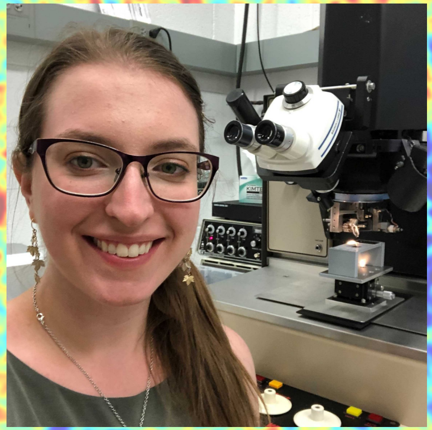
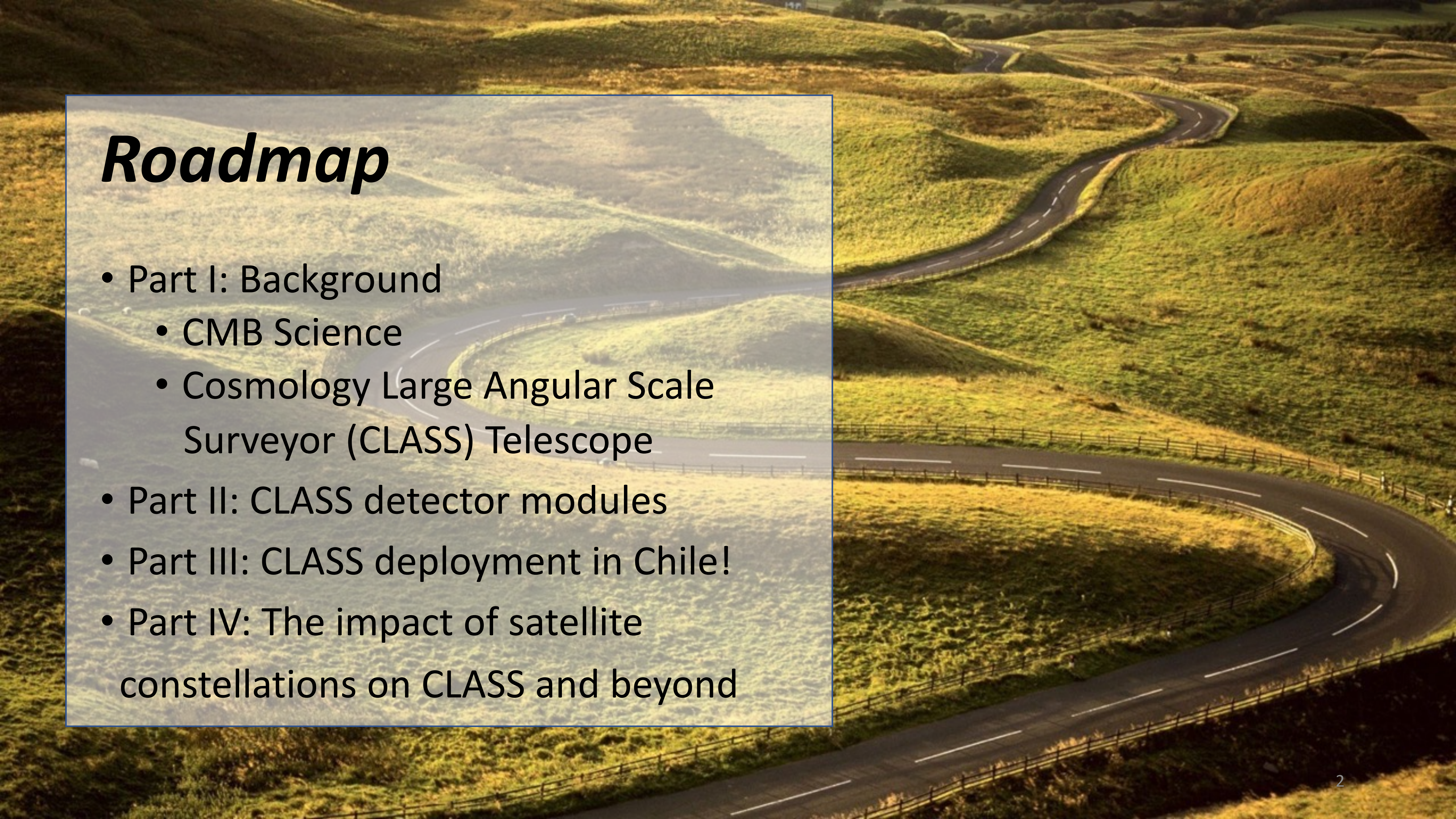
Microwave Telescopes: how *do* you get a camera to work at 0.1 Kelvin??

"Zen and the Art of Wire Bonding"

July 29, 2022



Sarah Marie Bruno
JHU QuarkNet
Johns Hopkins University
sbruno3@jhu.edu



Roadmap

- Part I: Background
  - CMB Science
  - Cosmology Large Angular Scale Surveyor (CLASS) Telescope
- Part II: CLASS detector modules
- Part III: CLASS deployment in Chile!
- Part IV: The impact of satellite constellations on CLASS and beyond

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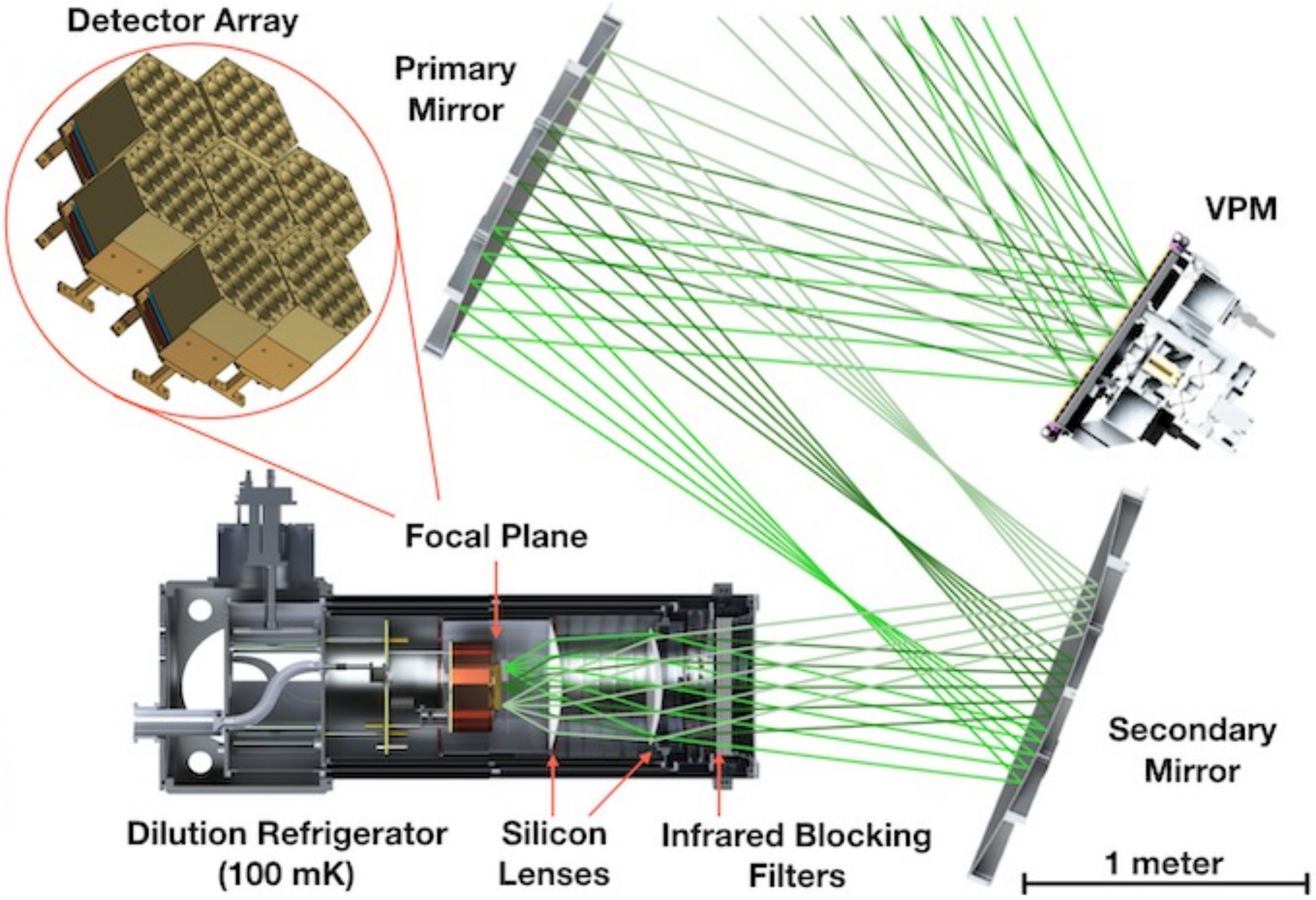
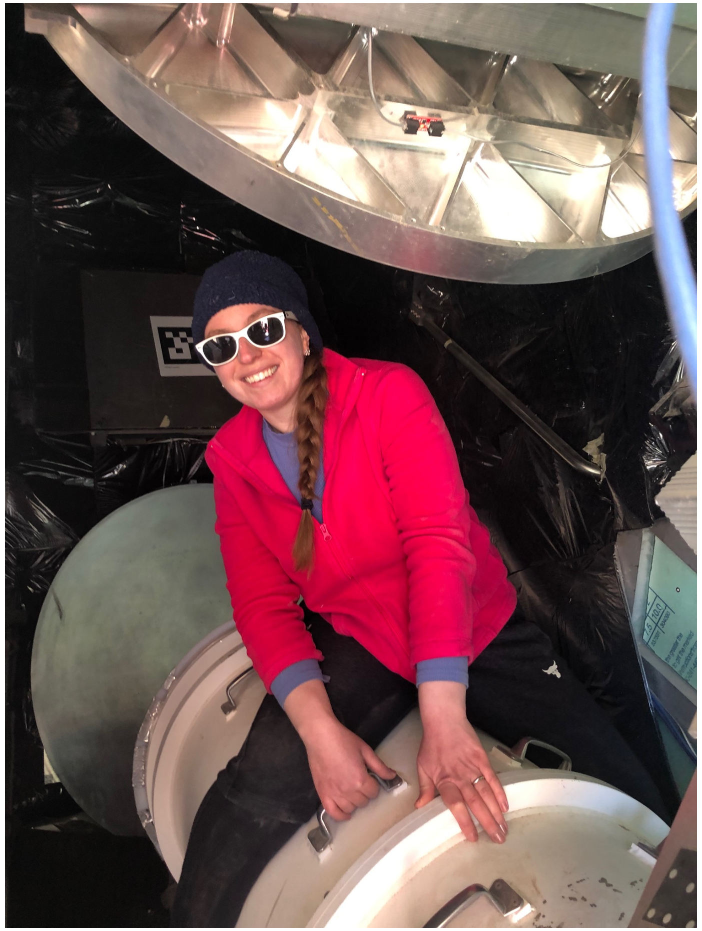
Part I

Introduction: CMB Cosmology & CLASS

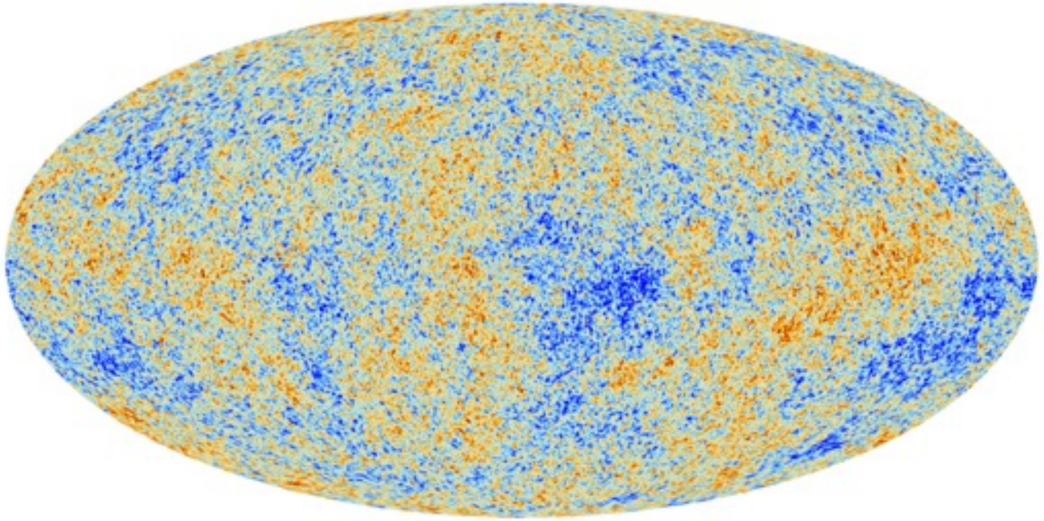
Cosmology Large Angular Scale Surveyor (CLASS) Telescope



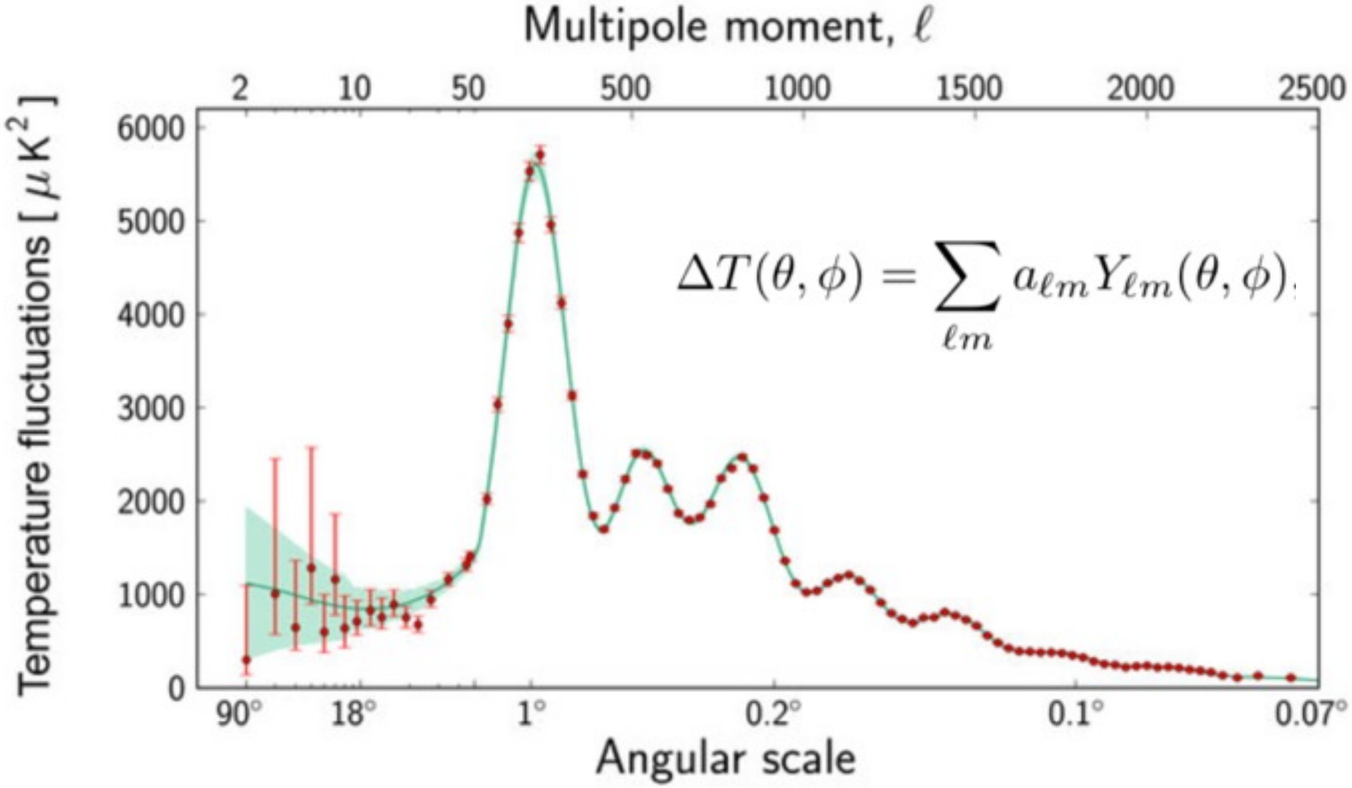
Inside the mount!



