Up, An Intro to Experimental Cosmology and Scientific Ballooning

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Physics Concerto – 09 April 2025

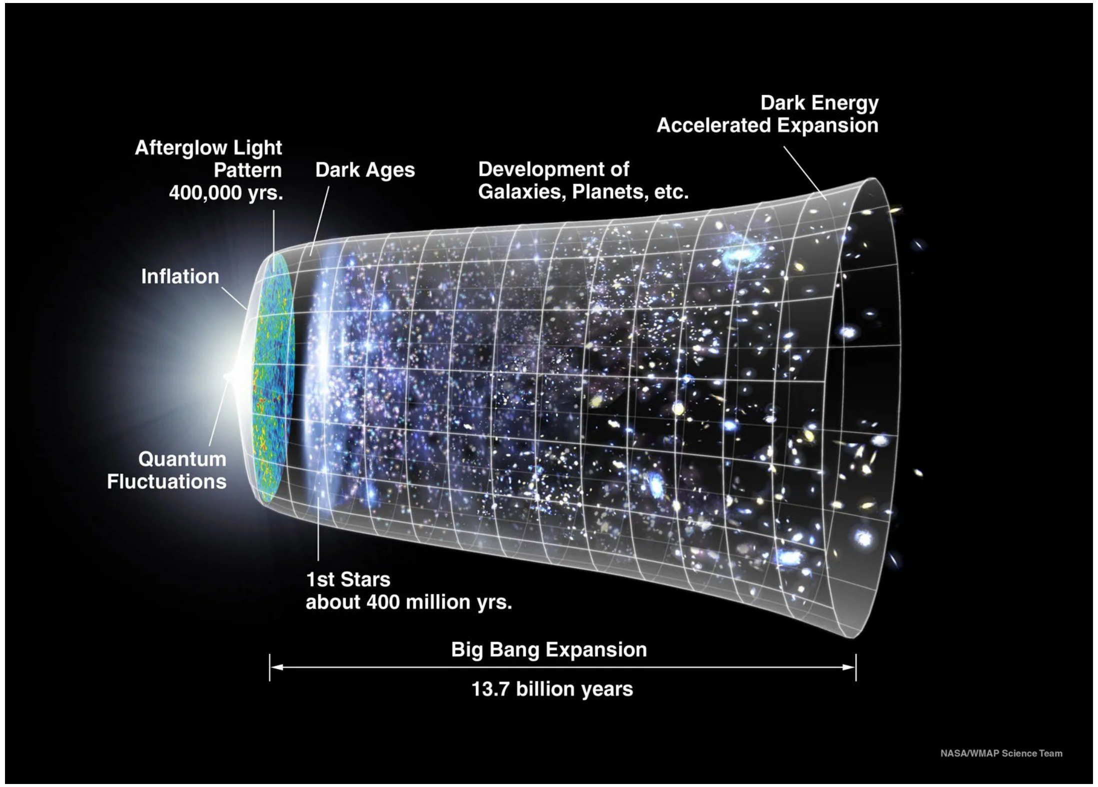
Outline

1. CMB Cosmology review
2. Experimental techniques in CMB cosmology
3. Scientific ballooning
4. BLAST Observatory and an optimization problem

CMB Cosmology

CMB Theory and Basics

- 380,000 yrs after the Big Bang the universe had expanded and cooled enough for atoms to form (without being immediately re-ionized)
- ‘Recombination’ produced free traveling photons imparted with information about their last scattering



CMB Discovery

- Bell Labs (of Holmdel NJ) had a big antenna – used for telecommunication research as part of the ECHO project.

The birth of CMB cosmology

- 1965 – 2 radio astronomers Penzias and Wilson began using the antenna for radio astronomy, but were mired by an unexplained background noise
- Further observation found the noise to be constant in all directions, and unaccounted for by a variety of other explanations.

  3.5° ± 1.0° K at 4080 Mc/s
- Penzias and Wilson spoke with Robert Dicke at Princeton who, along with his colleagues, had a cosmological explanation for the excess noise = the CMB.

COSMIC BLACK-BODY RADIATION*

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

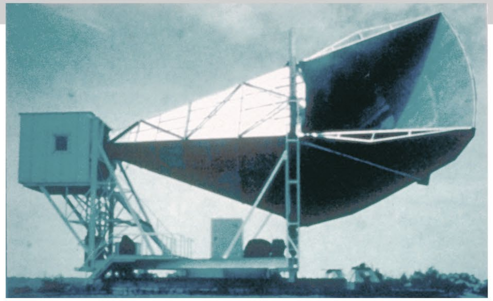
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

