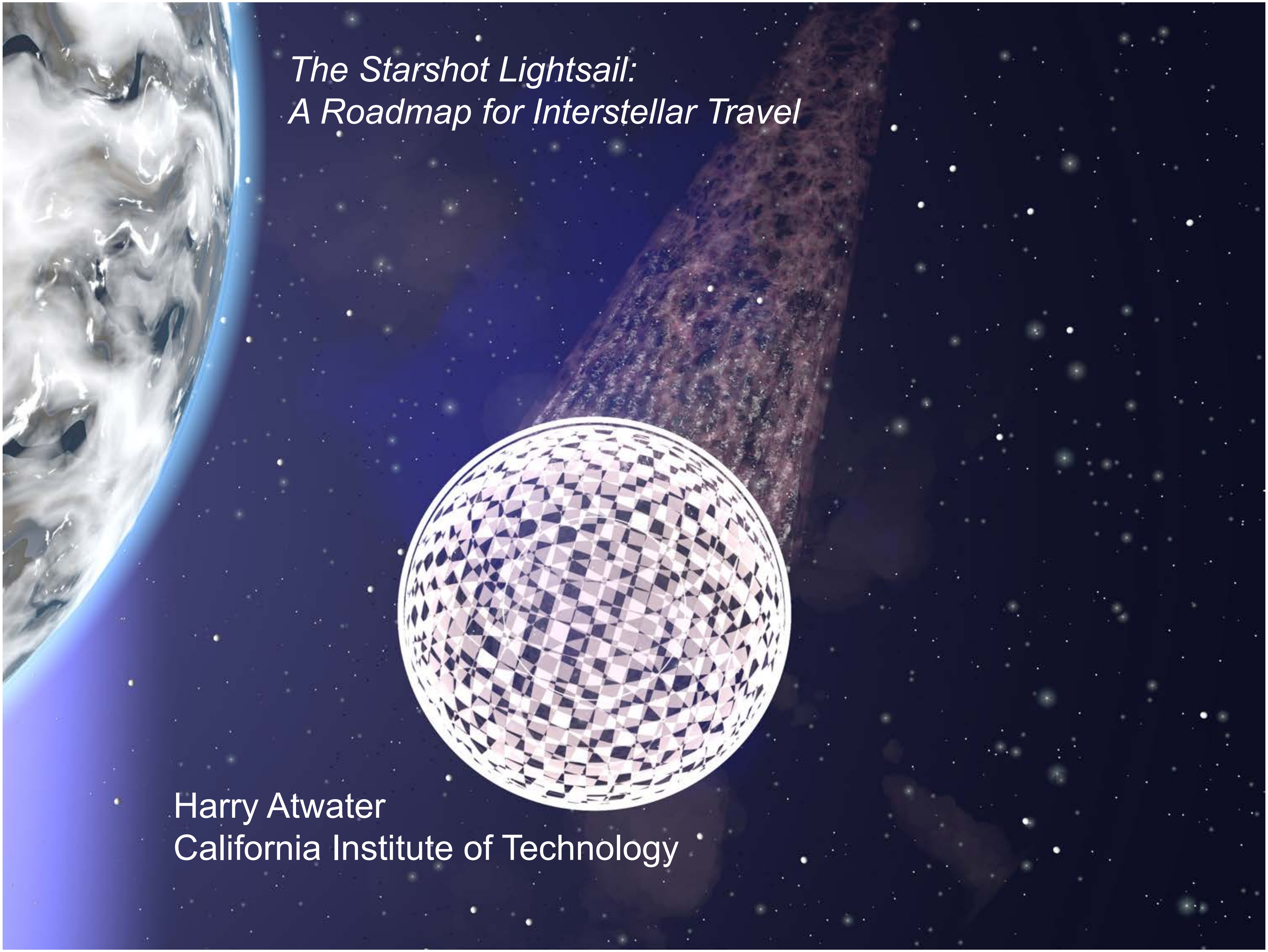
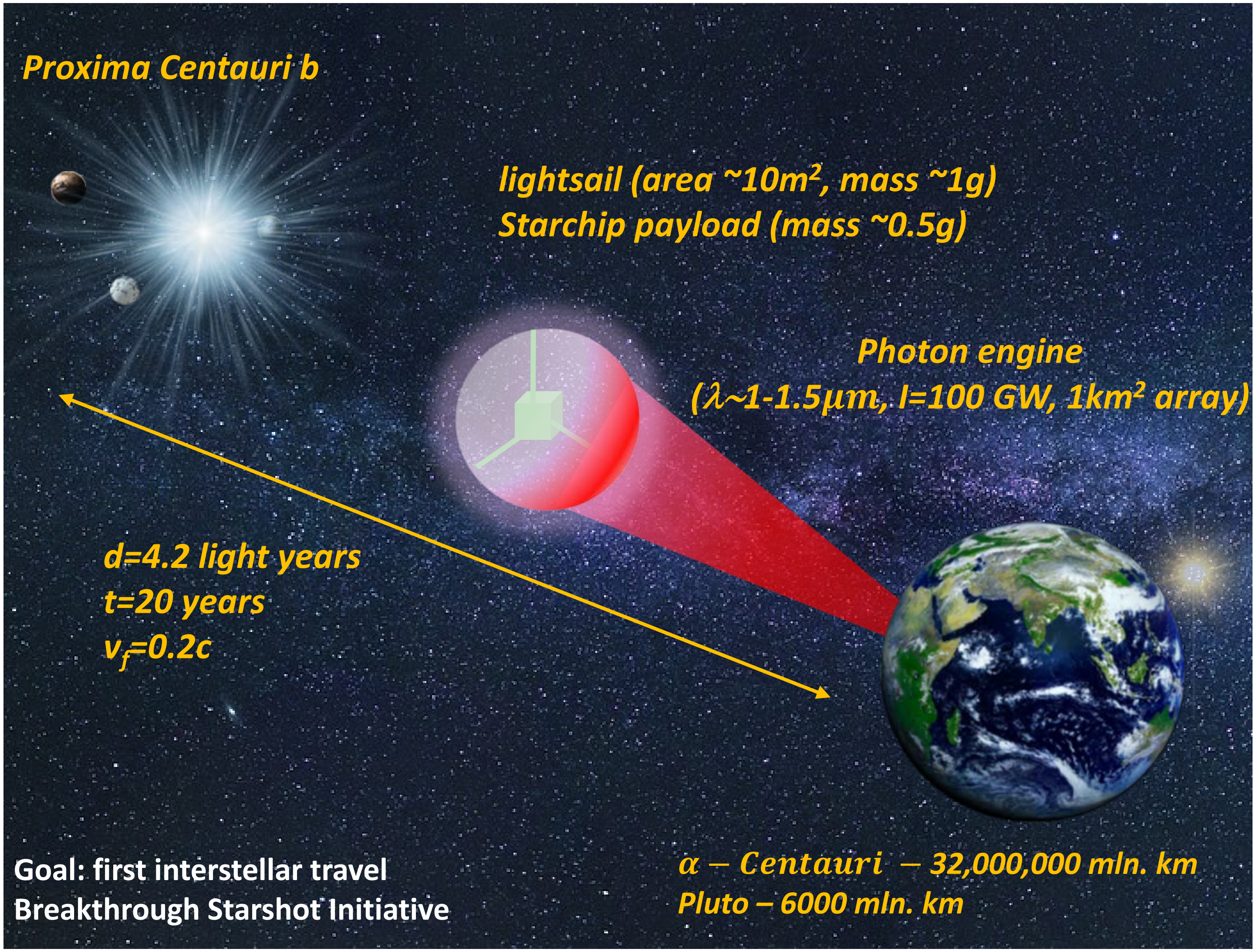
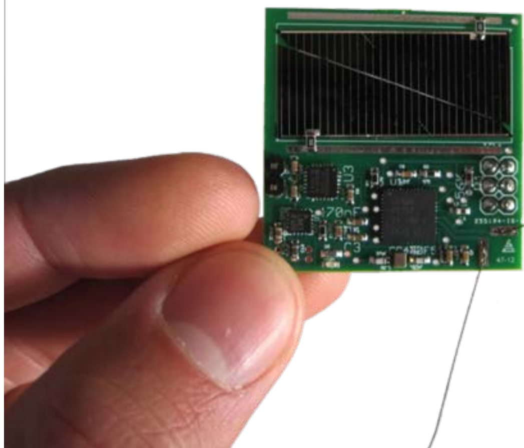

