

# Planetary Sunshades for Solar Radiation Management

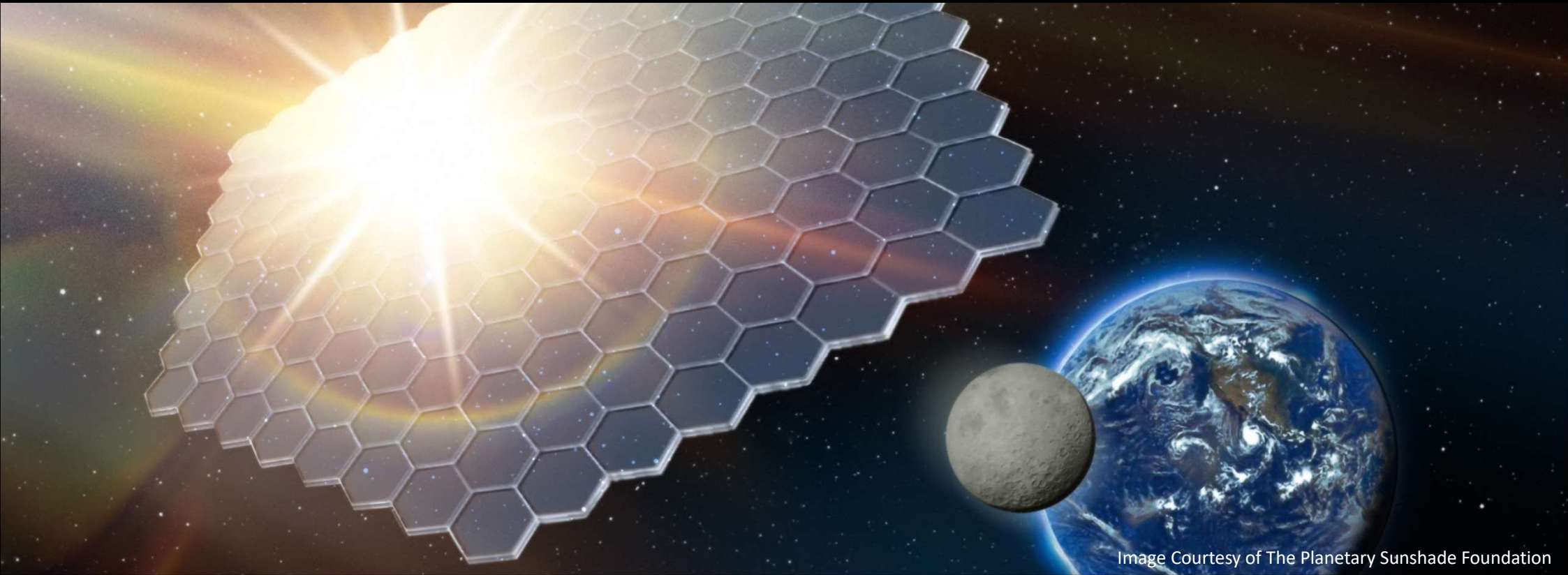


Image Courtesy of The Planetary Sunshade Foundation

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# The Earth's Radiation Balance is Out of Balance!

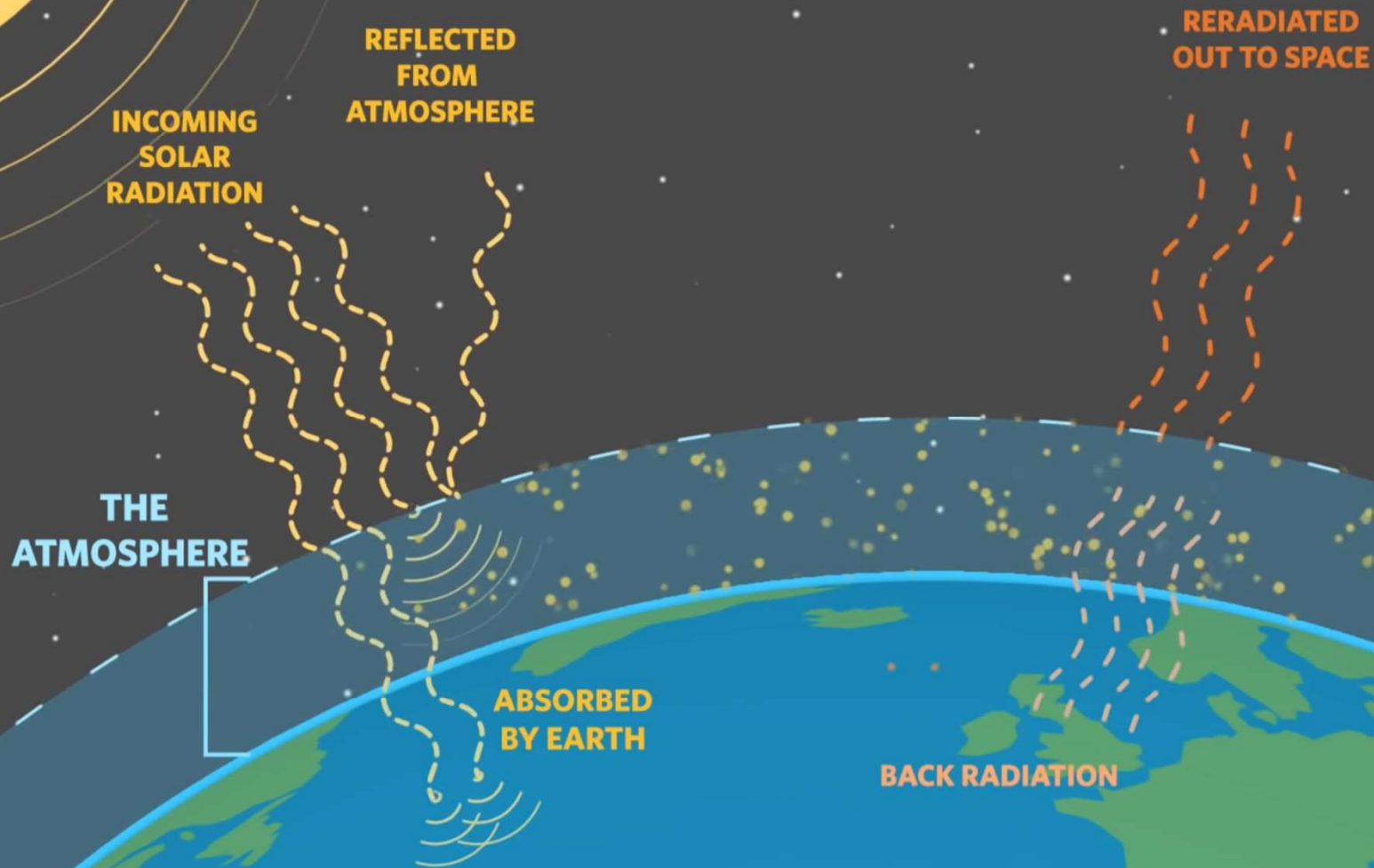
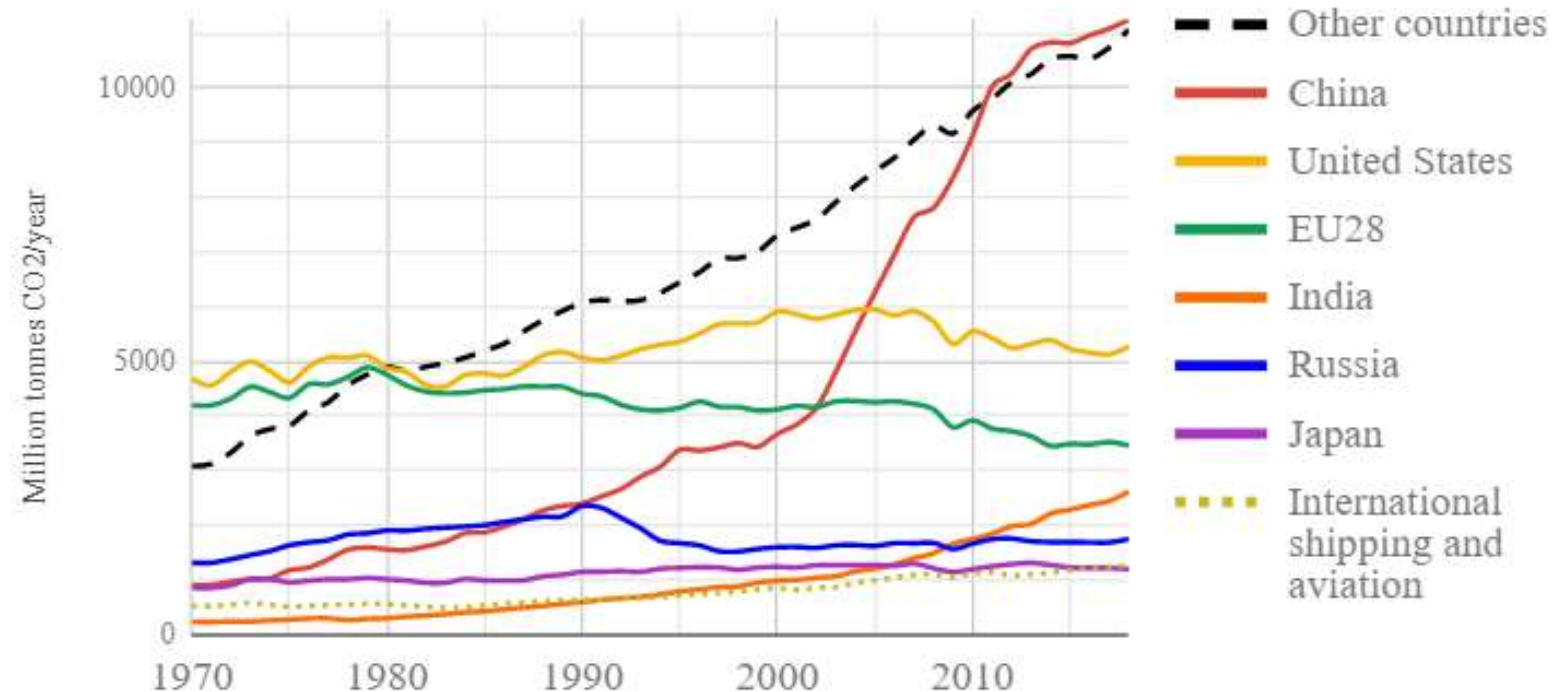