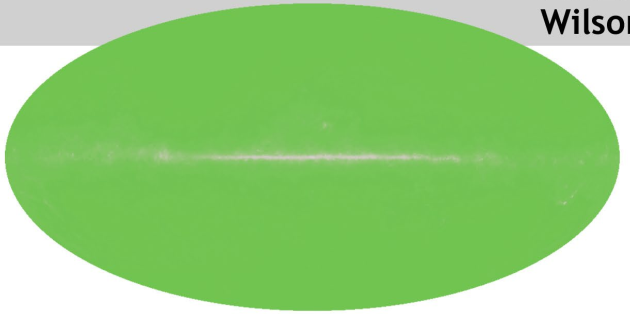
A. A. Penzias
R. W. Wilson

May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

1965

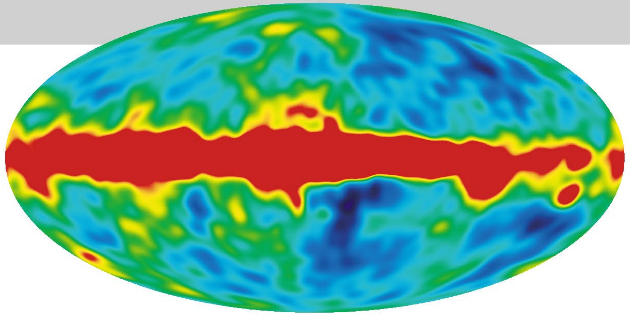
Penzias and Wilson





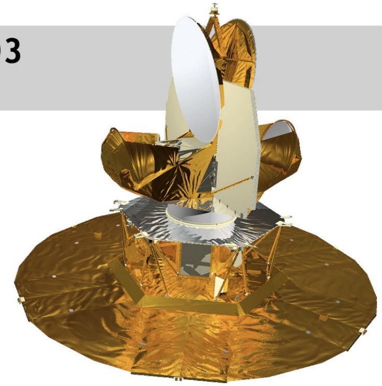
1992

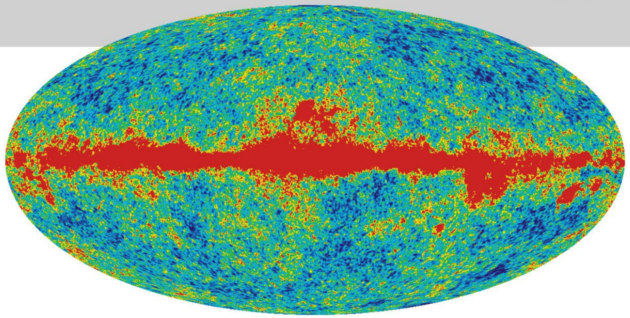
COBE



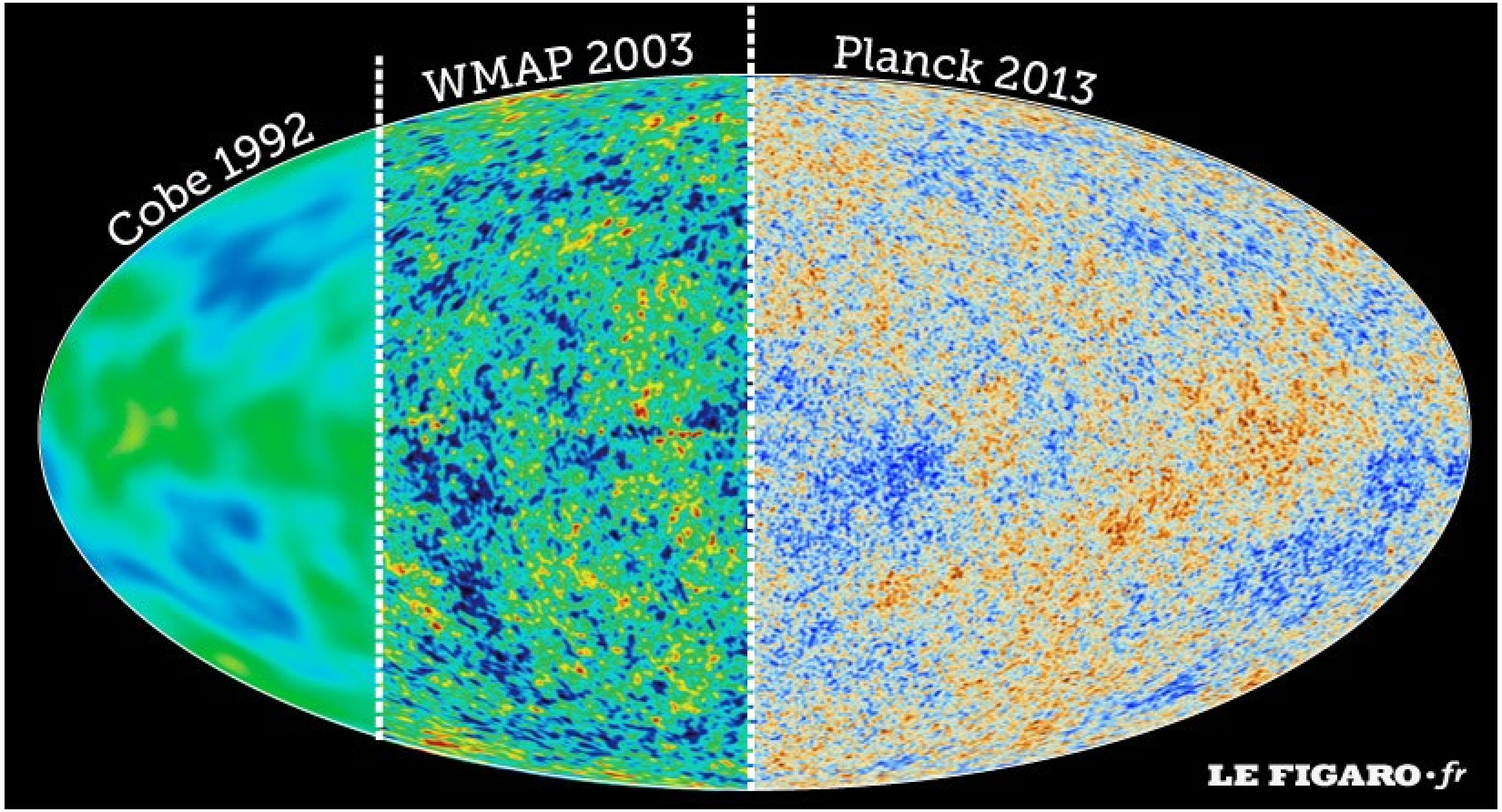
2003

WMAP

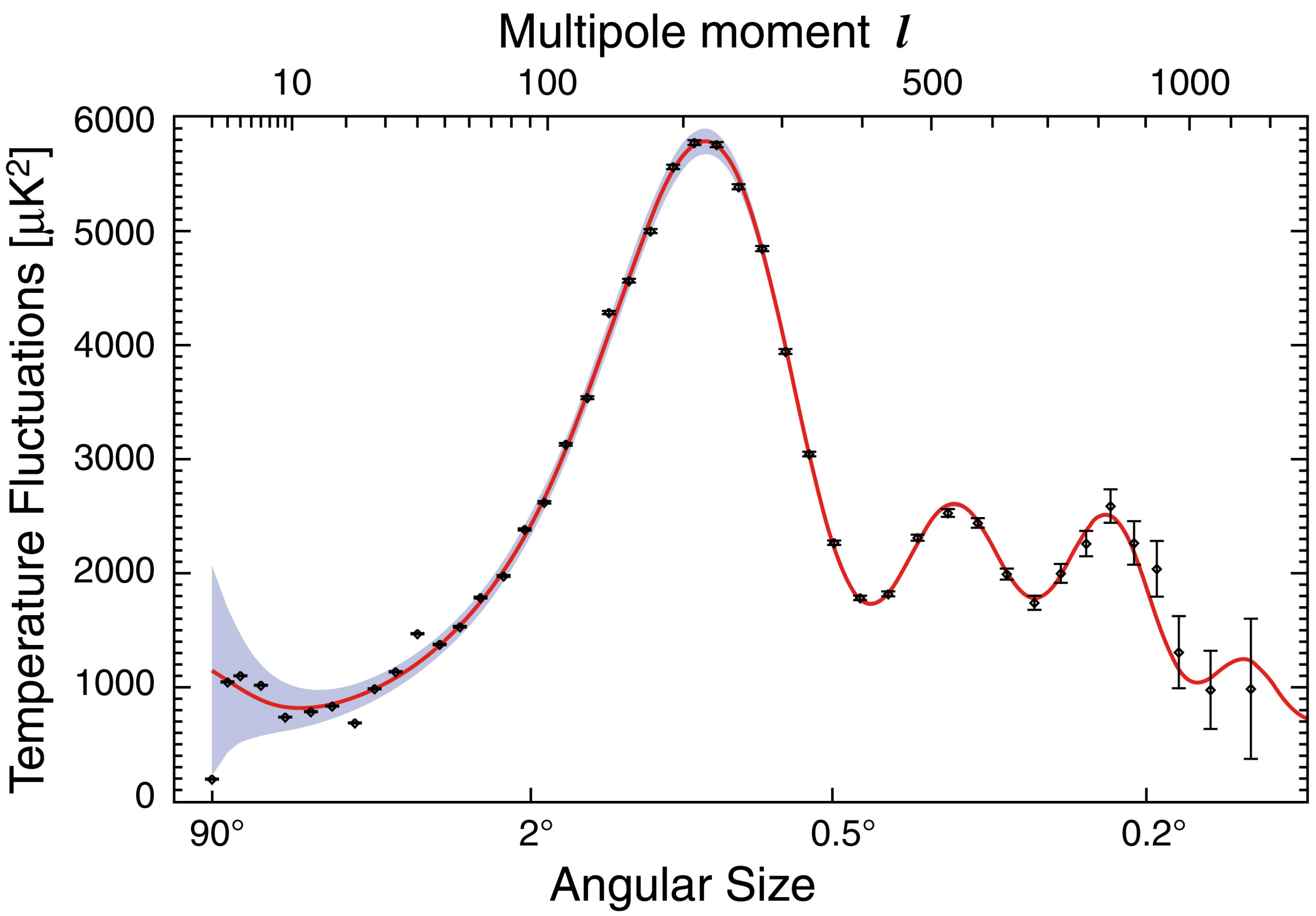




CMB Temperature Anisotropies



Power Spectra and Lambda CDM



- If you want to learn more check out CMBverse by Gab and friends.

CMB Polarization

- CMB photons are polarized via Compton scattering prior to recombination
- Incoming radiation (before being scattered) must have a nonzero quadrupole.
- The radiation field prior to recombination has a very small quadrupole → CMB polarization is small (compared to temperature anisotropies)

Why do we care about polarization

Spatial metric perturbation in Fourier space.

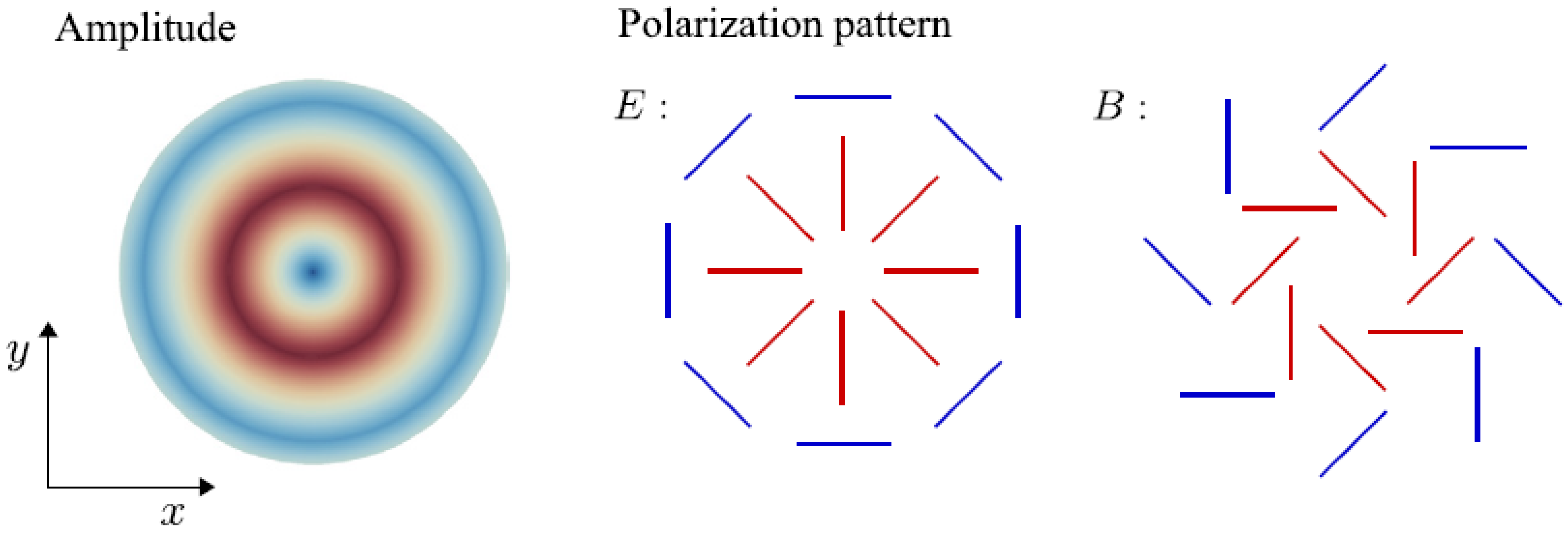
$$h_{ij} = 2D\delta_{ij} + 2k_i k_j E + ik_i V_j + ik_j V_i + h_{ij}^{TT}$$

Broken into scalar, vector, and tensor perturbations.

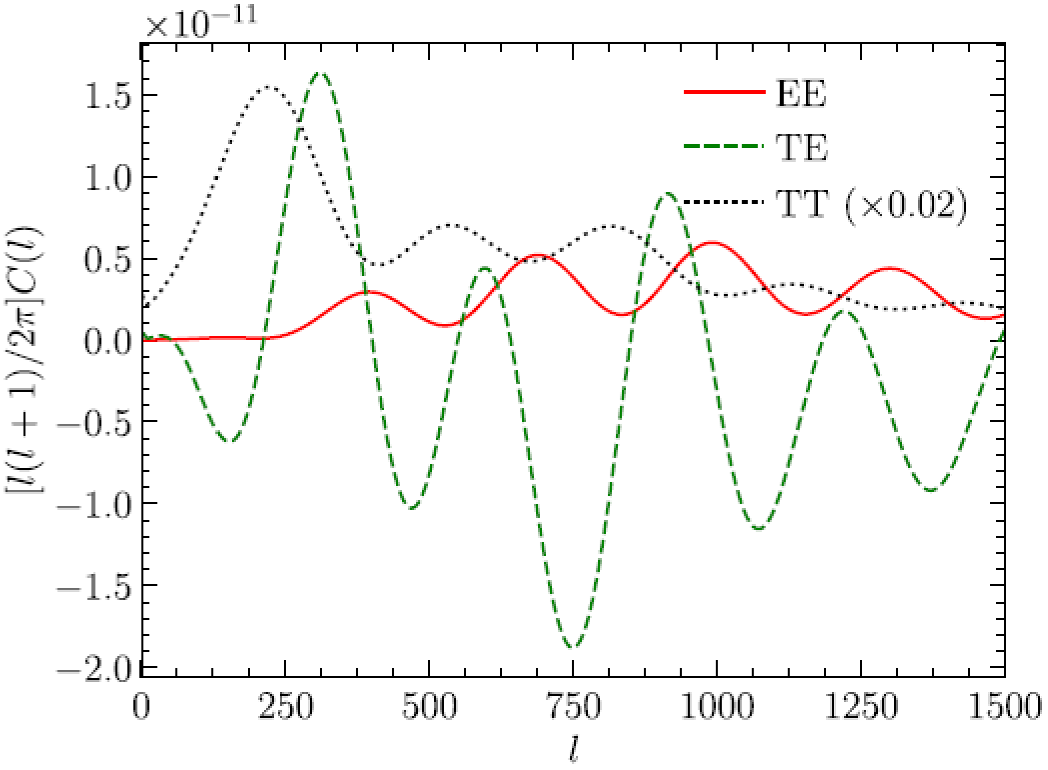
- Scalar perturbations sourced by density fluctuations
- Tensor perturbations correspond to gravitational waves

Polarization ‘tensor’ couples to scalar and tensor metric perturbations

- Can decompose the polarization tensor into two components – E(l) (scalar) and B(l) (tensor)
- Tensor perturbations such as gravitational waves from inflation contribute to both E and B modes.

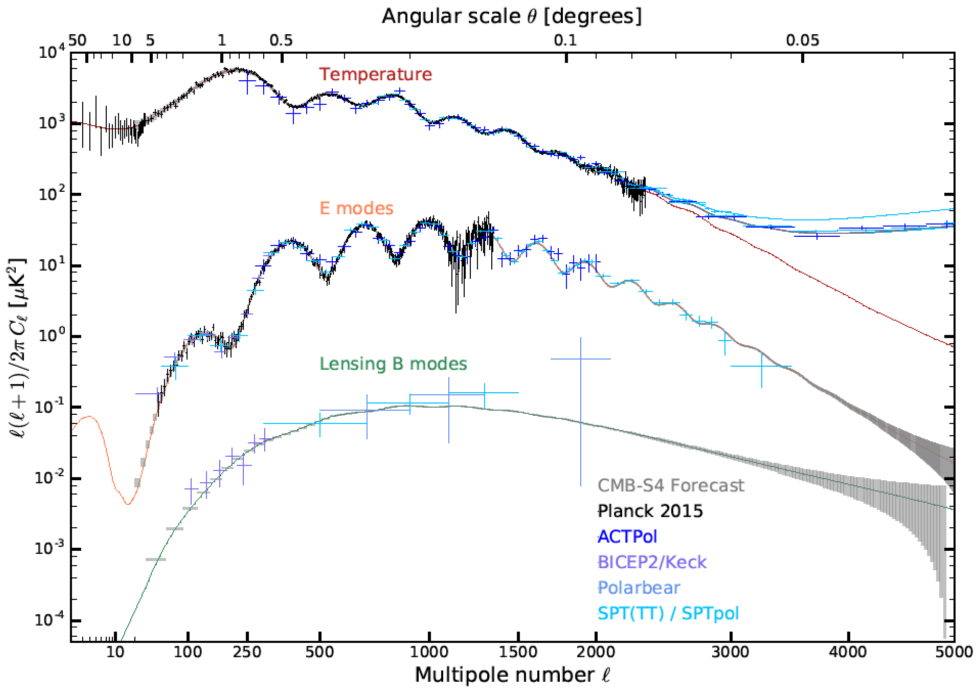


- To search for tensor perturbations in E mode, must distinguish between contributions from scalar perturbations (as a function of l).