The Starshot Lightsail:
A Roadmap for Interstellar Travel
Harry Atwater
California Institute of Technology

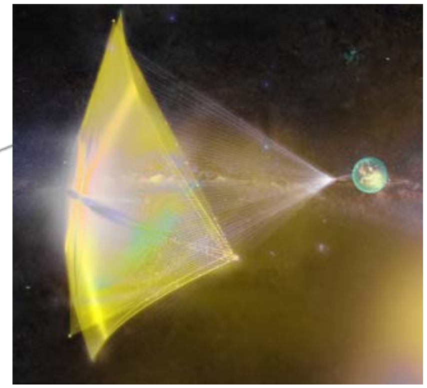
Breakthrough Starshot Initiative

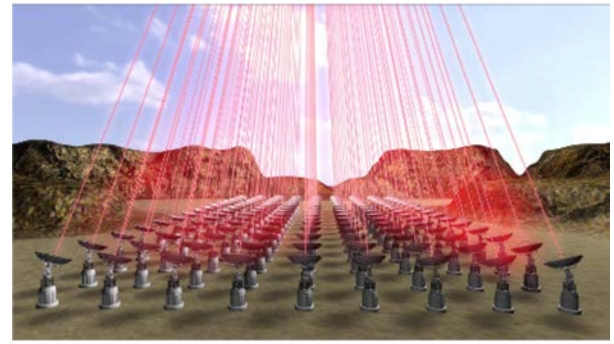


BREAKTHROUGH STARSHOT

3 Enabling Technologies for Laser-Driven Sails







Starchip:

Moore's Law for

Electronics Scaling

Lightsail:

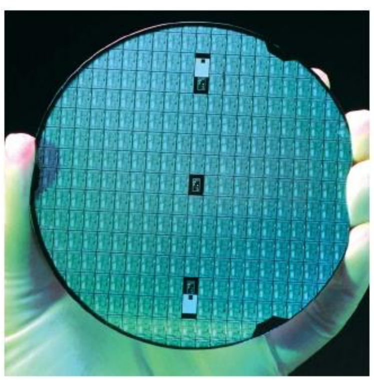
Nanotechnology

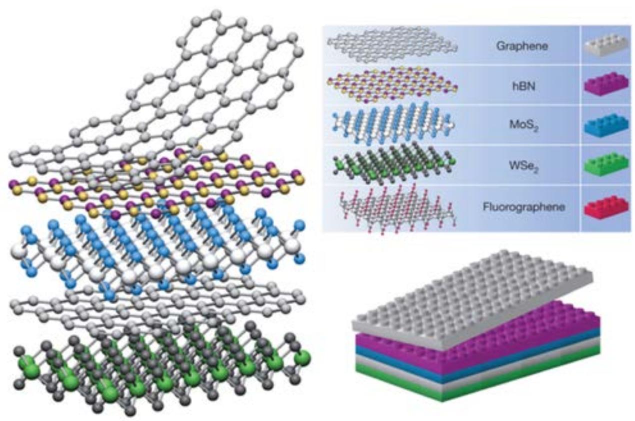
materials

Photon engine:

Solid-state lasers &

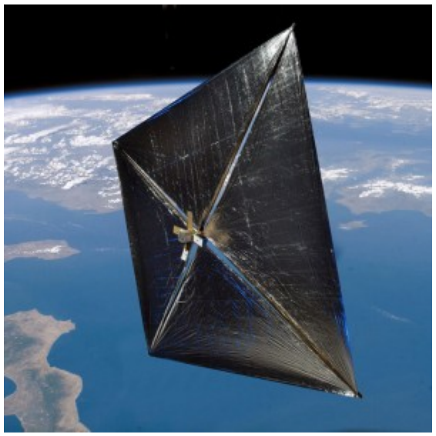
fiber optics





Solar sail missions flown and planned

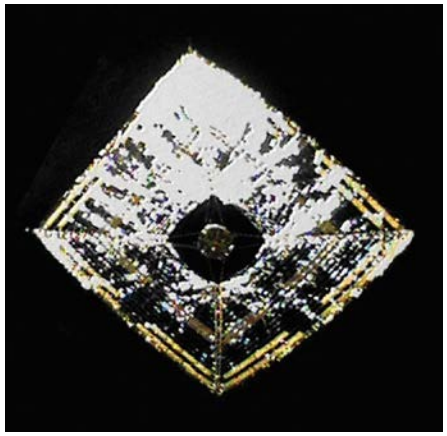
NanoSail-D (2010)
NASA



Earth orbit
Deployment Test

3U CubeSat
10 m^2

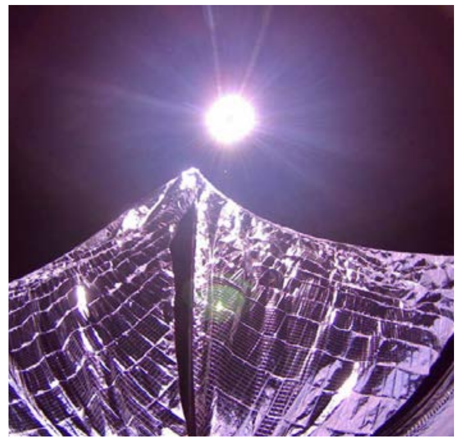
IKAROS (2010)
JAXA



Interplanetary
Full flight

315 kg, SmallSat
196 m^2

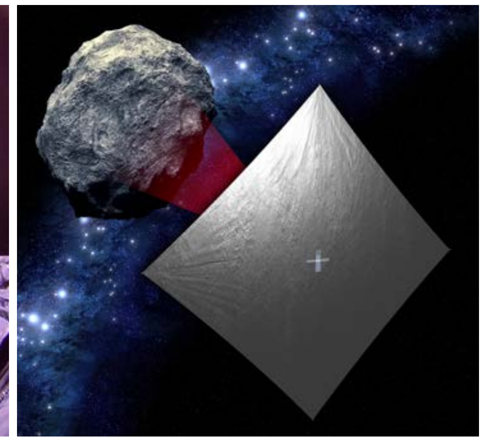
LightSail-1 (2015)
The Planetary Society
LightSail-2 (2018)