Image courtesy of the California Academy of Sciences

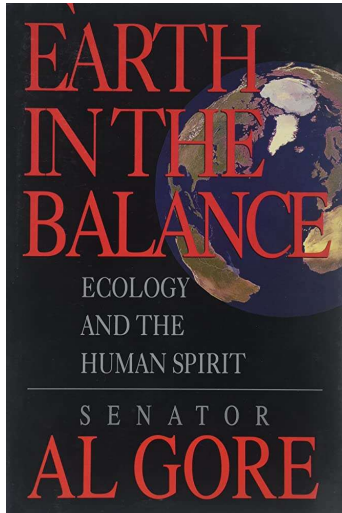
# The data that should cause you to wake up and pay attention

## World fossil carbon dioxide emission 1970-2018

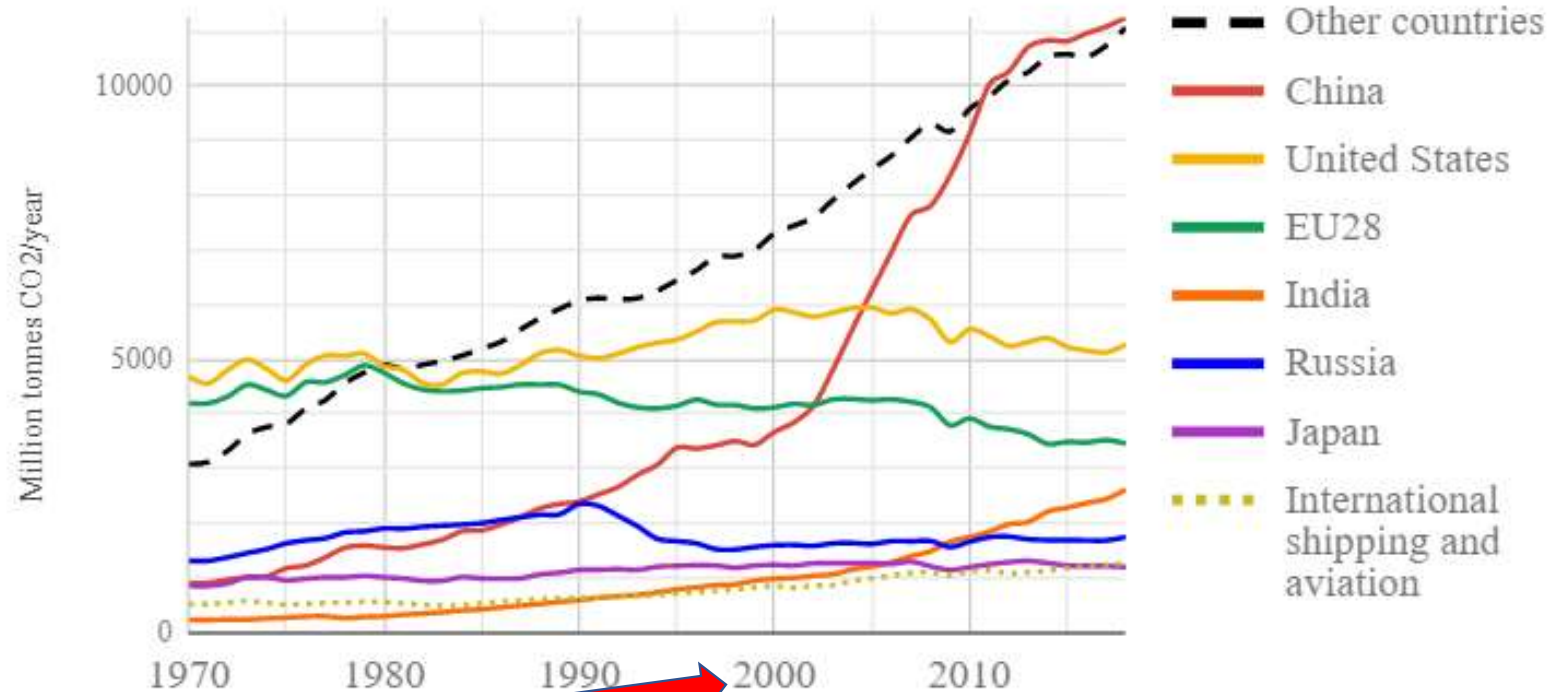


Data source: EDGAR - Emissions database for Global Atmospheric Research. Published in: Fossil CO2 and GHG emissions of all world countries - 2019 Report, EUR 29849 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-11100-9,, September 2019.

# The data that should cause you to wake up and pay attention



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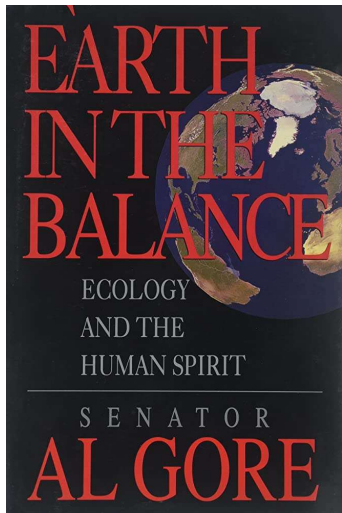


When published, the green emissions were significantly less than what they are today.

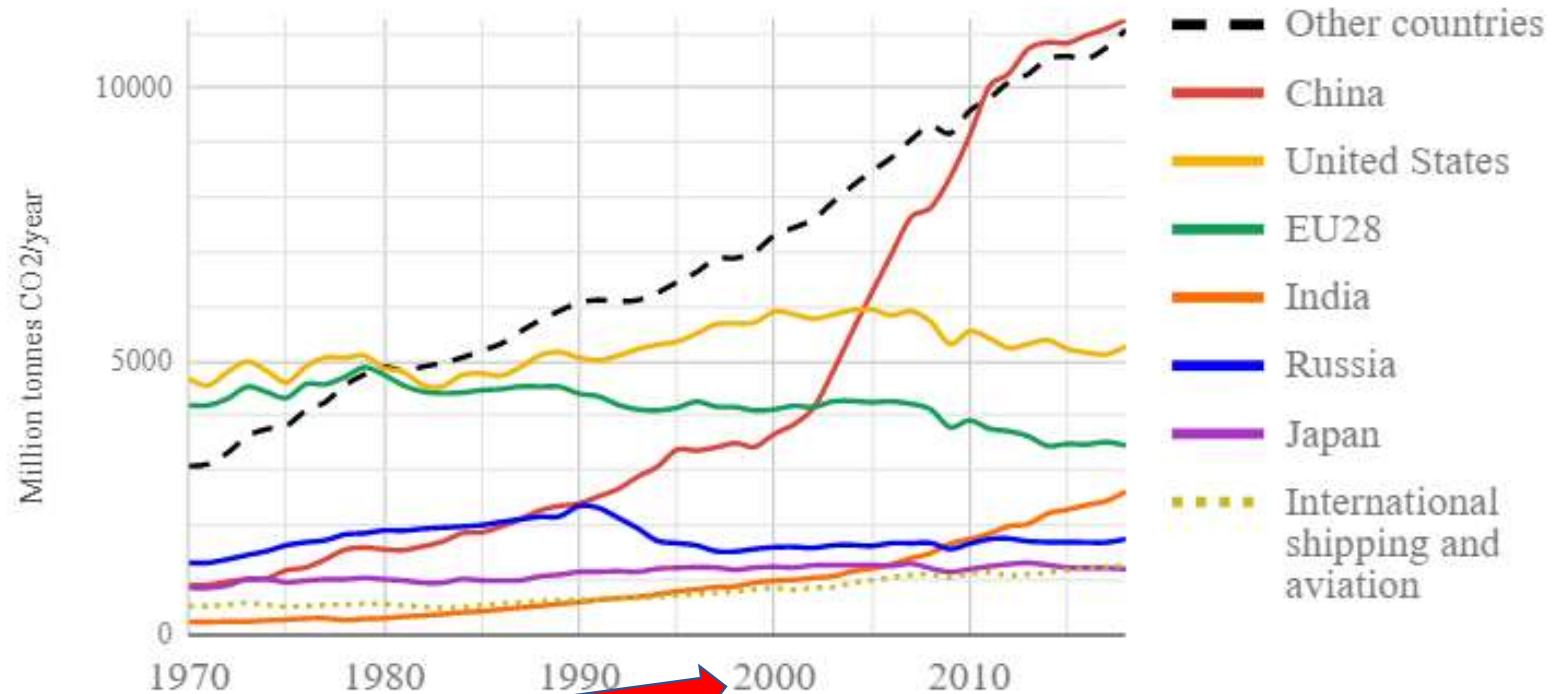
The problem has only gotten more difficult to solve...

Data source: EDGAR - Emissions database for Global Atmospheric Research. Published in: Fossil CO<sub>2</sub> and GHG emissions of all world countries - 2019 Report, EUR 29849 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-11100-9, September 2019.

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In May 3, 2023 US Congressional testimony from the US Deputy Secretary of Energy, it will take an estimated \$50 Trillion to decarbonize the US economy alone