CMB Observation: Temperature

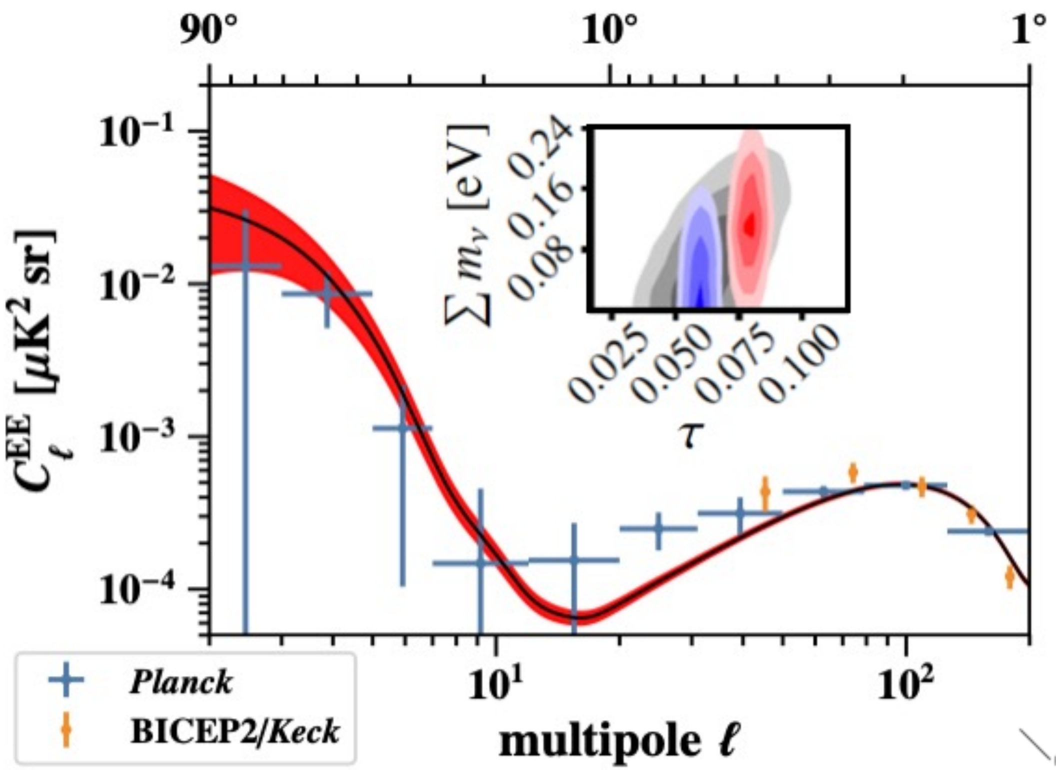


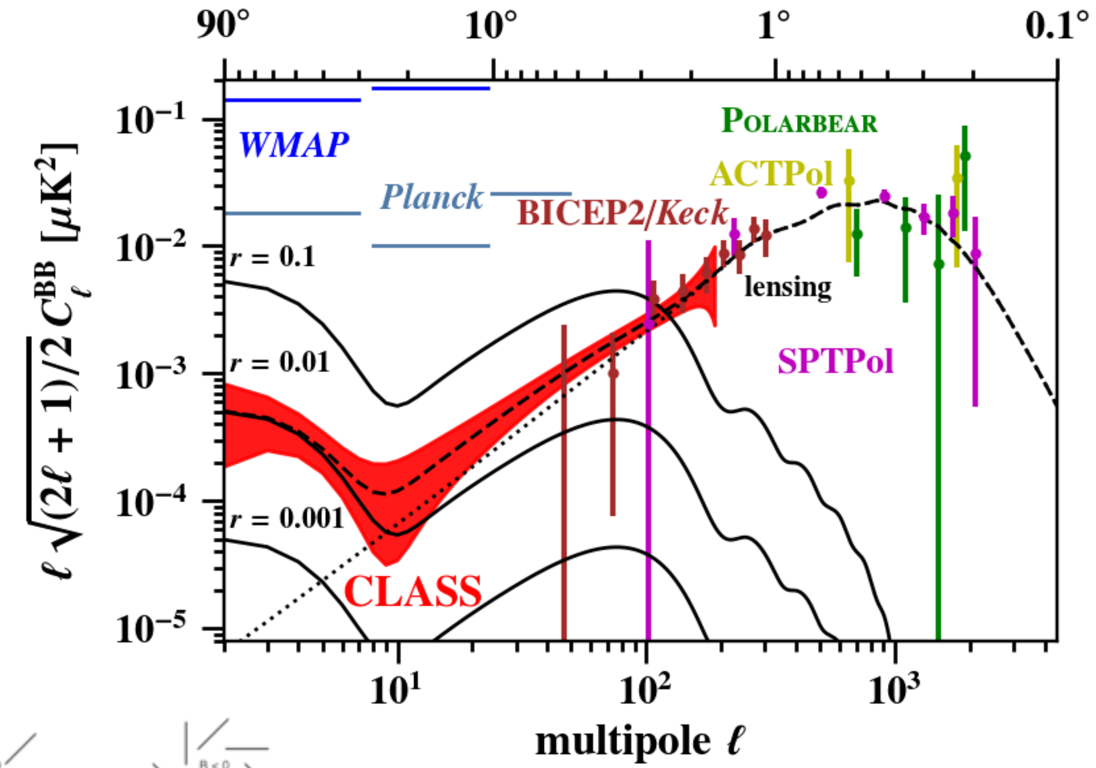
Planck map

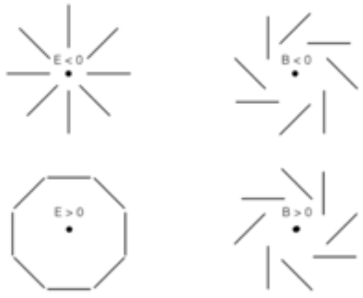


Temperature power spectrum measured by the Planck Science Team

CMB Observation: Polarization



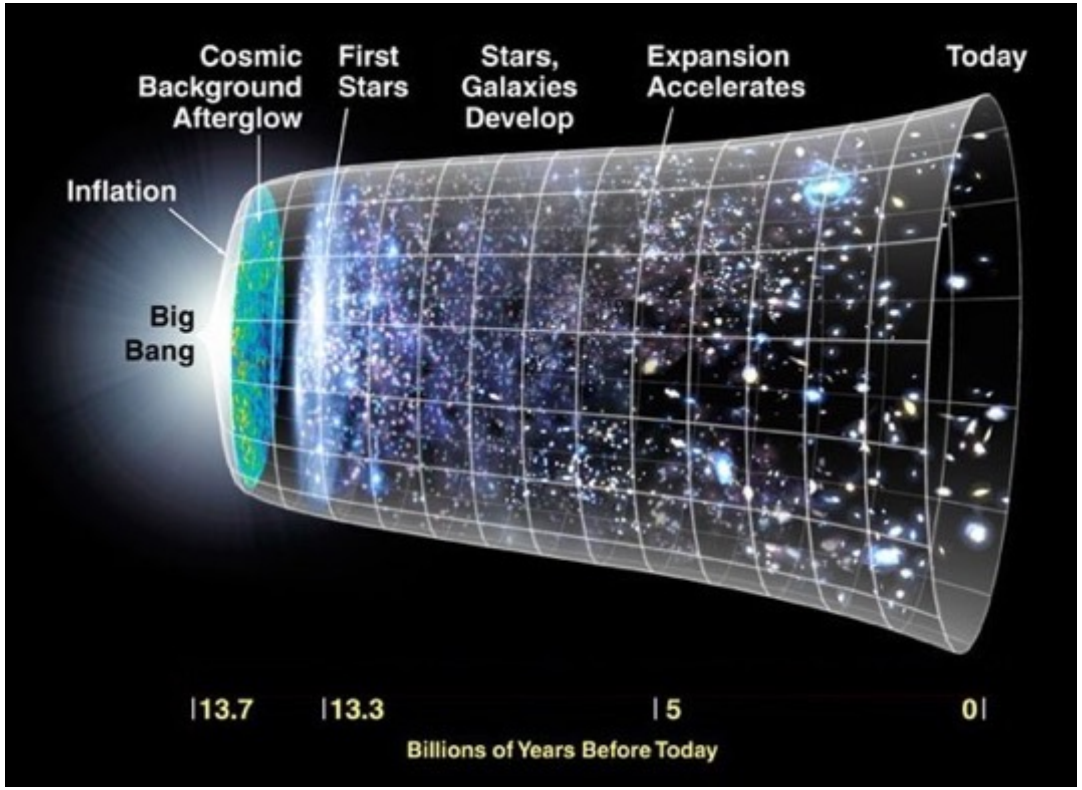




Polarization: E-modes and B-modes

CMB Science Goals

- Searching for evidence of inflation
- Constraining the optical depth to reionization
- Constraining the tensor-to-scalar ratio on large angular scales
- Studying secondary distortions such as those generated by gravitational lensing on small angular scales
- Characterizing galaxy clusters



NASA/WMAP Science Team

Location, Location, Location

Frequency Bands

Low-frequency (Q)

- 40 GHz
- Anomalous microwave emission
- Spinning dust
- Synchrotron dominates

Mid-frequency (W1, W2)

- 90 GHz
- CMB measurements
- W1 currently on-sky
- W2 to be deployed 2022

High Frequency (HF)

- 150/220 GHz dichroic
- Dust tracing
- Foreground removal

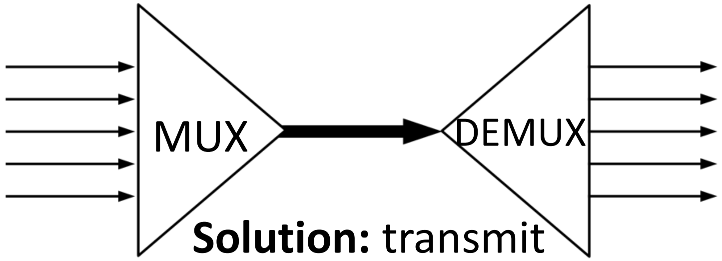
Part II

What I do….

Focal Plane Development

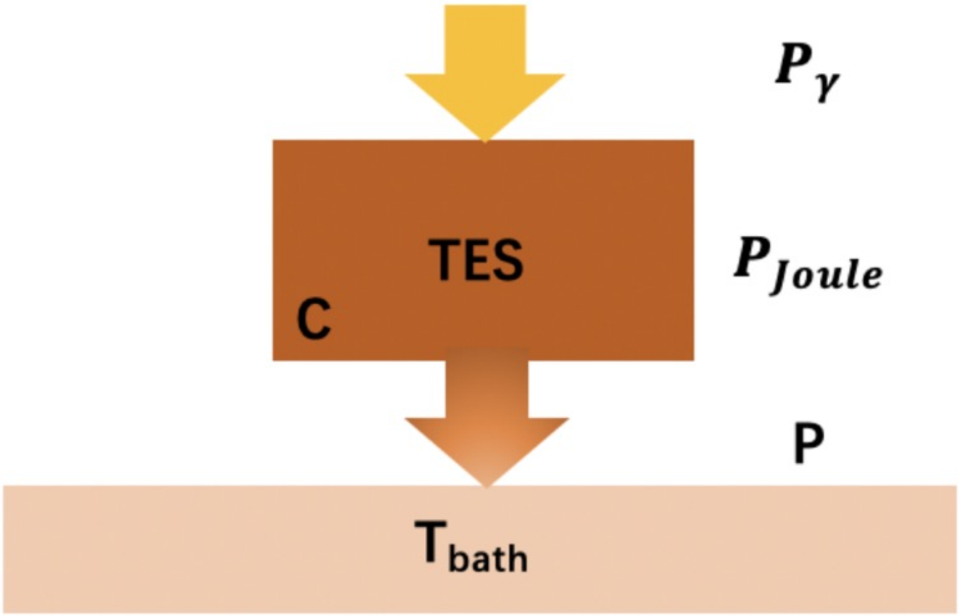
- Cryogenic: 100 mK focal plane
- Feedhorn-coupled Transition Edge Sensor (TES) bolometer with Tc = 150 mK
- Time-division multiplexing (TDM) with Superconducting Quantum Interference Devices (SQUIDs)

Challenge: read out many detectors without heating up the focal plane

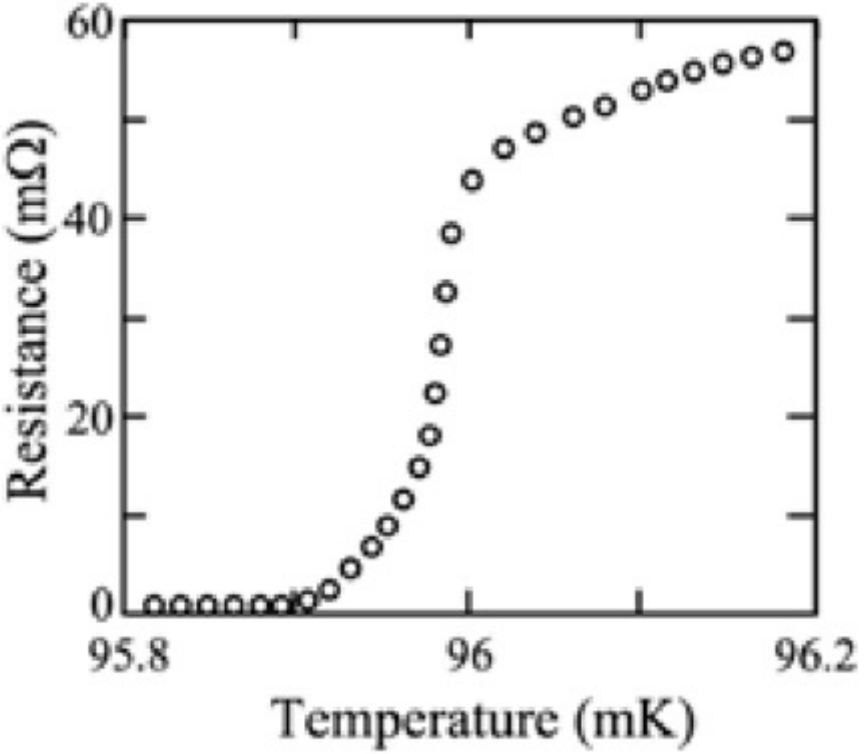


Solution: transmit multiple signals along a common line

TES bolometers



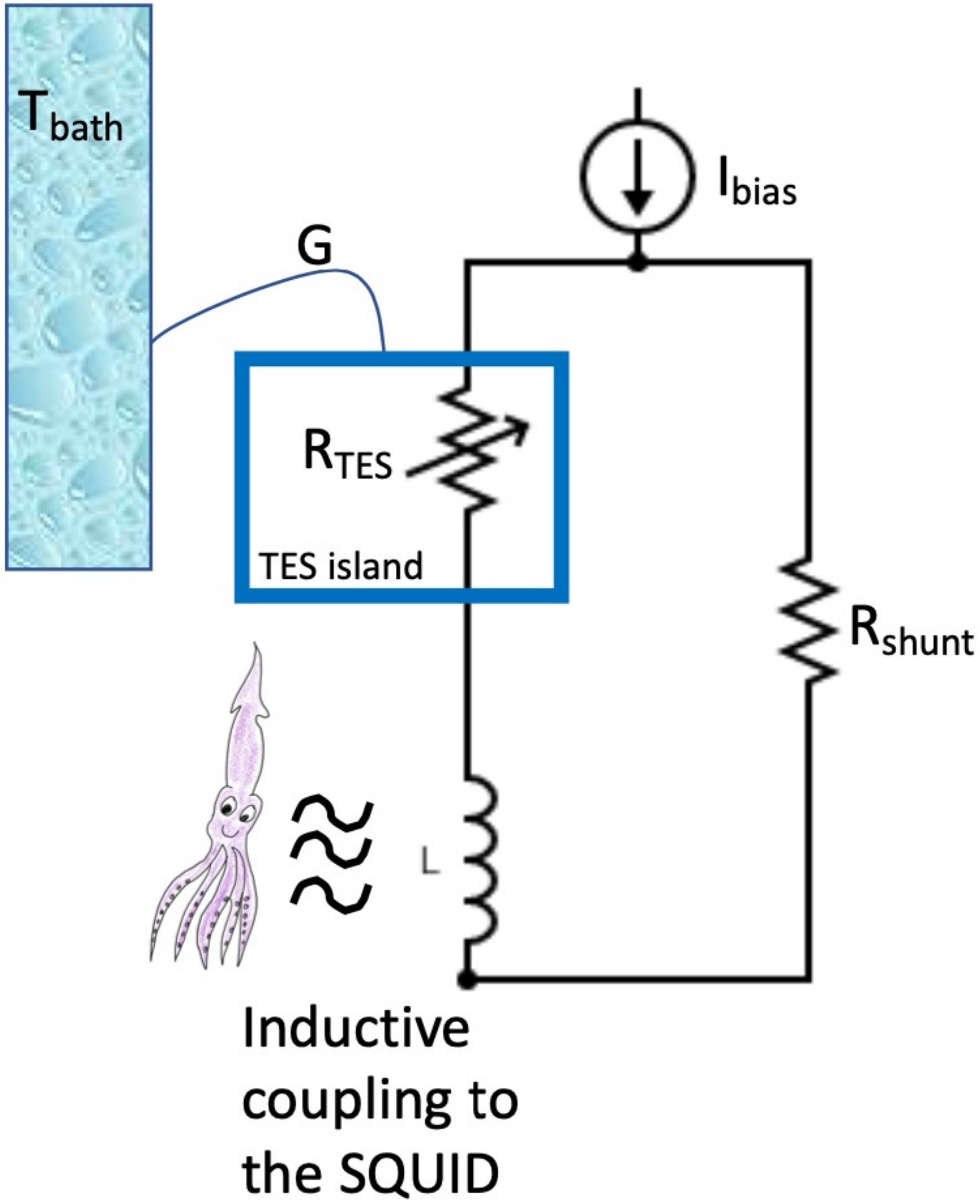
TES schematic
Image credit: Y. Li



Temperature dependence of TES resistance inits transition state
Irwin and Hilton, 2005

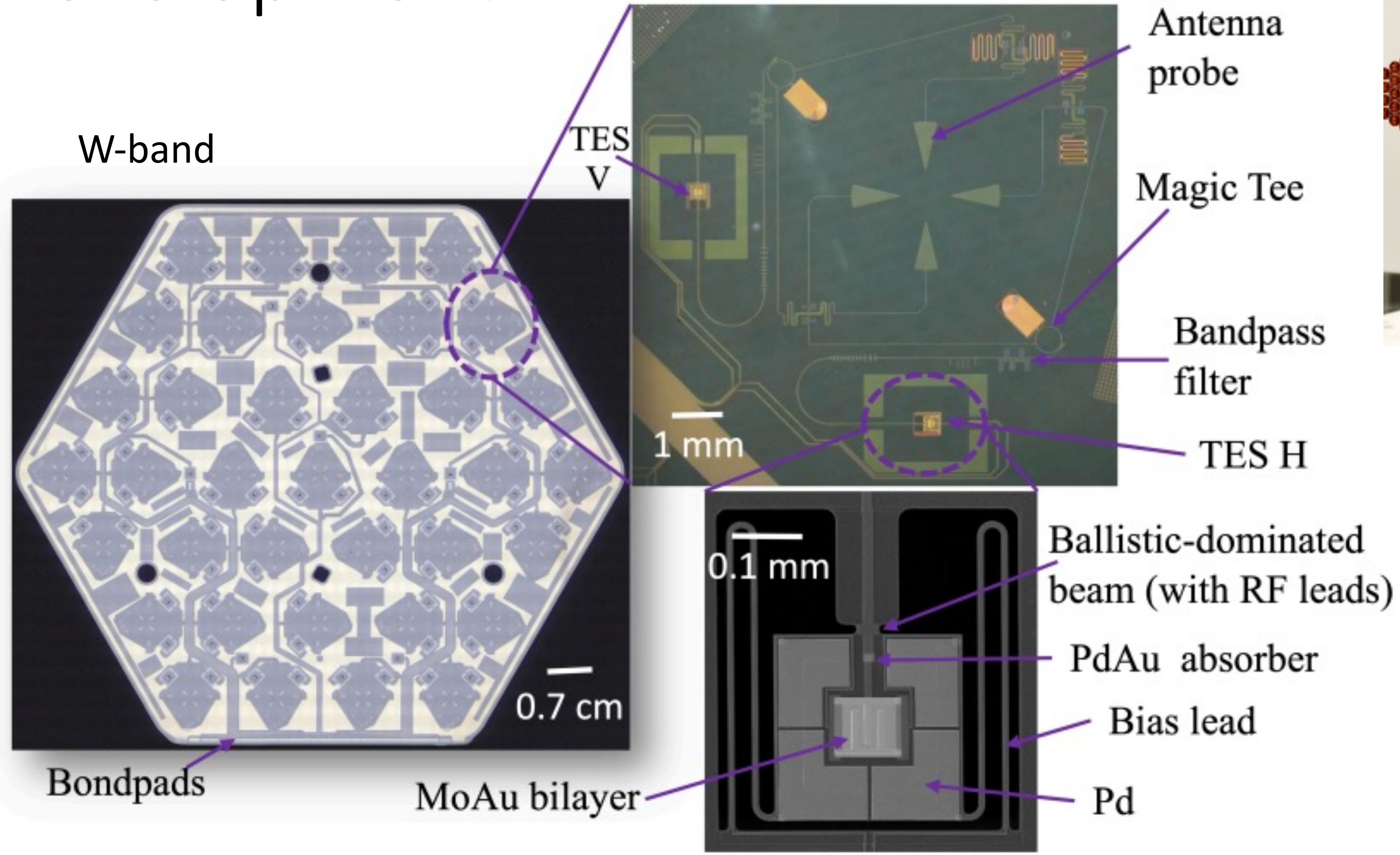
SQUIDs

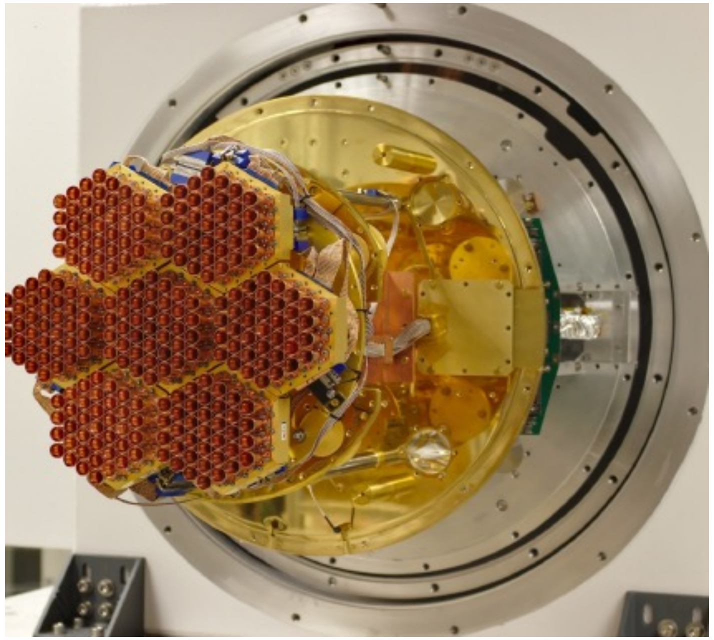
Circuit schematic of a single TES. The TES is biased by an incoming bias current. Its resistance is variable and is placed in parallel with a shunt resistor, R_{shunt} = 250 μΩ. An inductor couples the TES to a SQUID for readout. The TES island (blue box) is linked to the cold bath via its thermal conductance, G.