Earth Orbit
Deployment Test

3U CubeSat
32 m^2

NEA Scout (2019)
NASA



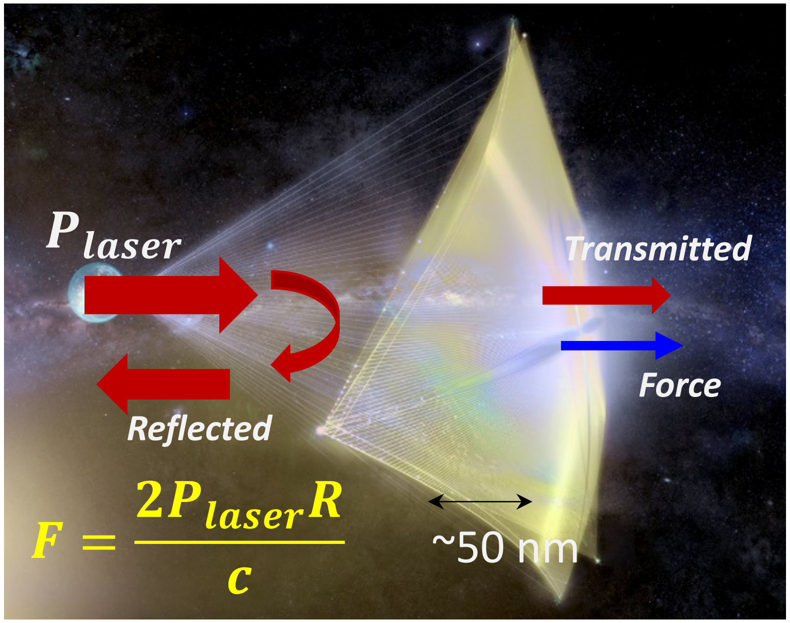
Interplanetary full flight
Deployment Test

6U CubeSat
86 m^2

Also CanX-7 (2016) and Inflate Sail (2017); CubeSAil @U. Illinois + NASA ELANA (2018)

Solar gravitational observatory @600 AU (The Planetary Society + JPL)

Starshot Lightsail



nature materials
PERSPECTIVE
https://doi.org/10.1038/s41563-018-0075-8

Materials challenges for the Starshot lightsail

Harry A. Atwater[1]*, Artur R. Davoyan[1], Ognjen Ilic[1], Deep Jariwala[1], Michelle C. Sherrott[1], Cora M. Went[2], William S. Whitney[2] and Joeson Wong[1]

The Starshot Breakthrough Initiative established in 2016 sets an audacious goal of sending a spacecraft beyond our Solar System to a neighbouring star within the next half-century. Its vision for an ultralight spacecraft that can be accelerated by laser radiation pressure from an Earth-based source to ~20% of the speed of light demands the use of materials with extreme properties. Here we examine stringent criteria for the lightsail design and discuss fundamental materials challenges. We predict that major research advances in photonic design and materials science will enable us to define the pathways needed to realize laser-driven lightsails.

Propulsion
- Momentum transfer
- Sail shape, trajectory and stability

Laser damage
- Absorption & heating
- Mechanical stress

Other considerations
- Fabrication, assembly, etc.
- External factors (dust, radiation, etc)

Nature Materials (https://doi.org/10.1038/s41563-018-0075-8)

2017 Committee Meeting Outcomes: Sail Research Topics

Material Development

- Ultralow Photonic Absorption material intrinsic & extrinsic absorption mechanism, with modest refractive index
- High refractive index materials
- Physically durable to sustain intense accelerations and ISM dust and gas
- Simulations
- Material Design
- Material Manufacturing

Sail Stability

- Beam Riding Simulation and Testing
- Host Star Chip

Testing

- Measure/calculate Optical Properties Emissivity vs. temperature, wavelength of $SiO_2$of higher index material such as Si, MoS_2 , TiO_2 or Si_3N_4
- Assess light-induced acceleration of microscopic objects

BREAKTHROUGH
STARSHOT

2017 Committee Meeting Outcomes: Sail Research Goals

Research 2 Years :

- Narrowed to 1-3 materials
  - Optical Tests optical properties of materials at the full-scale power density
  - ~1 mm^2 sample scale, over a wide range of wavelengths and temperatures
  - Measurements of reflectivity and absorption vs angle
  - Structural Tests, Elasticity, deformation and failure, Rotation/centrifugal forces
- Construction Methods
  - Develop joining method high-quality crystalline materials and/or wafer
  - Scale segments into a larger sail prototype

Brass Board in 3 Years size ~1 cm^2

- Realistic absorption, reflection, emissivity, and tensile strength
- Test Brass Board in earth-based test facility for acceleration, reliability, and stability

Space-based Prototype in 15 Years

- Wafer-scale physical Brass Board sail of size ~10-100 cm^2
- Test space-based acceleration with ~10 kW – 1 MW ground-based laser at 1 MW/cm^2

BREAKTHROUGH
STARSHOT

2017 Starshot LightSail Workshop

Tuesday October 24th
9:00 am – 3:30 pm

Location:
Keck Conference Center
California Institute of Technology
Pasadena, CA 91125

~60 Participants:
- Academic
- Industry
- Government

Format:
- Scene-setting presentations
- Capability Introductions
- Breakout Sessions

9:00 – 9:15 am	Workshop opening, goals and participant introductions (Harry Atwater)
9:15 – 9:50 am	Breakthrough Starshot Initiative (Pete Klupar)
9:50-10:25 am	Materials Challenges for the Starshot Lightsail (Ognjen Ilic)
10:25-10:45 am	Coffee break
10:45-11:20 am	Lightsail Propulsion and Stability (Zac Manchester)
11:20-12:00 noon	2 Minute Introductions to Capabilities and Experience of Participants (all)
12:00-12:45pm	Lunchtime talk Dr. Tayab Suratwala, LLNL (invited)
12:45-1 pm	Breakout Instructions (Harry Atwater)
1:00-2:45 pm	Breakout sessions (3 Topical Areas)
2:45-3:00 pm	Coffee Break

BREAKTHROUGH
STARSHOT

2017 Starshot LightSail Workshop

Breakout 1: Photonic Design of Lightsail

Top issues

1. Reflector consistent with mission requirement of achieving 0.2c for ~1g payload

2. (Passive / Active) Adaptive features for stability, damage resistance, thermal survival, deformation

3. Evaluate candidate materials
    1. including thin-films, micro/nano-patterned structures, 2D materials) for thermal/mechanical stability
    2. multi-band functionality: propulsion & cooling (communication?)

4. Modeling / optimization of a photonic system across vastly different length scales (including scattering?)
5. Photonic design for stability: decoupling rotational and translational modes of the lightsail
6. What *are* the relevant figures of merit (FOMs)?
7. Optical properties of materials at elevated temperatures

BREAKTHROUGH STARSHOT

2017 Starshot LightSail Workshop

Breakout 2: Sail Stability

Top issues

1. Multi-physics simulation (optics, mechanics, thermal, etc.)
2. Optimization-based tools for evaluating sail + beam designs
3. Roadmap for test and verification
    a) Measurement techniques for thin membranes
4. System-level requirements/constraints imposed by stability
5. Visionary concepts
    a) Active materials
    b) Closed-loop control
    c) Advanced laser ideas
    d) Active shape control

BREAKTHROUGH
STARSHOT

2017 Starshot LightSail Workshop

Breakout 3: Measurement, Characterization and Fabrication

Top issues

1. Invite proposers to develop & defend a FOM

Broad figure of merit:

1. reflection and absorption, angular dependence
2. mechanical properties, thermal props., thermorefractive props.
3. damage resistance
4. manufacturability (cost, max. area,
5. threshold temperature for stability against thermal runaway
6. Very high aspect ratio: Fabrication in 50 nm x 16m^2 without breaking (surface tension,
7. Launchability: stowage/deployment
8. Robustness to local damage – defects/edges produce ‘clean failure’
9. Attach payload to sail
10. Systems engineering: renegotiate FOM criteria in response learning at the R&D stage

