# THE SOUTH POLE TELESCOPE:

## CALIBRATIONS FOR THE COSMIC MICROWAVE BACKGROUND

Arielle Pfeil
Bartlett High School

Antony Simonoff
Adlai E. Stevenson High School

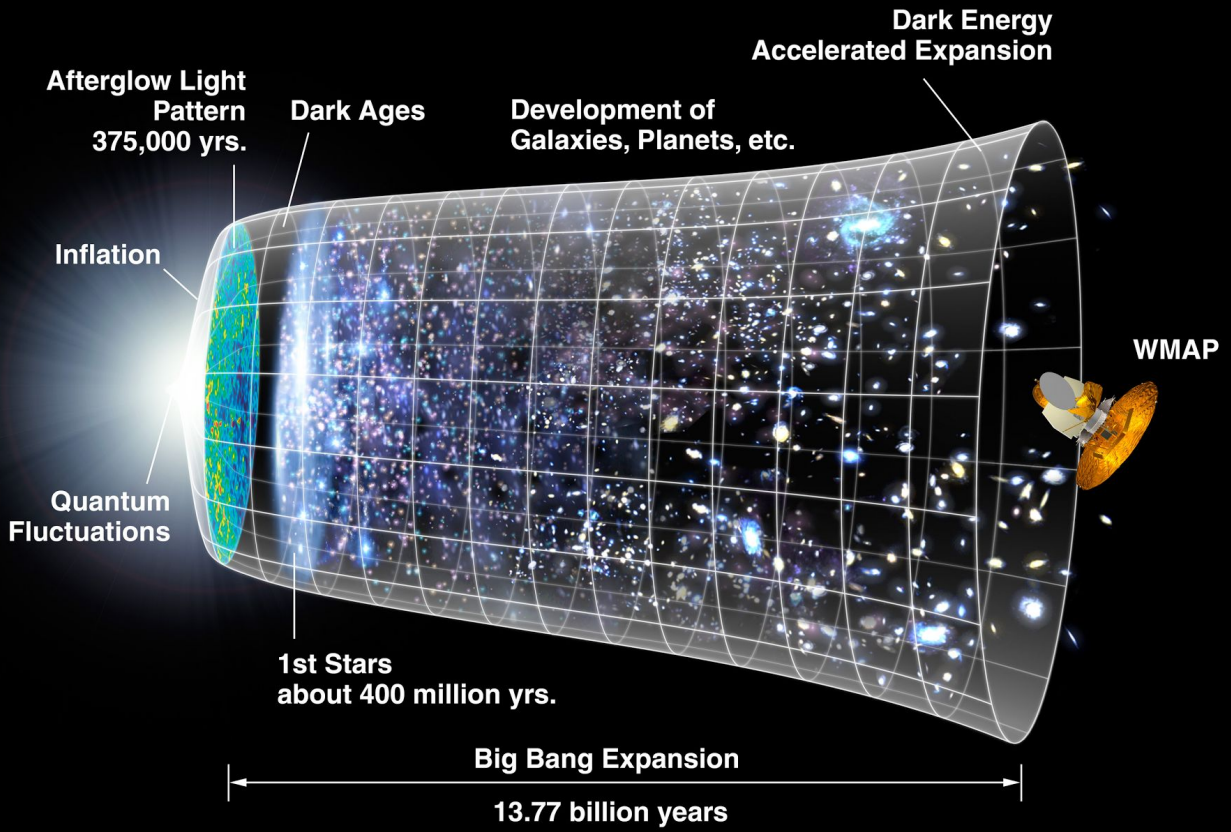
# Agenda & Introduction

History of The Universe

South Pole Telescope (SPT)

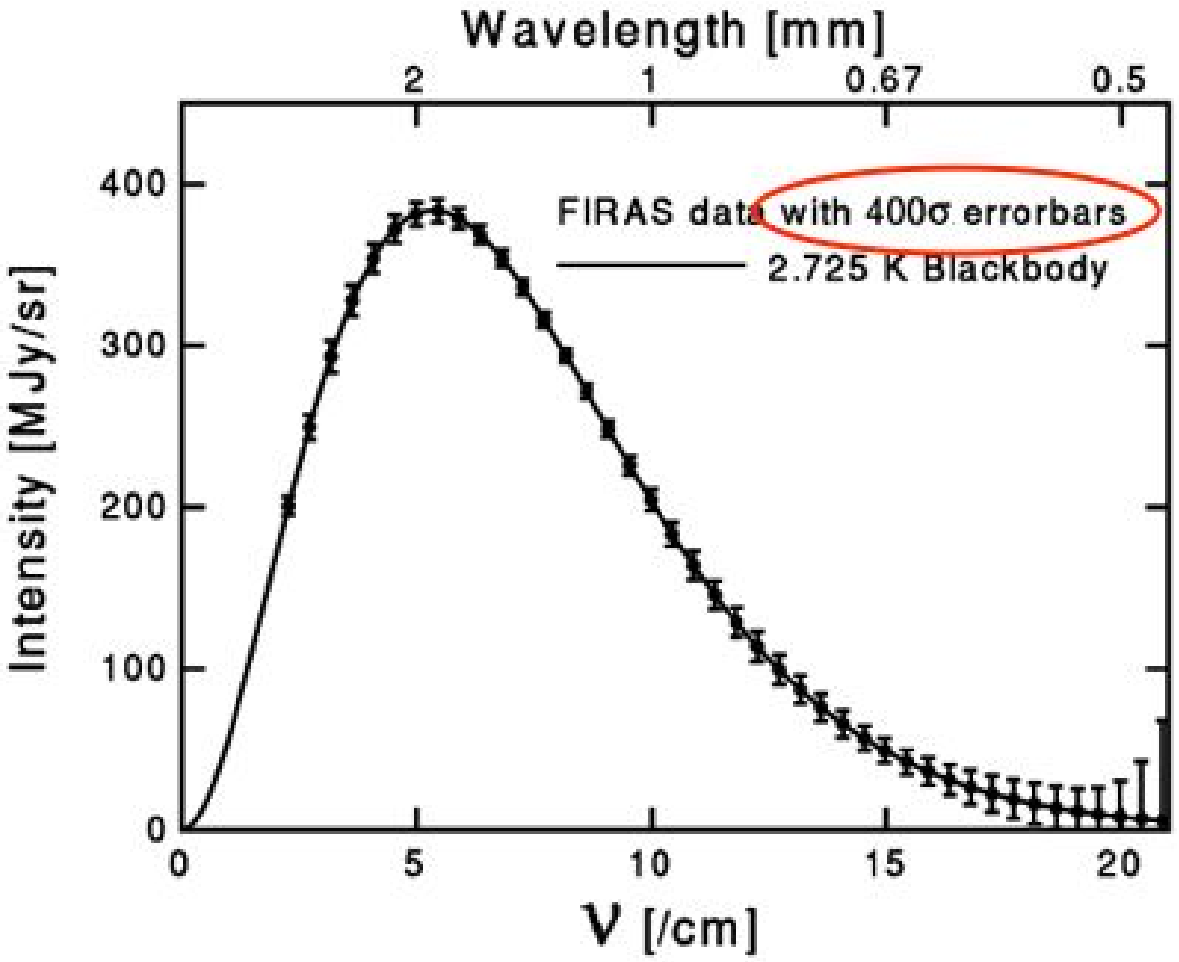
Projects & Contributions

# The Big Bang & Onwards



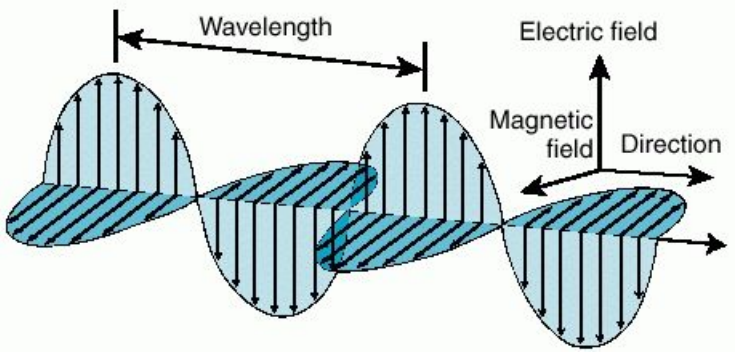
# Cosmic Microwave Background (CMB)

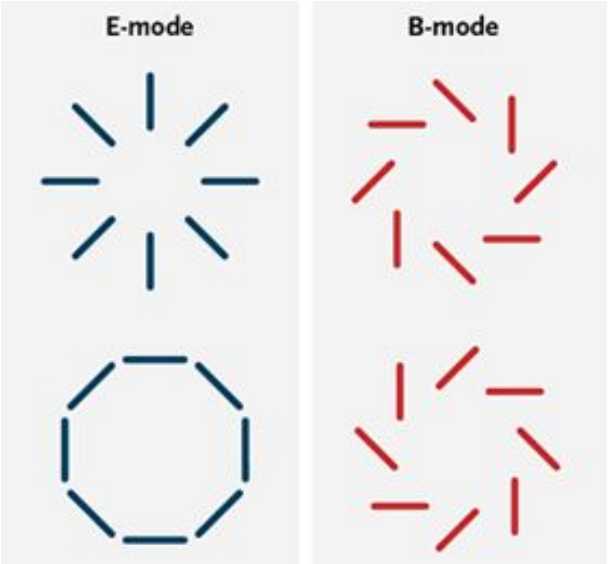
- Uniform thermal background
- 1965 by Arno Penzias & Robert Wilson
  - Nobel Prize in 1978
- Recombination period
- Microwave frequency
- ~3K (2.725K) blackbody
- Extremely uniform temperature