# Solar Climate Intervention Methods

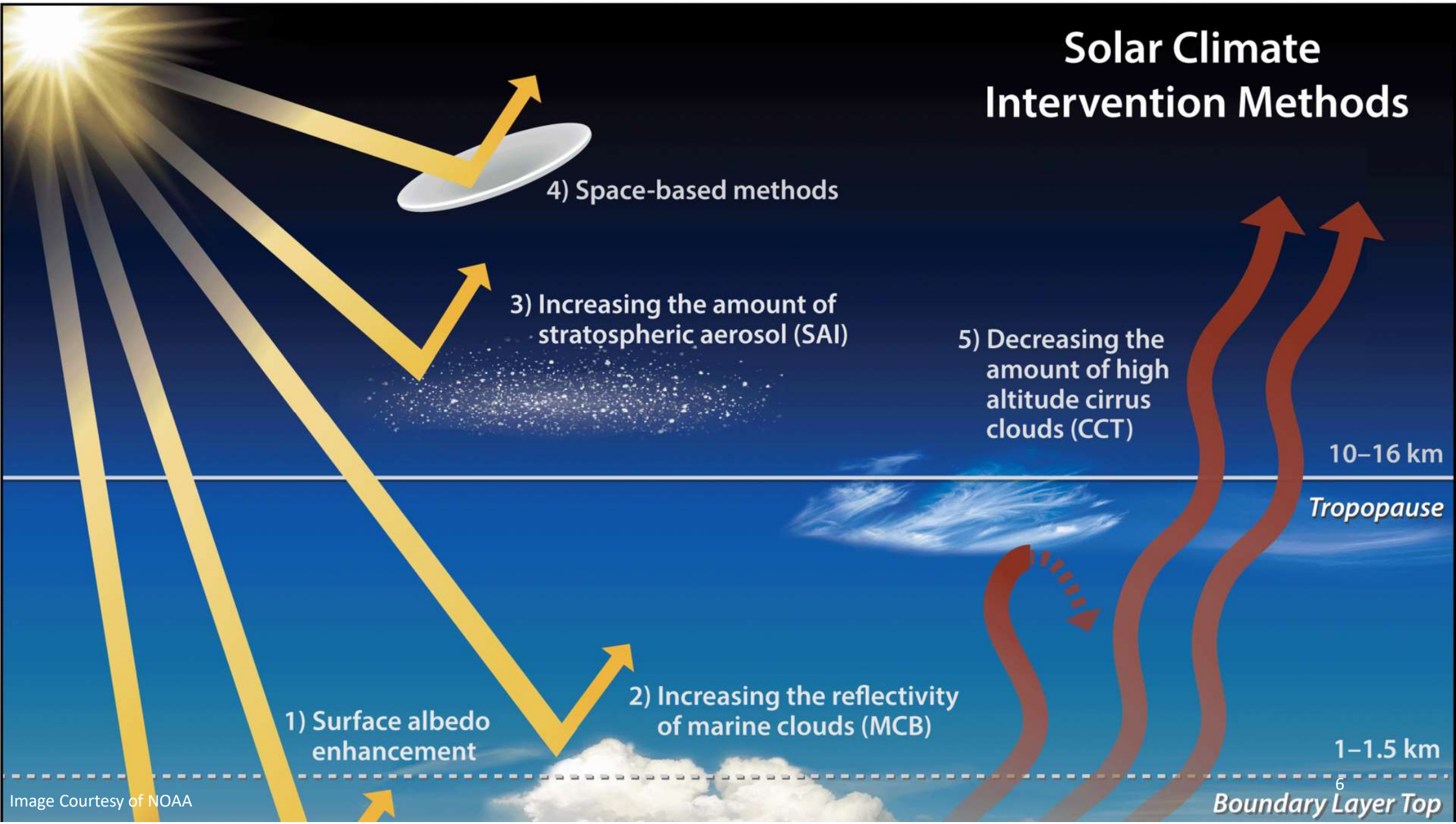
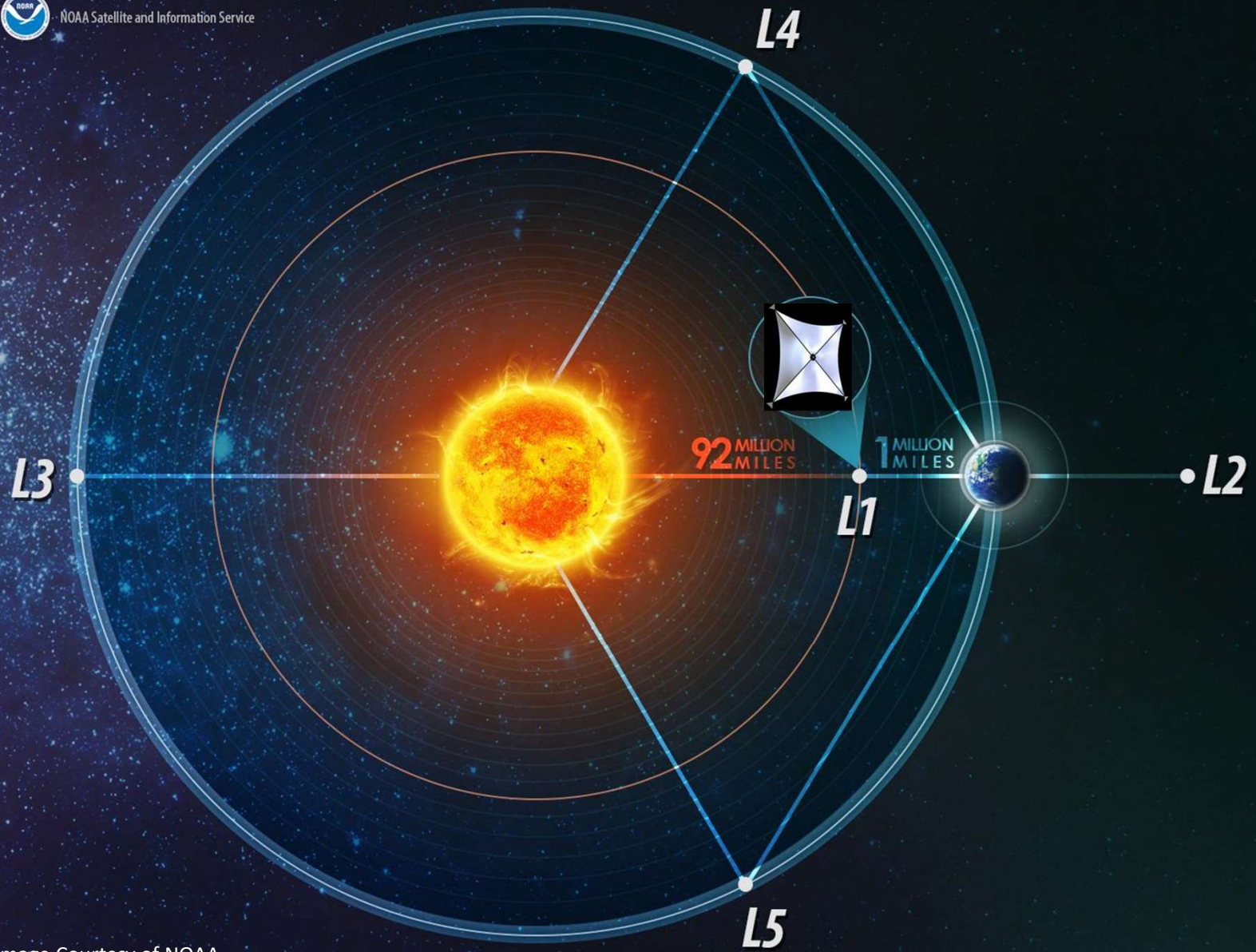


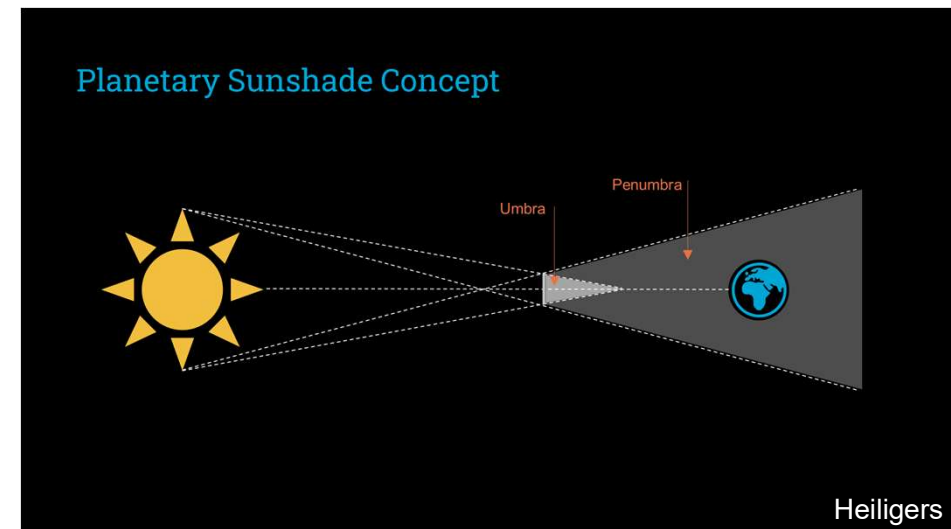
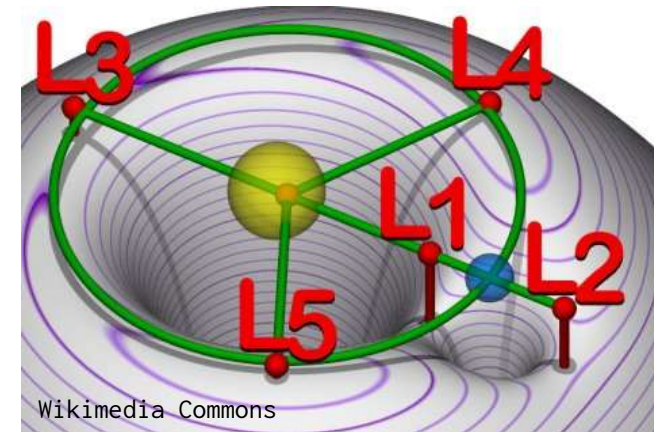
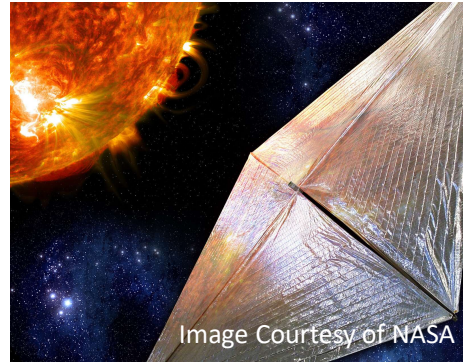
Image Courtesy of NOAA