Challenges for the Starshot Lightsail

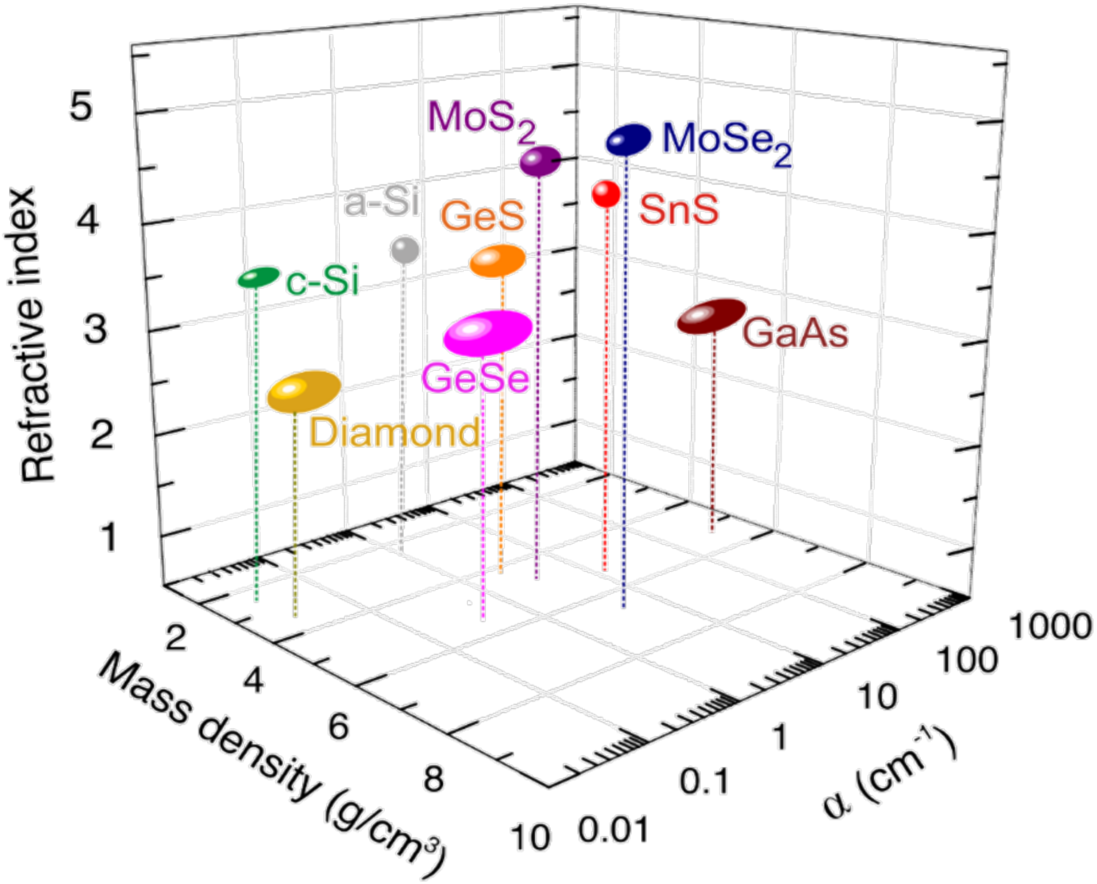
Lightsail specifications:

- Mass ~ 1 g
- Area ~ 10 m^2
- acceleration time ~ 1000 s
- absorption < 10^{-5}
- stable in flight
- *high** reflectance over a *broad** spectral range
- ground station / phased array

Challenges:

- **Material candidates**
- **Photonic design**
- **Thermal management**
- **Stable flight**
- **Fabrication**
- **Integration**
- **Measurement & Characterization**

Sail materials



Weight, index, absorption tradeoff

Nature Materials (https://doi.org/10.1038/s41563-018-0075-8)

Thermal Properties of LightSail Materials

Material	Linear Thermal Expansion [K^{-1}]	Phase Transition Temperature [K]
Diamond (CVD)	~0.8×10^{-6} @300K - 4×10^{-6} @1000K	~1800 (Graphitization)
Silicon (Crystalline)	2.6×10^{-6} @300K - 4.25×10^{-6} @1000K	1687 (Melting)
Silicon (Amorphous)	3.5×10^{-6} @ 300K	~875 (Crystallization)
MoS_2 (Bulk)	~$2\text{-}7\times10^{-6}$ [010], ~$8\text{-}18\times10^{-6}$ [001] @ 300K – 1000K	1458 (Melting)

Laser/Sail Interaction: Spectral Bandwidth

As the sail accelerates, laser light appears red-shifted.

Doppler shift

$$f_{observed} = \sqrt{\frac{1 - v/c}{1 + v/c}}\, f_{laser}$$

observed photon frequency

LightSail velocity

laser frequency (Earth)

Photonic properties of the LightSail need to be considered in the spectral bandwidth determined by v_f.

Initially: $f_{observed} = f_{laser}$

At $v_f = 0.2c$: $f_{observed} \approx 0.82 f_{laser}$

Starshot Lightsail Is a Complex Structure

determined by multiple (often competing) considerations (thrust, stability, low-absorption, mechanical strength, …).

Immediate goals for photonic design:

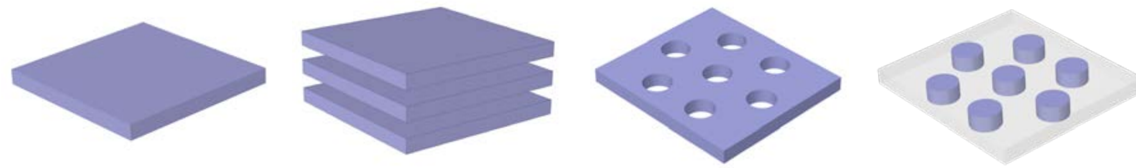
- Highlight (and quantify) tradeoffs between various sail properties (reflectance, mass density, absorbance, …)
- Identify candidate structures that could form a basis for the LightSail design.

Approach:

- Multivariate parameter optimization across several different classes of nanophotonic structures.
- Total of >100,000 simulations

Optimization flow

For each structure



For each material — Si, C, $MoSe_2$, MoS_2

Optimize for FOM — ??

Per structure & per material:

~*1000* initial points &
~*100s* local searches per initial point

Multi-start optimization + inner local, derivative-free, search algorithm

LightSail Dynamics

Acceleration distance

Total mass (per m^2)
sail mass + payload mass

$$D(v_f) = \left(\frac{c}{2IA}\right)\int_0^{v_f} \frac{m_T}{R(v)} \frac{\gamma(v)v}{\left(1-\frac{v}{c}\right)^2} dv$$

Laser Intensity

Sail Area

Reflectance (velocity dependent)

Optimization Assumptions

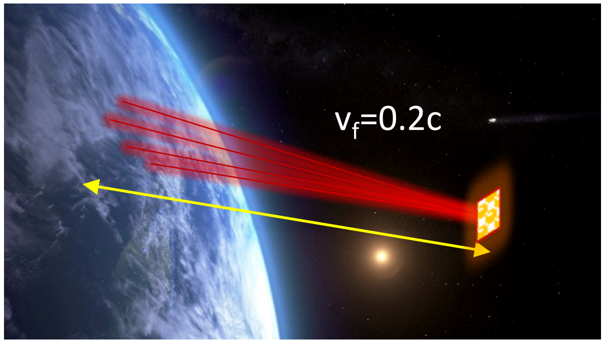
- I = 10GW/m^2
- M_{load} = 0.1g
- *Area* = 10m^2

Note:
We found optimal structures *specific to* these assumptions.