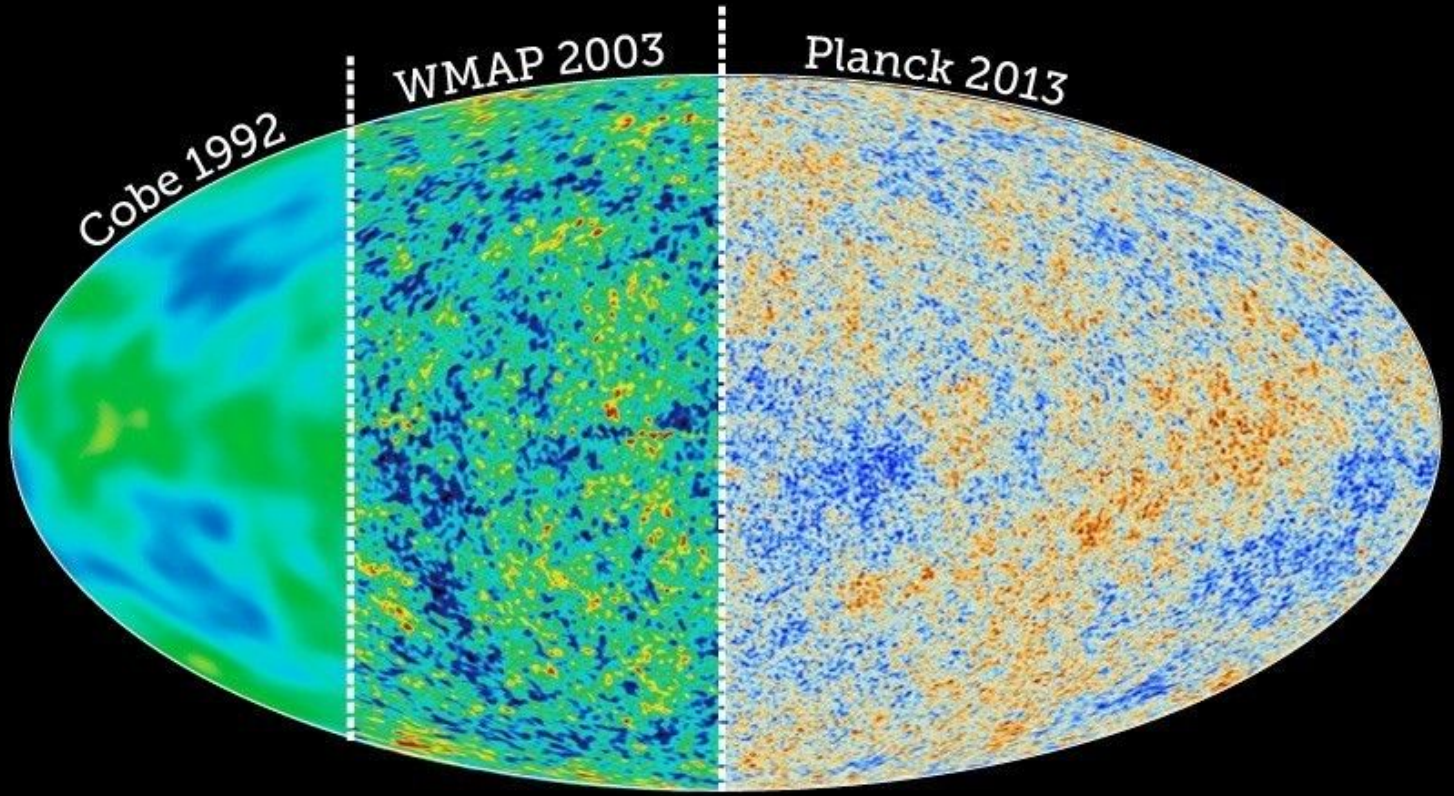

Wavelength [mm]
2
1
0.67
0.5
400
300
200
100
0
Intensity [MJy/sr]
FIRAS data with 400σ errorbars
2.725 K Blackbody
0
5
10
15
20
ν [/cm]

# Inflation

- Exponential expansion
- Background gravitational waves
- CMB temperature anisotropies
- E-mode and B-mode polarization
  - Predictable source of B-modes



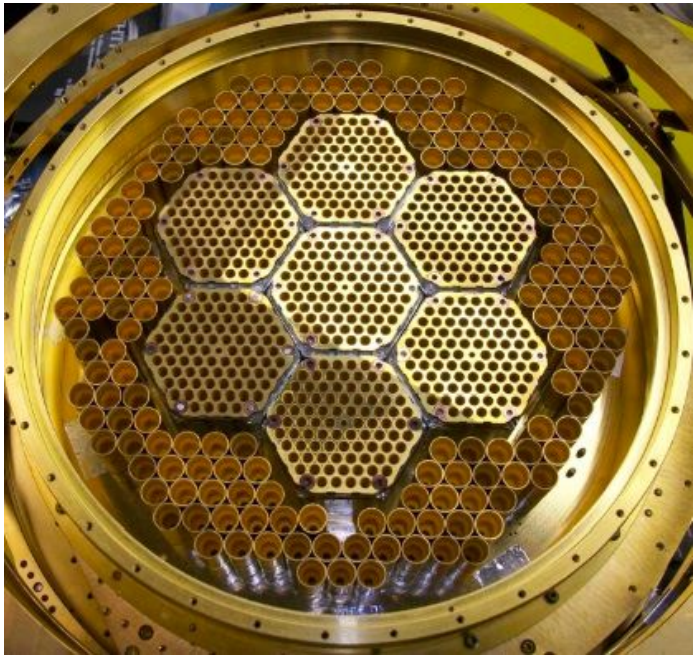

Cobe 1992
WMAP 2003
Planck 2013

# South Pole Telescope

- 10m sub-millimeter wave survey of faint emissions
- Detects B-mode polarization
  - Studying growth of early universe
- Looking at primary and secondary anisotropies in CMB

# South Pole Telescope

- South Pole is best place to observe
  - Dry
  - Less atmospheric interference
- Superconducting Transition-Edge Sensor Bolometers
- SPT focal plane — polarization sensitive