**A Planetary Sunshade Can Mitigate Some Effects of Global Warming**

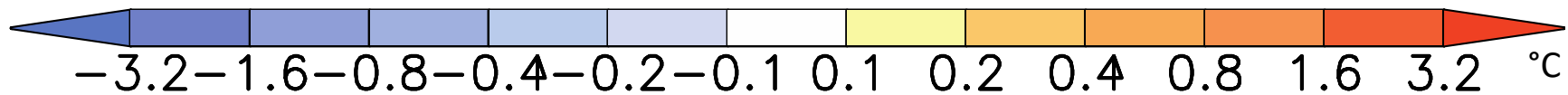
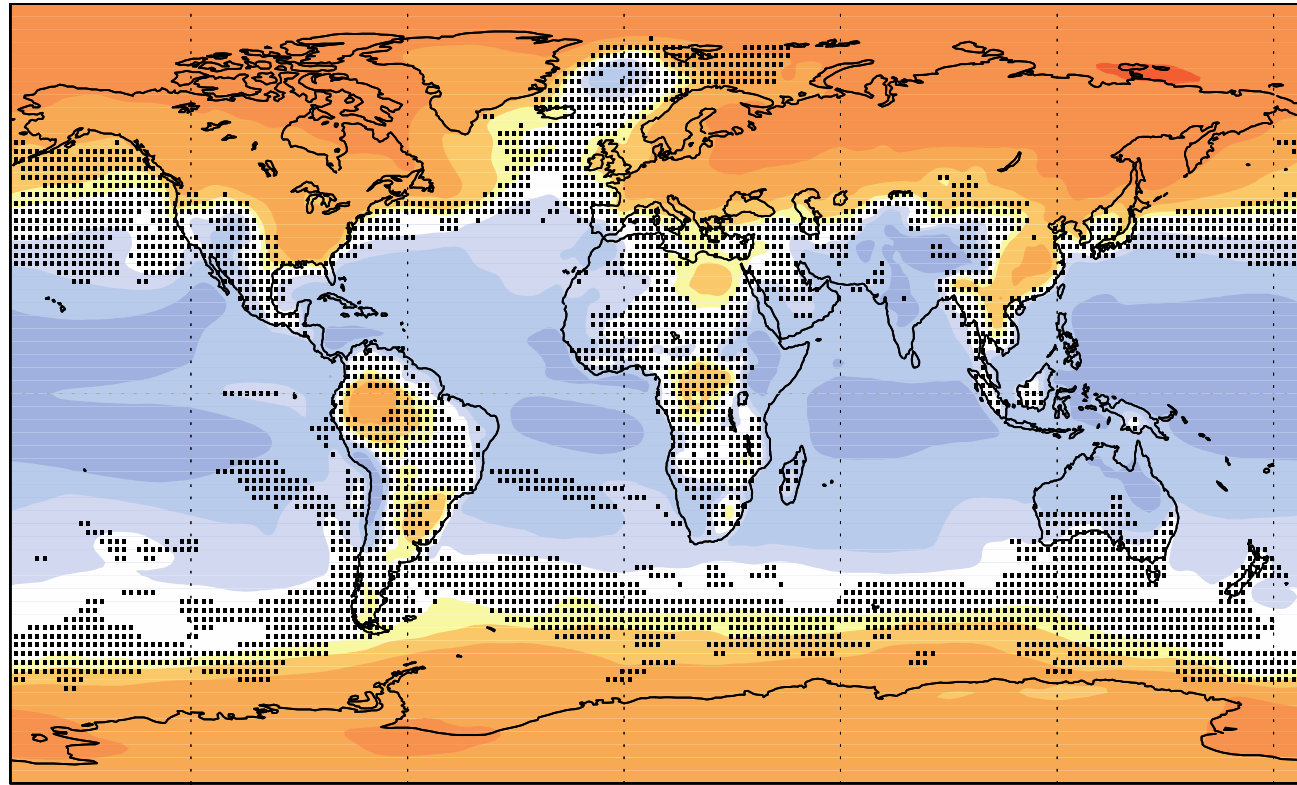
# Planetary Sunshade Fundamentals

- Orbits at Sun-Earth Lagrange 1
- Control by solar sailing
- Area: 1.5 - 2M km<sup>2</sup> for 1° cooling
  - Multiple smaller sunshades
- Positive externalities:
  - Easy to control and turn “on” and “off,” if needed
  - Can be a multinational collaboration
  - Could send 70TW to Earth if coupled with embedded photovoltaics and power beaming
  - Possible application to Planetary Defense





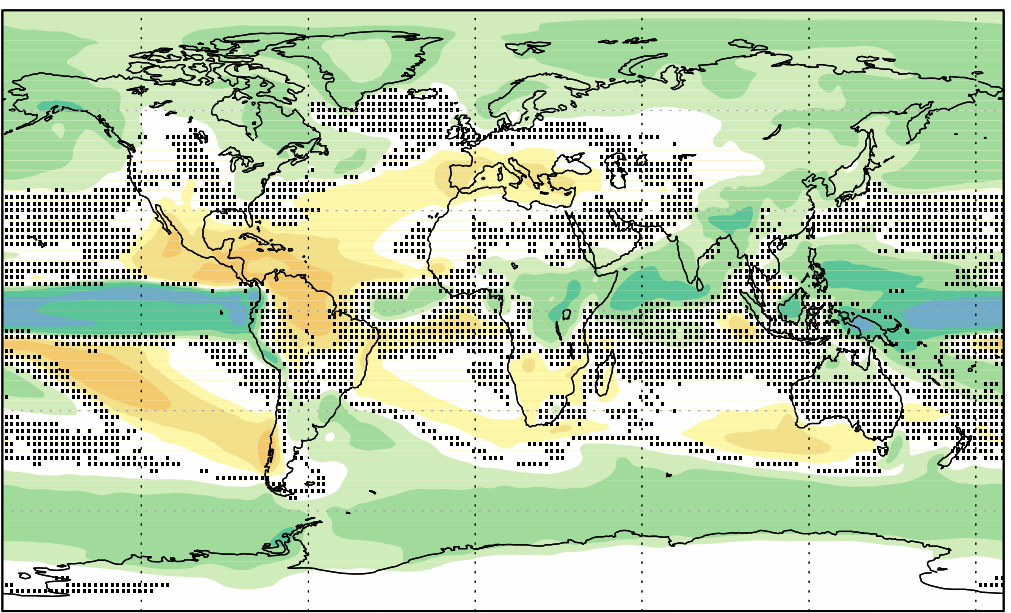
If you increase CO<sub>2</sub> and turn down the sun  
Sunshades “overcool” the tropics and “undercool” the poles



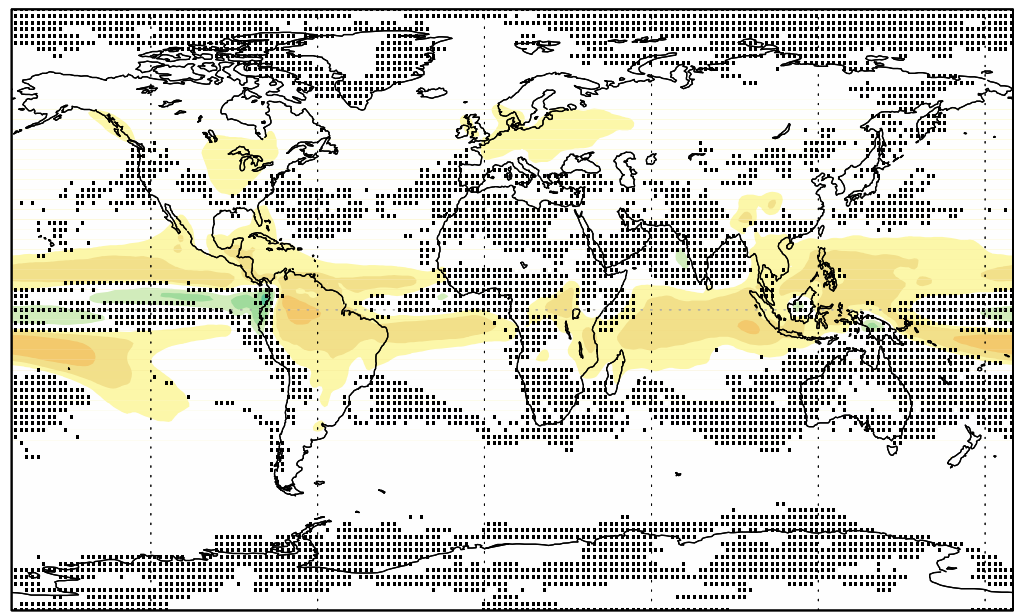
Stippling: disagreement on sign amongst 12 models

If you increase CO<sub>2</sub> and turn down the sun  
Precipitation goes down (but it would have gone up under global warming)