Nature Materials (https://doi.org/10.1038/s41563-018-0075-8)

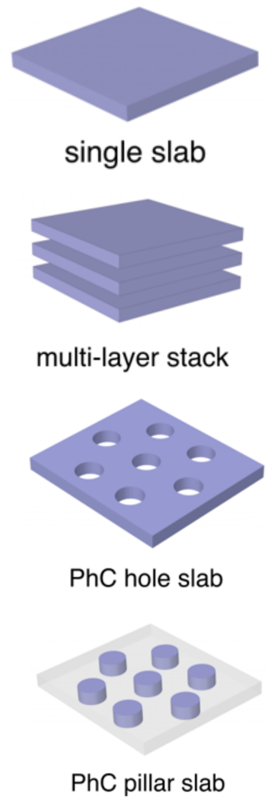
Photonic designs & Figure of Merit

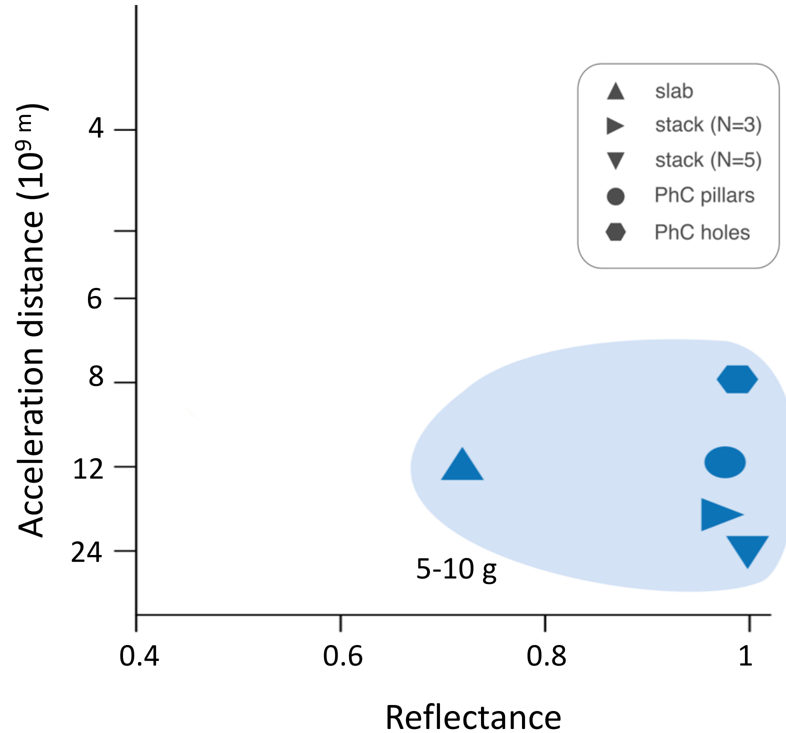
Nanophotonic designs for higher reflectance in $[\lambda_0 - 1.22\lambda_0]$



Acceleration distance

$$D(v_f) \sim \left(\frac{c}{2IA}\right) \int_0^{v_f} \frac{m_T}{R(v)} \frac{\gamma(v)v}{\left(1-\frac{v}{c}\right)^2} dv$$



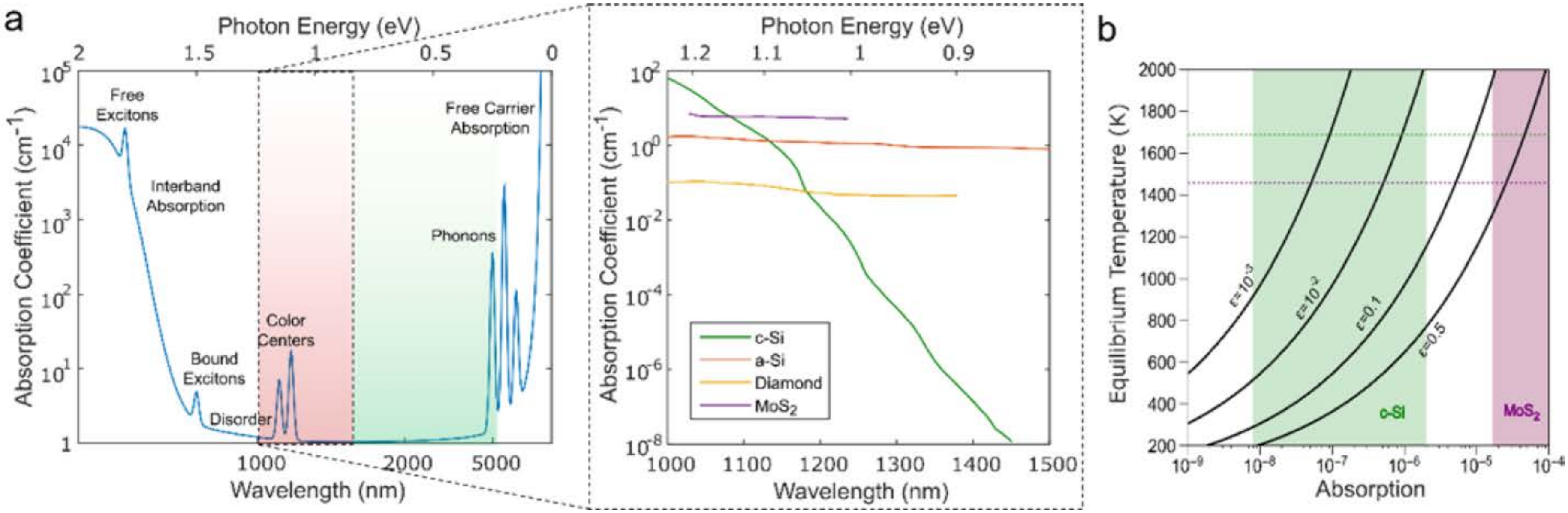


Contrast to common wisdom: optimize for mass, not reflection

Nature Materials (https://doi.org/10.1038/s41563-018-0075-8)

Materials Challenges for the Starshot Lightsail

Absorption mechanisms and measurements



Nature Materials (https://doi.org/10.1038/s41563-018-0075-8)

High sensitivity absorption measurements

Photothermal deflection spectroscopy (PDS)

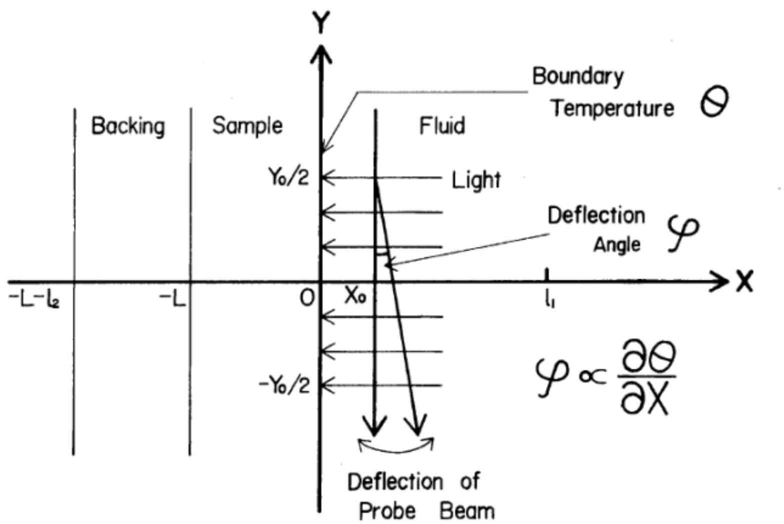


Fig. 1. Geometry of one-dimensional theoretical model for PDS.

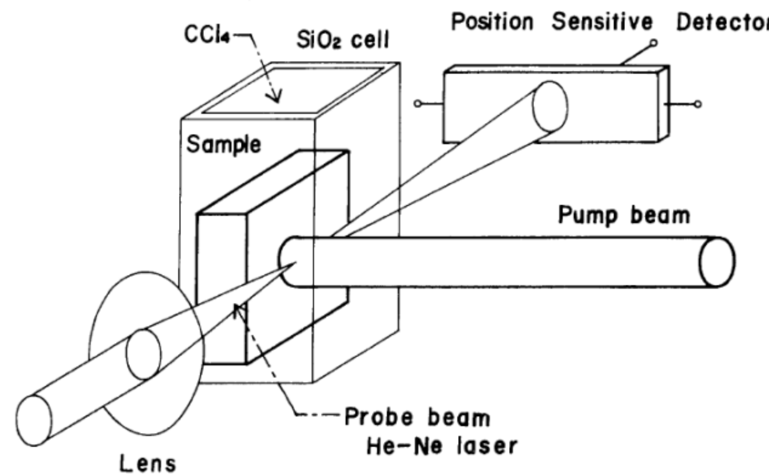


Fig. 3. Experimental apparatus for detecting PD signal.