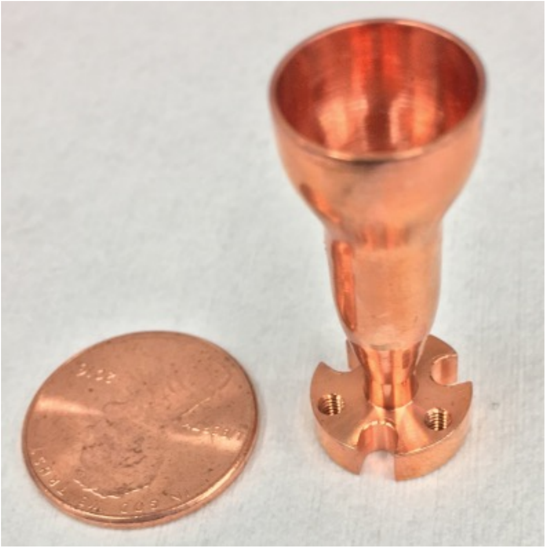


Focal Plane Development

W-band

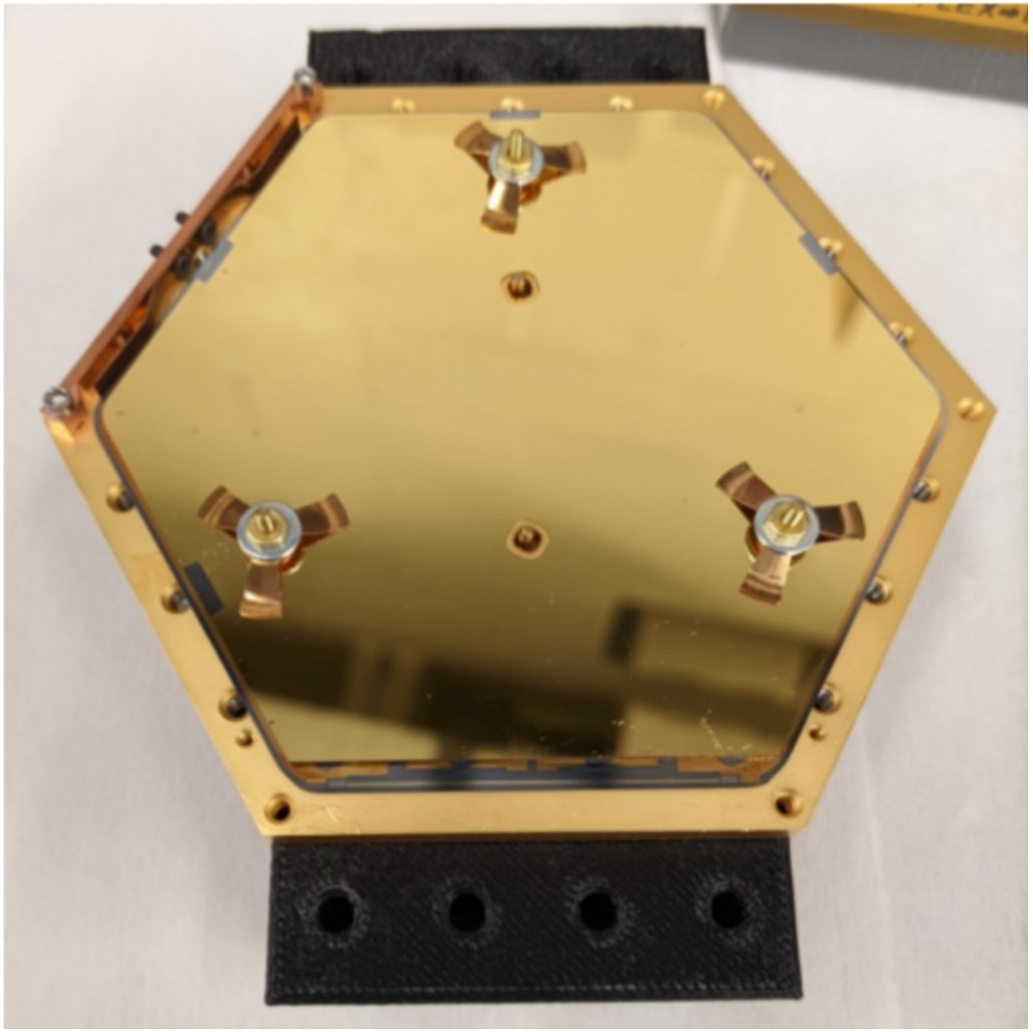


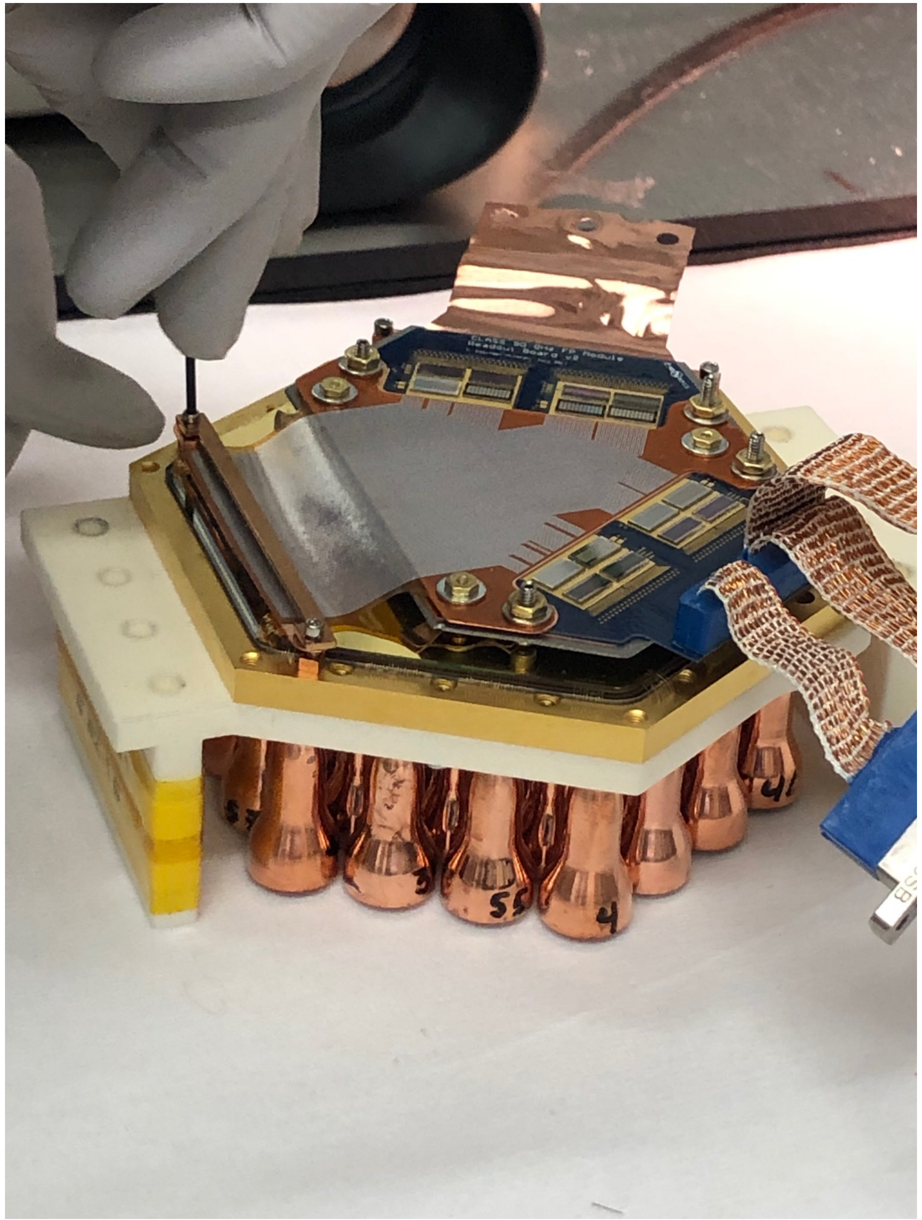




S. Dahal

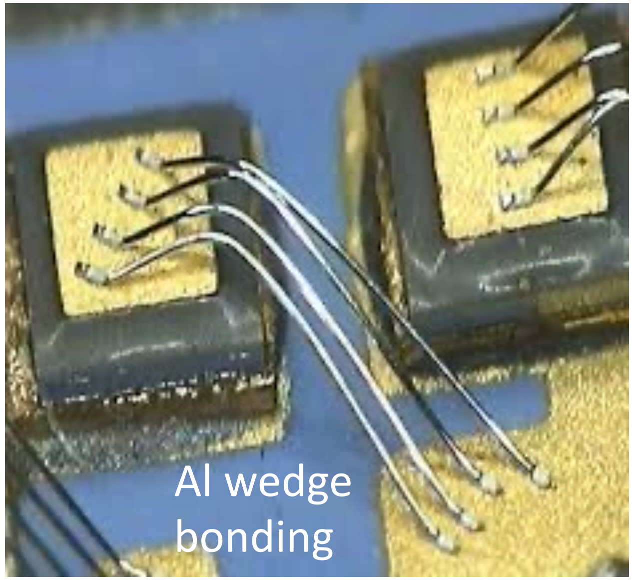
CLASS 90 GHz modules

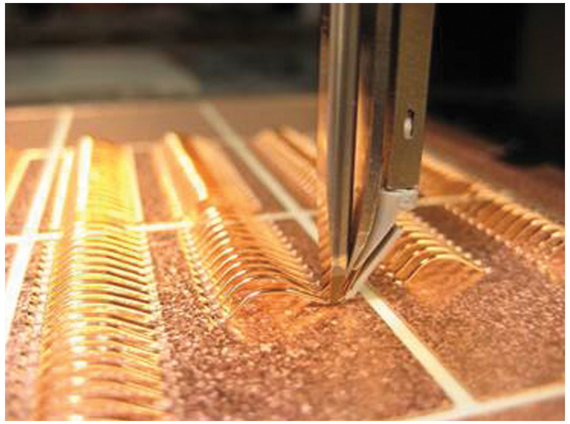




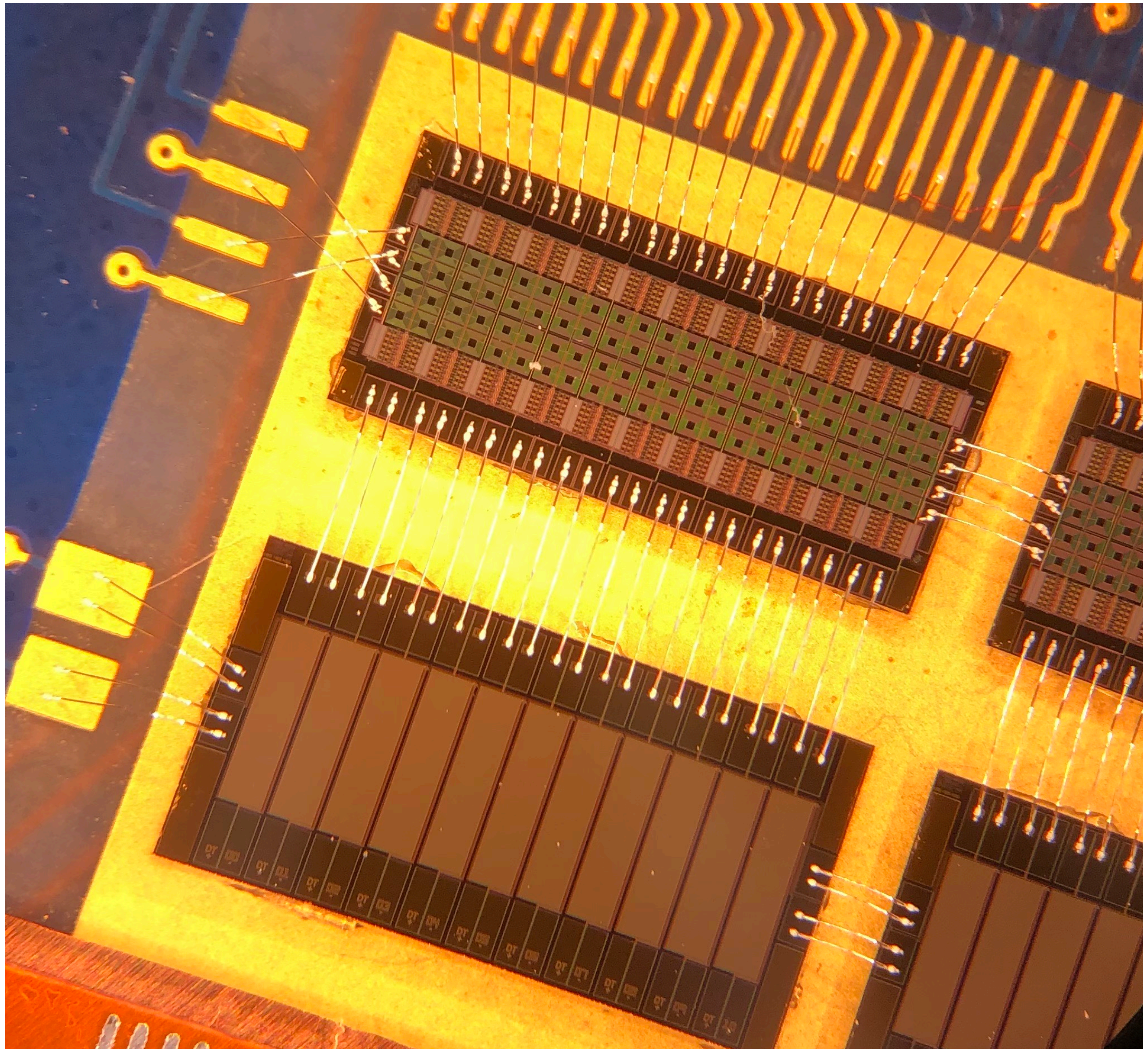
Wire bonding

- Aluminum wedge bonding for electrical connectivity (detectors and readout circuitry)
- Gold wedge bonding for thermal heat sinking
- Ultrasonic pressure and downward force