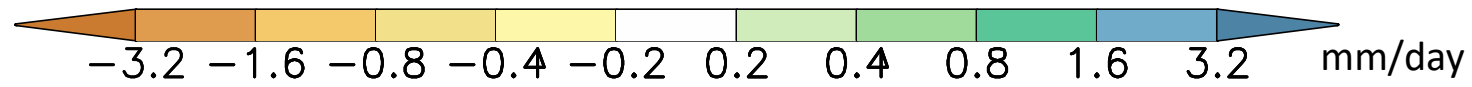
Change due to high CO<sub>2</sub>



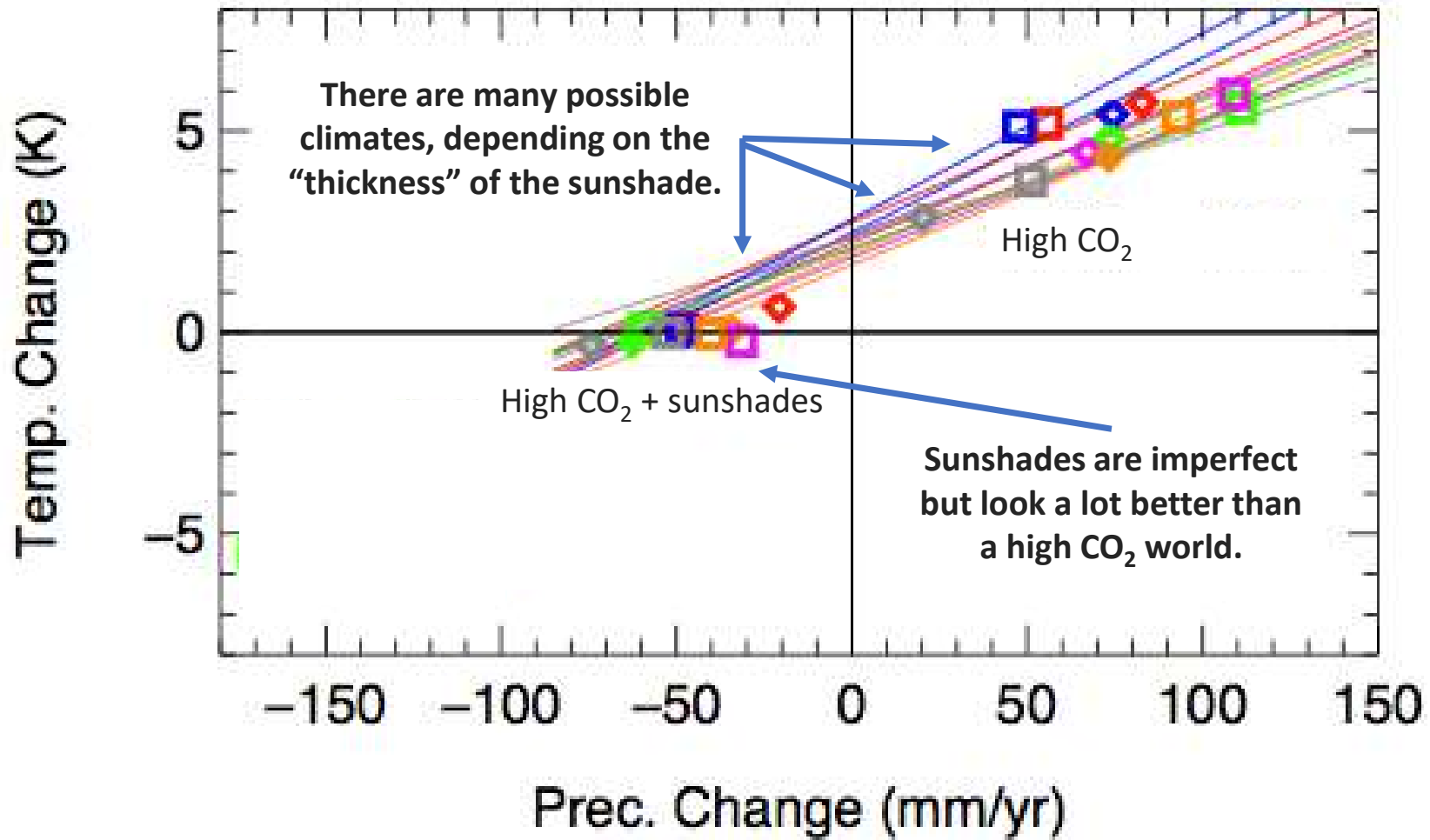
Change due to sunshades



Precipitation



Stippling: disagreement on sign amongst 12 models



Wiley light-jammer – 1951 – 61,000,000+ m<sup>2</sup>

# Global Progress of Solar Sail Technology

## From Research & Development ...

Concepts...  
Materials...  
Components...  
Mechanisms...  
System Testing...  
Qualification...  
Launch...  
Deployment...  
Orientation...  
Sailing...  
Control...  
Mission...

**Halley JPL**  
1977 – 722,500 m<sup>2</sup>

**Halley Helio gyro**  
1976 – 595,200 m<sup>2</sup>

**MASA MSFC 1/2 km**  
2002 – 250,000 m<sup>2</sup>

**UltraSail**  
2003 – 100,000s m<sup>2</sup>

**UltraSail**  
2018 – 100,000 m<sup>2</sup>

**ENEAS-/+SR**  
2005 – 2,500... 19,321 m<sup>2</sup>

**I-Sail**  
2017 – 2,500 m<sup>2</sup>

**GSWG MNR**  
DL1, SPO  
2013  
≥2,900 m<sup>2</sup>  
4,225 m<sup>2</sup>  
≥10,000 m<sup>2</sup>

**Gossamer-3**  
2015 – ≥2,500 m<sup>2</sup>

**Znamya-3**  
1999 – ≈2,500 m<sup>2</sup>

**OKEANOS**  
2021 – ≥2,000 m<sup>2</sup>

**Solar Cruiser**  
2022 – 1,650 m<sup>2</sup>

**Sunjammer**  
2014 – 1,444 m<sup>2</sup>

**Gossamer-2**  
2015 – ≥400 m<sup>2</sup>

**DLR ground test**  
1999 – 400 m<sup>2</sup>

**World Space Foundation**  
early 1980s – ≈200 m<sup>2</sup>

**ACS3**  
2023 – 81 m<sup>2</sup>

**NEA Scout**  
2023 – 85 m<sup>2</sup>

**Cosmos-1**  
2005 – 600 m<sup>2</sup>

**Znamya-2.5**  
1999 – ≈350 m<sup>2</sup>

**Znamya-2**  
1993 – ≈220 m<sup>2</sup>

**Cubesail (Surrey)**  
2011 – 25 m<sup>2</sup>

**Gossamer-1 EQM**  
2015 – 25 m<sup>2</sup>

**10s m<sup>2</sup>**

**CubeSail**  
2018 – 20 m<sup>2</sup>

**NanoSail-D**  
2008 – 10 m<sup>2</sup>

**LightSail-1**  
2015 – 32 m<sup>2</sup>

**NanoSail-D2**  
2010 – 10 m<sup>2</sup>

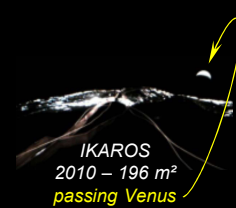
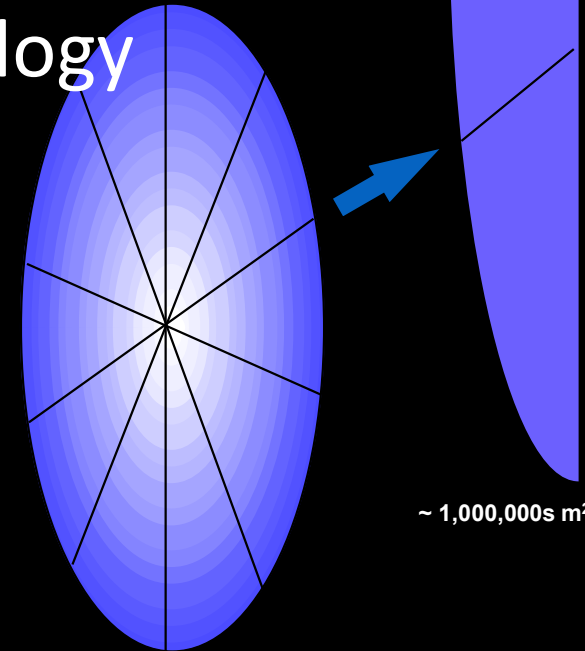
**InflateSail**  
2017 – 10 m<sup>2</sup>

**PW-Sat2**  
2018 – 4 m<sup>2</sup>

**LightSail-2**  
2019 – 32 m<sup>2</sup>


**1s m<sup>2</sup>**

← **Immega/PSF mini Solar Sail** – 2022 – ≈1 m<sup>2</sup>



... to flight & destination



 **Elon Musk** ✓  
@elonmusk

Replying to @elonmusk and @Erdyastronaut

Building 100 Starships/year gets to 1000 in 10 years or 100 megatons/year or maybe around 100k people per Earth-Mars orbital sync

6:01 PM · Jan 16, 2020 · Twitter for iPhone

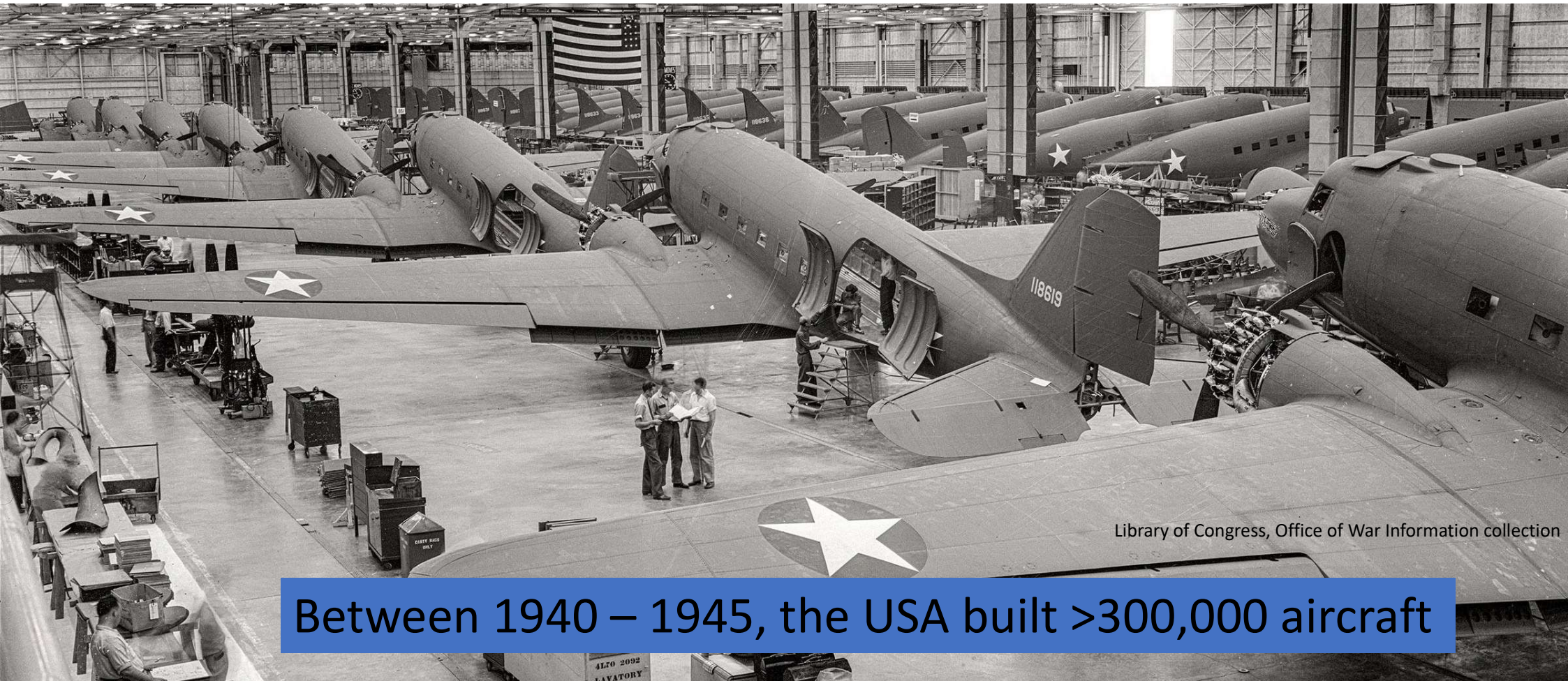
 **Elon Musk** ✓  
@elonmusk

Replying to @Erdyastronaut

Starship design goal is 3 flights/day avg rate, so ~1000 flights/year at >100 tons/flight, so every 10 ships yield 1 megaton per year to orbit