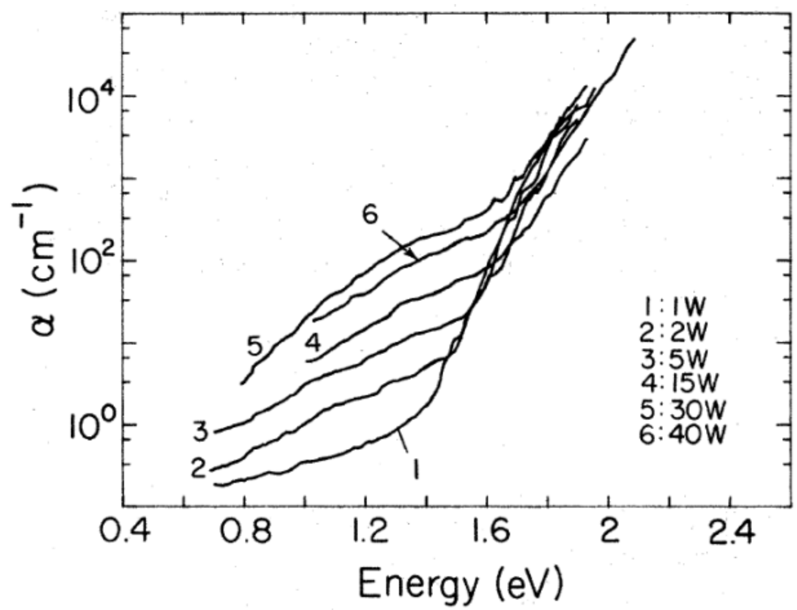
Photothermal and photoacoustic deflection spectroscopies are known tools for measuring accurate absorption values in the very low limit as well as laser induced damage thresholds at high intensities.

W. B. Jackson et al. , Appl. Phys. Lett. 20, (1981)

High sensitivity absorption measurements

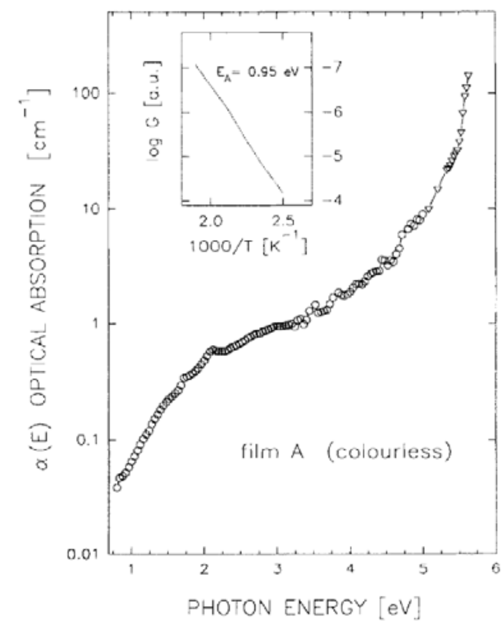
Photothermal deflection spectroscopy (PDS)

a-Si



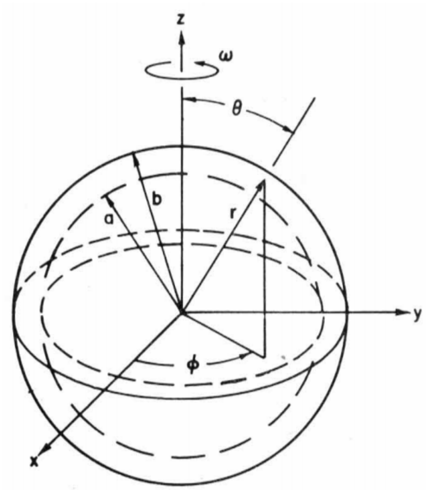
a-Si sputter deposited at various powers
Jackson and Amer, Phys. Rev. B, 25, 1982

CVD diamond



M. Nesladek et al. Diamond and Related Materials 4, 1995

Tensile Stress in a Rotating Spherical Shell



Stress,
Normalized

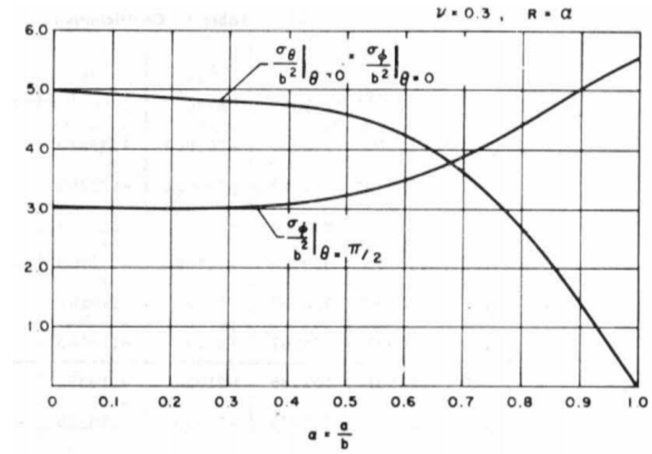
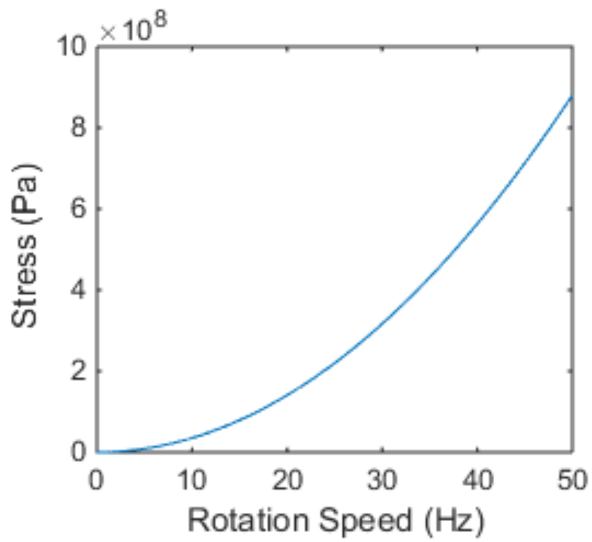
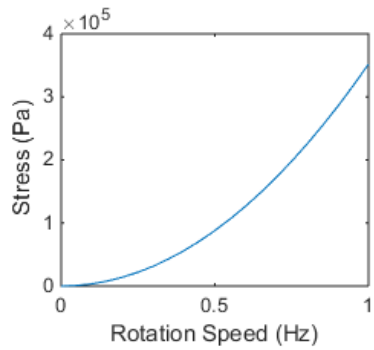