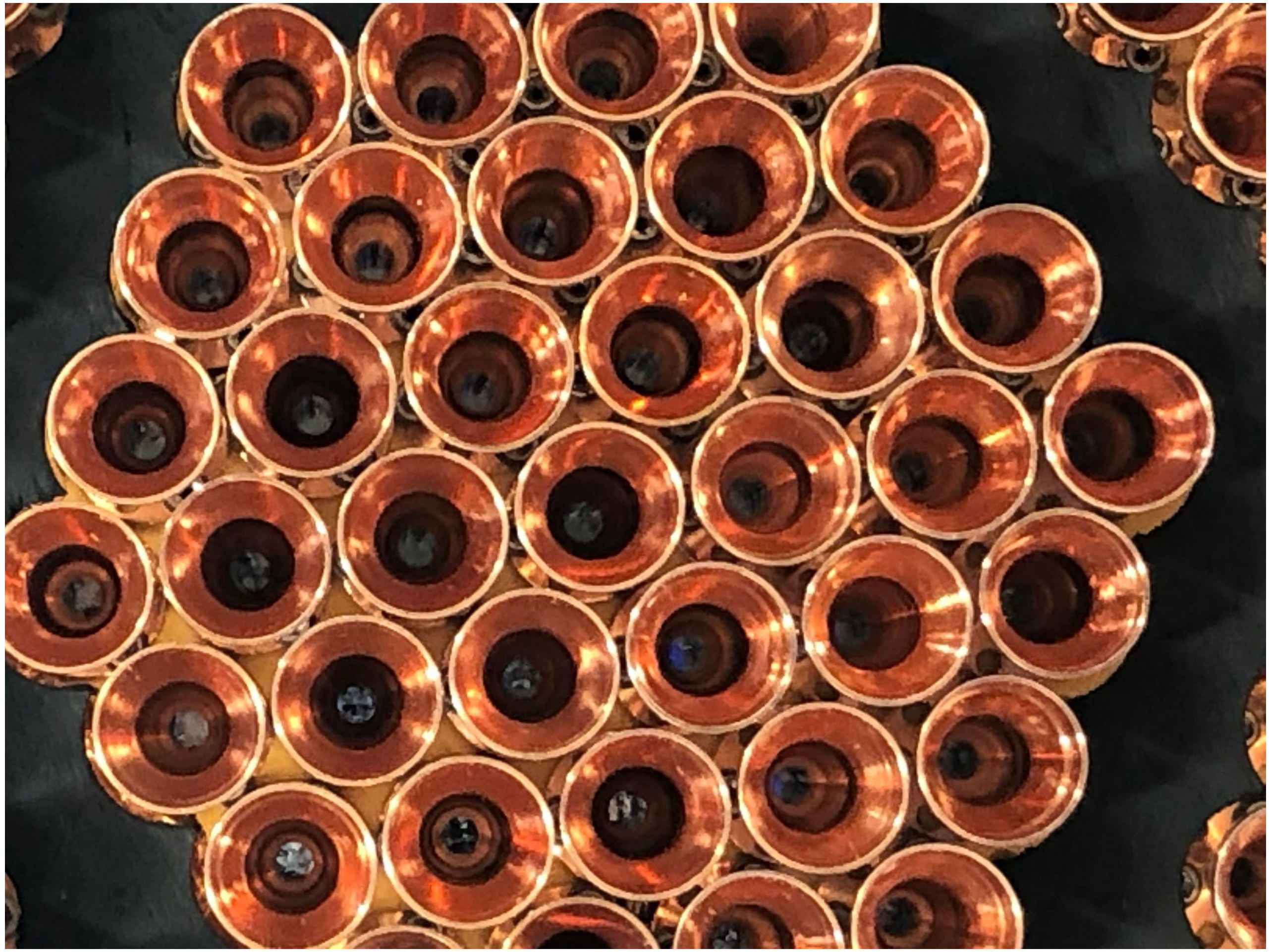


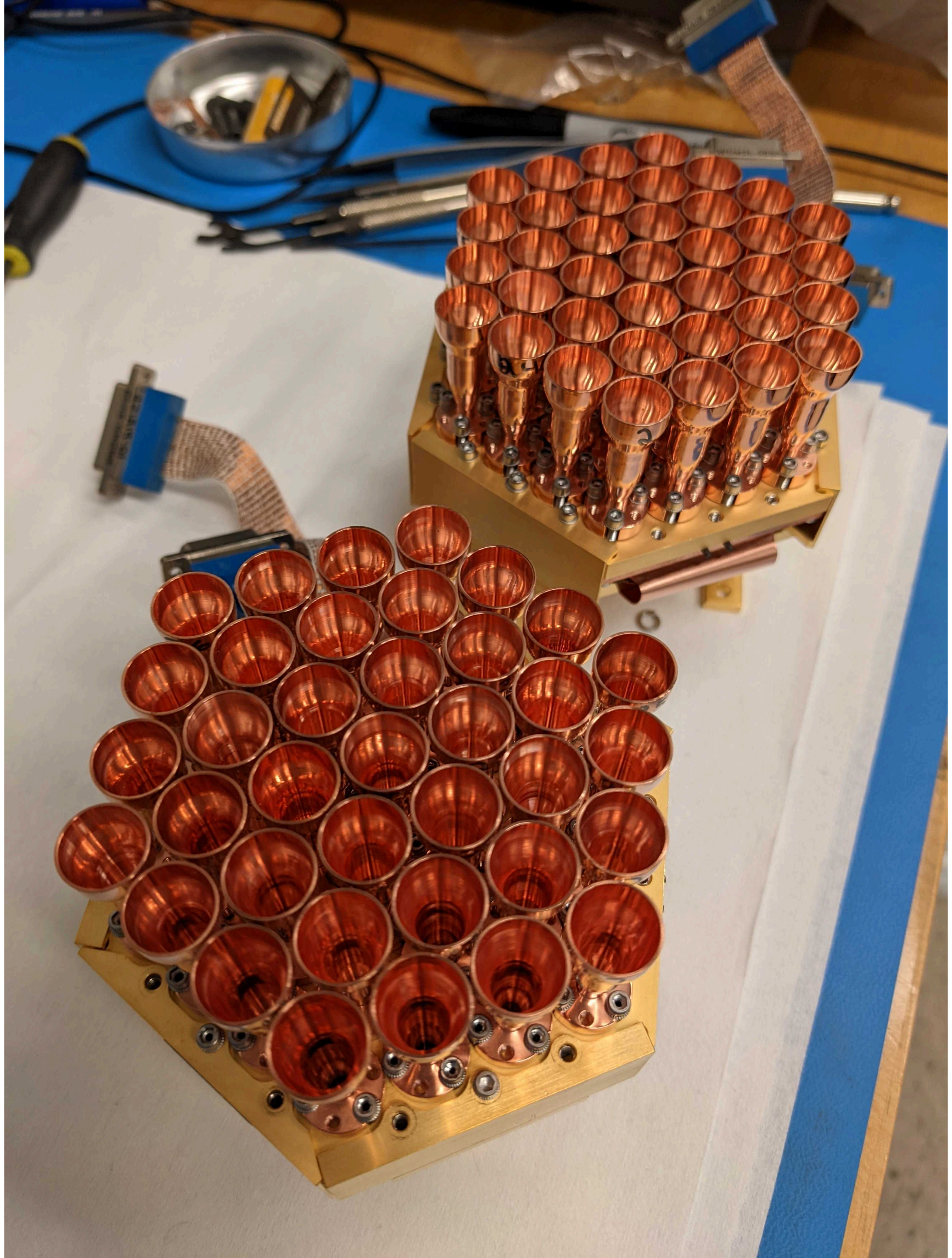
Hesse Mechatronics



CLASS readout circuit

Completed modules

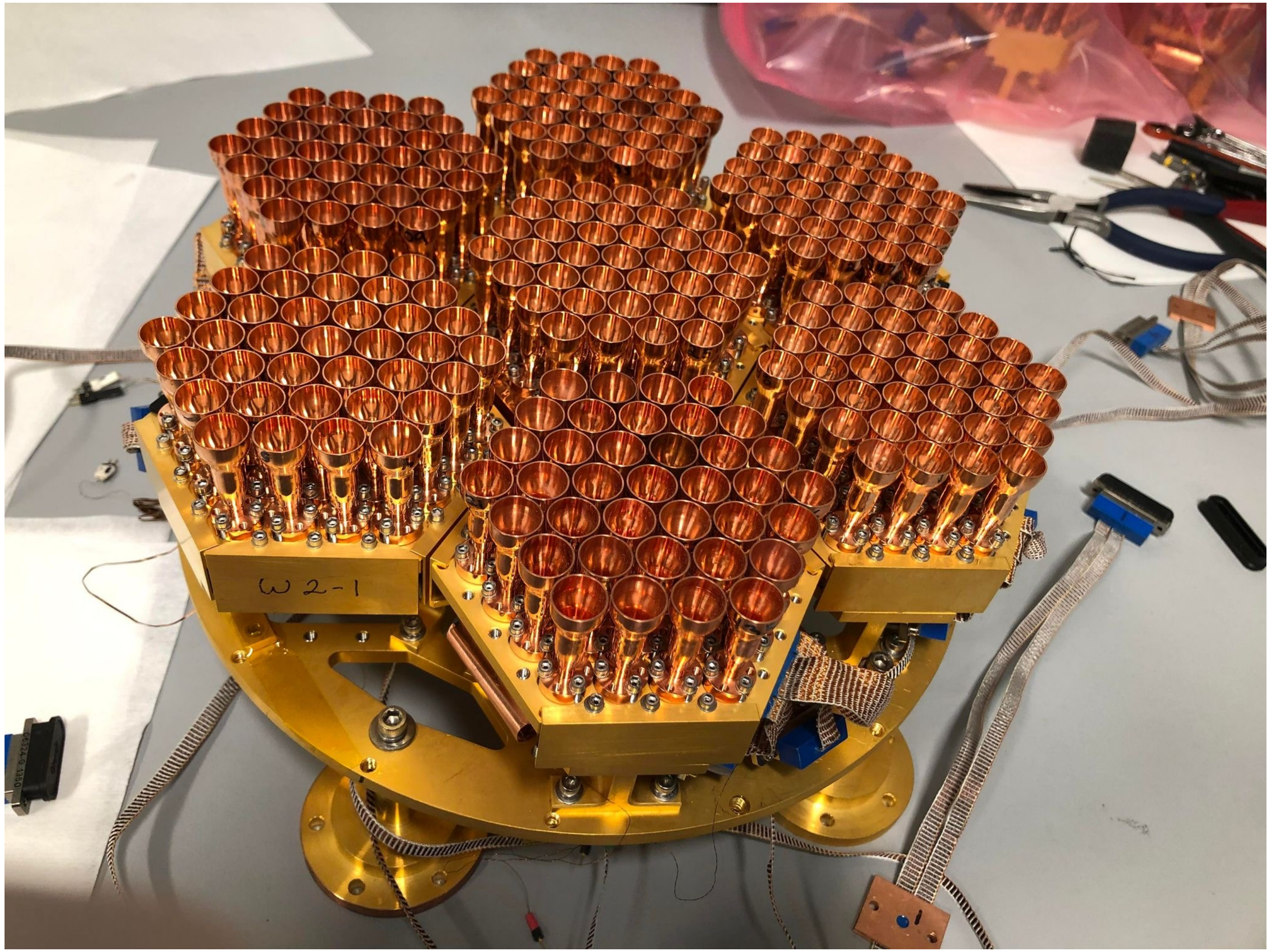




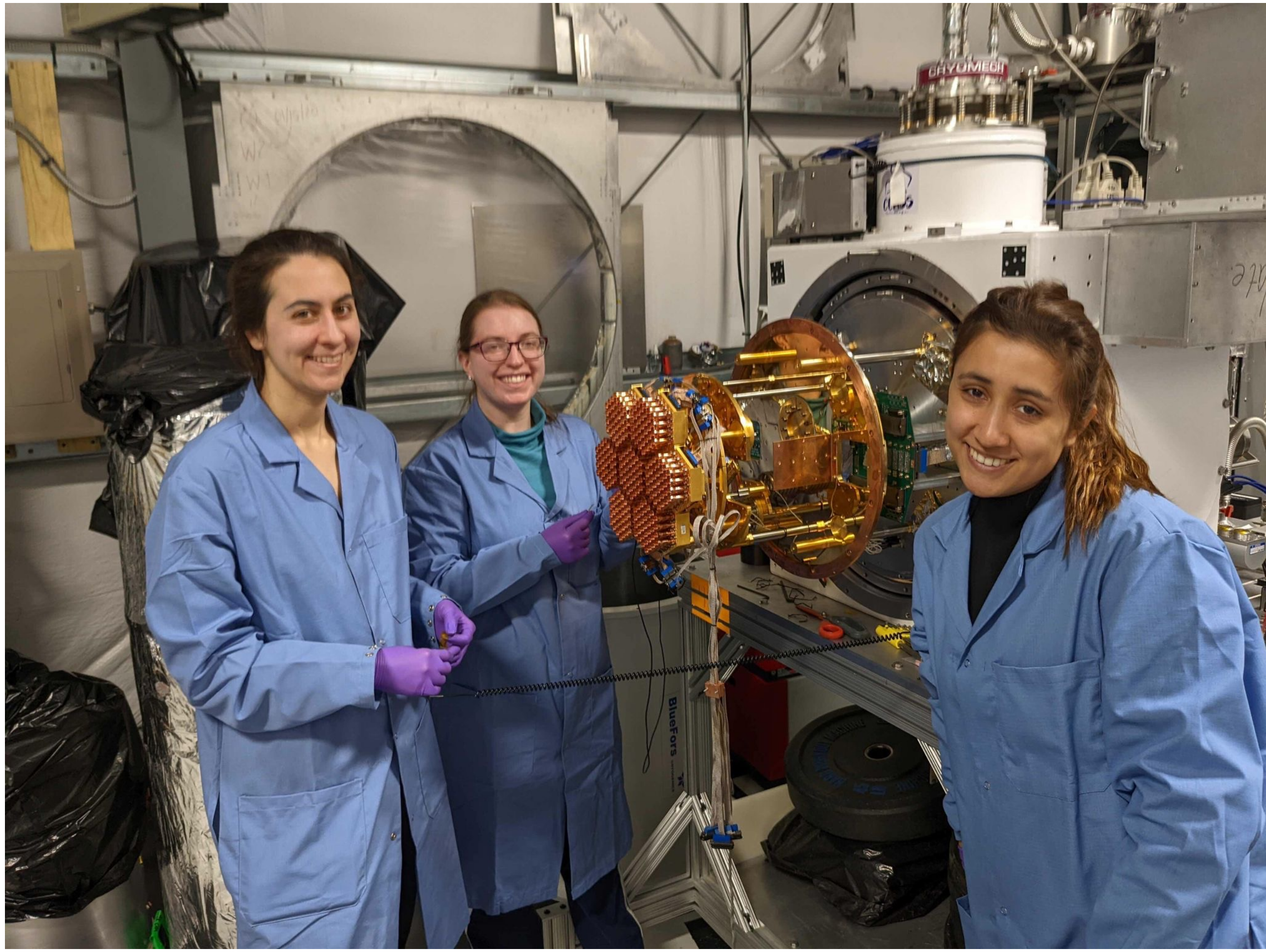
Part III

CLASS Deployment!

Deployment in Chile! Upgraded 90 GHz focal plane



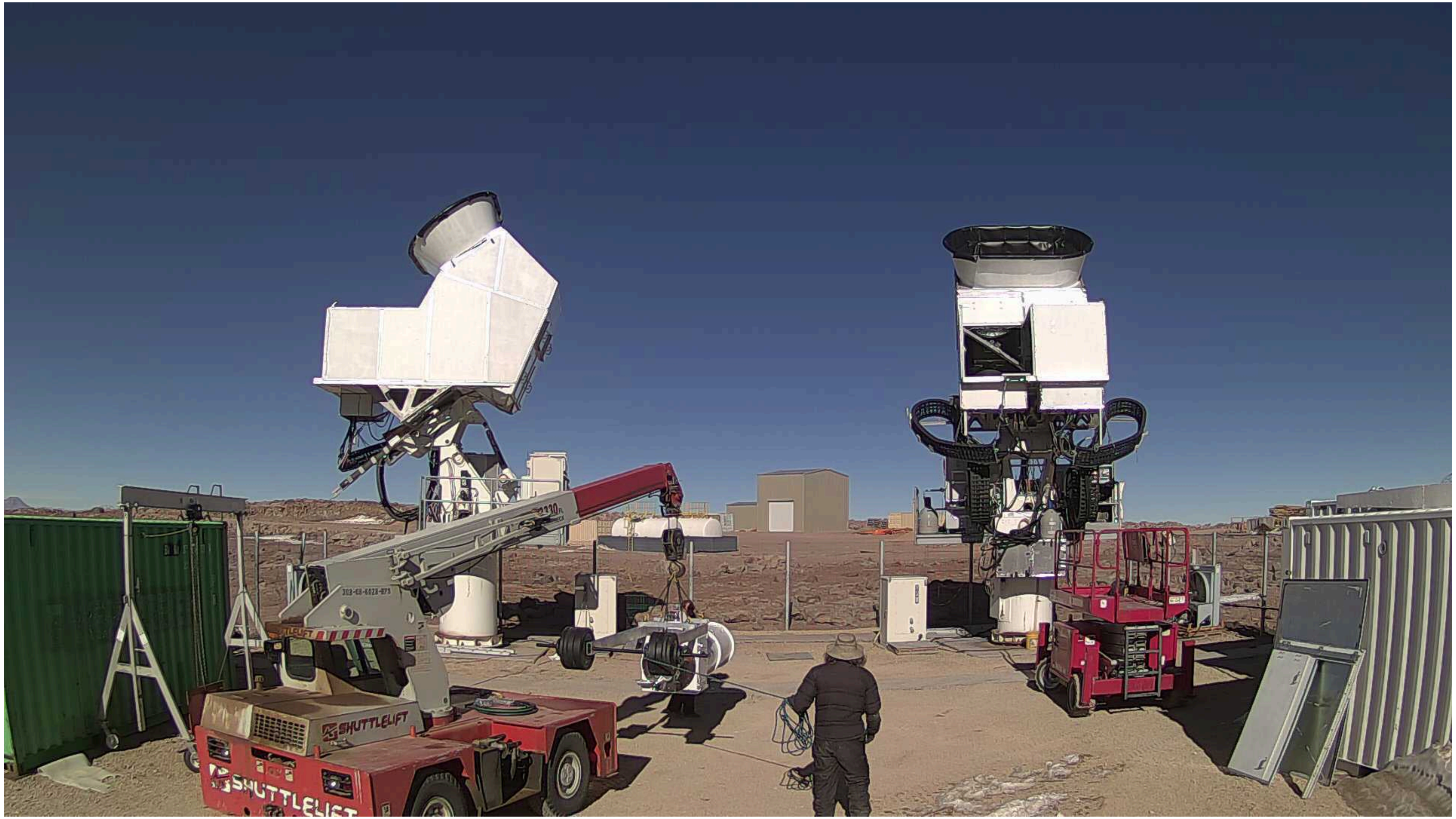

CRYOMECH
MCE Plate
BlueFors


CRYOMECH
BlueFors


CLASS

CLASS 90 GHz cryostat in the high bay at the site

Breaking News!! Happening now in Chile…



Part IV

Satellite Interference


Image credit: Neal Herbert/National Park Service via Flickr

Satellite Reflections

Image by Marco Langbroek

Looking ahead: Are satellites a new foreground contamination?

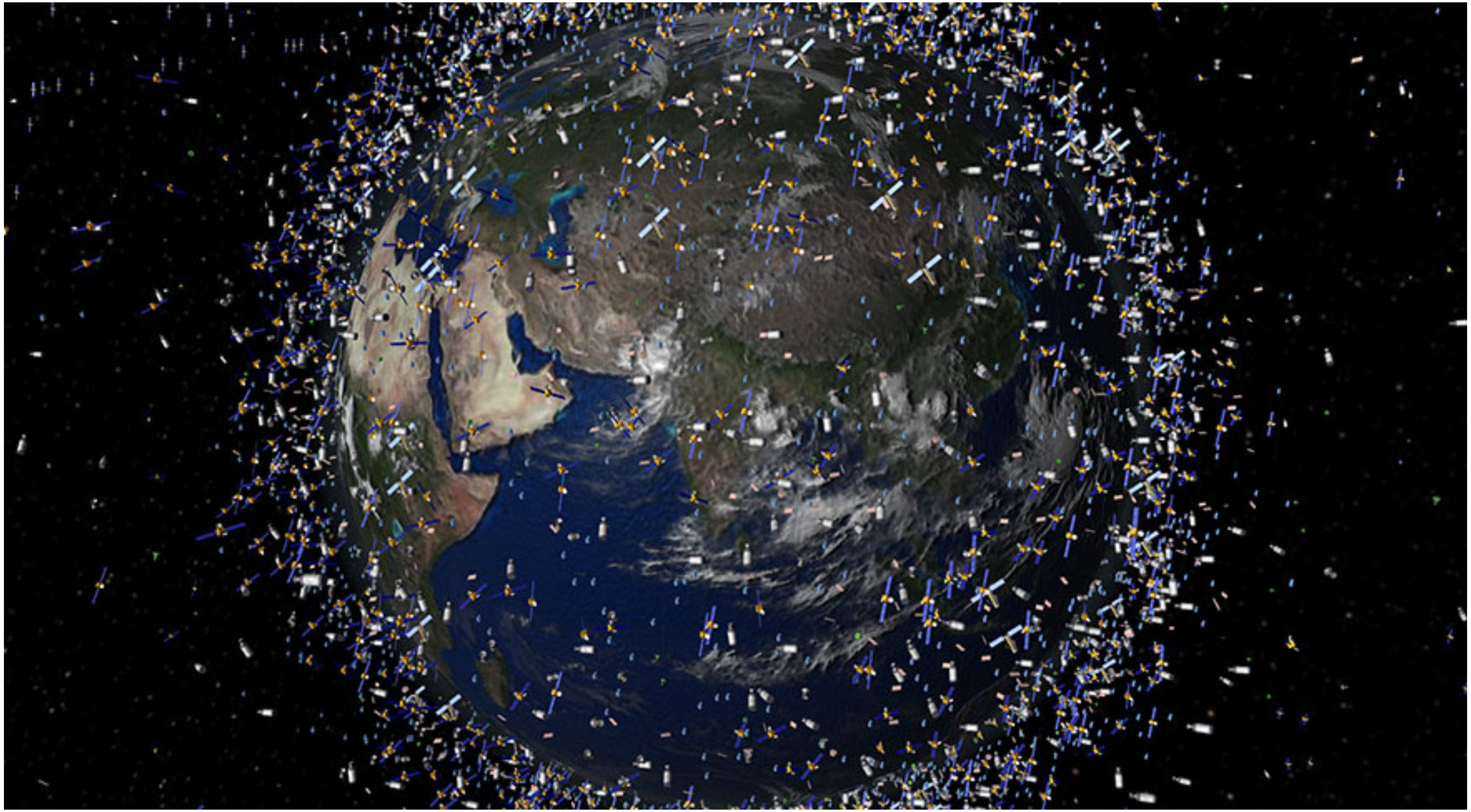
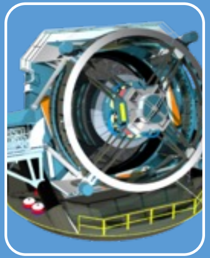