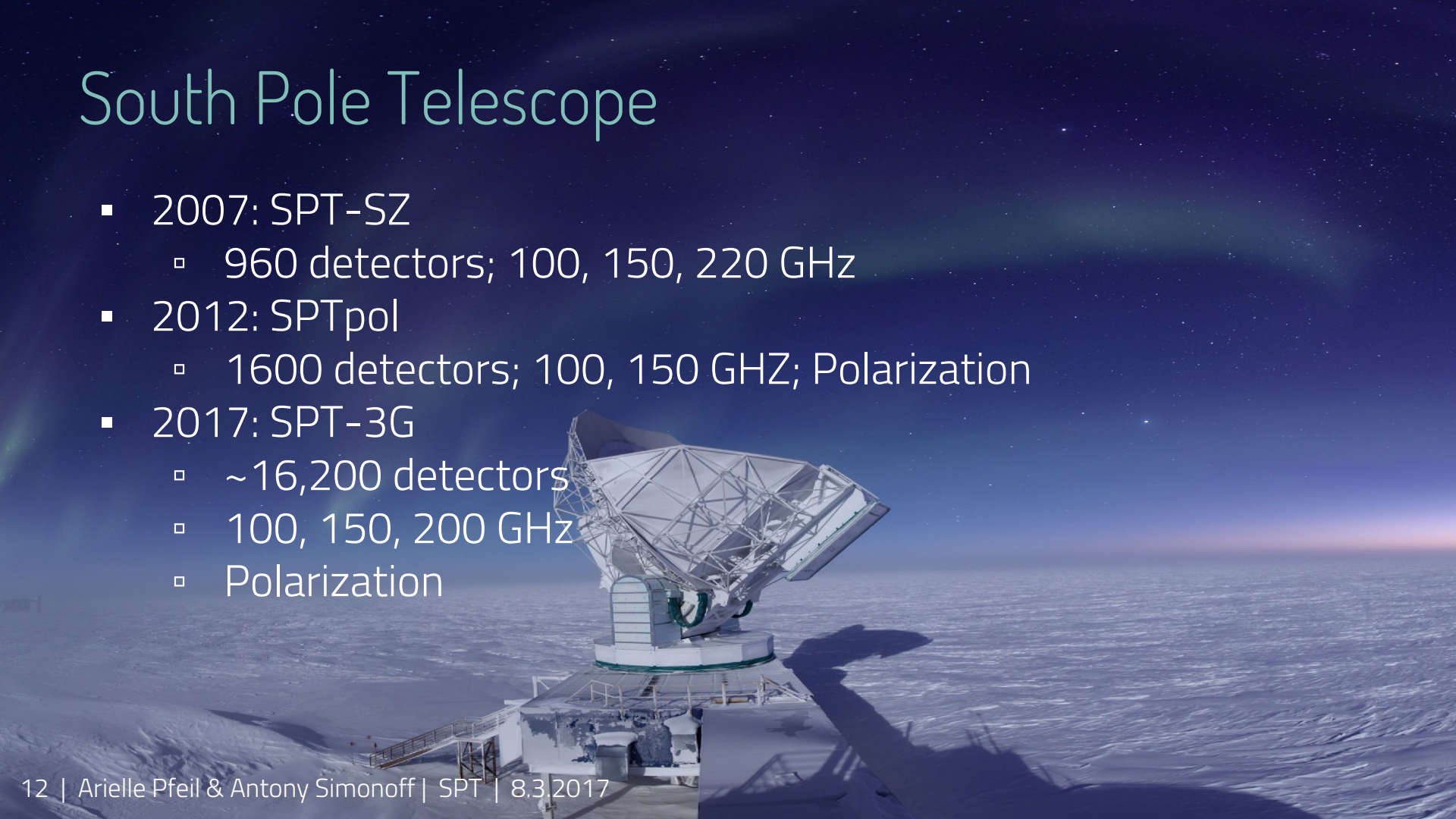


# Polarization

- Orientation of light orthogonal to propagation
  - Unpolarized light has all orientations
- Purpose:
  - Polarize light into x and y polarizations
    - SPT pixels only have those two
- Polarization of the CMB
  - Linearly polarized at 10% level

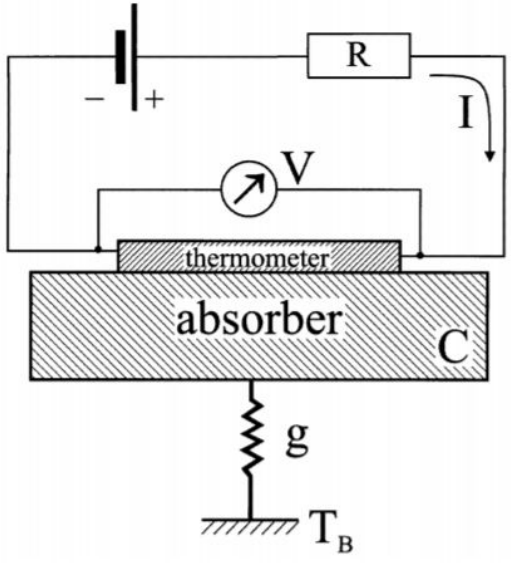
# South Pole Telescope

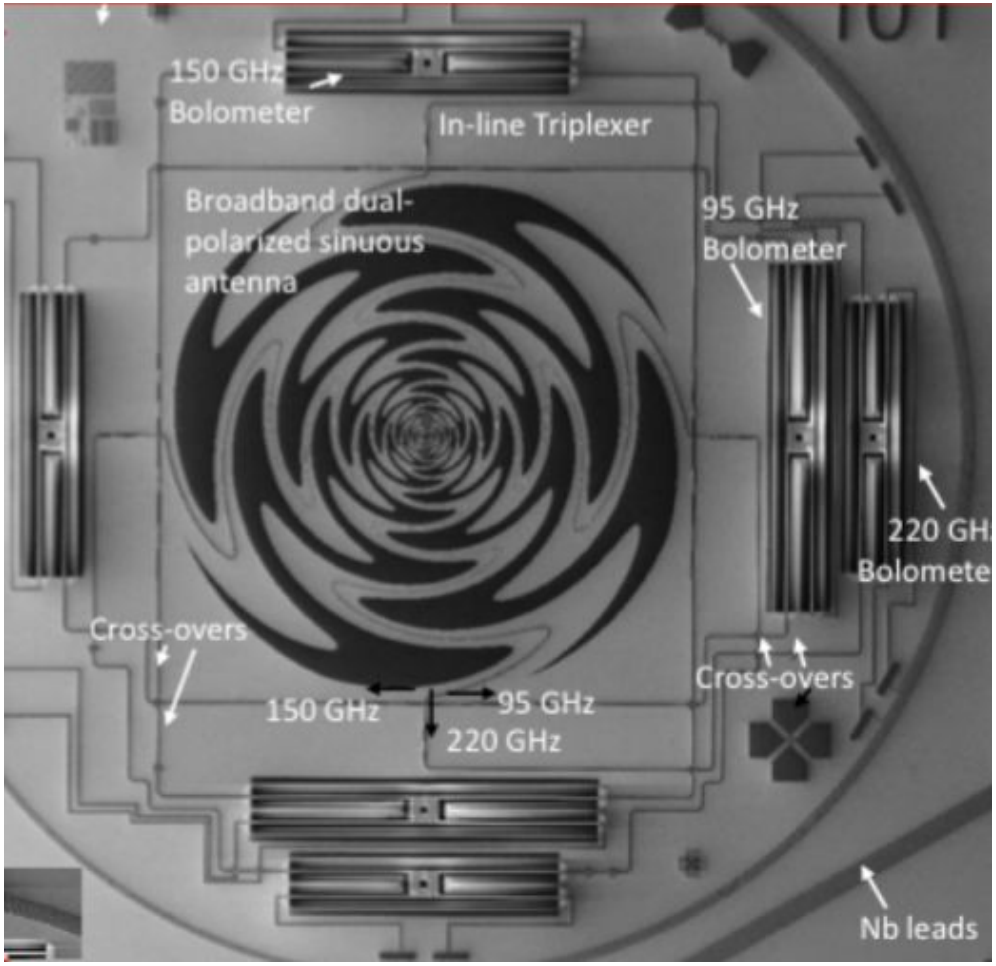
- 2007: SPT-SZ
  - 960 detectors; 100, 150, 220 GHz
- 2012: SPTpol
  - 1600 detectors; 100, 150 GHZ; Polarization
- 2017: SPT-3G
  - ~16,200 detectors
  - 100, 150, 200 GHz
  - Polarization



# How CMB is Detected: Bolometers

- Absorber (with a specific heat)
- Thermometer + thermal link (g) to thermal bath ($T_B$)
- Process:
  - Radiation to absorber
  - Thermometer responds and changes thermistor temperature
  - Determine R by passing current
    - Observing change in current



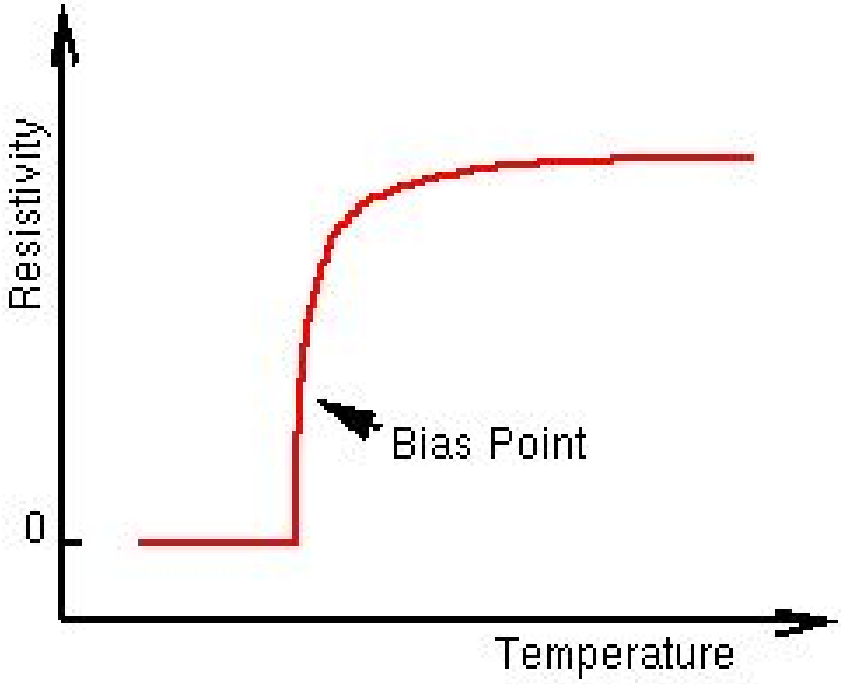

150 GHz
Bolometer
In-line Triplexer
Broadband dual-
polarized sinuous
antenna
95 GHz
Bolometer
220 GH
Bolomete
Cross-overs
150 GHz
95 GHz
220 GHz
Cross-overs
Nb leads