Fig. 2 Meridian and circumferential stresses versus α

Normalization: $\beta = \gamma\omega^2/8(1-\nu)$, $\alpha = a/b$





Typical Tensile Yield Strengths (Pa):

h-BN ~ $1 \cdot 10^{11}$

Si_3N_4 ~ $4 \cdot 10^8$

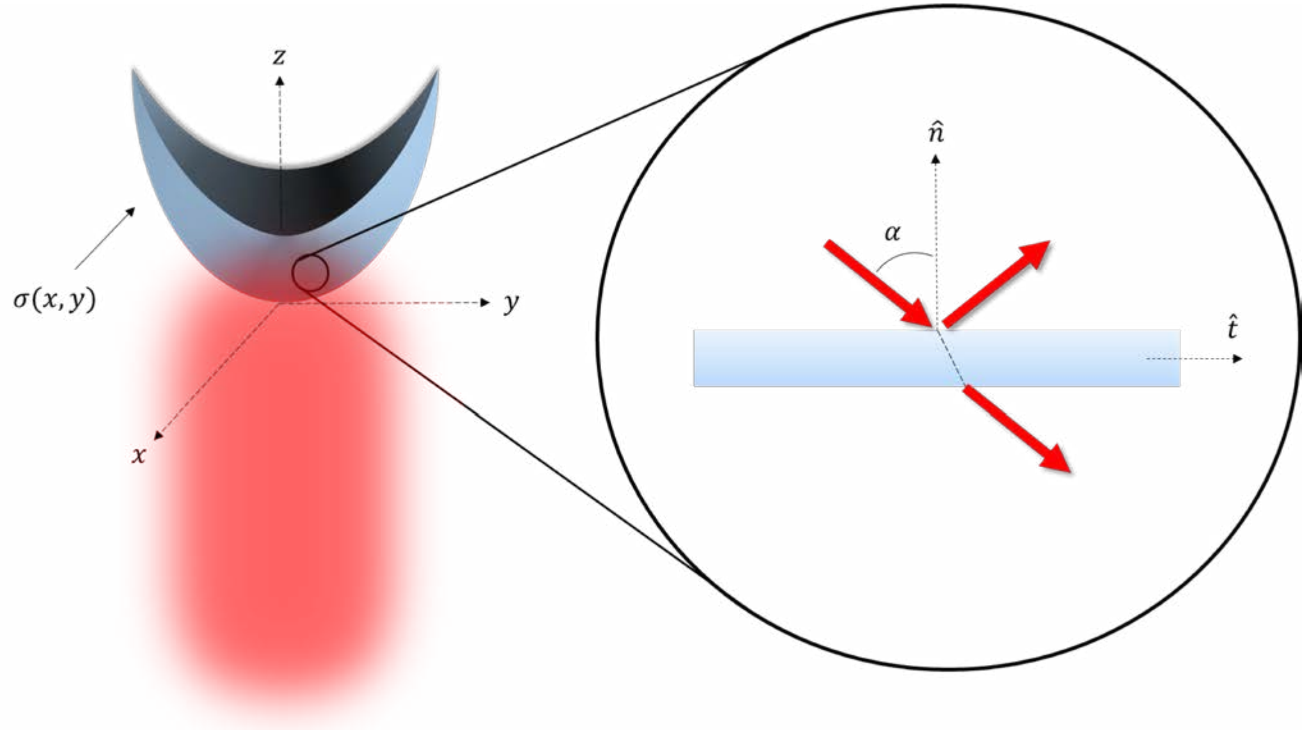
AlN ~ $3 \cdot 10^8$

a-Si ~ $1 \cdot 10^8$

SiO_2 Aerogel ~ $2 \cdot 10^4$

Goldberg, M.A., et. al., J. Appl. Mech., 1961.

Light-material interactions and sail stability



Assumptions

- Surface described by $z = \sigma(x, y)$
- Beam incident from -$\hat{z}$
- Specular Reflection & Direct Transmission

Force Field Distribution

Beam Profile (W/m²)

Normal vector of surface

Absorptivity of sail

$$\vec{P}(x,y) = \frac{I(x,y)}{c}\left[-2R(\alpha)\cos(\alpha)\hat{n} \; + A(\alpha)\hat{z}\right]$$

Force Field (N/m²)

Speed of light

Reflectivity of sail

Angle of incidence

Direction of beam propagation

$$\vec{F}_{total} = \int \vec{P}(x,y)\, dx\, dy$$

$$\alpha(x,y) = \arccos\left(\frac{1}{\sqrt{1+(\partial_x\sigma)^2+\left(\partial_y\sigma\right)^2}}\right)$$

Nature Materials (https://doi.org/10.1038/s41563-018-0075-8)

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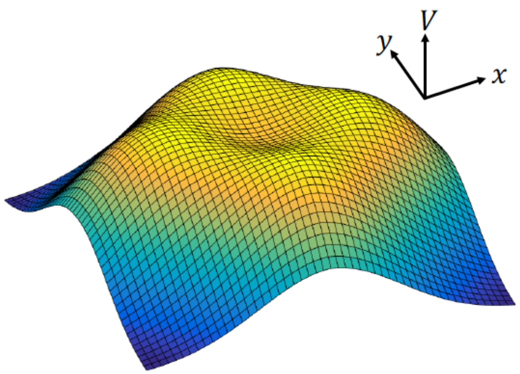
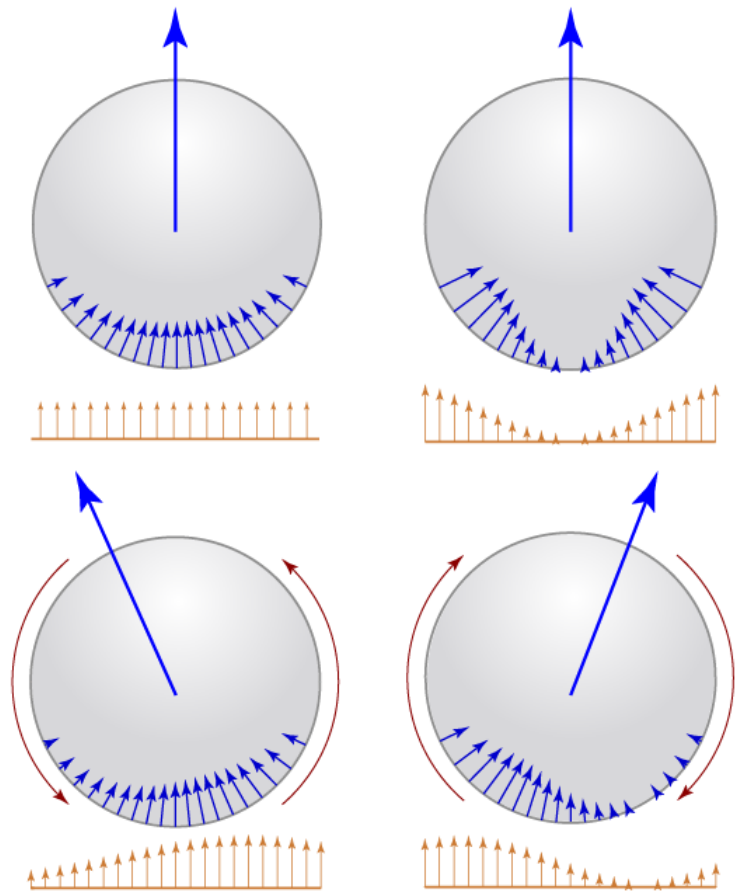
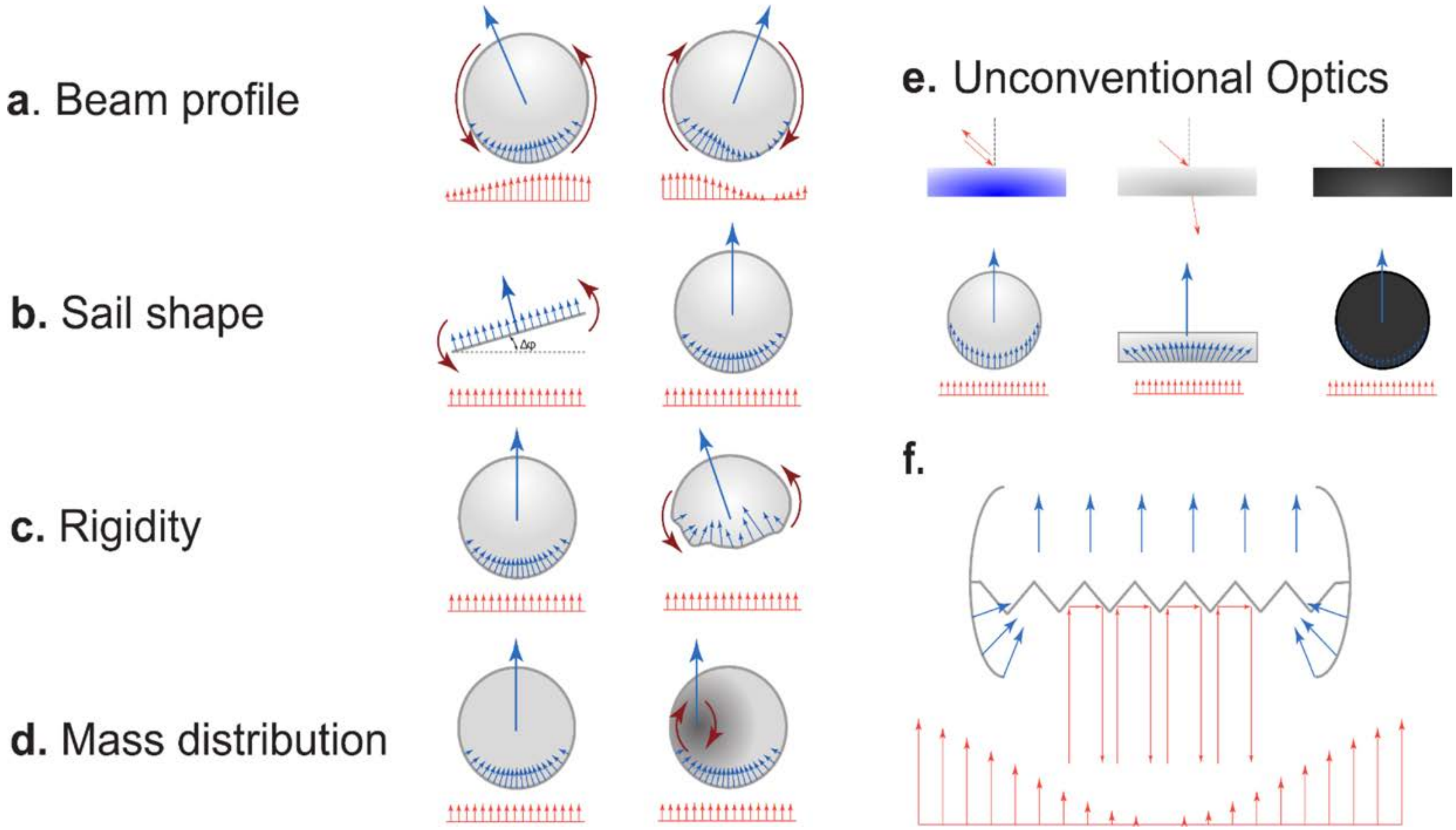
Lightsail Stability: the case of Spheres