Image credit: European Space Agency

Why we care

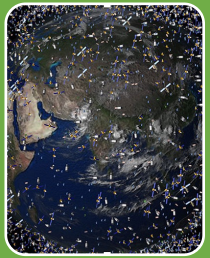


Solar Reflections

- Impacts optical astronomy
- Reflected sunlight
- Example: Rubin/LSST

Radio Interference

- Impacts radio and mm-wave astronomy
- Examples: Very Large Array, Arecibo, ALMA, SO, ACT, SPT, CLASS, BICEP



Changing Space Environment

- LEO crowding
- Kessler syndrome
- Satellite-based telescopes impacted
- Example: Hubble

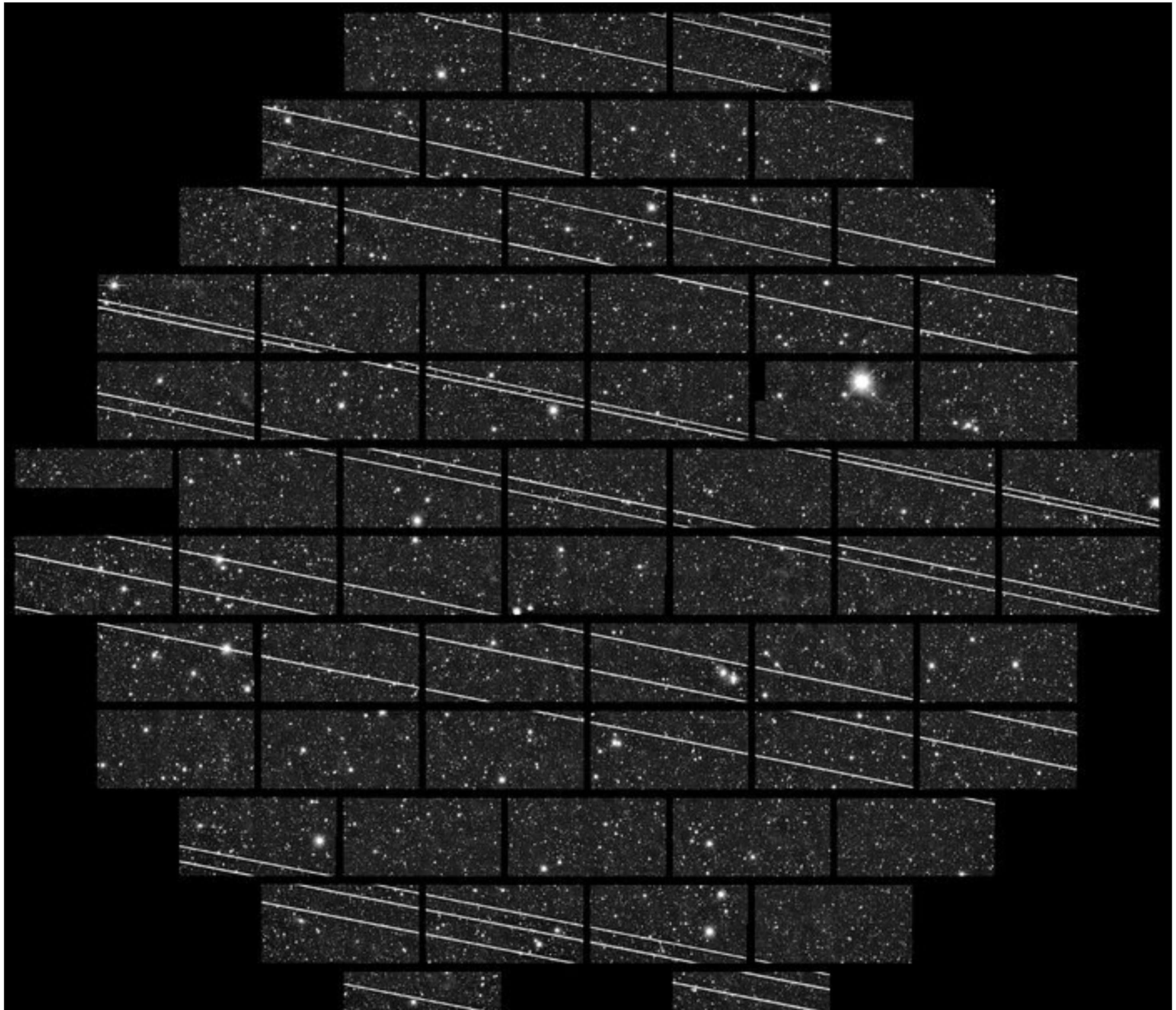
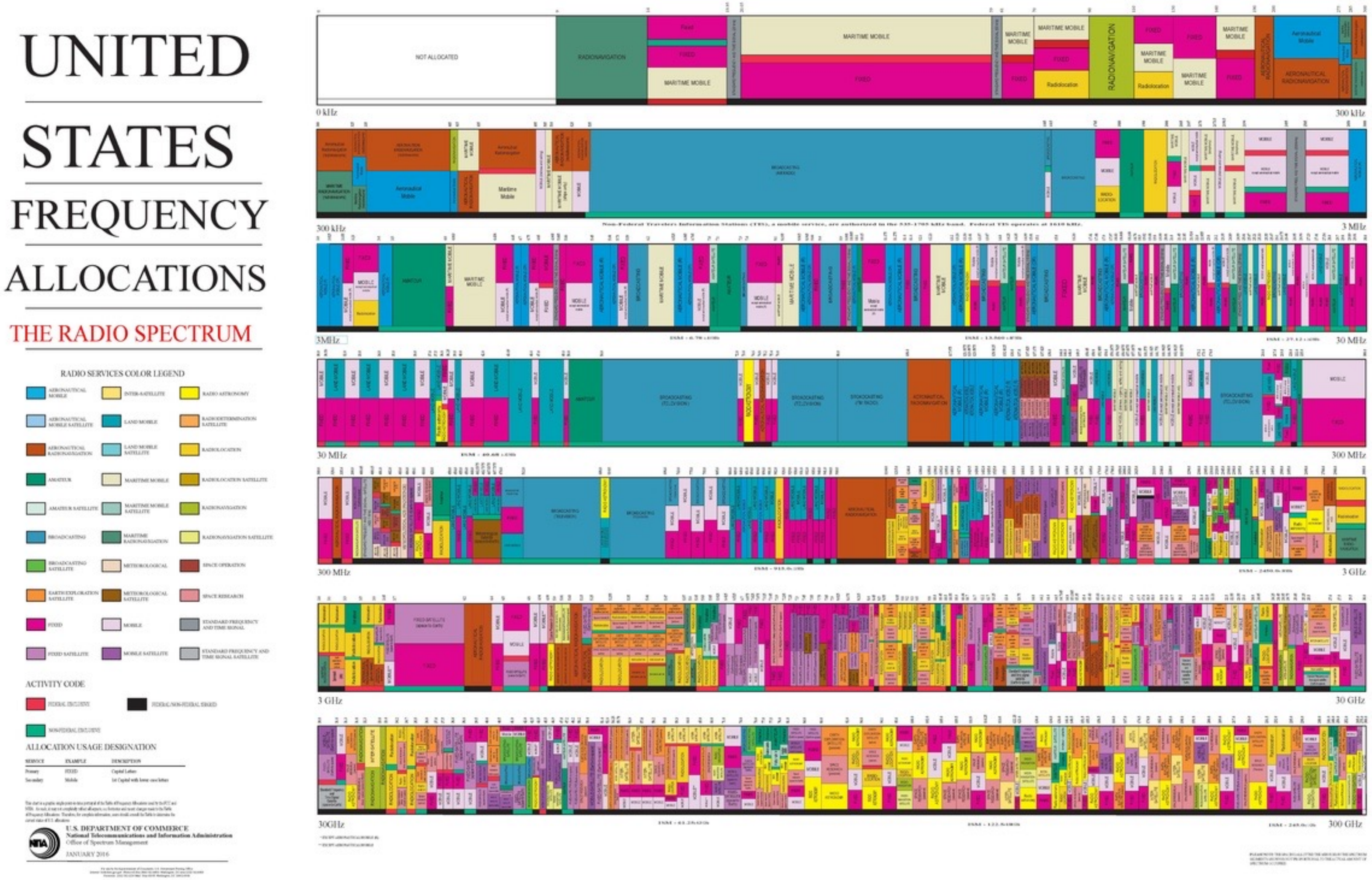


Image credit: CTIO/NOIRLab/NSF/ AURA/DECam DELVE Survey

Radio Interference

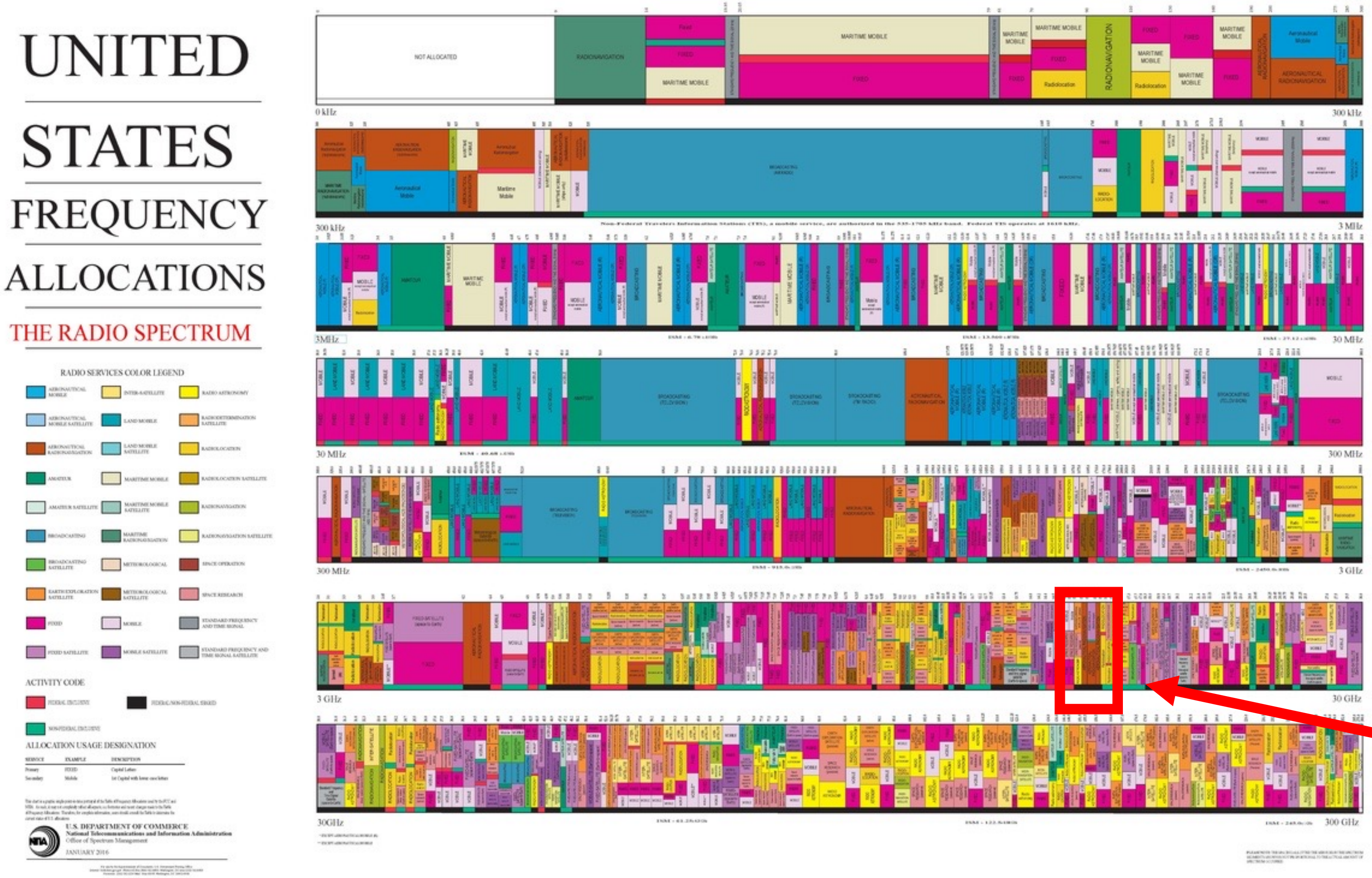


Downlink frequency bands:

Amazon/Kuiper	Starlink
17.7-20.2 GHz & 27.5-30 GHz	10.7-12.7 GHz & 37.5-42.5 GHz

Note: these bands may expand within the next decade, which would be very bad news for us!

Radio Interference



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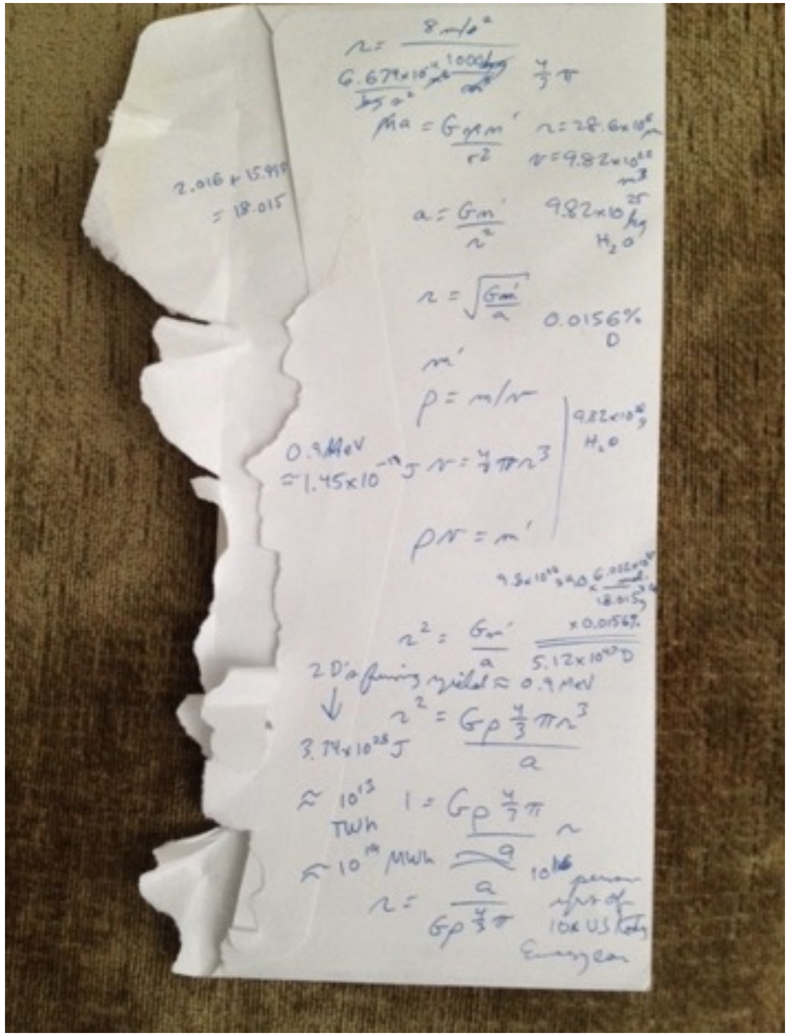
You are here

“Back of the Envelope”

Goal: determine how many pixels on detector are compromised any given time

Parameters at play:

- Apparent magnitude of satellites
- Emission spectrum of satellites
- Number of satellites
- Altitude of satellites
- Orbital velocity (depends on altitude)
- Integration time



“Back of the Envelope”

Starlink: 550km in altitude

7.8km/s LEO orbital velocity

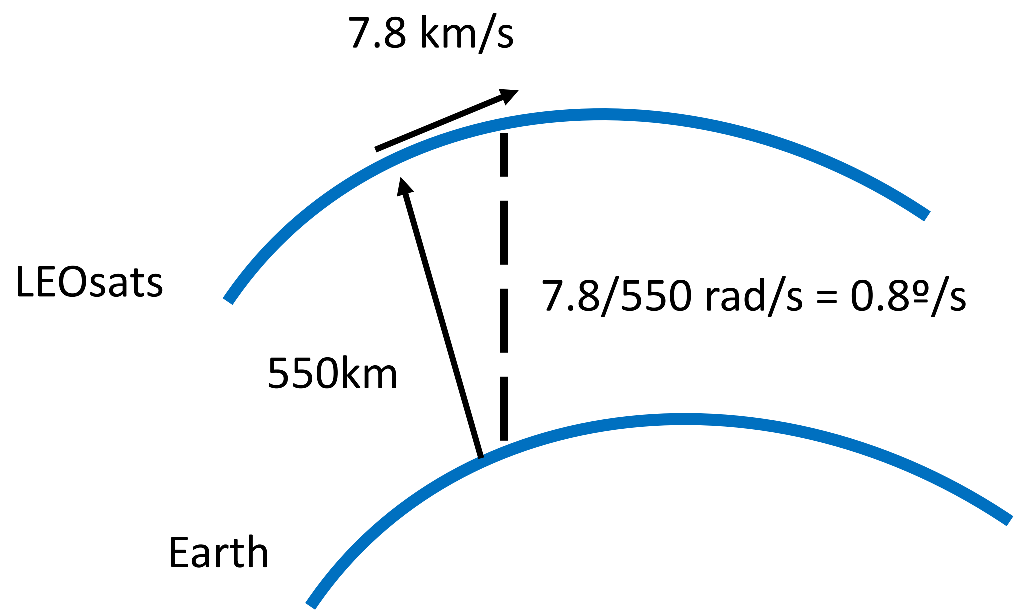
Field of View (FOV):

- SUPERBIT: 0.5º
- ACT: 1º

Creates streaks!

100,000 satellites – what’s the chance of being in a 1º field of view?