# Bolometer Power

$$P_{Total} = P_{elec} + P_{opt} = \int_{T_{Earth}}^{T_{bolo}} G(T)dT$$

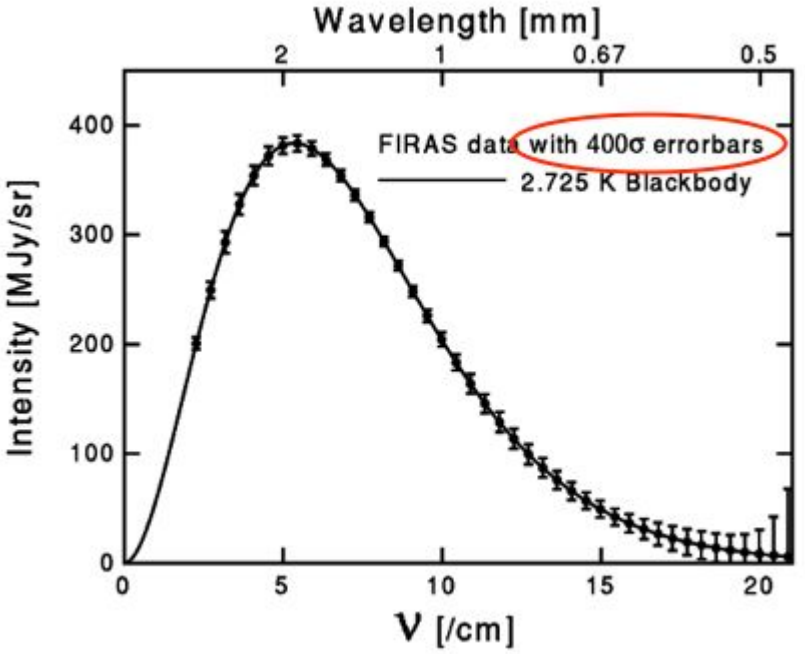
$$P_{opt} = \int B(\nu, T) \cdot f(\nu) \cdot A\Omega \cdot d\nu$$

$$P_{opt} = 2k_B \cdot T_{RJ} \cdot \mu \cdot \Delta\nu$$



# Blackbody Radiation

- $B(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{k_BT}}-1}$ Planck's Law
- Power radiated = $\iiint B(\nu,T)\mathrm{d}\nu\mathrm{d}A\mathrm{d}\Omega$
  - $\Delta\,\nu$ = 150GHz ± 30.0 GHz
- If $h\nu \ll k_BT$ then
  - $B(\nu,T) = \frac{2k_BT\nu^2}{c^2}$



# Measured Blackbody Radiation

- Suppose an antenna with efficiency $\epsilon$ and a filter with a transmission efficiency depending on $\nu$ : $T(\nu)$
  - Then the measured power in both polarizations is:

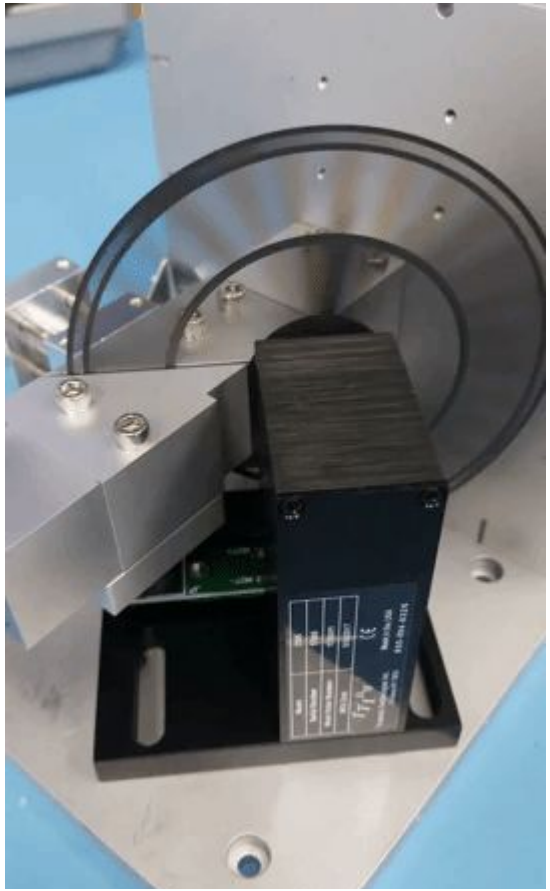
$$P^{x+y}_{measured} = \int B(\nu, T)\epsilon T(\nu)\, A_{eff} d\nu = \int \frac{2h\nu}{e^{\frac{h\nu}{k_B T}} - 1} \epsilon T(\nu) d\nu$$

  - Then for the x and y polarizations the measured power is:

$$P^x = \frac{1}{2} P^{x+y} \quad \text{and} \quad P^y = \frac{1}{2} P^{x+y}$$

# Our Role

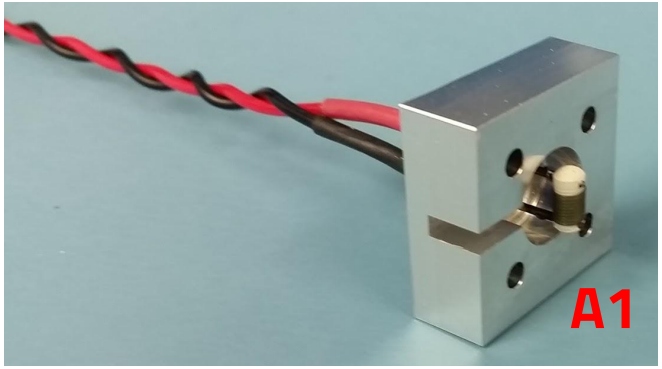
- Why characterize detectors?
  - Have good polarization sensitivity
- Prepare for South Pole viewing
- Combined systems
  - IR source at frequency
  - Polarization

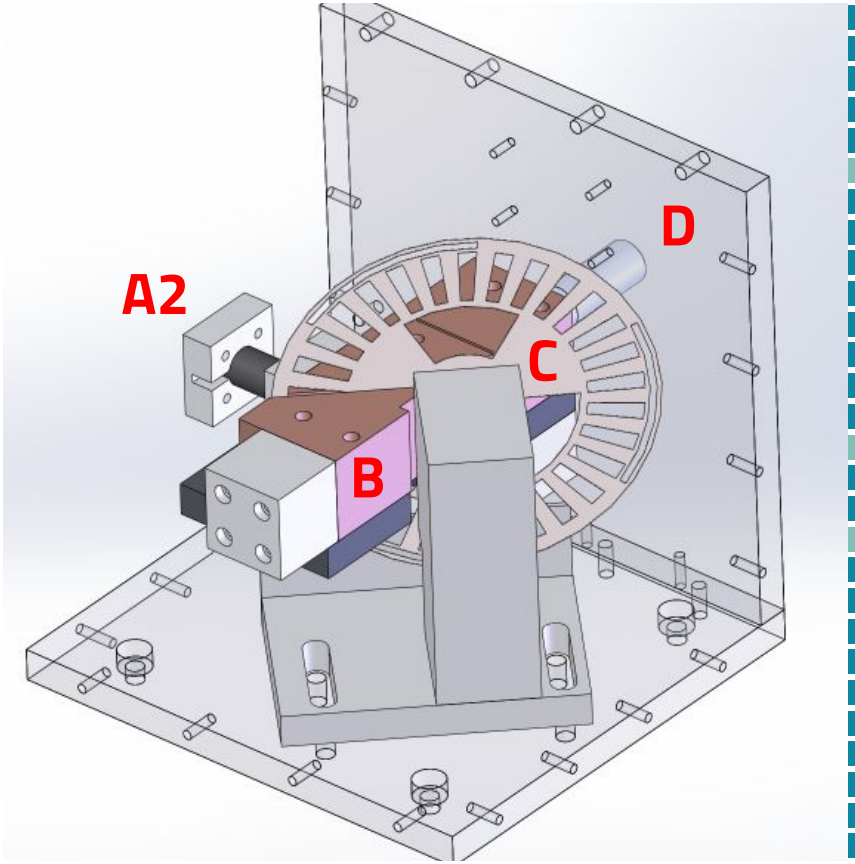


# Optical Chopper

# Optical Chopper

- Infrared source emitter
- Frequency pulse
  - HIGH/LOW: 4-5000 Hz
- IR source to lock-in amplifier



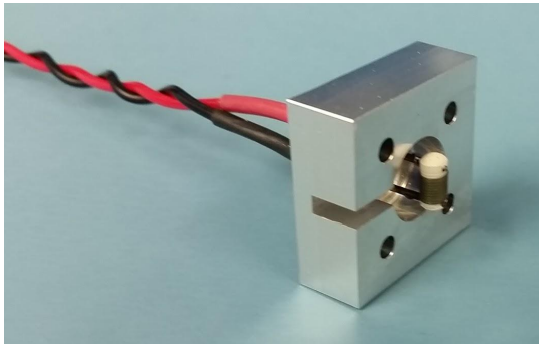



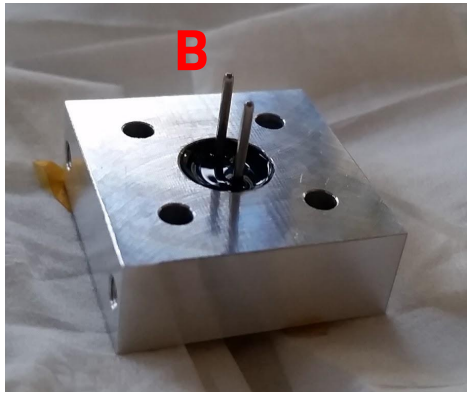
# Why Use an Optical Chopper?