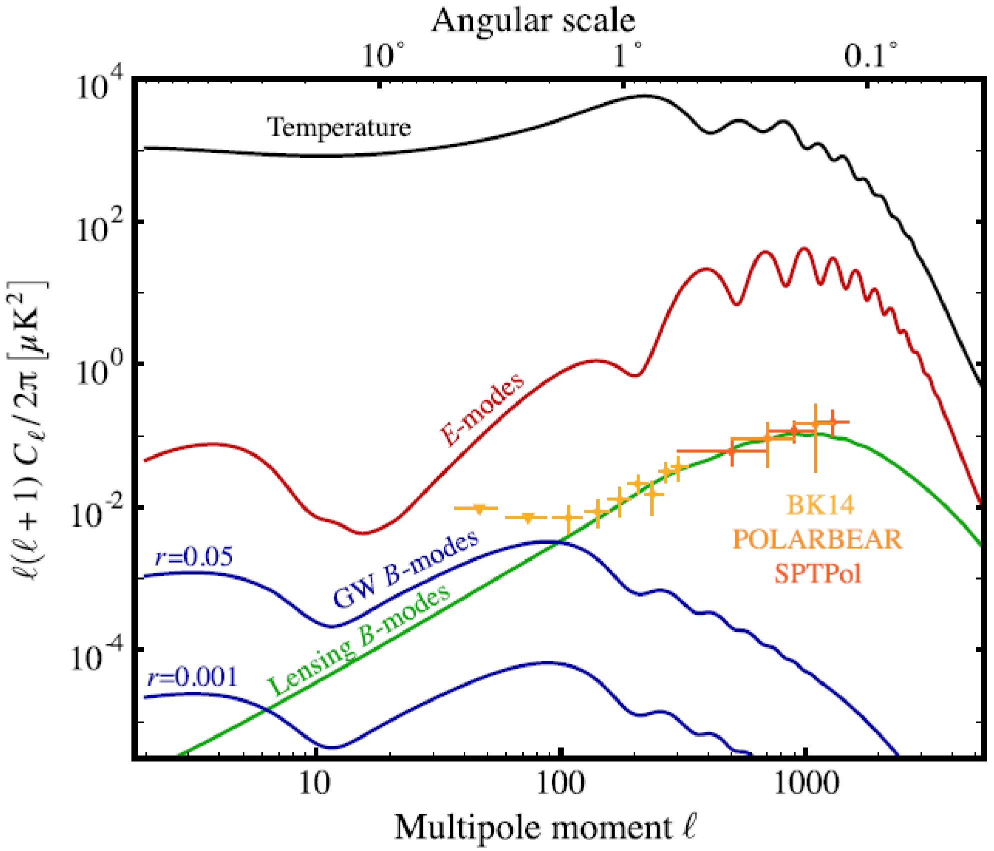


B modes signal

- Parametrized by ***r*** the tensor-to-scalar ratio – ratio of contributions to the temperature quadrupole from tensor and scalar perturbations.



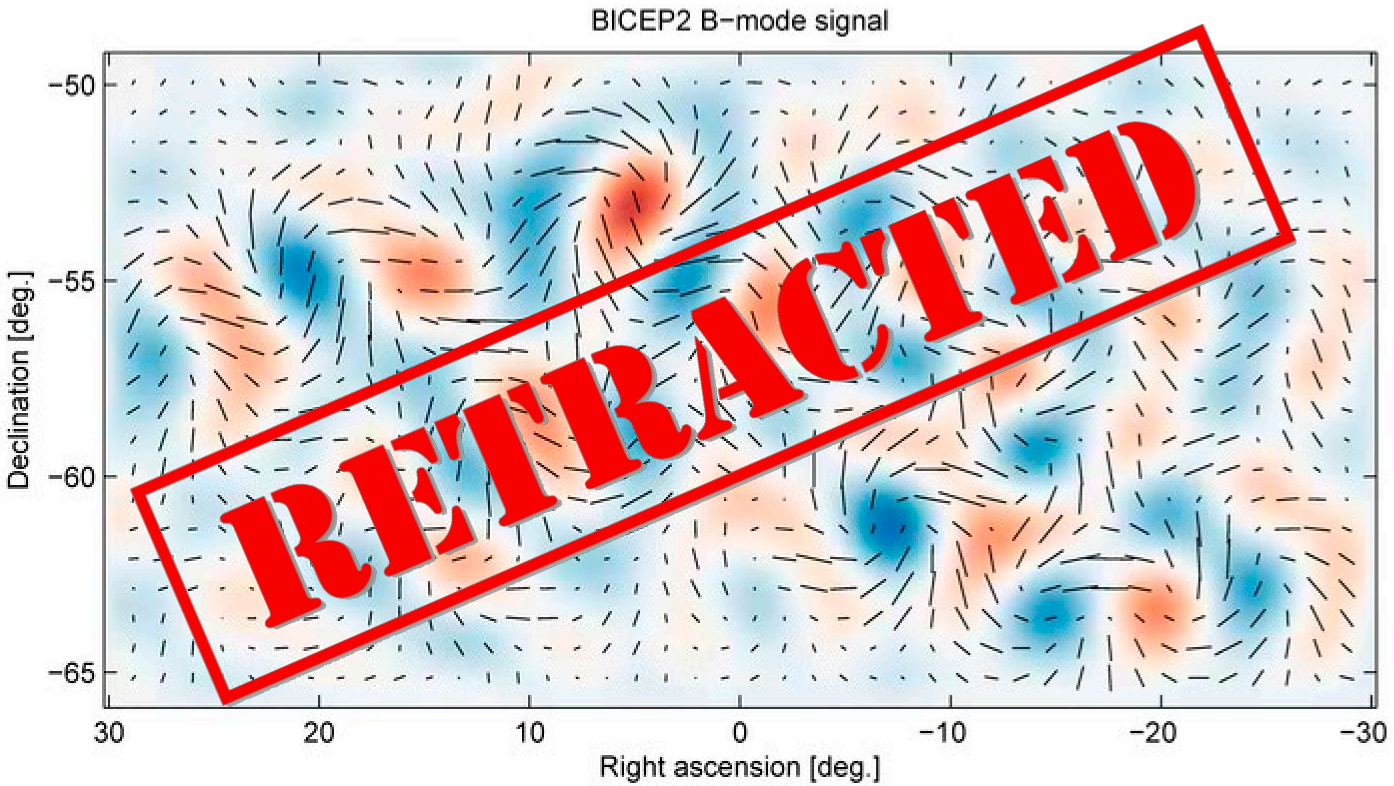
Angular scale θ [degrees]
Temperature
E modes
Lensing B modes
CMB-S4 Forecast
Planck 2015
ACTPol
BICEP2/Keck
Polarbear
SPT(TT) / SPTpol
Multipole number ℓ

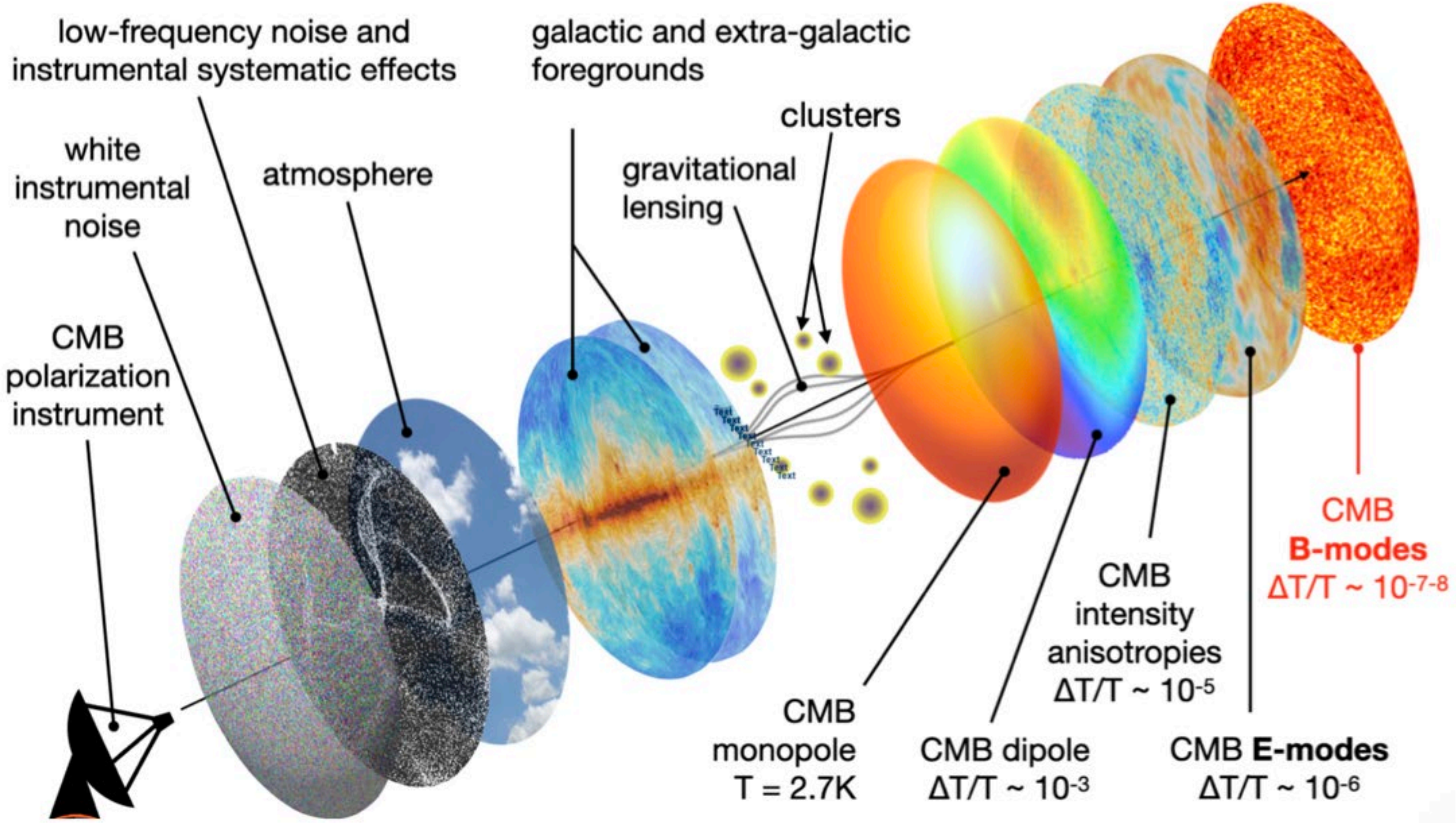


Angular scale
Temperature
E-modes
r=0.05
r=0.001
GW B-modes
Lensing B-modes
BK14
POLARBEAR
SPTPol
Multipole moment ℓ

Instead, we search for B modes

- Only tensor perturbations yield B modes.