100,000($^{1}/_{4\pi sr/deg2}$) = 2.42 → 2 satellites in FOV at any given time

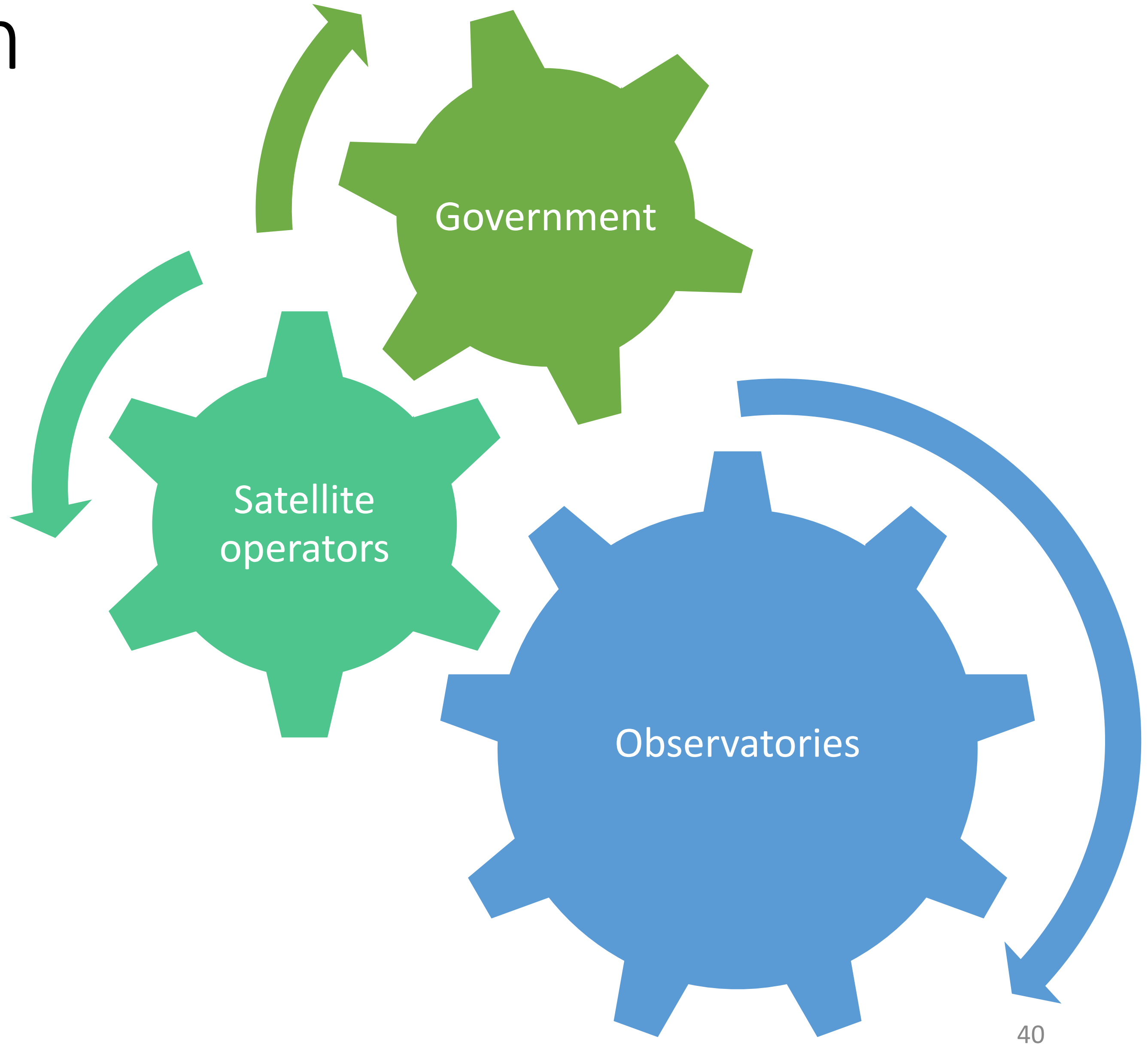


The Future of Astronomy

Image credit: Alex Savello/NRAO

Tackling the Problem

- New data analysis methods to remove contaminations
- Avoid satellites in observing window (hard)
- Joint operations solutions
- Policy changes to govern satellite operations and protect ground-based observatories



Astronomers engaging in space policy

SATCON-1 Workshop in June 2020

Dark & Quiet Skies Report
December 2020

What can be accomplished via policy changes?

- Space Traffic Management
- Spectrum Management
- Radio Quiet Zones
- Domestic vs. International policy

The Future of Astronomy

Image credit: Alex Savello/NRAO

The Fut

Image credit: Alex Savello/NRAO

Radio Quiet Zones

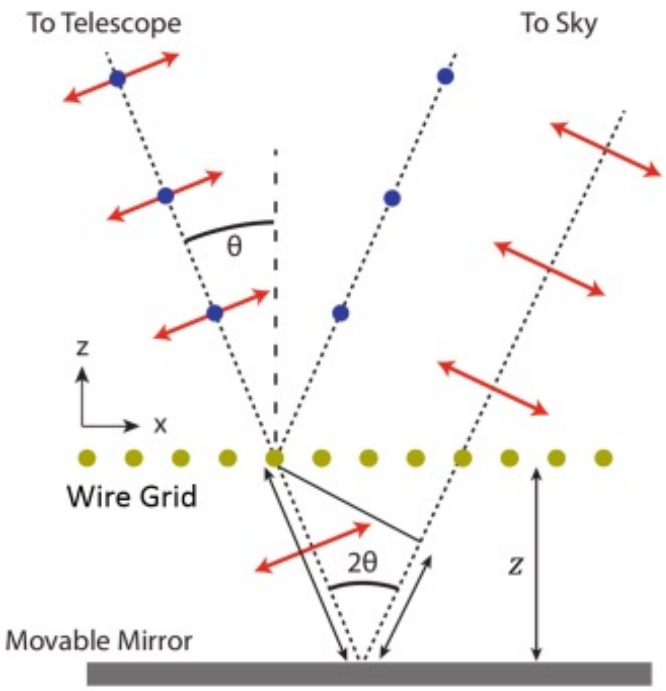
A community of telescopes

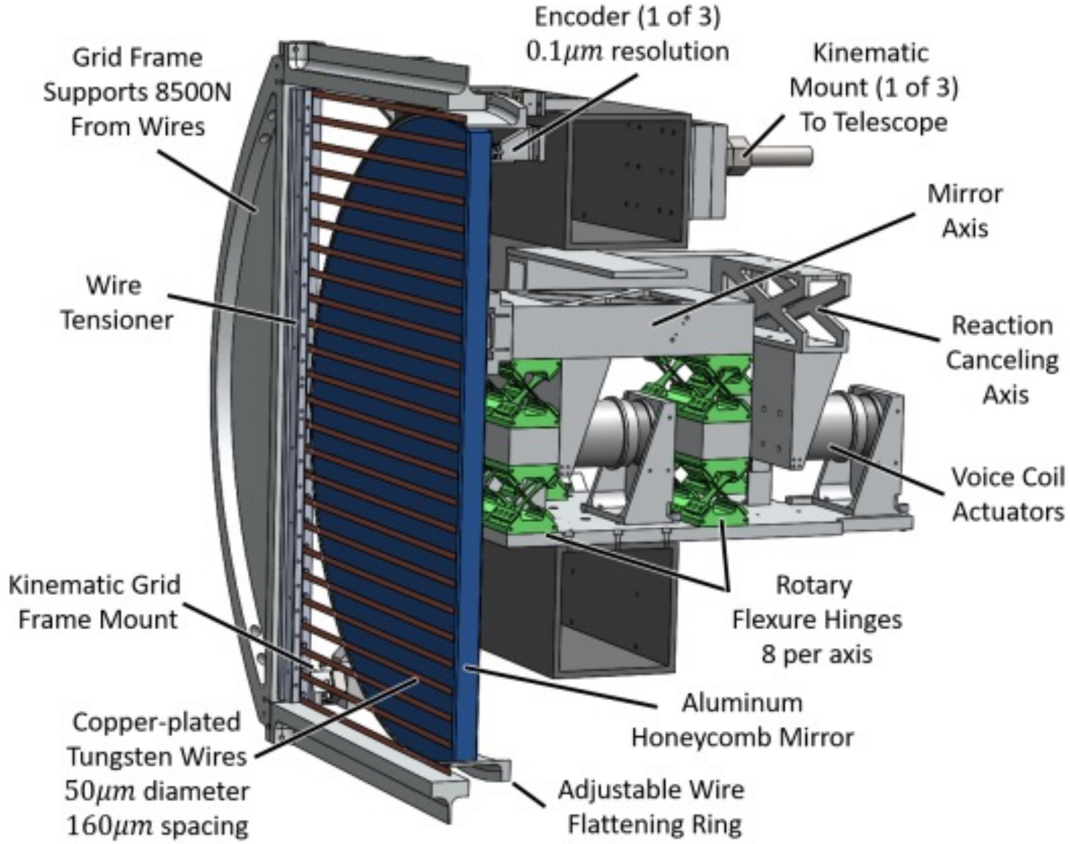

Chajnantor Region

Any questions?

Backup Slides

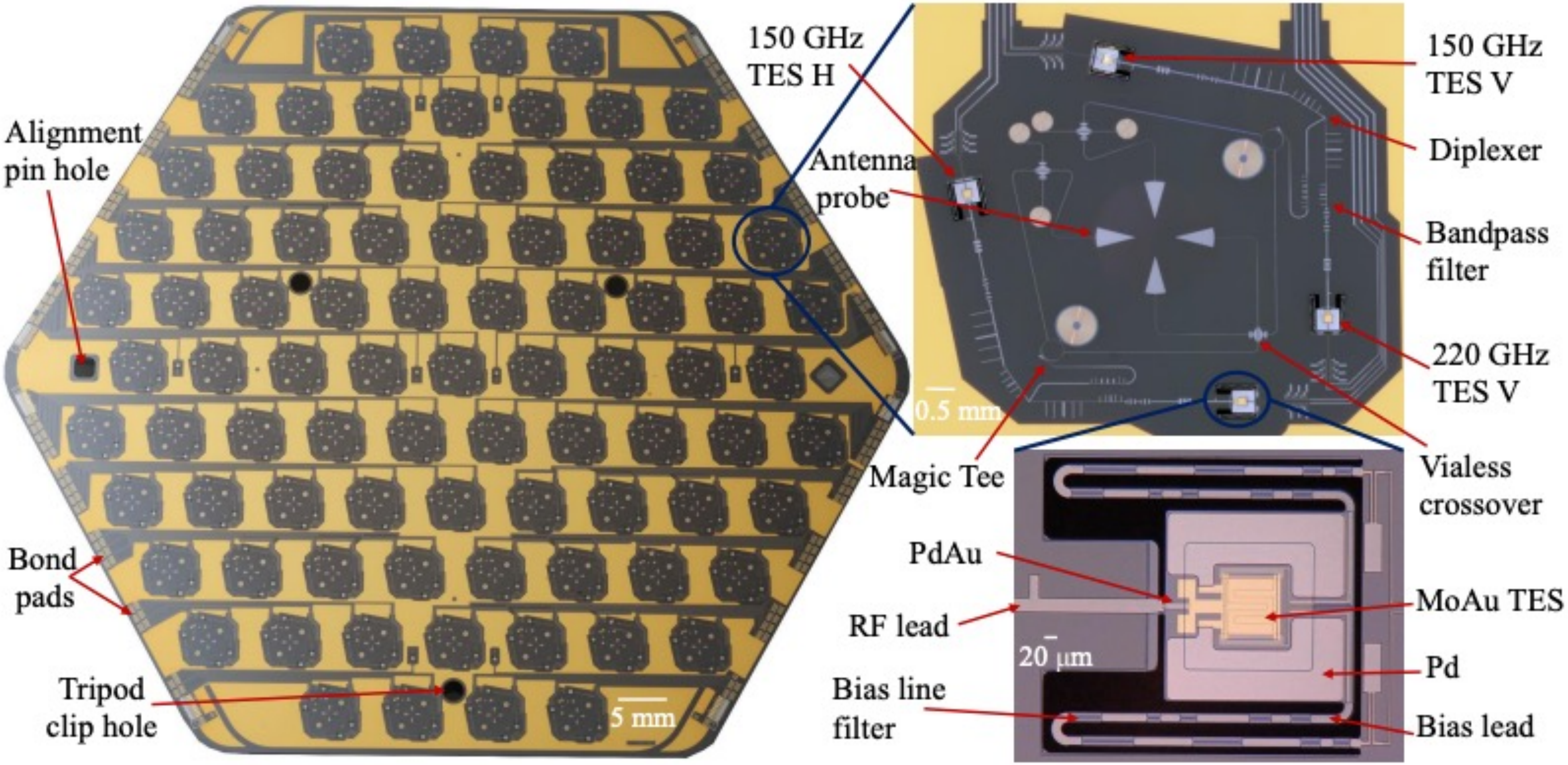
Variable-delay polarization modulator (VPM)





K. Harrington

HF



Alignment pin hole
Bond pads
Tripod clip hole
5 mm
150 GHz TES H
Antenna probe
Magic Tee
0.5 mm
150 GHz TES V
Diplexer
Bandpass filter
220 GHz TES V
Vialess crossover
PdAu
RF lead
20 µm
Bias line filter
MoAu TES
Pd
Bias lead

S. Dahal

Gold wire bonds

- Perimeter gold bonds from backshort to baseplate
- Purpose: heat sinking

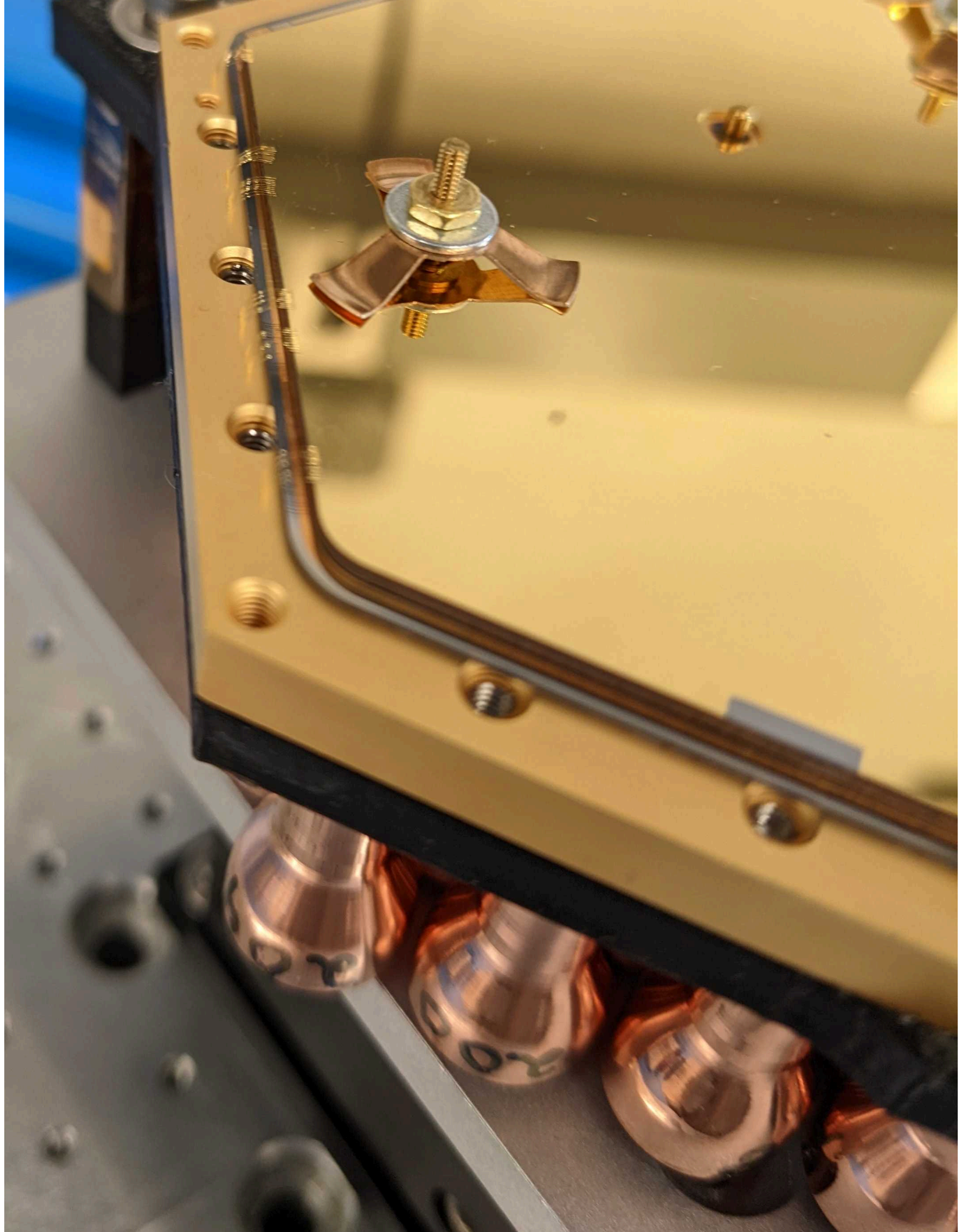
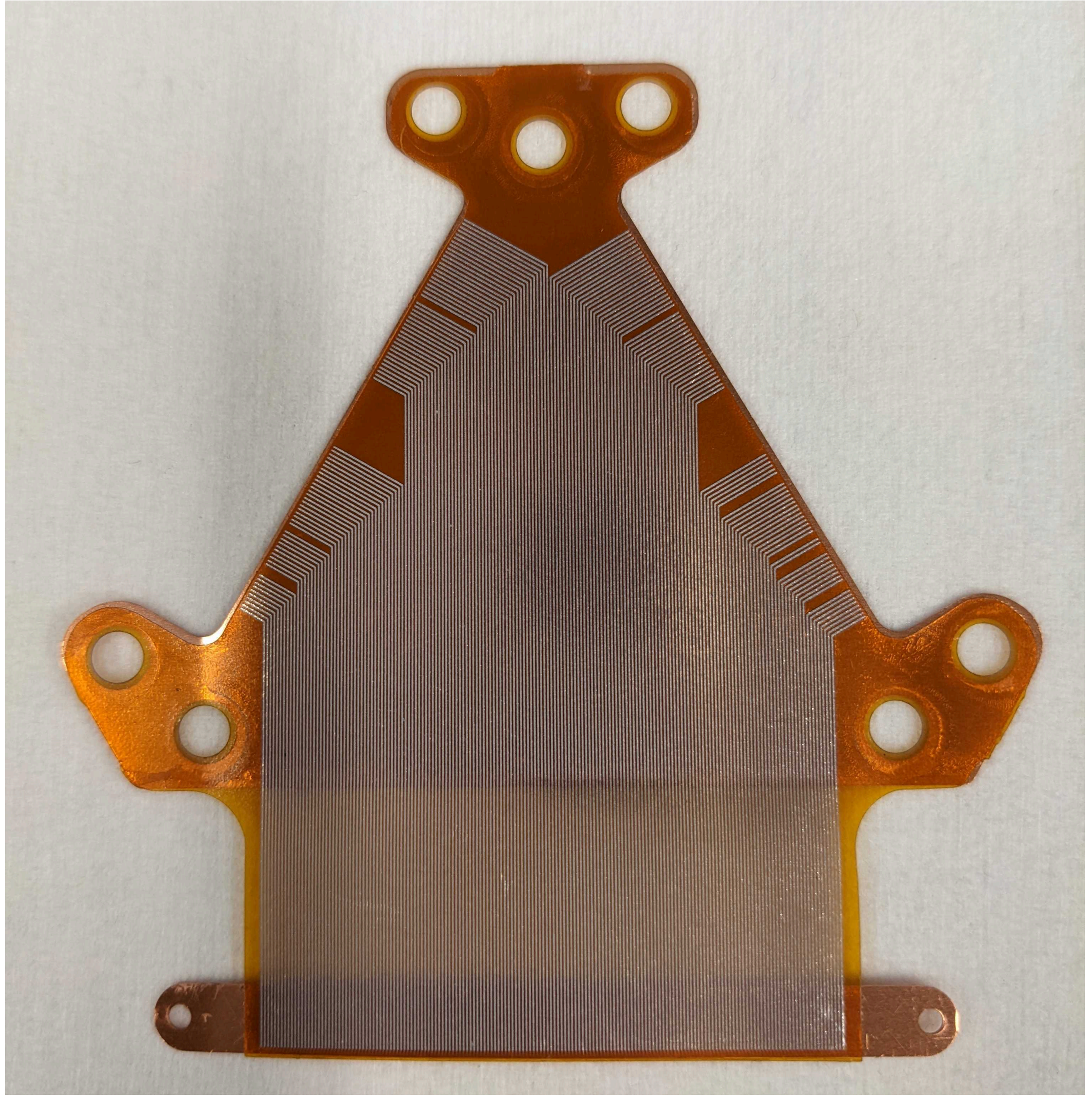
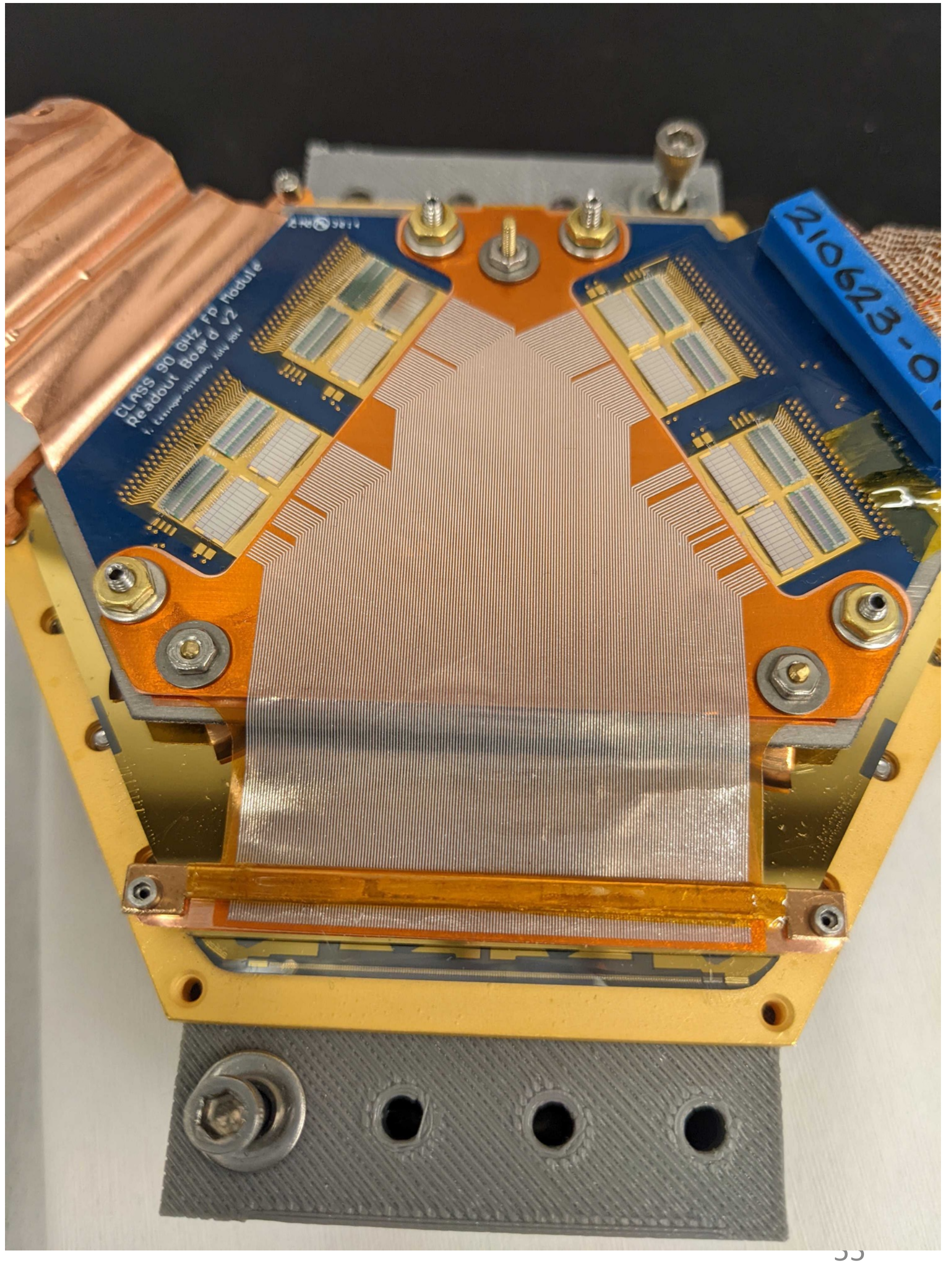