5:56 PM · Jan 16, 2020 · Twitter for iPhone

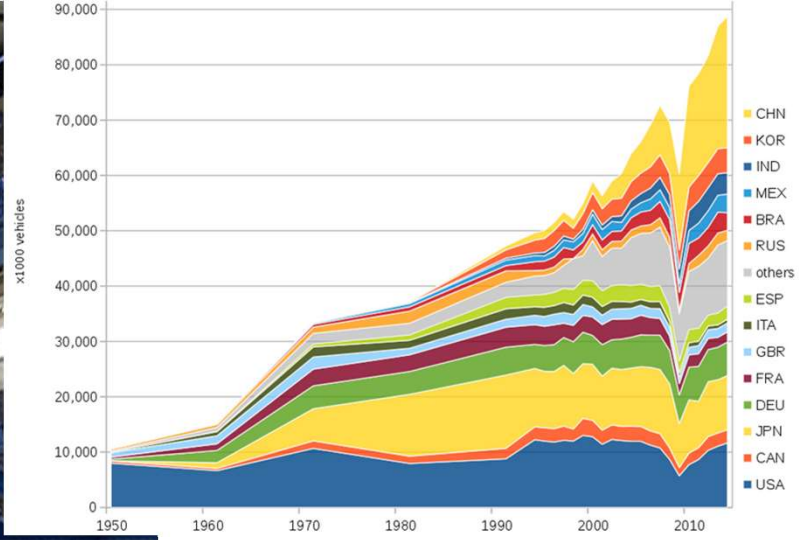
# Building and Launching Sunshade Sailcraft at Industrial Scale is Doable



Library of Congress, Office of War Information collection

Between 1940 – 1945, the USA built >300,000 aircraft

# Building Sunshade Sailcraft at Industrial Scale is Doable

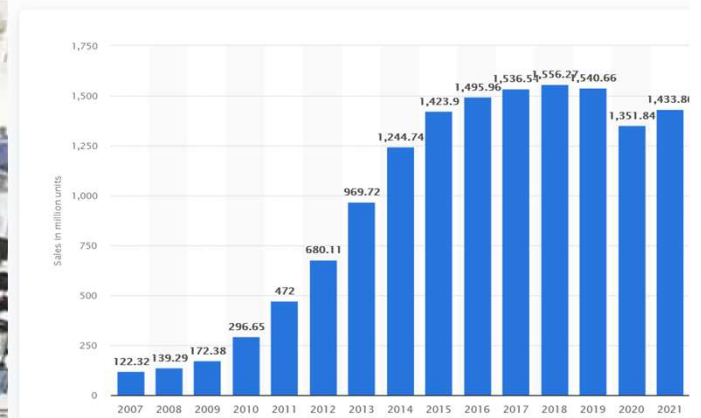


today, the world builds >85,000,000 cars per year in 2022

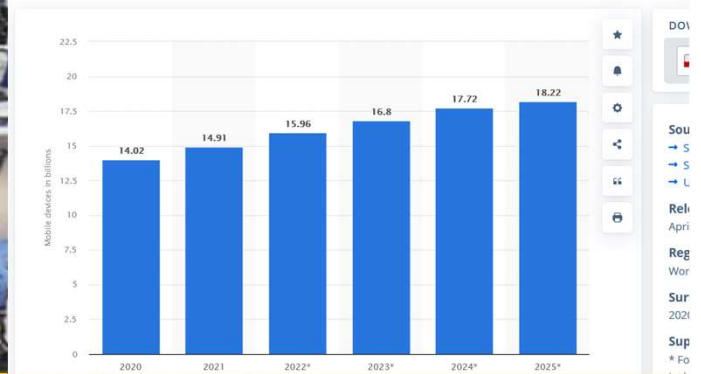
# Building Sunshade Sailcraft at Industrial Scale is Doable



Number of smartphones sold to end users worldwide from 2007 to 2021 (in million units)



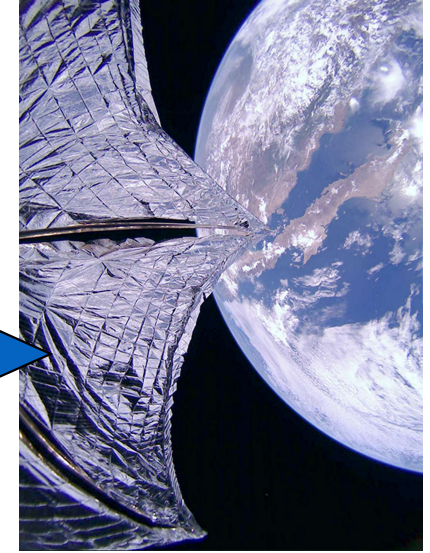
Forecast number of mobile devices worldwide from 2020 to 2025



today, the world builds >1,400,000,000 mobile phones per year in 2021



## Building Sunshade Sailcraft at Industrial Scale is Doable



- >85M vehicles built in 2022 worldwide
- average weight per car in the U.S.: 1,945 kg
- >165 Mt moving product mass per year
- equivalent of 2 to 3 Planetary Sunshades

...rolled out to 40 g/m<sup>2</sup>:

- 48,000 m<sup>2</sup> = (220 m)<sup>2</sup> per avg. car
- >4 M km<sup>2</sup> per year
- ≈2 Planetary Sunshades per year

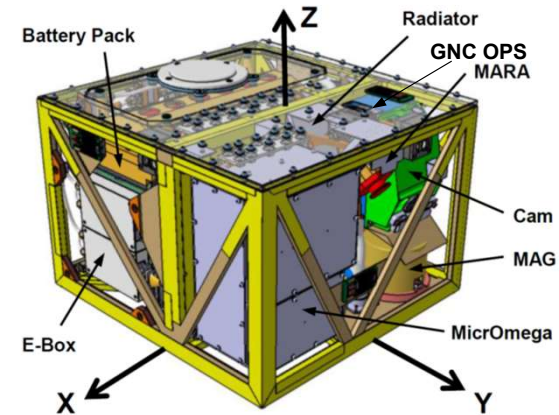
# Building Sunshade Sailcraft at Industrial Scale is Doable

new one comes in –  
serious money goes out for 2 years

serious money comes in –  
new one goes out 2 years later



- ← 4x 2 GHz OBC 2x 40 MHz →
- ← 128 GB Flash 0.88 GB →
- ← 12 Mpx Camera 1 Mpx →
- ← 54 MB/s WiFi 30 KB/s →
- ← buzzes motor jumps →
- ← Hall eff. MAG fluxgate →
- ← MEMS ACC almost... →
- ← included charger next time →



*(almost to scale)*

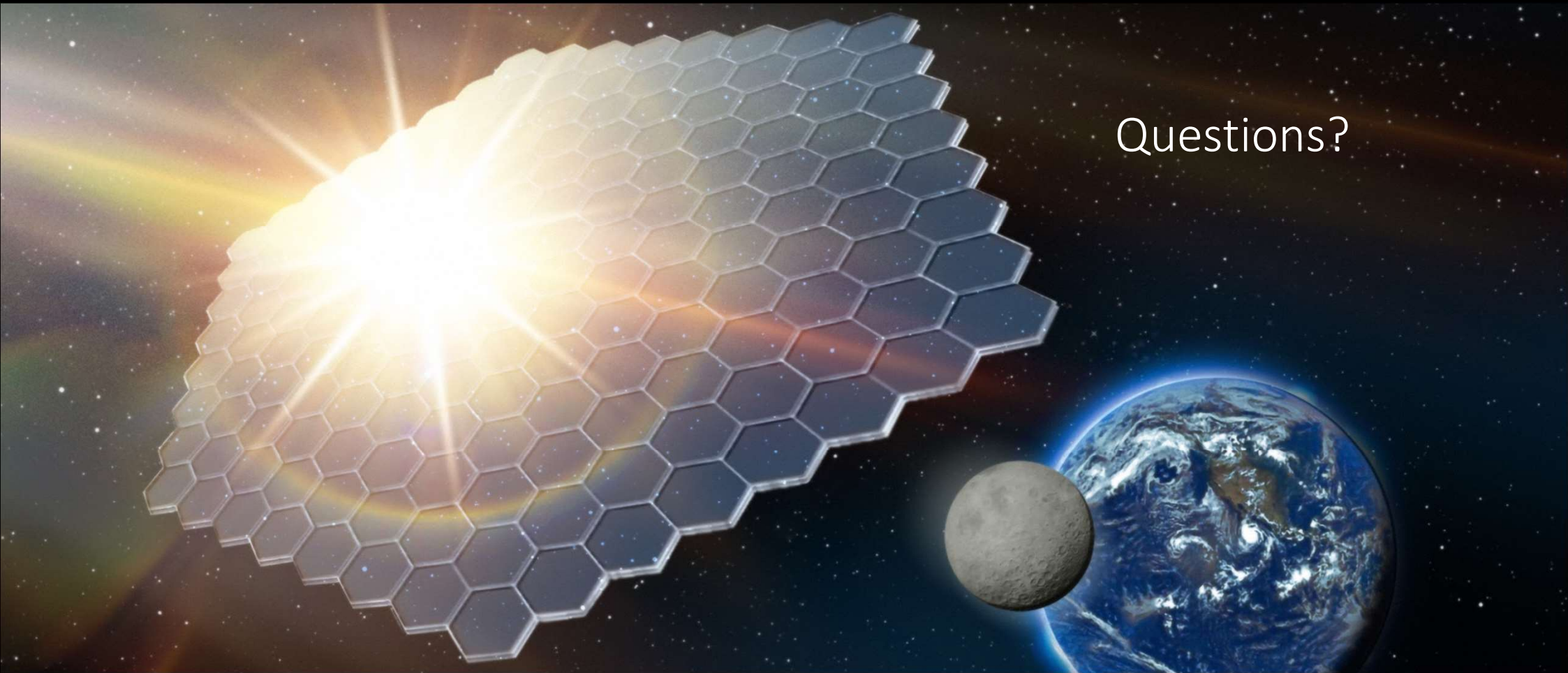
## Planetary Sunshades Are Part of a Comprehensive Strategy

- Reuse / Recycle
- Improve energy efficiency
- Net zero or negative carbon emissions
- Carbon capture
- Solar radiation management using planetary sunshades