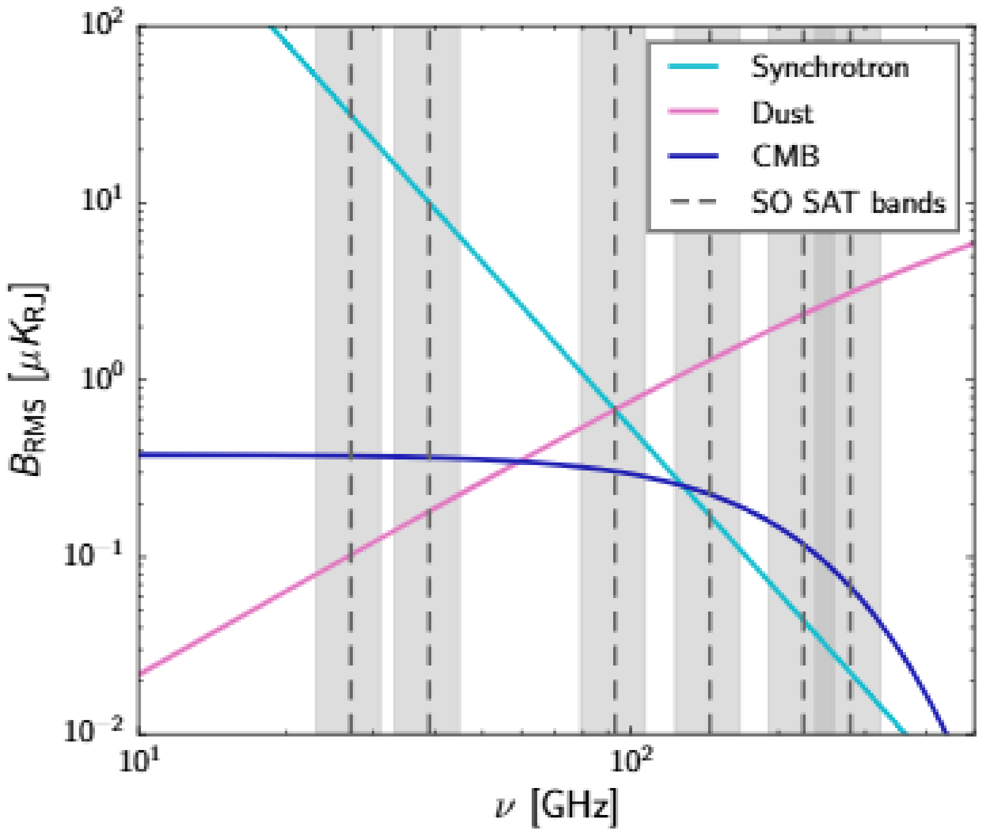


Credit: J. Errard

Foregrounds

- Detecting B-mode signature complicated by other extraneous signals
- Foregrounds such as dust and galactic synchrotron emission
- Component separation via Spectral Energy Distribution distinction.

- Experiments often dedicate extra frequency bands to better constrain foregrounds.



Experimental Cosmology

How to measure CMB polarization

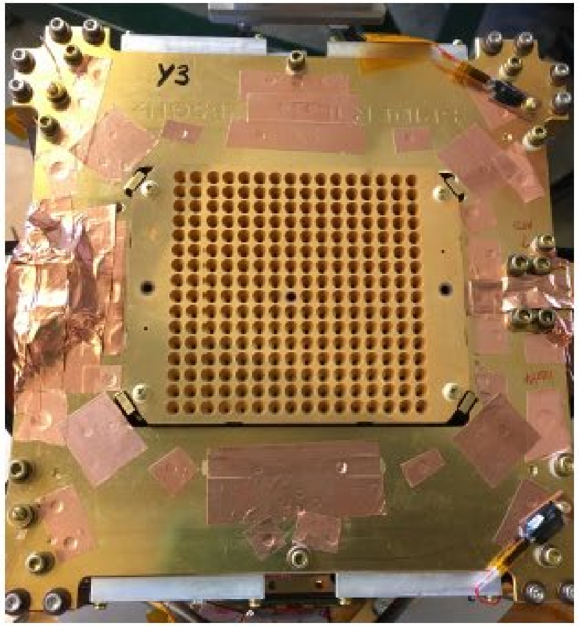
1. Measure polarized photons coming from CMB
2. Scan your detectors/telescope across a patch of sky
3. Turn time-ordered-data (TOD) into map of sky patch
4. Remove foregrounds and other systematics
5. Decompose map into spherical harmonics to obtain power spectrum – or other analyses

1. Measure polarized photons

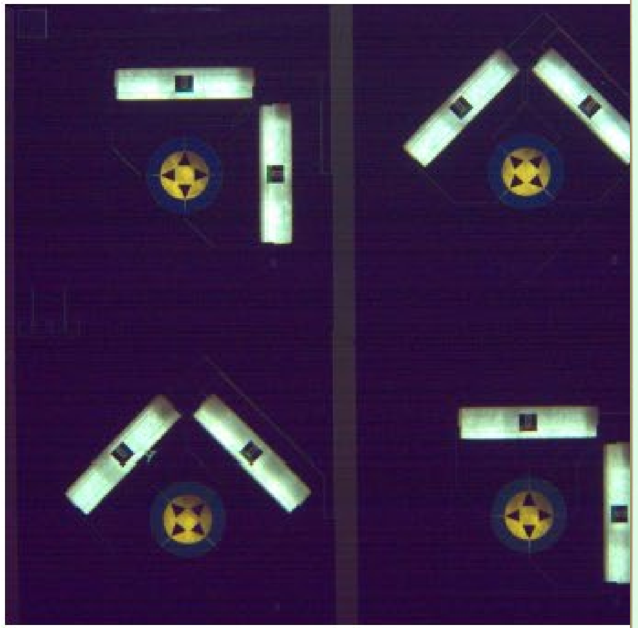
- 2 primary detector technologies. Transition Edge Sensors (TES) and Kinetic Inductance Detectors (KIDs)

Transition Edge Sensors	Kinetic Inductance Detectors
Superconductors – operate at cryogenic (~0.1K temperatures)	
Bolometers – Detect photons via temperature difference	Photons break apart superconducting Cooper pairs – changes surface impedance/inductance
Subject to phonon and Johnson noise	Subject to other noise e.g. generation/recombination
Multiplexing electronics make large arrays impractical	Designed for large arrays

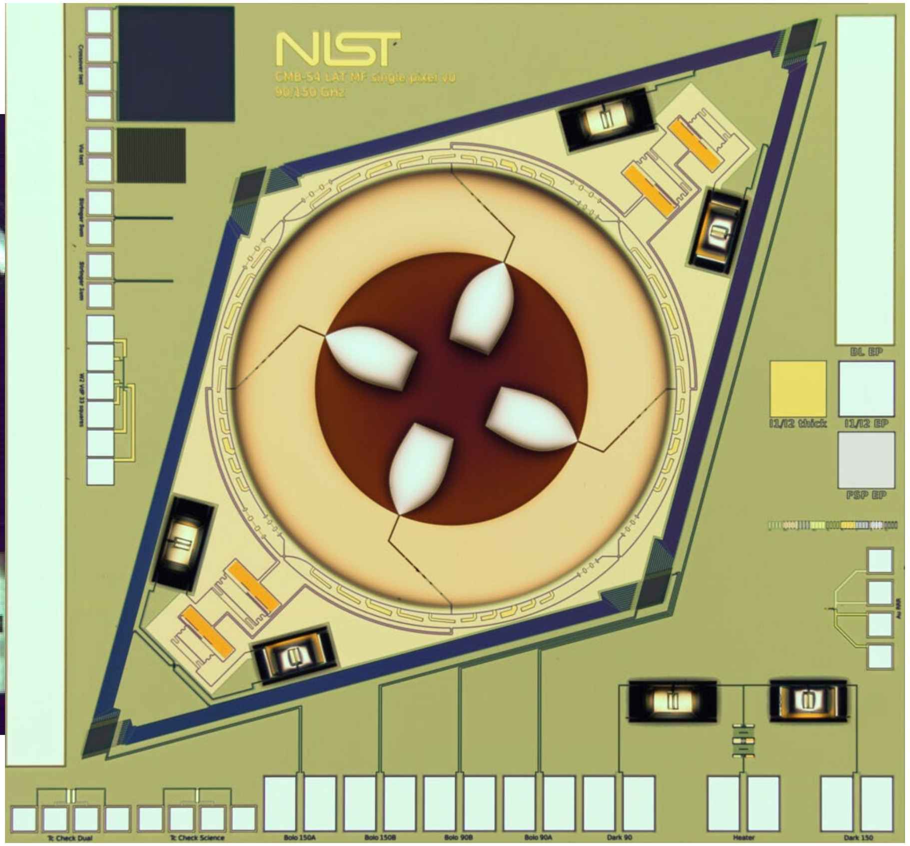
TESs



(a)



(b)



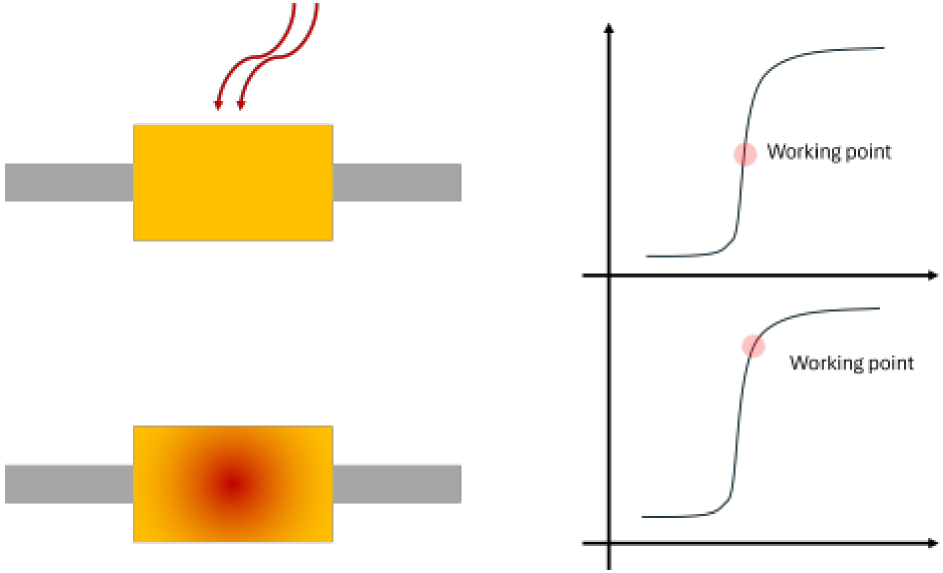
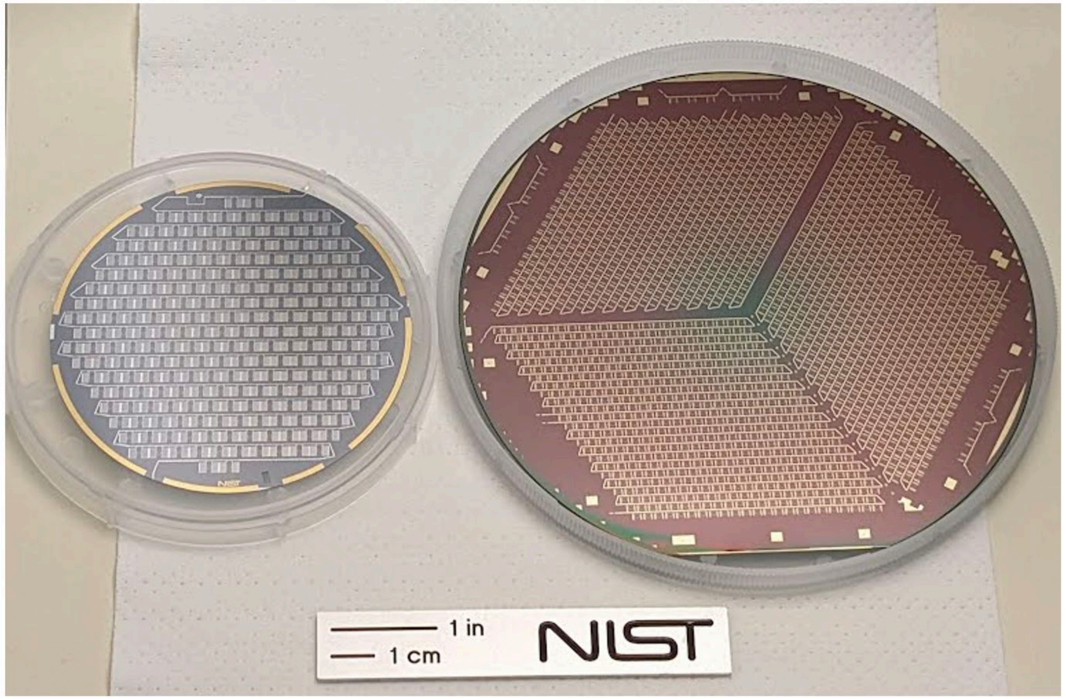
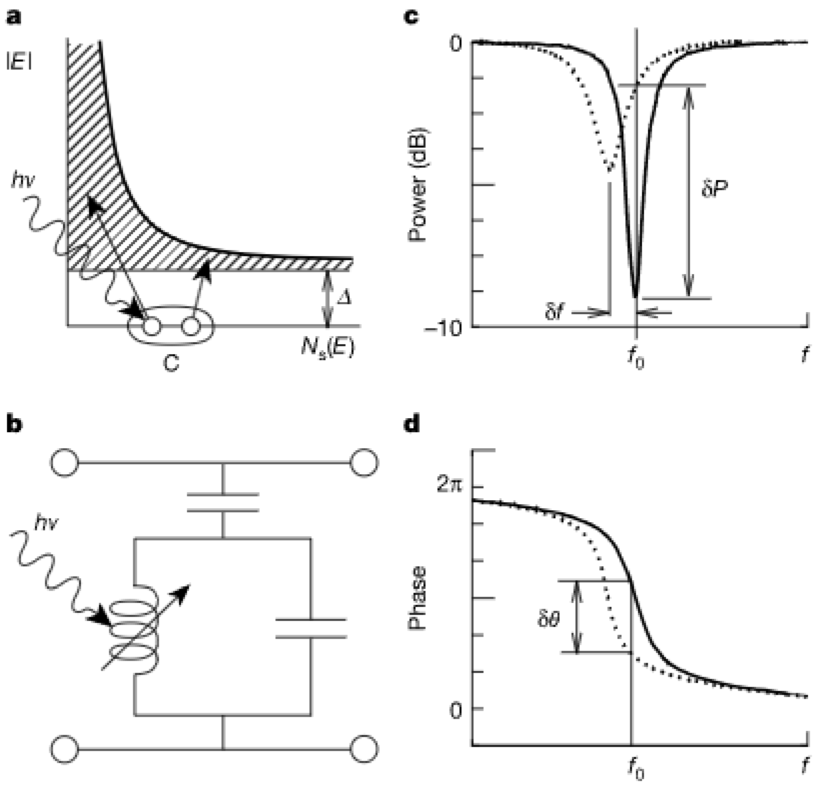