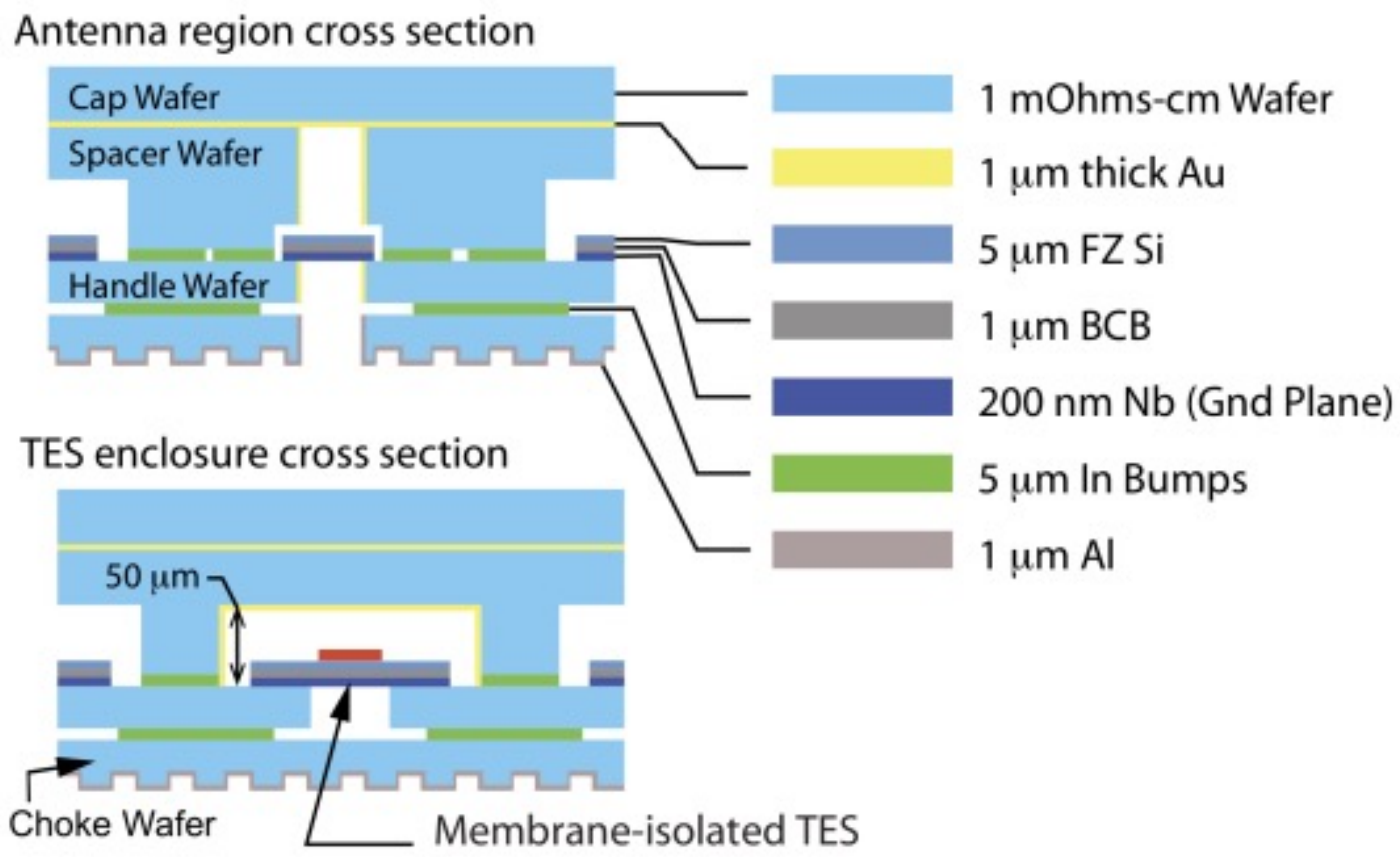
Photo credit: Caro Nunez

Readout Circuit Assembly

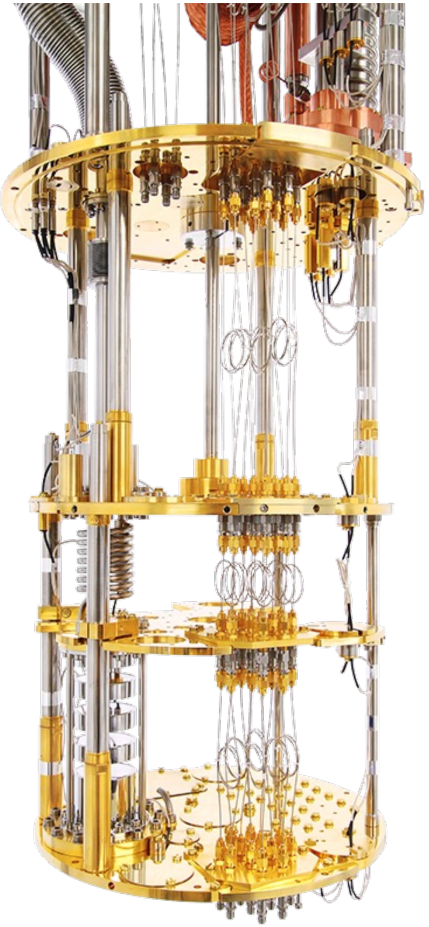




Wafer Stackup



Cryostats



How bad is light pollution?

Photo by Todd Carlson, International Dark Sky Association

Satellite launch cost reduction

1970-2000: Average launch cost = $18,500/kg

2018: With Falcon 9 launch, SpaceX reduced cost to $2,720/kg

Falcon 9 launch, SpaceX

Exponential increase in the number of active satellites from 1957 to 2021

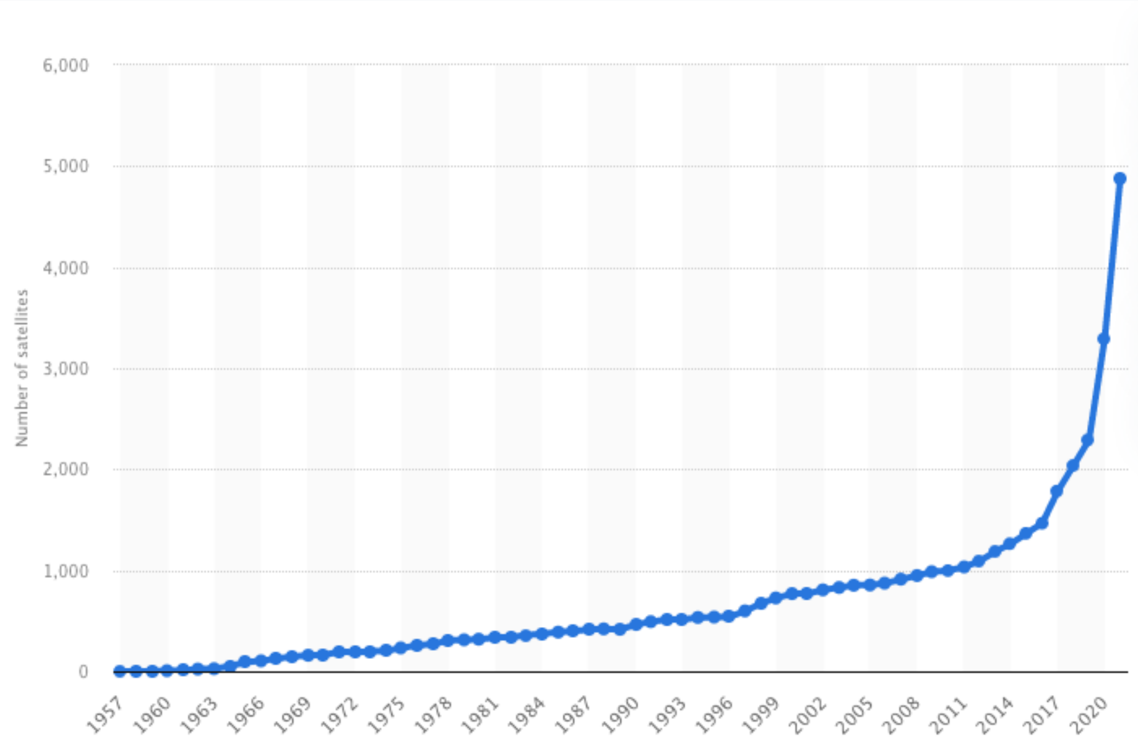


Figure credit: Erick Burgueño Salas

Notable decline in number of satellites launched by governments since 1960

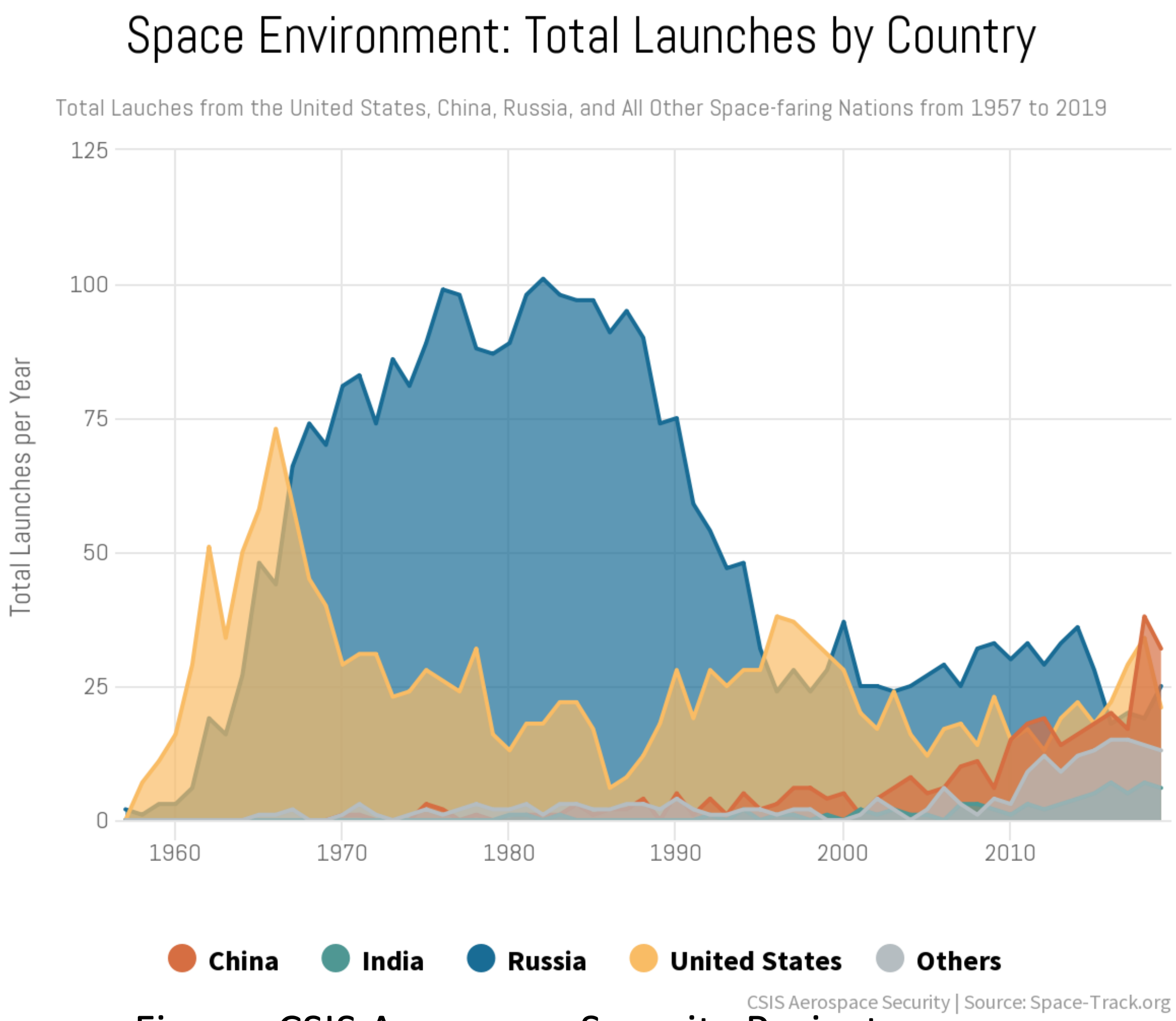
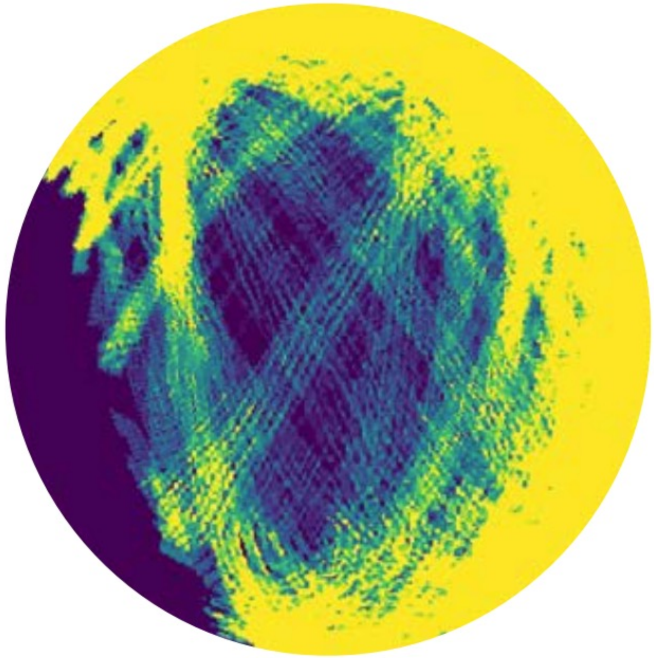


Figure: CSIS Aerospace Security Project

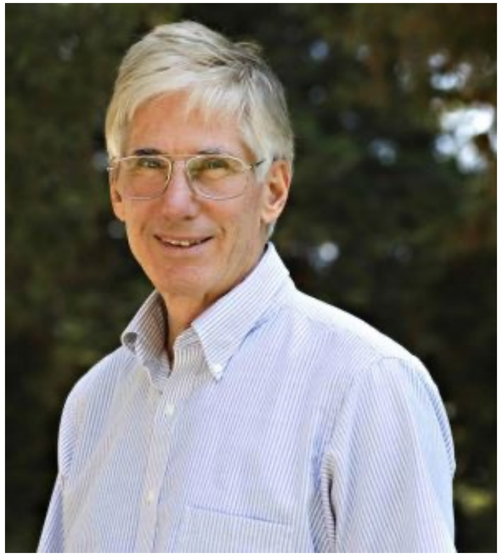
- Data validation and cybersecurity
- New regulatory institutions
- Militarization of Space
- Space as an environmental resource
- Space Situational Awareness
- Space Traffic Management
- Economic ramifications

Impact on Visible Spectrum



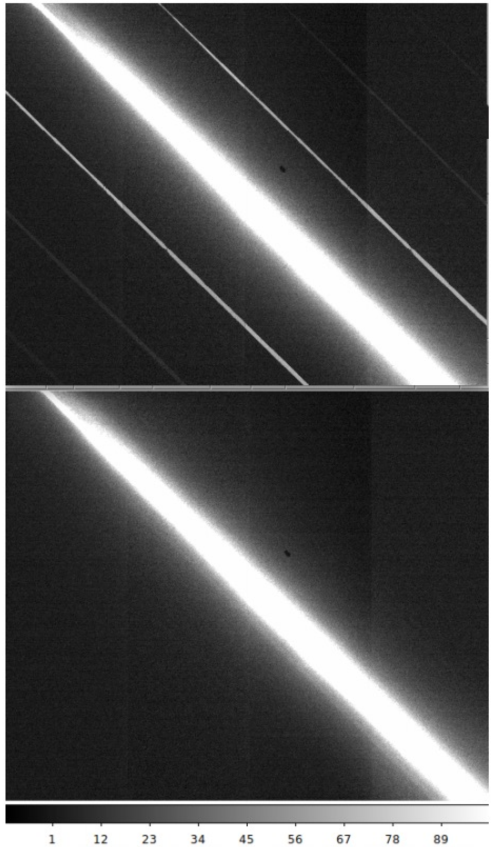
Credit: P. Yoachim (U. Washington/ Rubin Observatory), as shown in SATCON-1 report

- Solar reflection causes trails
- Altitude matters – want orbits as **low** as possible
  - Starlink primarily at 550km altitude (328-614km) ☺
  - OneWeb at 1200km ☹
  - Amazon/Kuiper (590-630km) ☺



Tony Tyson, UC Davis
LSST Chief Scientist

Impact on Visible Spectrum



Credit: Tony Tyson, shown as Fig. 11 on p. 12 of https://arxiv.org/pdf/2006.12417.pdf

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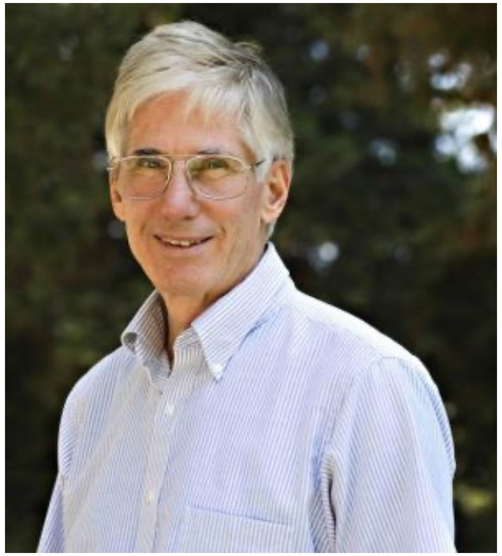
  - Amazon/Kuiper (590-630km) ☺
- Crosstalk (Rubin)



Tony Tyson, UC Davis
LSST Chief Scientist

Impact on CMB observation

- 37.5-42.5 GHz range impacts LF band – (SO LF is 27/39GHz dichroic)
- Sidelobes
- Thermal power: Blackbody from heat
- Even if signal were 1000x smaller, would still be seen

Lyman Page,
Princeton

Grant Teply,
SO Postdoc at UCSD

Brad Johnson,
UVA

Ben Mazin,
UCSB

What can we (observatories) do?