Z. Manchester and A. Loeb, 2016 arXiv:1609.09506 [astro-ph.IM]

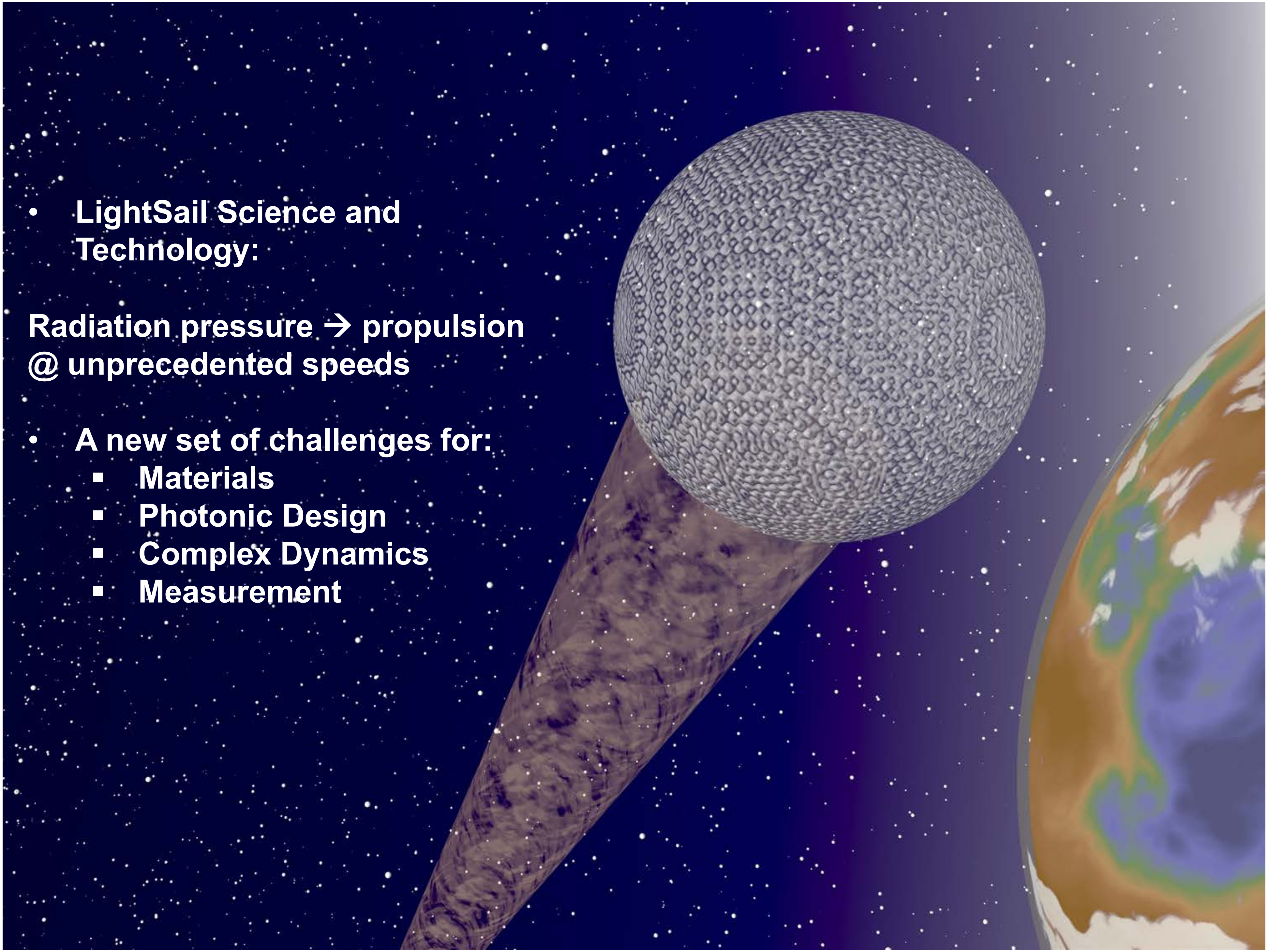
Light-material interactions and sail stability



Nature Materials (https://doi.org/10.1038/s41563-018-0075-8)

Expected Outcomes of Research Program

- Prioritized List of photonic designs
- List of usable sail materials
- Develop measurement methods
- Insight about how materials/design could enhance/enable intrinsic sail stability
- Fabrication and test – make a prototype!



- LightSail Science and Technology:

Radiation pressure → propulsion @ unprecedented speeds

- A new set of challenges for:
  - Materials
  - Photonic Design
  - Complex Dynamics
  - Measurement

Artur. Davoyan

Oggy Ilic

Deep Jariwala

Michelle Sherrott

Cora Went

Will Whitney

Joeson Wong