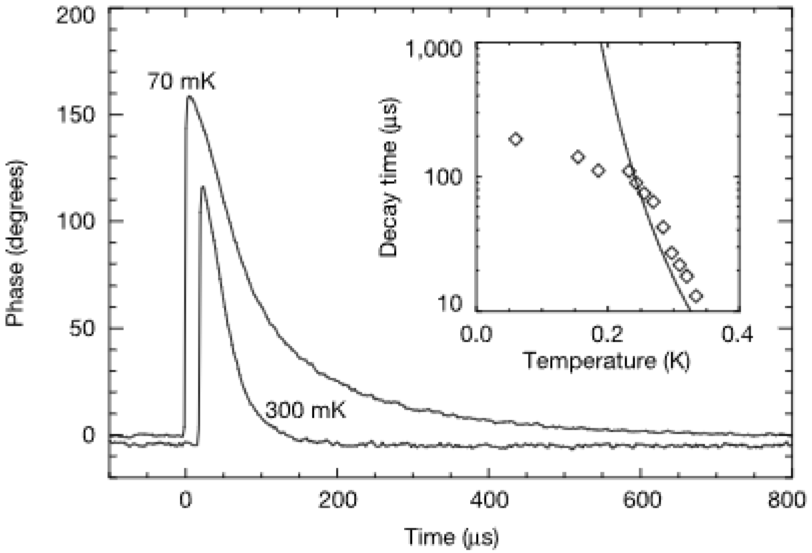
Figure 2. Working principle of a Transition Edge Sensor. An event (e.g., photon/phonon absorption) heats the superconductor, moving its temperature from the ideal working point (center of the normal to superconducting transition).

MKIDs

- Photons (of sufficient energy) break apart Cooper pairs (electron pairs in a superconductor)
- This increases the ‘quasiparticle’ density of the material and in turn the surface impedance of the super conductor.
- When coupled with a capacitor, MKIDs form a resonator with a specific resonant frequency.
- Allows for simple frequency-division multiplexing

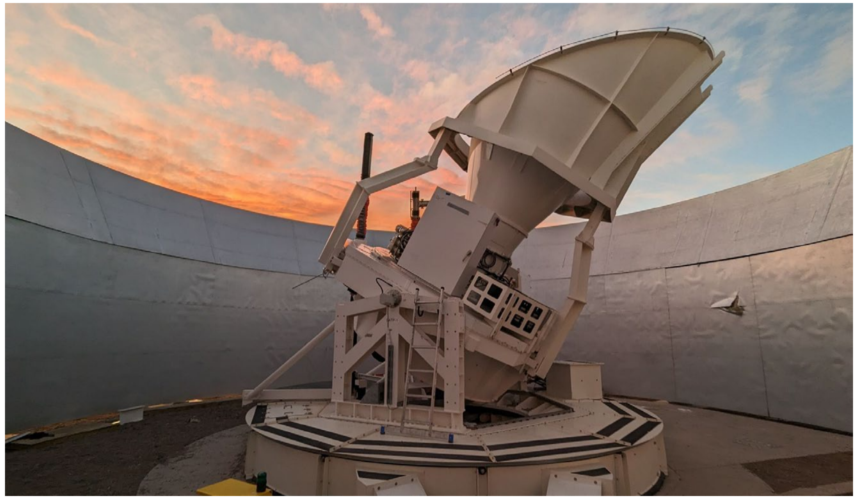



a
|E|
hν
Δ
C
$N_s(E)$
b
hν
c
0
−10
Power (dB)
δP
δf
f_0
f
d
2π
0
Phase
δθ
f_0
f


200
150
100
50
0
Phase (degrees)
70 mK
300 mK
0
200
400
600
800
Time (µs)
1,000
100
10
Decay time (µs)
0.0
0.2
0.4
Temperature (K)

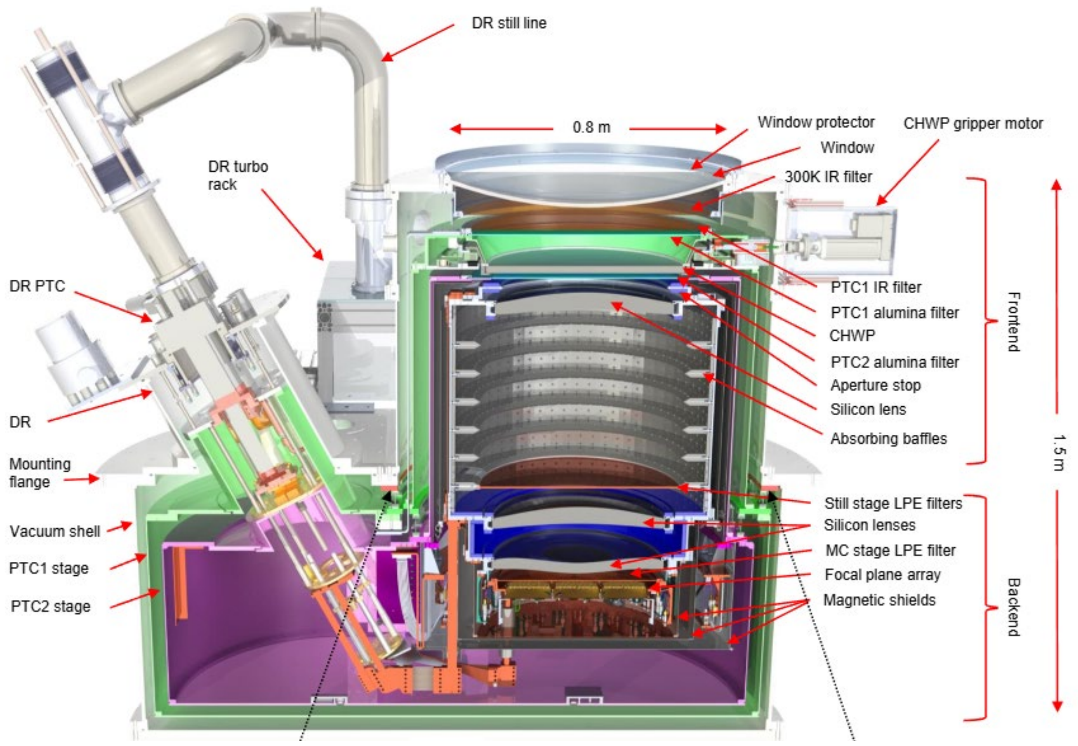
Simons Observatory

CMB Polarimeter searching for B mode signal
Consists of 3 Small Aperture Telescopes (SATs) and 1 Large Aperture Telescope (LAT)



SAT - Cryogenic design

- Need to cool detector arrays down to 100mK

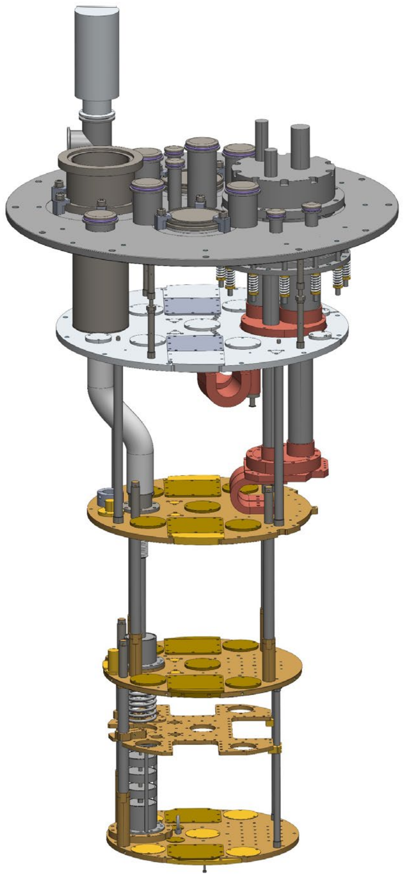


Dilution Refrigeration

Achieves millikelvin temperatures by diluting He3 into He4 in the mixing chamber.

Energy is needed to move He3 (fermions) into the dilute He4 (bosons) phase. This energy comes from the environment.

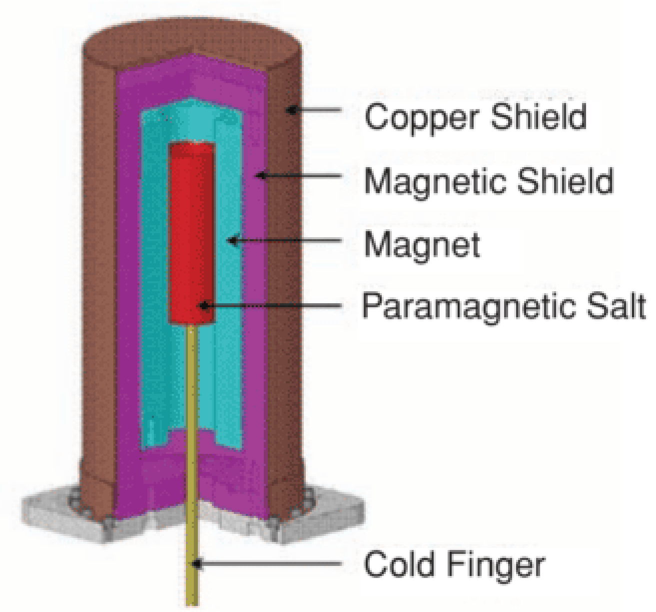
The 'still' evaporates He3 from the mixture leaving room for more He3 to dilute into the mixture to continue cooling.