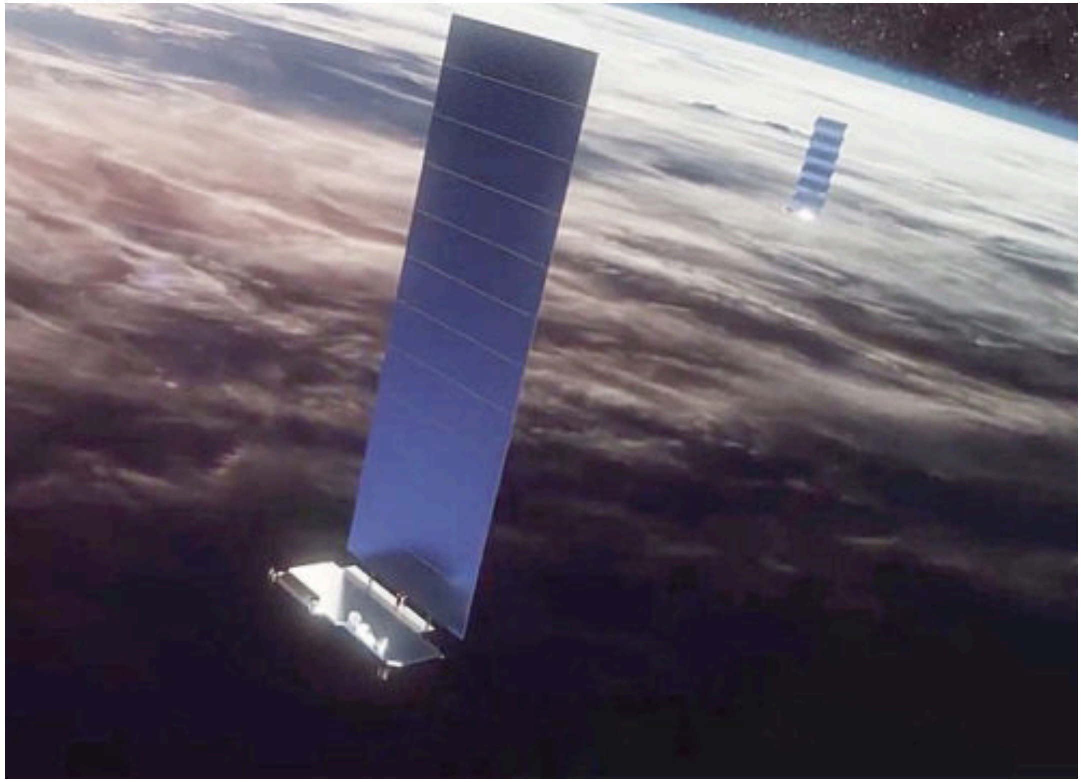
(SATCON-1)

- Open-access software to identify, model, subtract/mask trails from satellites
- Open-access software to predict time situational awareness data of satellites
- Simulations of effects on data analysis systematics
- Maintain dialogue with commercial sector

Very Large Array in Socorro, New Mexico

What can Satellite Operators do?

- Supply high-accuracy orbit information from on-board GPS
  - Allows evasive maneuvers
  - Facilitates removing contamination from data
- Hardware changes to reduce reflection (Starlink)
  - DarkSAT: I see a white panel and I want to paint it black
  - VisorSAT: sunshades to prevent solar reflection



Credit: SpaceX

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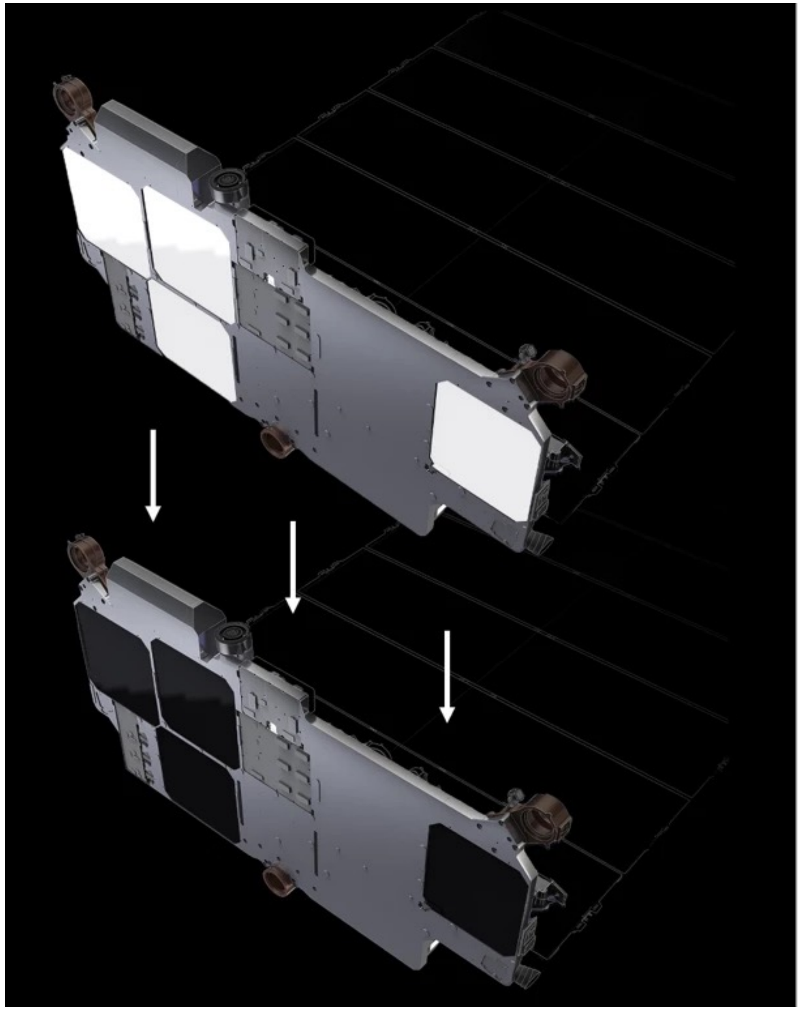
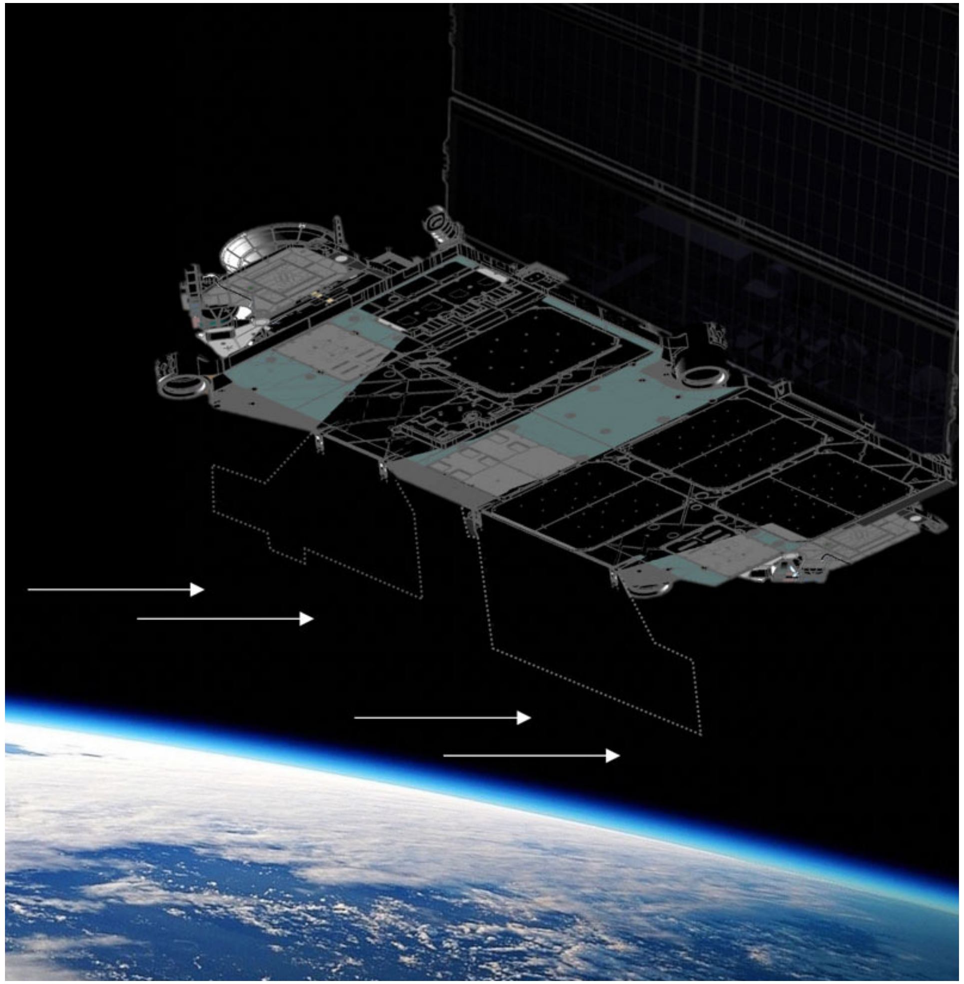


Credit: SpaceX

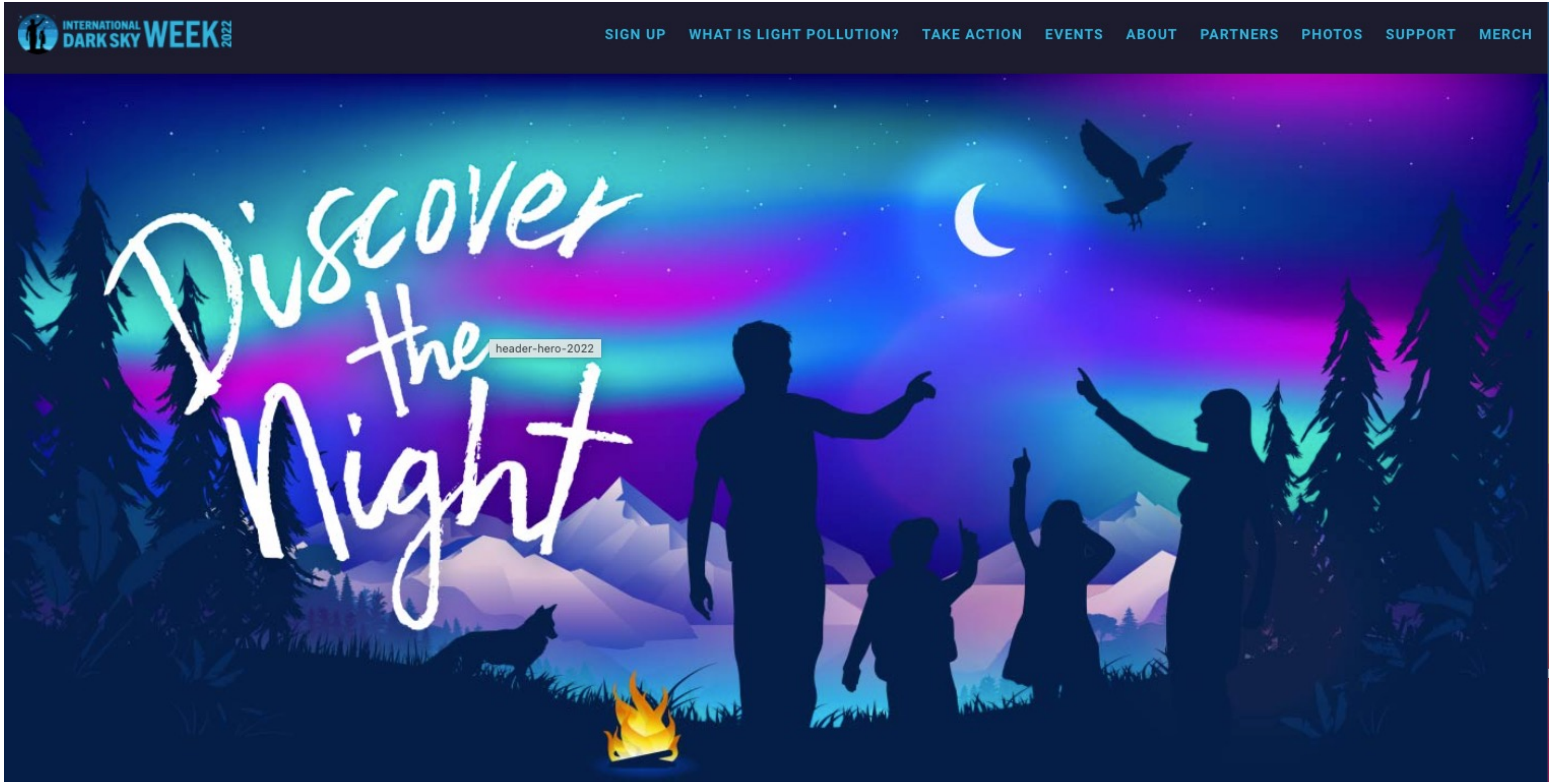
What can Satellite Operators do?

- Supply high-accuracy orbit information from on-board GPS
  - Allows evasive maneuvers
  - Facilitates removing contamination from data
- Hardware changes to reduce reflection
  - DarkSAT: I see a white panel and I want to paint it black
  - VisorSAT: sunshades to prevent solar reflection



Credit: SpaceX

International Dark Sky Week: April 22-30, 2022



The Outer Space Treaty and Beyond

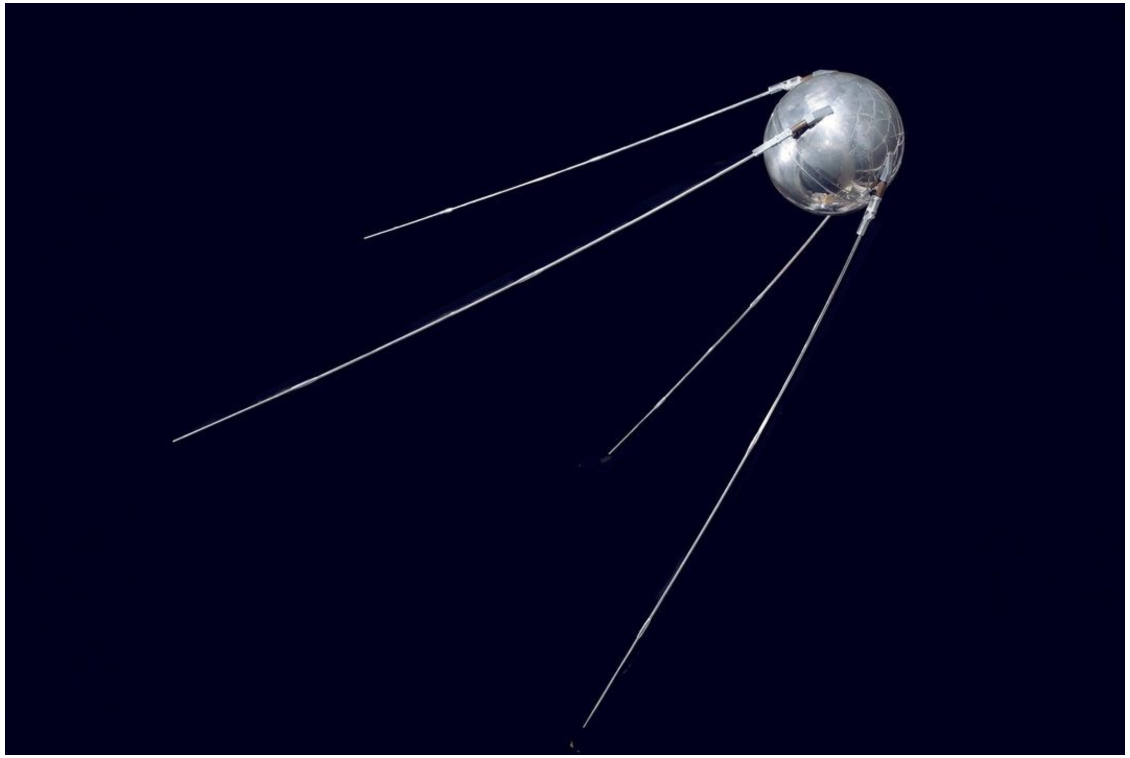


Image of Sputnik from Air and Space Magazine; Sputnik, the first artificial satellite was launched on October 4, 1957

Soviet Ambassador Anatoly F. Dobrynin, UK Ambassador Sir Patrick Dean, US Ambassador Arthur J. Goldberg, US Secretary of State Dean Rusk, and US President Lyndon B. Johnson at the signing of the Outer Space Treaty on January 27, 1967 in Washington. (credit: British Pathé)

United States Space Force