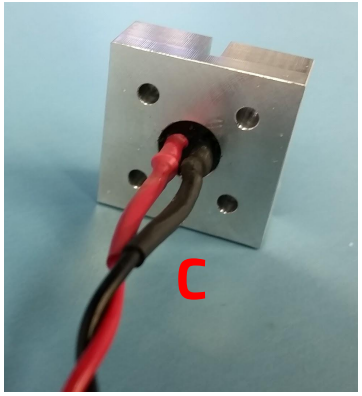
- Creates specific reference frequency
- Reduces noise from outside frequencies
- Characterize frequency response

$$V_r = A_r \sin(\omega_r t + \phi_r)$$

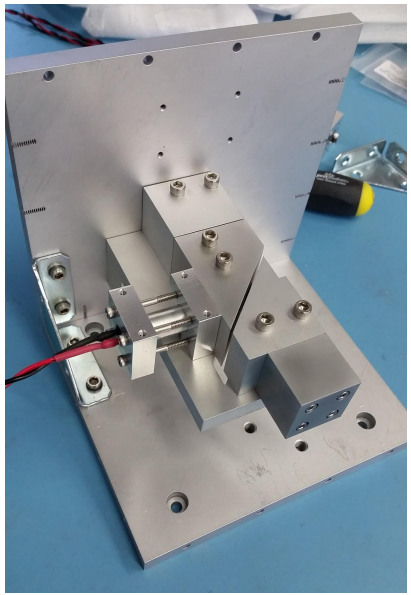
# IR Source: Stycast/Soldering

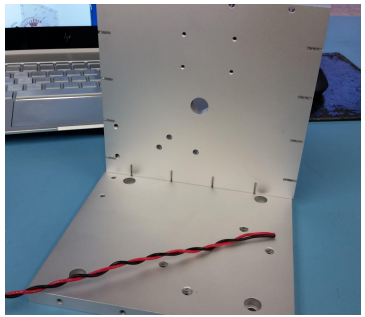


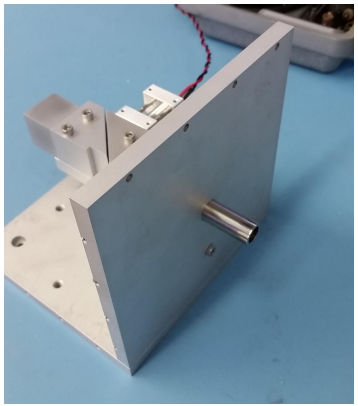


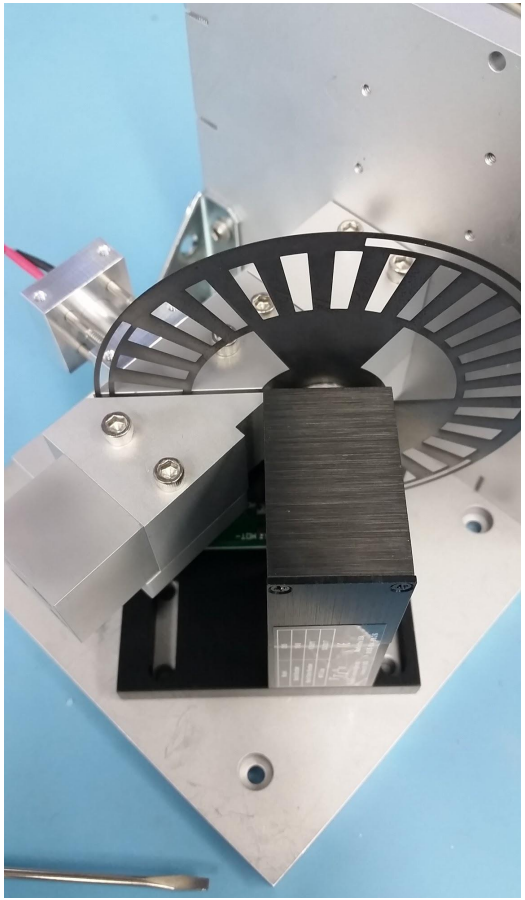




# Chopper Stand

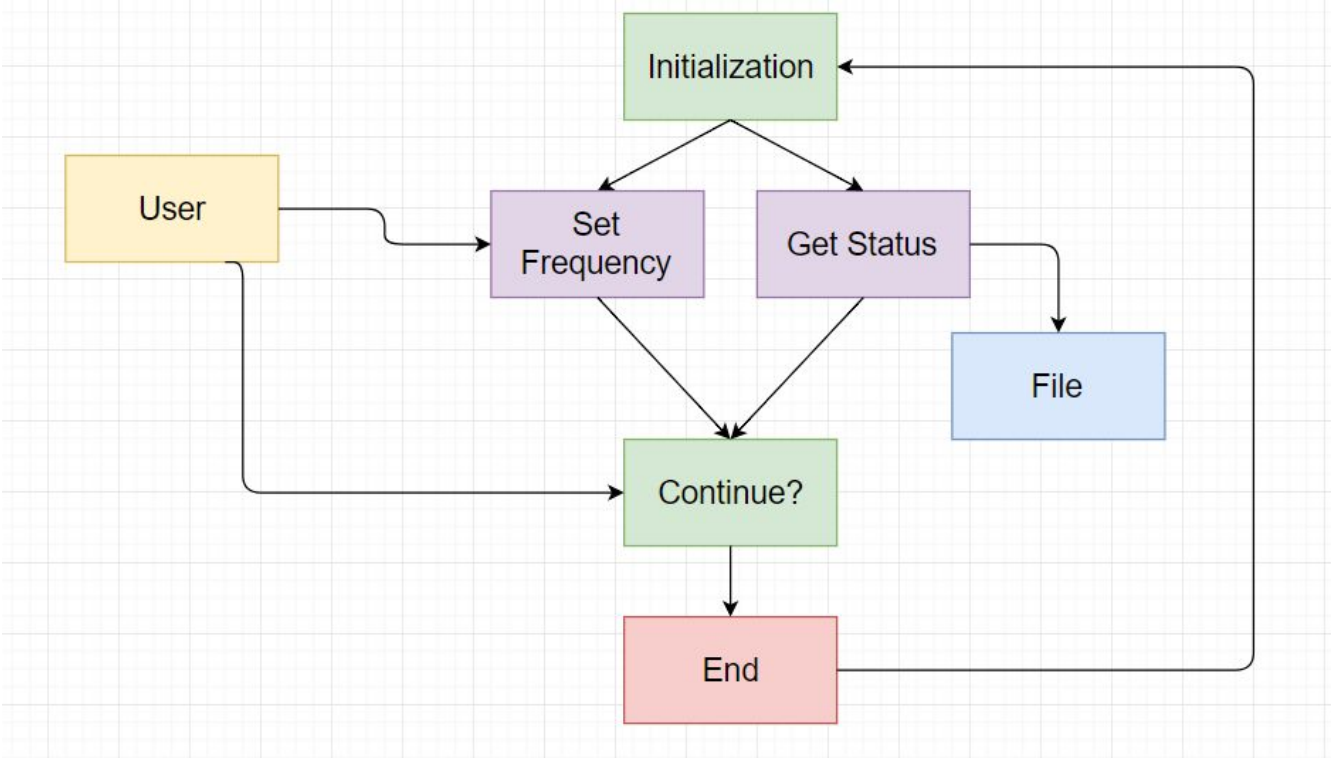






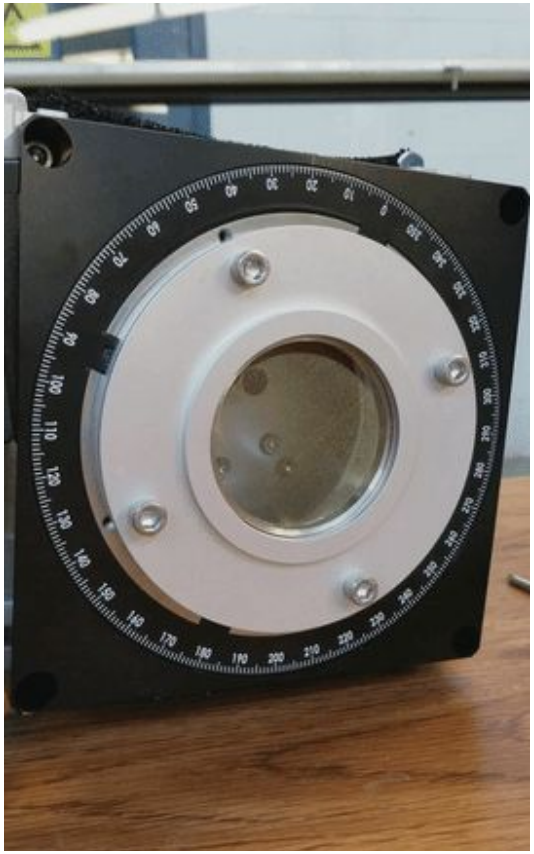


# Chopper Code Flowchart



```
Frequency is: INT SYNC
LO SPEED RANGE
0004.000 Hz
Hz


Frequency is: 1200.0Hz
Time in UTC: 2017-07-21 17:17:18.584541
Frequency is: 1200.0Hz
Time in UTC: 2017-07-21 17:17:31.130433
Frequency is: 1200.0Hz
Time in UTC: 2017-07-21 17:17:38.393155
Frequency is: 1200.0Hz
Time in UTC: 2017-07-21 17:17:49.320841
Frequency is: 1000Hz
Time in UTC: 2017-07-21 17:18:10.076614
Frequency is: 600.0Hz
Time in UTC: 2017-07-21 17:18:41.577836
Frequency is: 384.0Hz
Time in UTC: 2017-07-21 17:18:59.353369
Frequency is: 600.0Hz
Time in UTC: 2017-07-21 17:19:11.641369
Frequency is: 600.0Hz
Time in UTC: 2017-07-21 17:19:27.593666
```