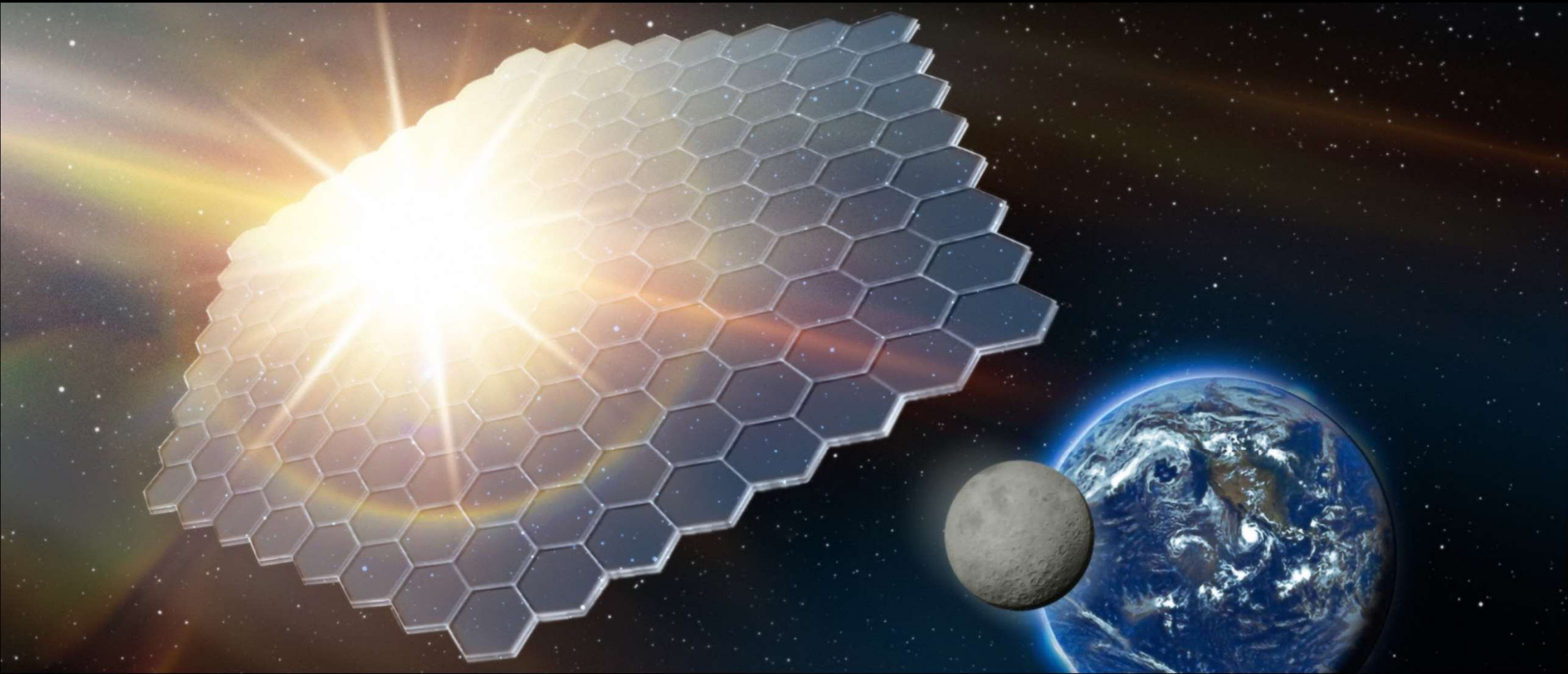
The Earth straddling the limb of the moon, as seen from above Compton crater by NASA's Lunar Reconnaissance Orbiter on October 12, 2015 NASA / GSFC / Arizona State University

# Planetary Sunshades for Solar Radiation Management



Questions?

# Backup Files



# Climate Economists Forecast Damage

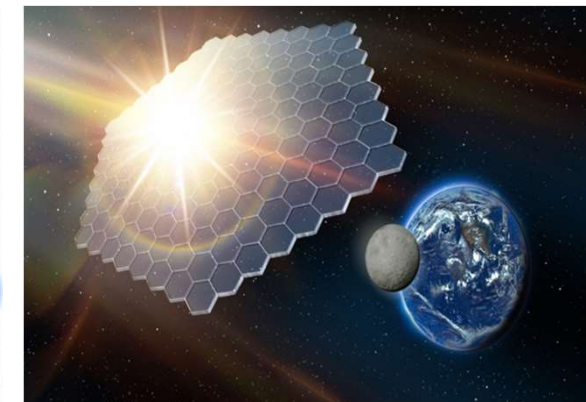
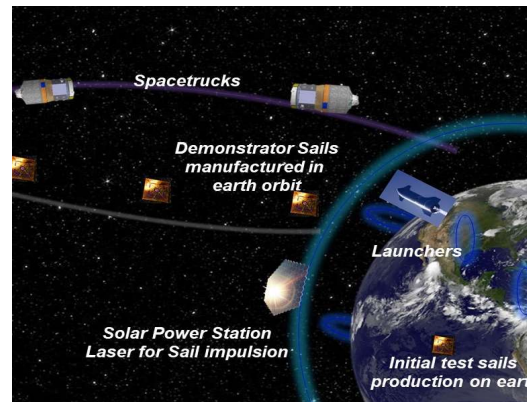
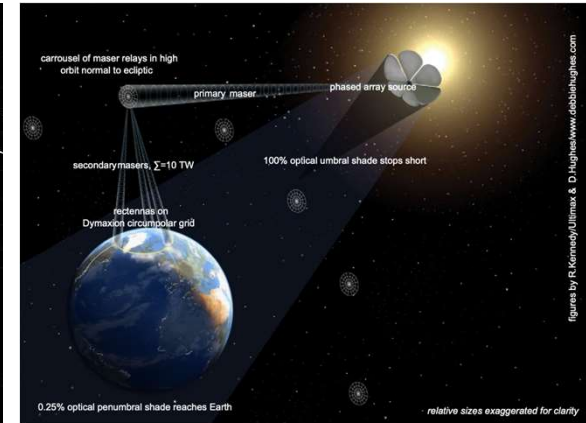
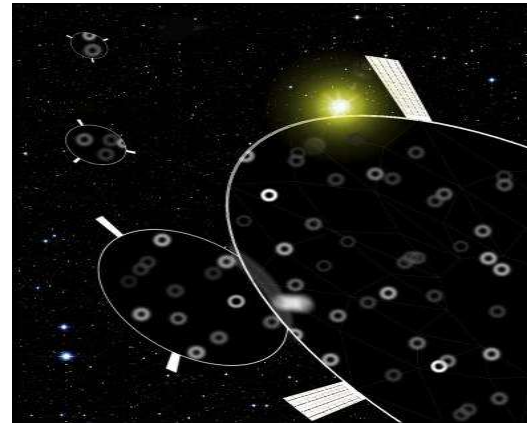
## Climate Damage Estimates

Year	2025	2075	2130	2220
Temperature increase (relative to pre-industrial era)	1.2°C	3°C	5°C	7°C
<b>Economic damages (% of global GDP) - Median estimate</b>	<b>-1%</b>	<b>-5%</b>	<b>-10%</b>	<b>-20%</b>
<b>Economic damages (trillions of 2019 USD) - Median estimate</b>	<b>-\$1.7</b>	<b>-\$29.8</b>	<b>-\$143.0</b>	<b>-\$730.9</b>
Economic damages (% of global GDP) - Mean estimate	-2.2%	-8.50%	-16.10%	-25.20%
Economic damages (trillions of 2019 USD) - Mean estimate	-\$3.8	-\$50.6	-\$230.3	-\$920.9
Standard deviation	2.9	7.6	13.3	20.7

*Results above reflect the trimming of outlier estimates below the 5<sup>th</sup> percentile or above the 95<sup>th</sup> percentile of total responses.*