This system uses a pulse tube cryocooler to achieve 4K temps.

ADR

1. Molecules in the paramagnetic salt align to the magnetic field.
2. As the B field strength is decreased, the molecules want to twist out of alignment. This absorbs energy from the surrounding.
3. Eventually the B field strength is reduced to 0, and all the energy that can be absorbed has been.
4. The B field is turned back on to heat the pill, at which point it is connected to the thermal sink, dumping heat.
5. Salt pill is disconnected from sink – restarting cycle.



Section view of typical ADR, showing paragmagnetic salt pill in the bore of a superconducting magnet, surrounded by magnetic and thermal shielding.

An Intro to Ballooning

Science takes flight

- 1783
  - The Montgolfier brothers invent the hot air balloon.
  - Jacques Alexandre Charles develops a hydrogen balloon.
- 1802
  - Advent of ‘scientific ballooning’
- 19th-20th centuries:
  - Bigger, and higher.

Molynk, A.

High altitude scientific ballooning

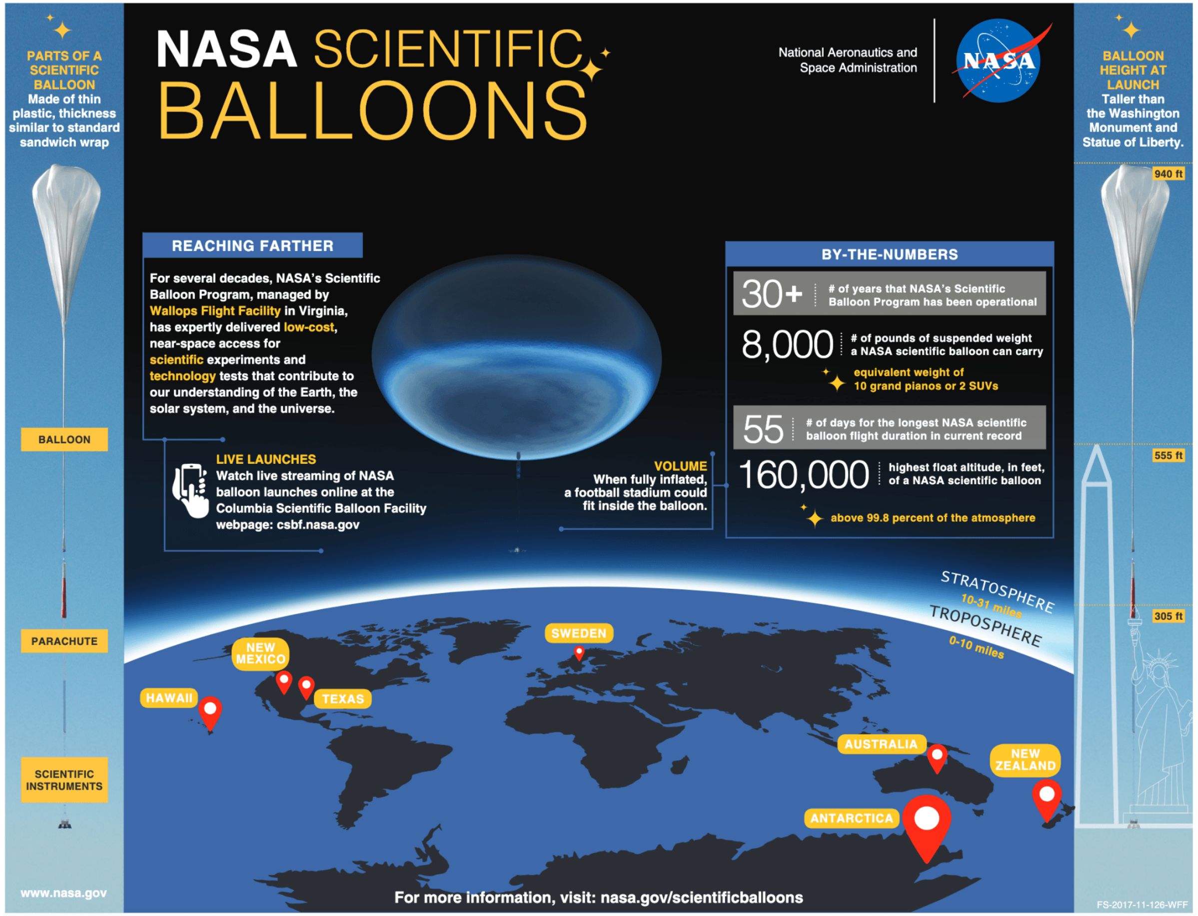
- Victor Hess – 15000 ft to discover cosmic rays (1936 Nobel Prize in Physics)
- 1960s - NASA (and others begin using balloons (both manned and unmanned).

Project ECHO

– radio communications →

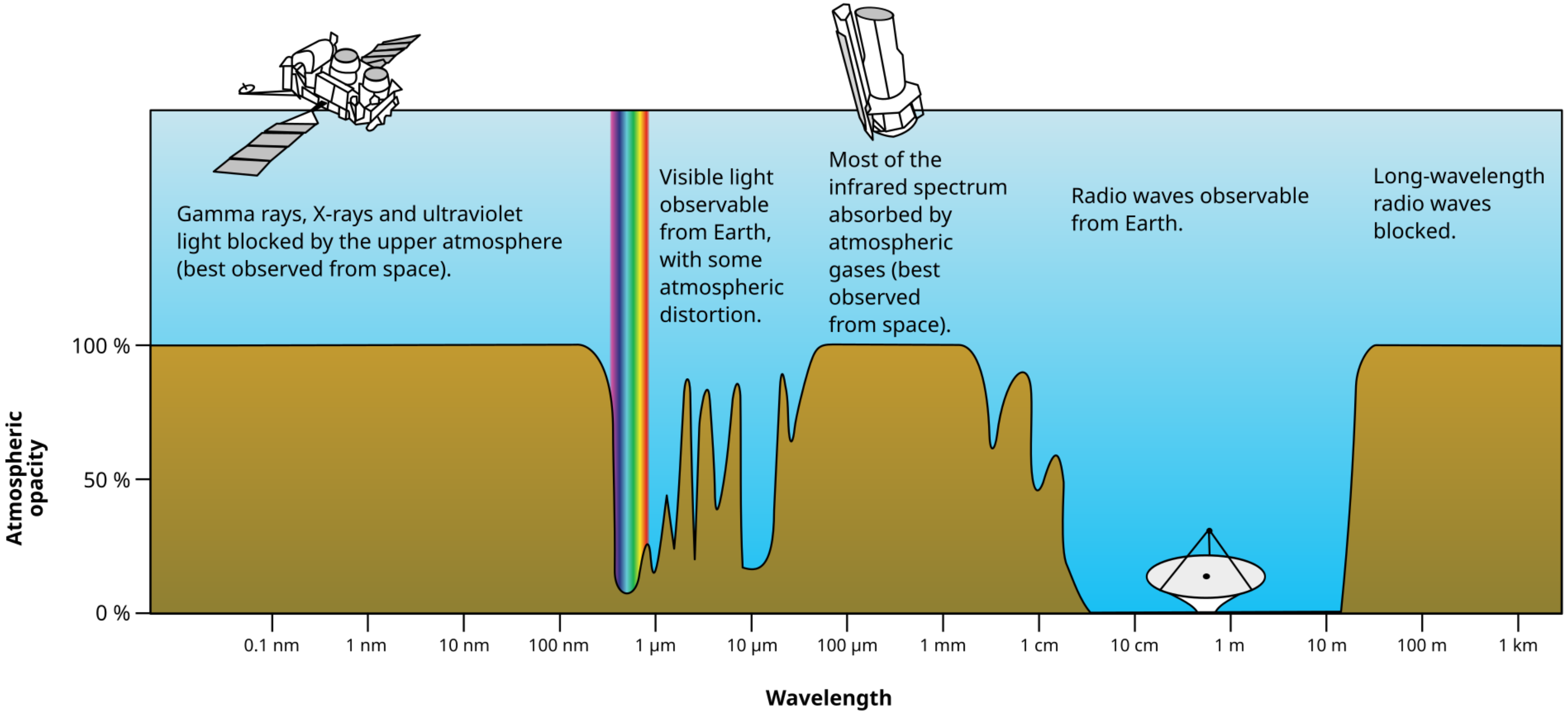
NASA/Goddard

NASA balloons



Why fly a balloon

1. Avoid the pesky atmosphere



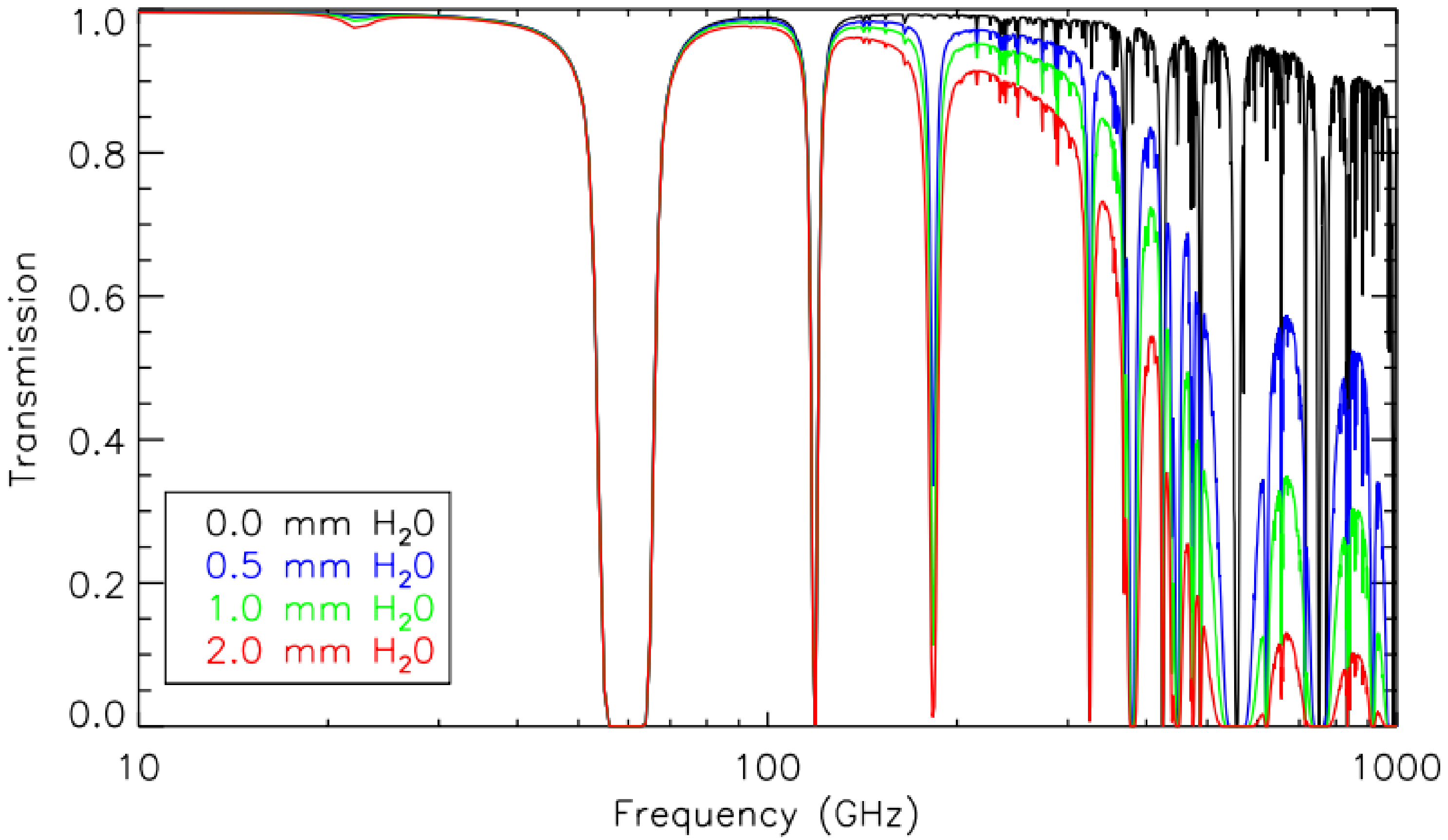


FIG. 1.— Atmospheric transmission from the Atacama plateau at the zenith for different amounts of precipitable water vapor. This is obtained using the ATM code, Pardo et al. (2001).