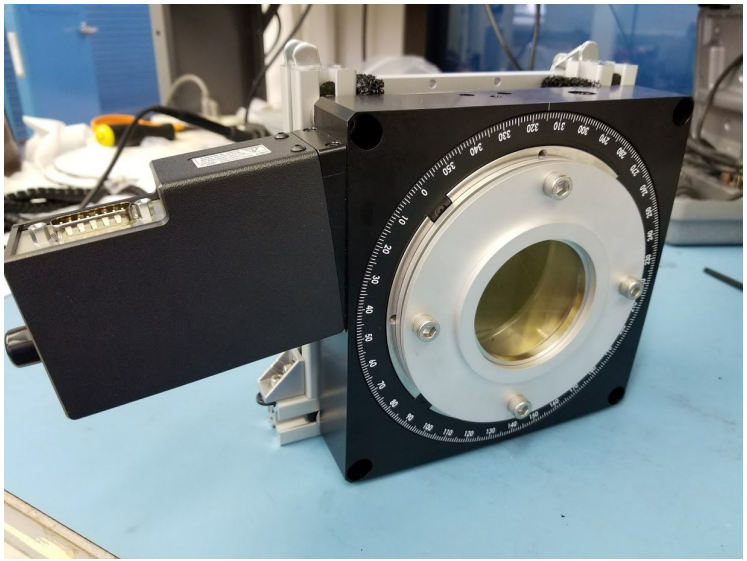
# Chopper Output



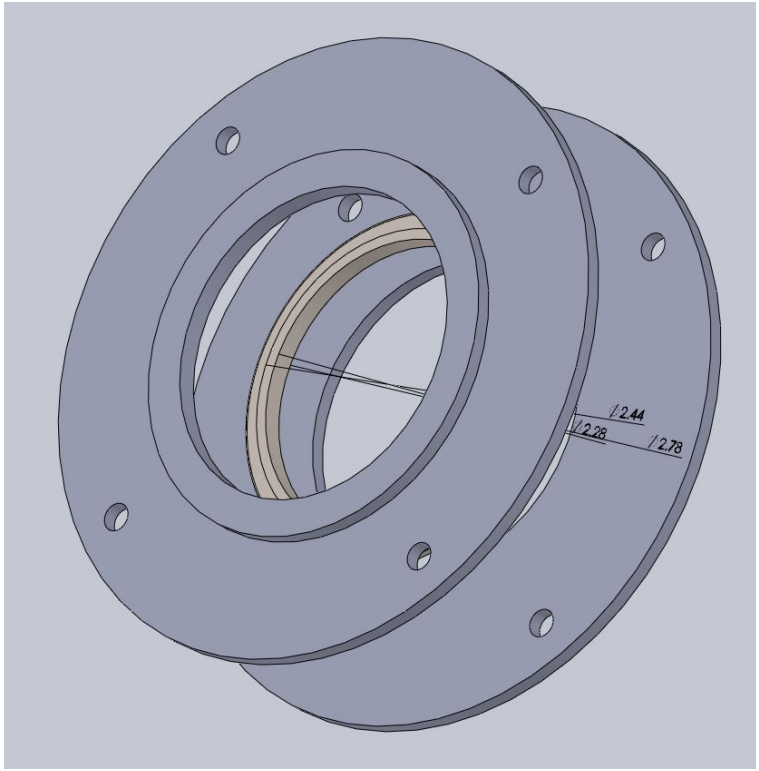
# Wire Stage

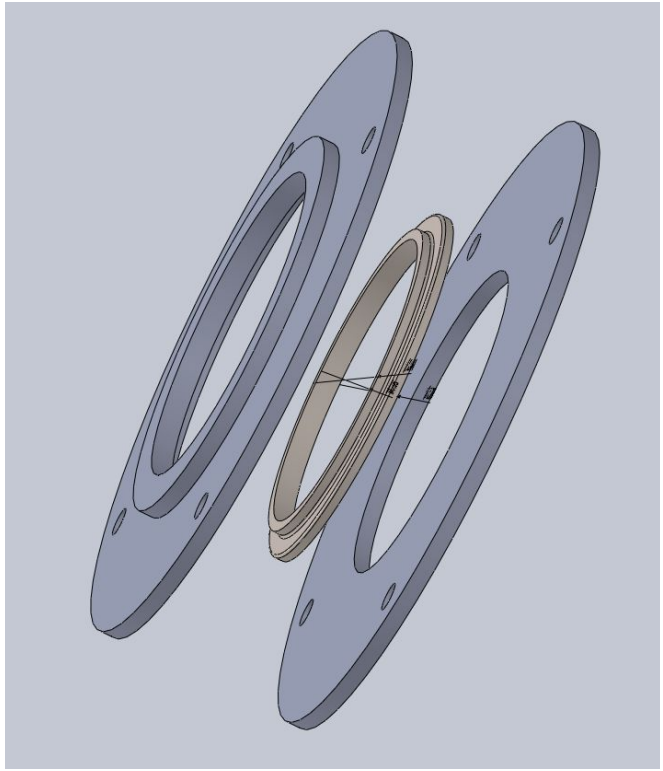
# Wire Stage

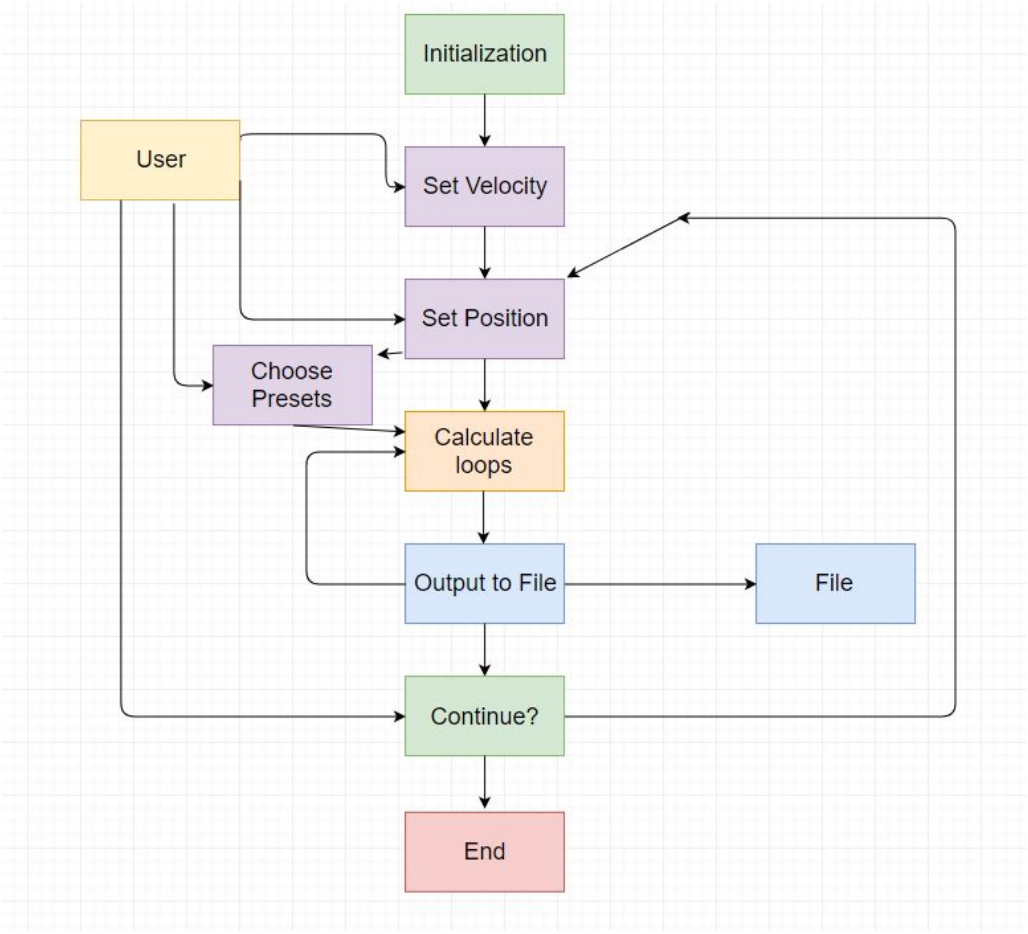
- Rotating mount for wire grid
  - Grid polarizes light