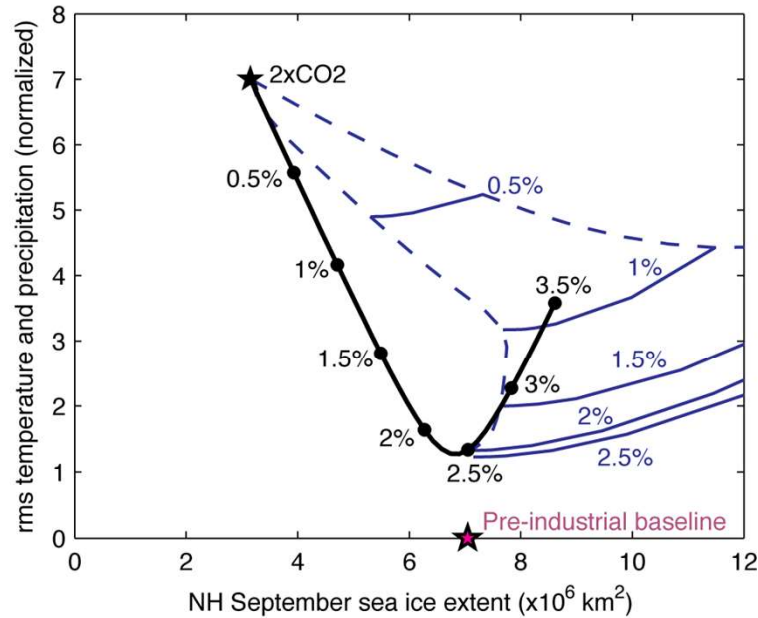
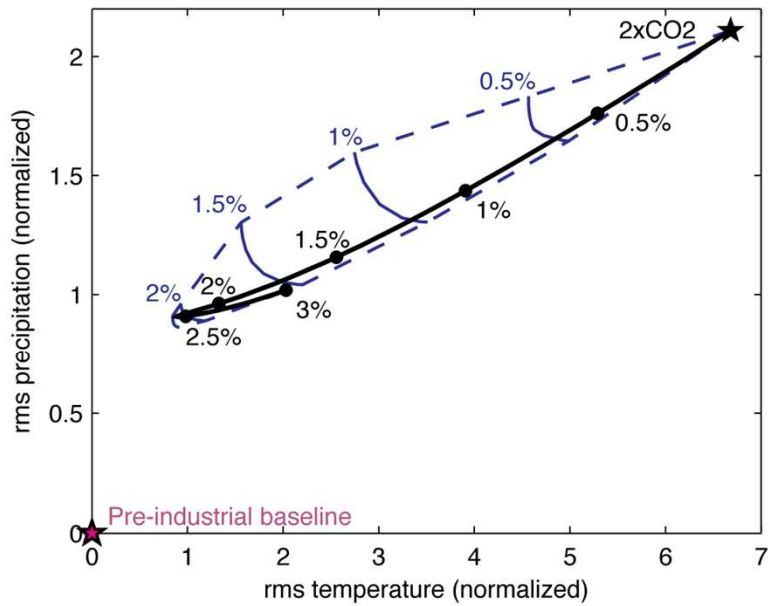
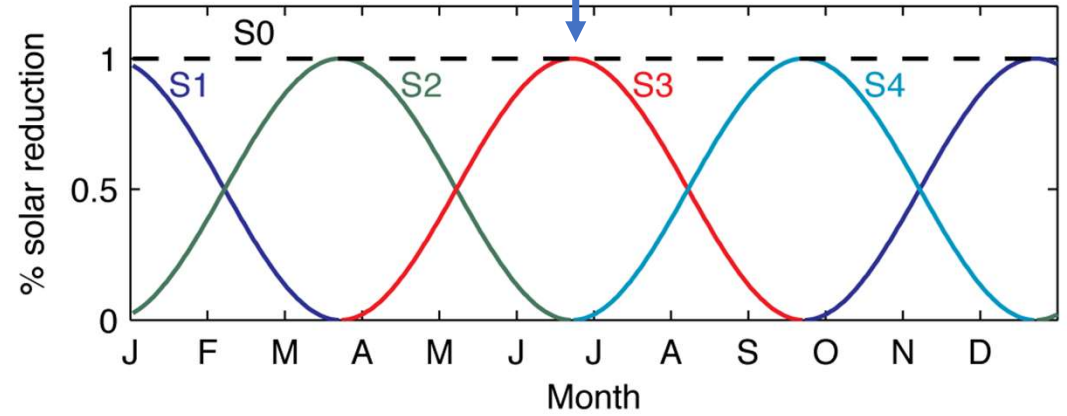
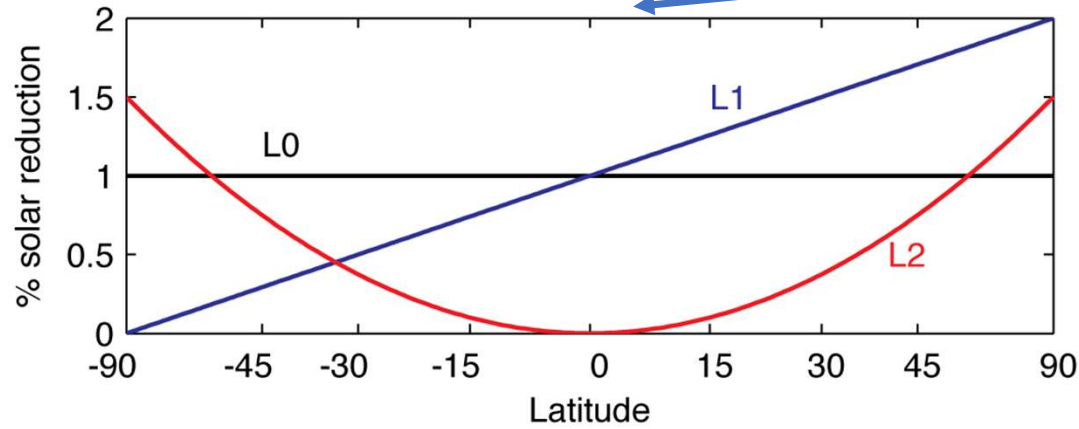
# Sunshade Concept History

- Early, 1989  
Identified principles, lunar resources
- McInnes, 2002  
Refined concept, identified minimum mass
- Angel, 2006  
Proposed swarm launched from Earth
- Kennedy et al., 2012  
Photovoltaic “Dyson Dot”
- Sanchez & McInnes, 2015  
Identified control law, modeled climate effect
- Centers et al., 2020  
Incorporated Starship
- Brauer, 2020  
IPSS concept (in development)
- Fix, Maheswaran, 2021  
Masters theses on IPSS
- Fuglesang, 2021  
Feasibility of Earth-launched architecture



Bibliography (courtesy Yomay Shyur)  
<https://planetarysunshade.org/publications>

You can get a wider variety of net climates by varying the latitude or season of the sunshades



Black solid line = uniform, annual sunshades (effects vary depending on how much the sun is turned down)

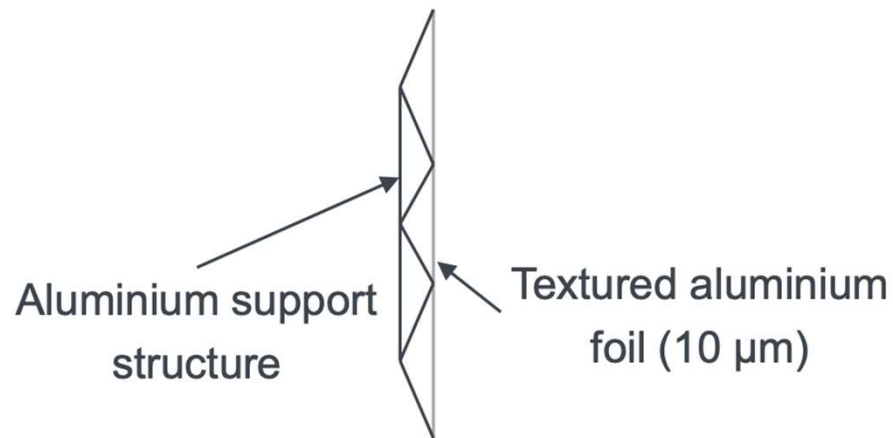
Blue lines = achievable climates by varying latitude and season



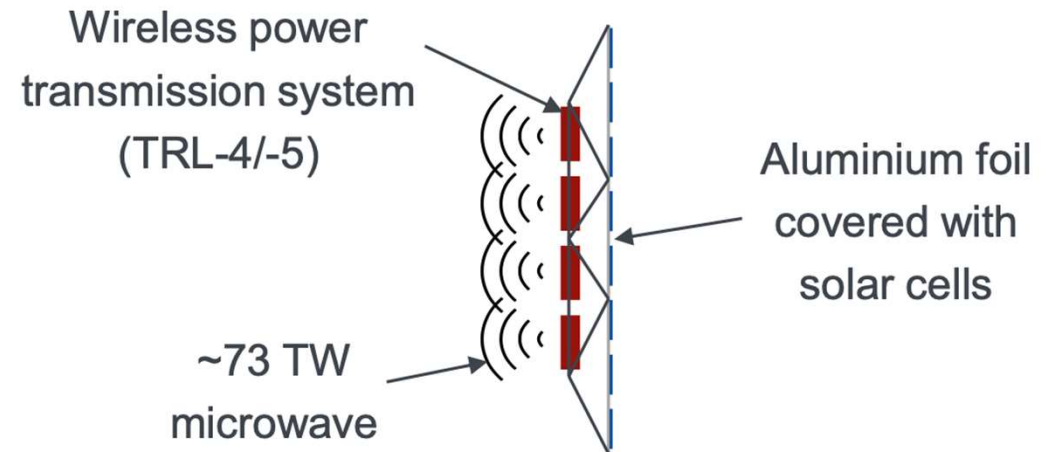
# Sunshade Design Concepts

Sebastian Fix, 2021

## Aluminium Sunshade

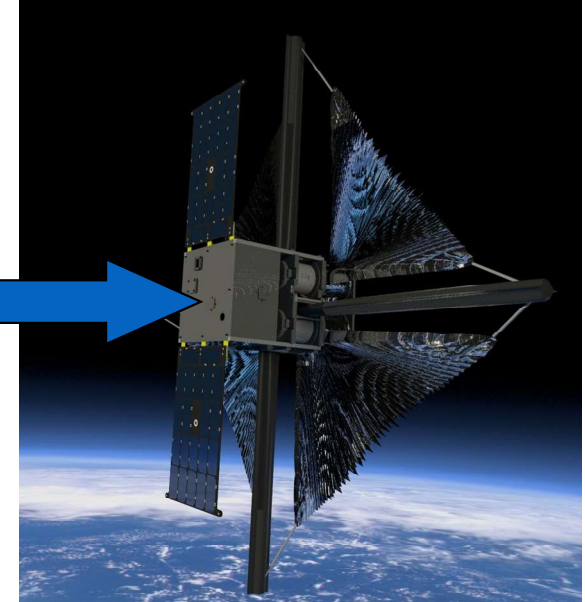
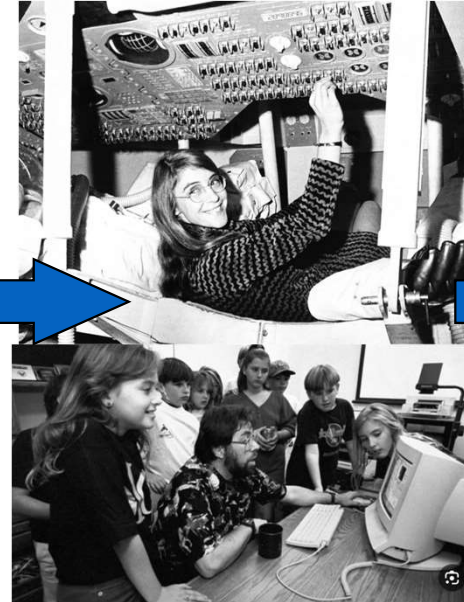


## Photovoltaic Sunshade



$\Delta T = 1 \text{ K}$	Aluminium Sunshade	Photovoltaic Sunshade
Areal Density	$43.2 \frac{\text{g}}{\text{m}^2}$	$334 \frac{\text{g}}{\text{m}^2}$
Distance to Earth	$2.199 \times 10^9 \text{ m}$	$1.558 \times 10^9 \text{ m}$
Total area	$1.708 \times 10^6 \text{ km}^2$	$857,128 \text{ km}^2$
Total mass	$73.74 \times 10^6 \text{ t}$	$286 \times 10^6 \text{ t}$

# Building Sunshade Sailcraft at Industrial Scale is Doable



- >1.4 G mobile phones built in 2021
- >16 G mobile devices operate worldwide
- typical mass 120 ... 250 g  $\rightarrow$  0.3 Mt/year
- 10's to  $\approx$ 2000 ICs per mobile device (incl. cars)

- ...in a sunshade of various small sails:
- 2 M km<sup>2</sup>  $\rightarrow$   $\geq$ 200 M sails of (100 m)<sup>2</sup>
- 2 M km<sup>2</sup>  $\rightarrow$   $\geq$ 2 T mini-sails of 1 m<sup>2</sup>
- IC supply > several Sunshades/year