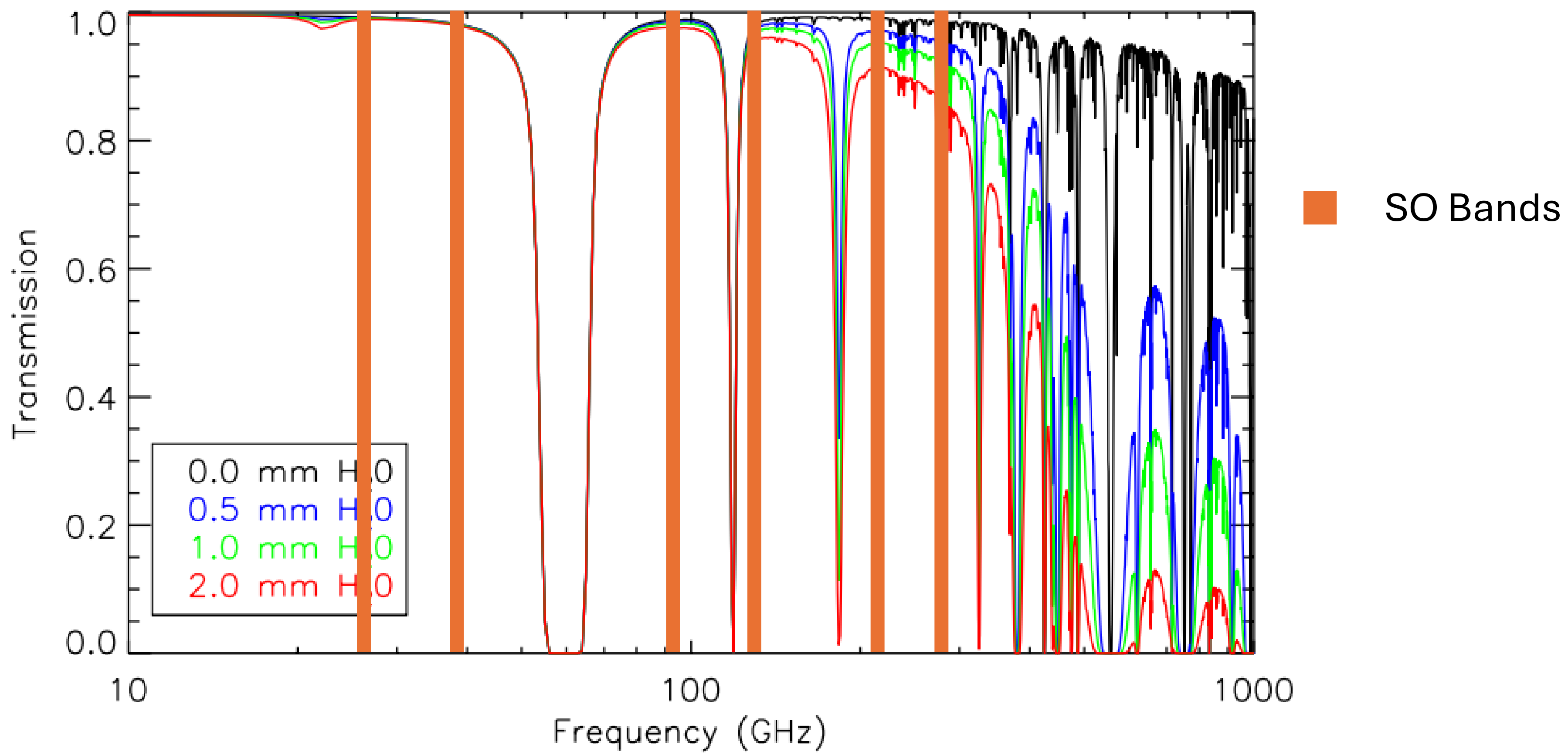


FIG. 1.— Atmospheric transmission from the Atacama plateau at the zenith for different amounts of precipitable water vapor. This is obtained using the ATM code, Pardo et al. (2001).

2. It is cheaper than launching a satellite

Hard to find hard numbers but balloon missions cost ~10-20 M$ compared to ~1-10B$ for satellite missions

Types of NASA balloons

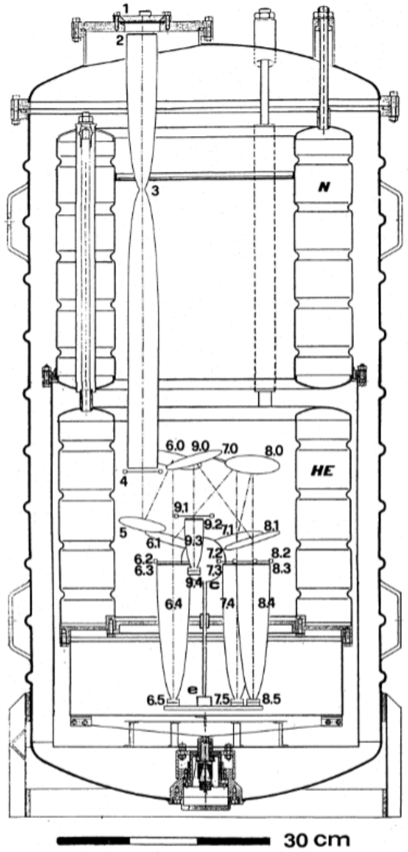
Zero-Pressure Balloons (ZPB)	Super-Pressure Balloons (SPB)/Ultra-Long Distance Balloon (ULDB)
Open bottom allows gas to vent as the balloon rises and expands (to prevent rupture), or as the temperature rises	Sealed positive pressure balloons
Day/night temperature differences cause rise and fall of balloon	More stable to day/night fluctuations
Gas eventually leaks out	Potential for longer flights
Max payload : 2948 kg (6500 lbs)	1360 kg (3000 lbs)
~33-40 km altitude, above 99.5% of atmosphere	
Polyethylene 0.8 mil (0.02mm)	
Inflated with Helium (1:6.2 - He:Payload)	
$F_B = -\rho g V$	

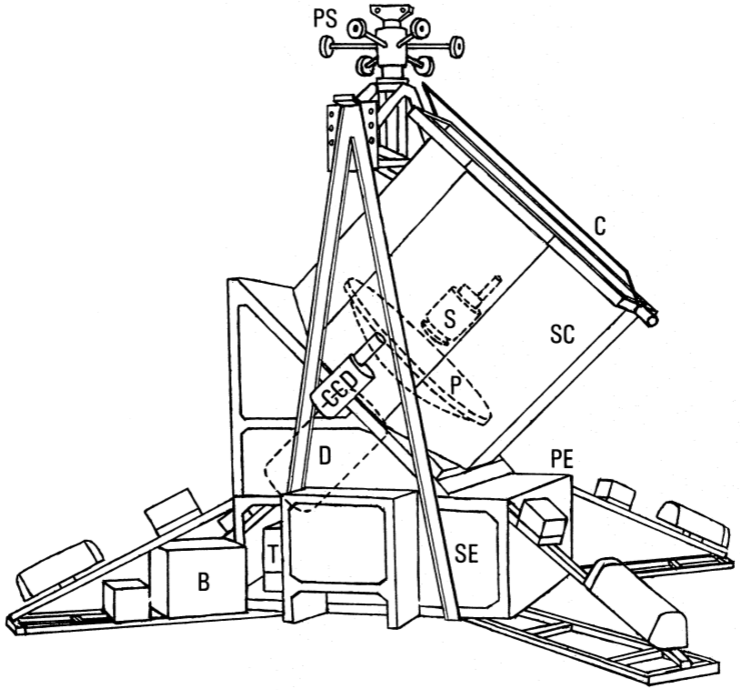
Balloon downsides.

- Design constraints
  - Mass
    - ZP ~ 2948 kg (6500 lbs)
    - SP ~ 1360 kg (3000 lbs)
  - Power
    - Photovoltaic power generation (daytime)
    - Batteries
  - Thermal Power/Cryogens
    - Cryogen-free systems require lots of power.
- Time constraint
- Hands off (after LOS)
- Risk
  - Crash

CMB balloons –

- 1988 – ARGO -





BOOMERanG

Spider

- Polarimeter at 3 wavelength bands
- Large angular scales (20deg FOV)
- Spun the whole payload at ~1 RPM

BLAST Observatory

The BLAST Observatory

- Balloon-borne Large Aperture Sub-millimeter Observatory
- Proposed balloon polarimeter
- 3 wavelength bands : 175 μm, 250 μm, 350 μm
- 1.8m Primary Mirror
- 0.9 deg FOV
- 300 L L^4He reserve
- Based operating temperature 100 mK via adiabatic demagnetization refrigerator

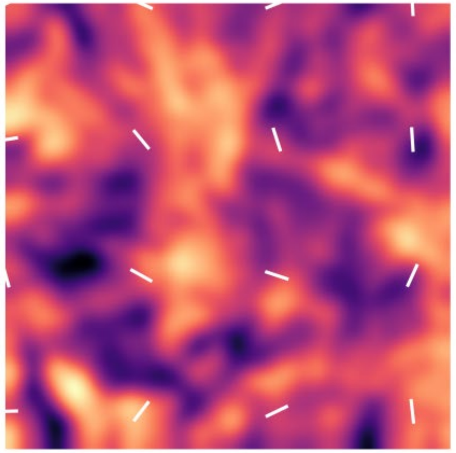
Science Objective

- Investigate the interplay between star formation and the interstellar environment.

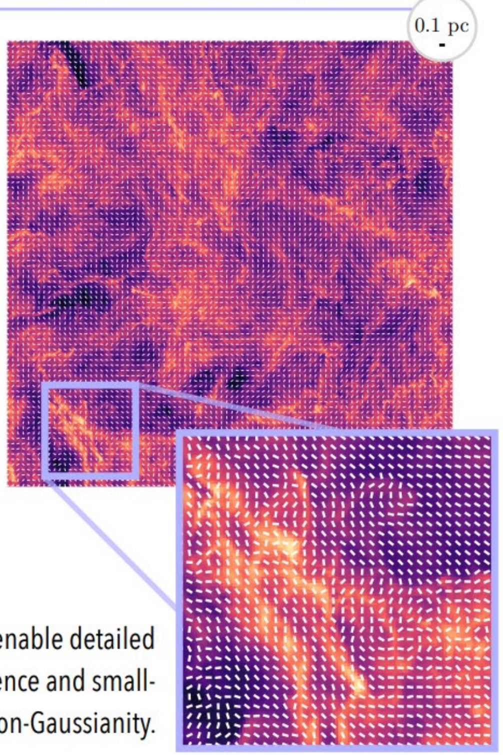
Explore:

1. Magneto hydrodynamic (MHD) turbulence.
2. Energy density of magnetic fields, turbulence , and gravity
3. Distinguish between different dust models.