# Wire Stage Clamp Design



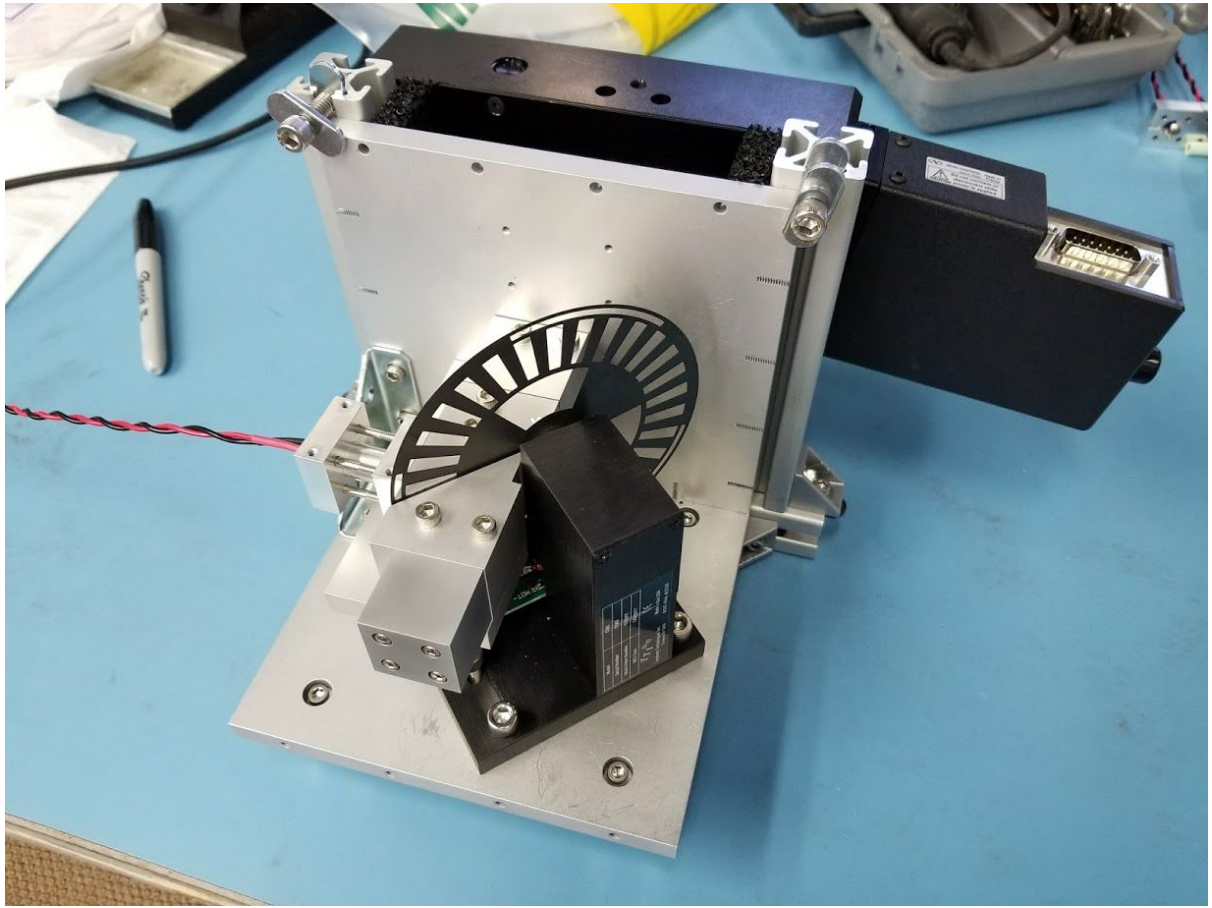





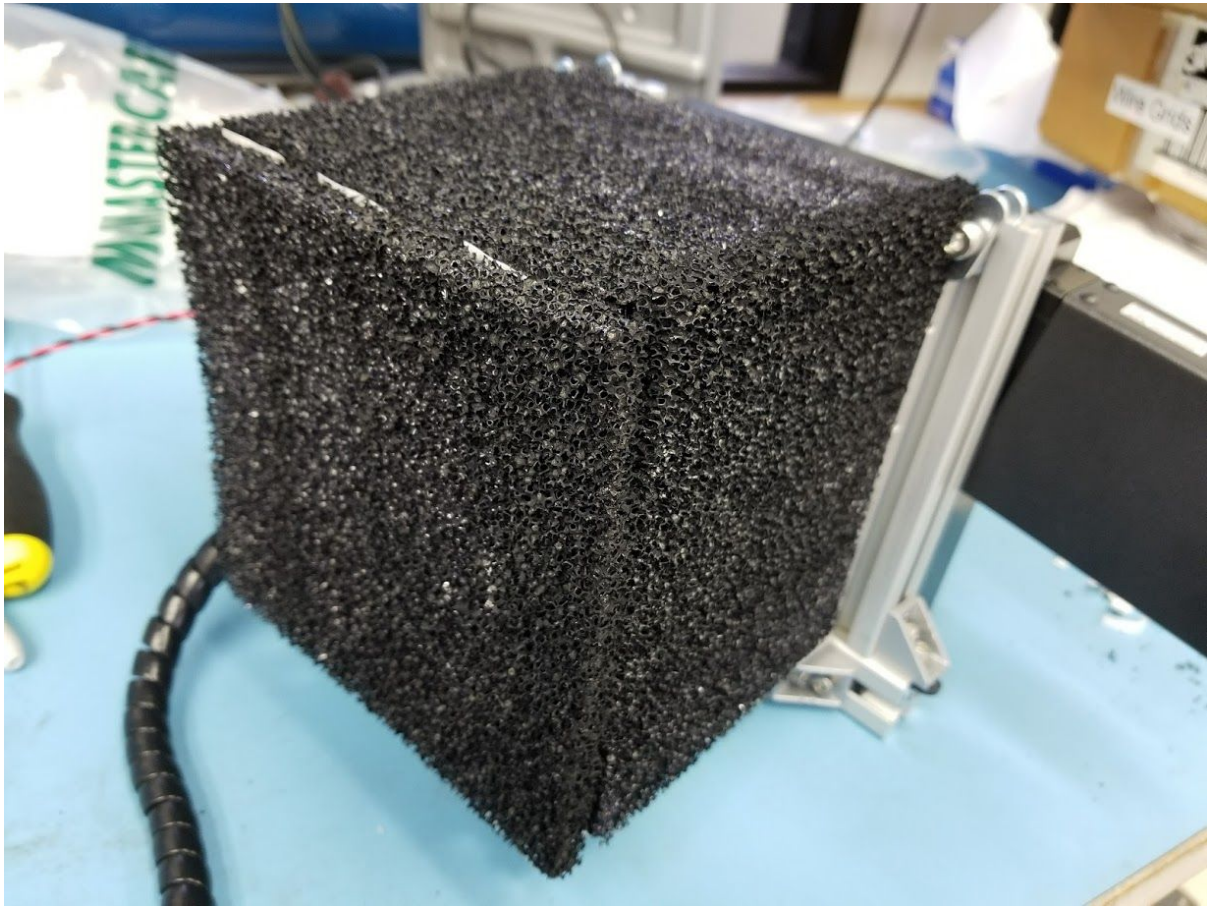

# Wire Grid Code Flowchart

```
Position: 45.0
Velocity: 10
Time in UTC: 1501014221.13
Current Loop: 1

Position: 34.413
Velocity: 10
Time in UTC: 1501014222.23
Current Loop: 2

Position: 23.392
Velocity: 10
Time in UTC: 1501014223.33
Current Loop: 3

Position: 12.382
Velocity: 10
Time in UTC: 1501014224.44
Current Loop: 4

Position: 1.372
Velocity: 10
Time in UTC: 1501014225.54
Current Loop: 5

Position: -9.642
Velocity: 10
Time in UTC: 1501014226.64
Current Loop: 6
```

