<u>Kinematics and Stability</u>: Acceleration, and speed of sail:

- **video movie of trajectory**
- **radar Doppler shift monitor**

<u>Force on Sail</u>:

- **with probes measure radial power distribution vs. distance along flight path prior to launch**

<u>Sail Temperature</u>:

- **IR imaging and spectroscopy**

<u>Reflected Microwaves</u>:

- **power monitors outside chamber, reverse power in directional coupler**

CONCLUSIONS

◆ **Dielectric sails turn interstellar fly-by missions from science-fiction to technology**

■ **near-term laser-pushed sails** will allow outer-planet and Kuiper-belt missions in months or years, not decades

■ **farther-term laser-pushed sails** will allow interstellar flyby missions with mission times of decades, not centuries

◆ **Millimeter-wave technology has been identified that may allow high-acceleration demonstration sails using existing equipment**

■ wavelength is too high for fast interstellar mission, but possibility of asteroid mission with travel time of few **weeks**