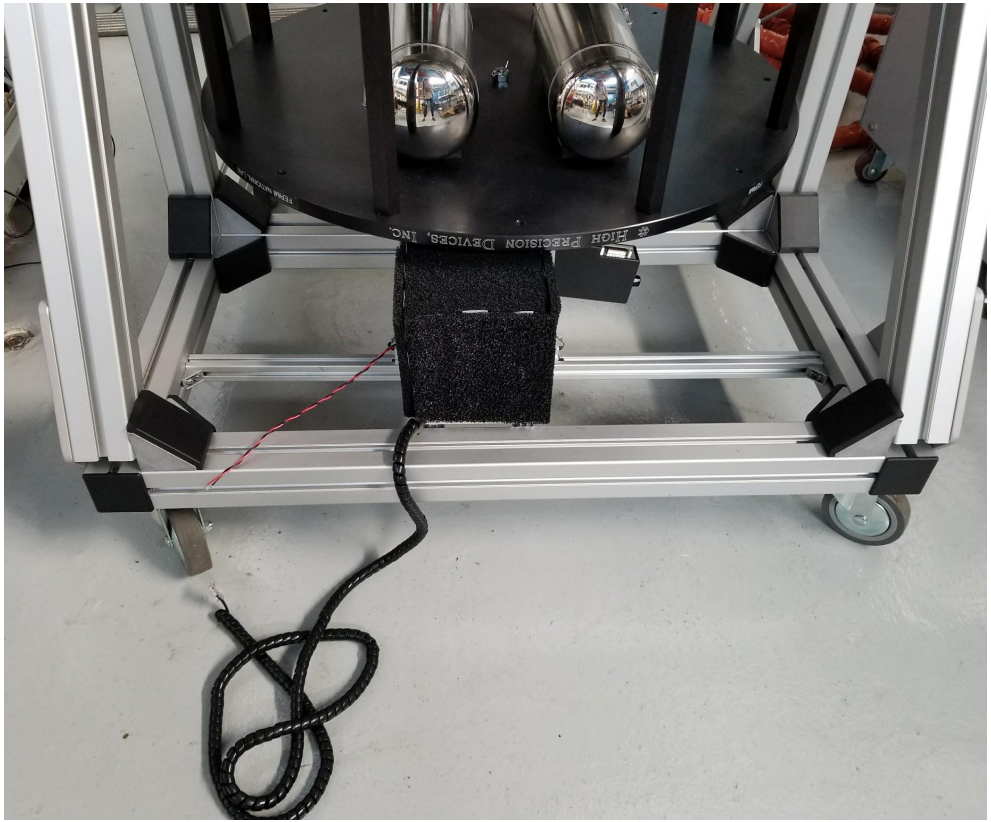
# Wire Grid Output



# Setup



# HR-10




# Application

# Summary

- Cosmic Microwave Background (CMB) from Big Bang
- South Pole Telescope detects CMB using bolometers
- Verify polarized pixels are orthogonal
  - Use wire grid & optical chopper
  - Analyze data output, calibrate as necessary
- Next steps:
  - Extract data from bolometers
  - Repeat calibrations for multiple detectors

# References


Berkeley Spiderweb VSBs - Introduction. (2017). Bolo.berkeley.edu. Retrieved 28 July 2017, from http://bolo.berkeley.edu/bolometers/introduction.html

CMB Polarization. (2017). Cfa.harvard.edu. Retrieved 28 July 2017, from https://www.cfa.harvard.edu/~cbischoff/cmb/

Echo of the Big Bang - One Universe at a Time. (2013). One Universe at a Time. Retrieved 28 July 2017, from https://briankoberlein.com/2013/09/12/echo-of-the-big-bang/Galtseva, E. (2017). South Pole Telescope. Pole.uchicago.edu. Retrieved 28 July 2017, from https://pole.uchicago.edu/

Koberlein, B., Outler, A., Koberlein, B., & Koberlein, B. (2015). What does the cosmic microwave background tell us?. One Universe at a Time. Retrieved 28 July 2017, from https://briankoberlein.com/2015/06/15/science-in-the-raw/

Meaning of the divergence and curl of a vector field. (2017). Www2.sjs.org. Retrieved 28 July 2017, from http://www2.sjs.org/raulston/mvc.10/topic.6.lab.1.htm

Polarization Primer. (2017). Background.uchicago.edu. Retrieved 28 July 2017, from http://background.uchicago.edu/~whu/polar/webversion/node8.html

South Pole Telescope to help astrophysicists learn what universe is made of, how it evolves. (2007). Www-news.uchicago.edu. Retrieved 28 July 2017, from http://www-news.uchicago.edu/releases/07/070226.southpole.shtml

Terahertz. (2017). Terahertz.co.uk. Retrieved 28 July 2017, from http://www.terahertz.co.uk/index.php?option=com_content&view=article&id=214&Itemid=532

THE BIG BANG . (2017). Umich.edu. Retrieved 28 July 2017, from http://umich.edu/~gs265/bigbang.htm

Wayne Hu. (2017). Background.uchicago.edu. Retrieved 28 July 2017, from http://background.uchicago.edu/~whu/index.html

WMAP Big Bang CMB Test. (2017). Map.gsfc.nasa.gov. Retrieved 28 July 2017, from https://map.gsfc.nasa.gov/universe/bb_tests_cmb.html

WMAP CMB Fluctuations. (2017). Wmap.gsfc.nasa.gov. Retrieved 28 July 2017, from https://wmap.gsfc.nasa.gov/universe/bb_cosmo_fluct.html

# ACKNOWLEDGMENTS


Bradford Benson

SPT Scientist , Mentor

Donna Kubik

SPT Scientist

Adam Anderson

SPT Scientist

Sasha Rahlin

SPT Scientist

Andrea Bryant

SPT Intern

Cory Cotter

SPT Intern

George Dzuricsko

QuarkNet Instructor

QuarkNet Program

# BACKUP SLIDES

```
class OpticalChopperC995:
    def __init__(self): #initialize and open port
        self.serial_interface = serial.Serial(port='/dev/ttyUSB0', baudrate=9600, #linux port
                            bytesize=serial.EIGHTBITS, parity=serial.PARITY_NONE,
                            stopbits=serial.STOPBITS_ONE, xonxoff=True)

    def get_frequency(self): #get current frequency
        self.serial_interface.write('F:STATUSRQ\r\n')
        time.sleep(.1)
        recieve = self.serial_interface.read(self.serial_interface.inWaiting())
        return recieve

    def send_frequency(self,input_frequency): #input frequency to chopper
        input_frequency = "F:" + str(input_frequency) + "\r\n"
        #input_frequency = "F:" + str(input_frequency)
        #print(input_frequency)
        self.serial_interface.write(input_frequency)
        time.sleep(.1)
        sent = self.serial_interface.read(self.serial_interface.inWaiting())
        return sent

chopper = OpticalChopperC995() #rename chopper

#user information and frequency input
print("LOW frequencies are 4-500 Hz \nHIGH frequencies are 501-5000 Hz")


outputFile = open('Chopper_Frequency_Output.txt', 'a')
```

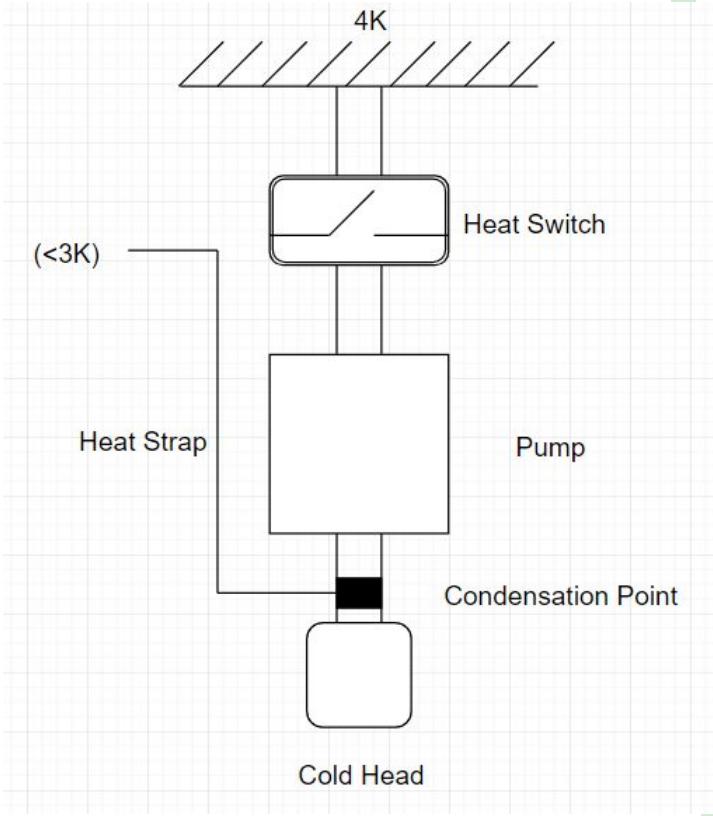
# Optical Chopper

```
177    #timePrint = "Time in UTC:" + " " + str(datetime.utcnow()) +"\n"
178    #outputFile.write(timePrint)
179         timePrint = "Time in UTC:" + " " + str(time.time()) +"\n"
180         outputFile.write(timePrint)
181         currentLoopPrint = "Current Loop:" + " " + str(currentLoop) +"\n"
182         outputFile.write(currentLoopPrint)
183         outputFile.write("\n")
184         time.sleep(pauseBetweenLoops) #sets pause length between loop runs, each run takes about 200ms
185
186 def continueFunc():
187     continueInput = raw_input("Continue Y/N? ")
188     if continueInput == "Y" or continueInput == "y":
189         continueInput = "Yes"
190         rotateFunc()
191     elif continueInput == "N" or continueInput == "n":
192         continueInput = "No"
193         outputFile.close()
194         sys.exit()
195     else:
196         continueFunc()
```

# Wire Stage

# Cryogenics & Supercooling

- Start with a 4K bath
- Piping to a heat switch (HSw)
- Piping to He3 or He4 pump
- Piping through a condensation point to a cold head
- Heat strap from condensation point



# The Immediate Universe

Big Bang

Matter/antimatter collisions

Baryons: photons, neutrinos, quarks, electrons

Nucleosynthesis: protons, neutrons (hadrons) at 300 MeV

Particle interaction & hydrogen (deuterium) formation