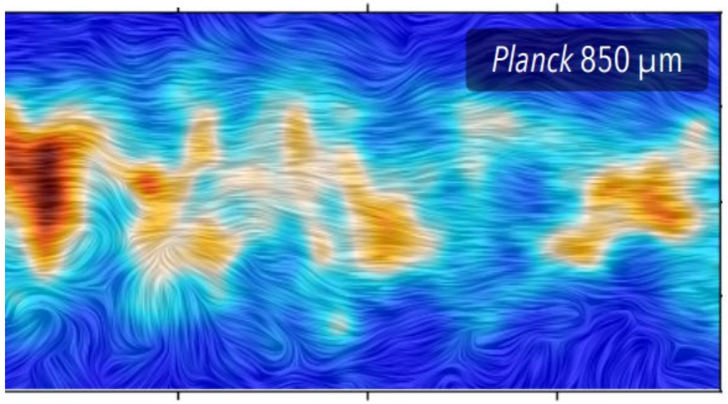
The BLAST Observatory measures magnetic field structure in the diffuse ISM where the polarized emission is localized in three-dimensional space.

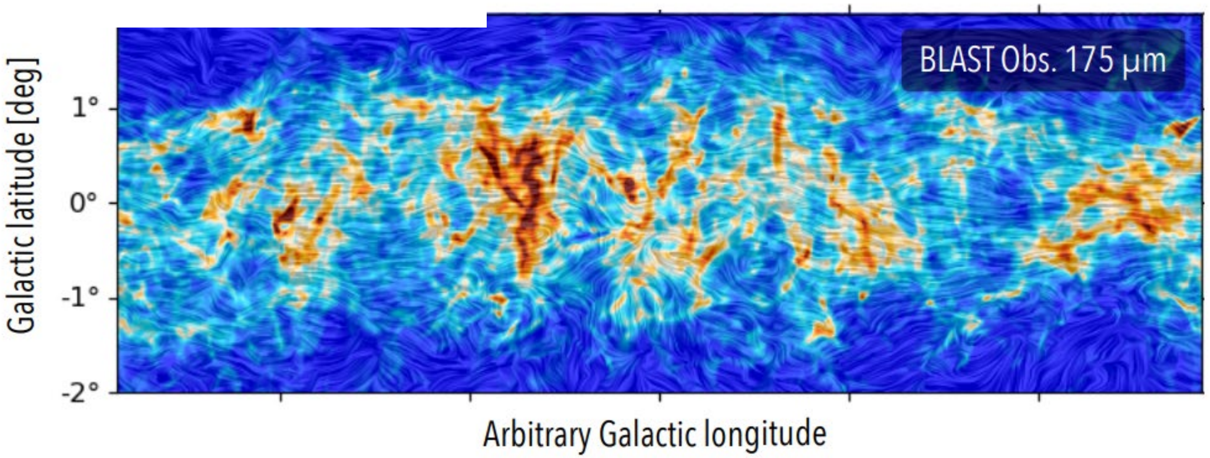


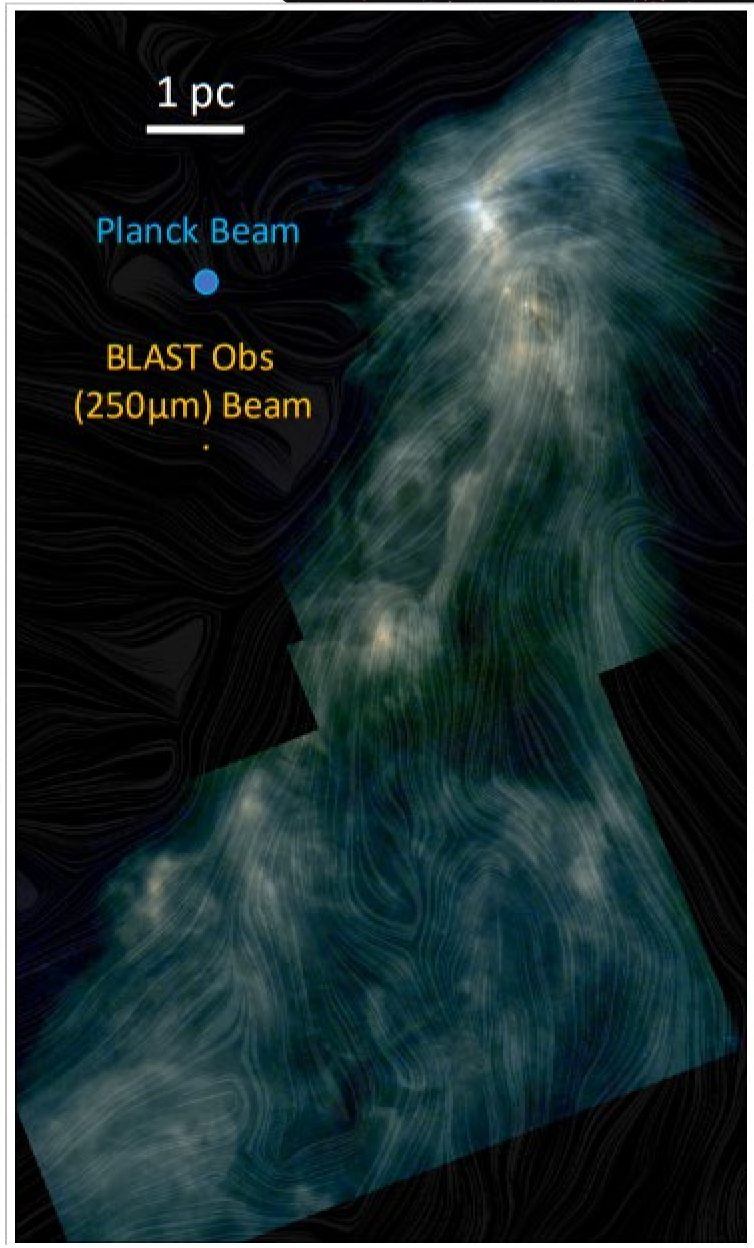
Planck data must be smoothed to 80′ resolution to achieve 3σ polarization maps in the diffuse ISM.

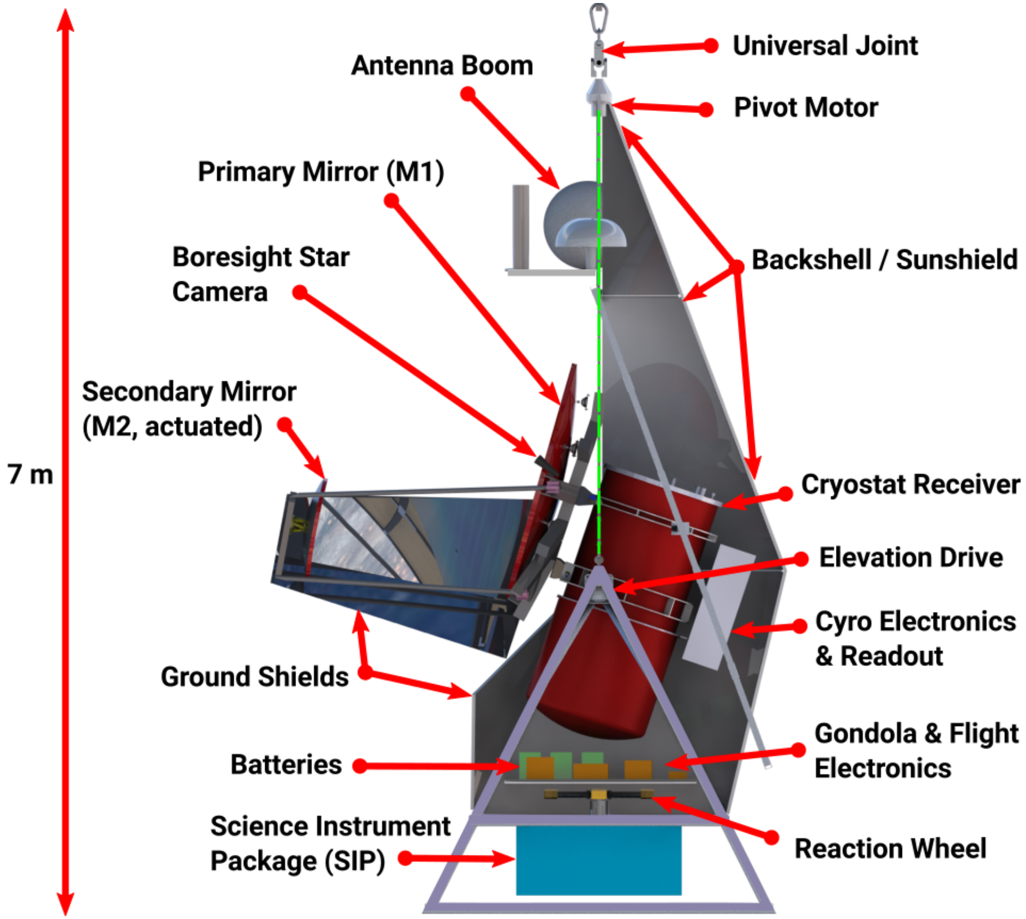


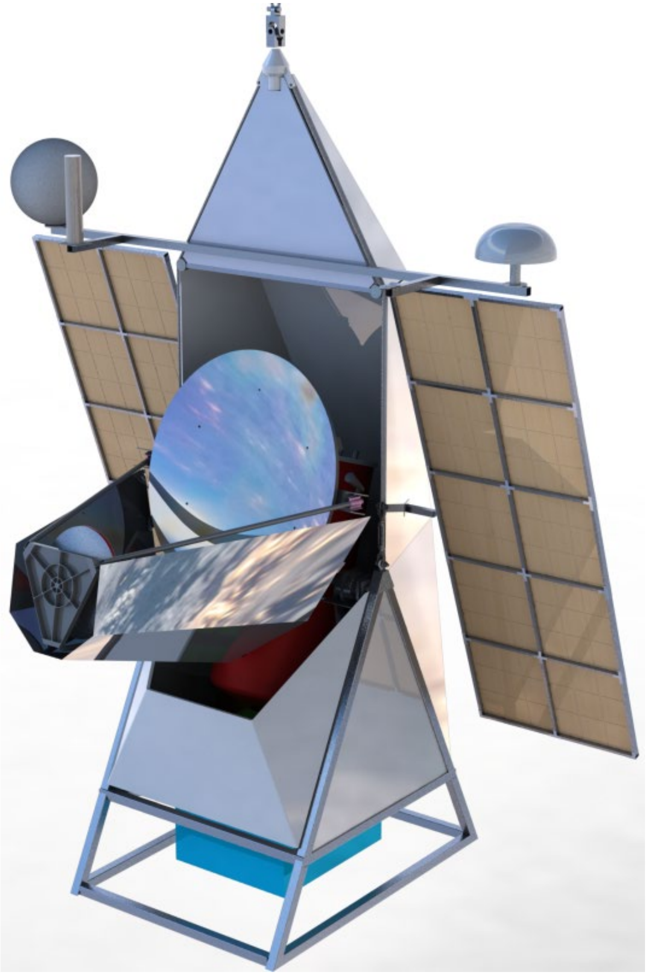
BLAST Obs. will enable detailed study of turbulence and small-scale non-Gaussianity.








Universal Joint
Antenna Boom
Pivot Motor
Primary Mirror (M1)
Boresight Star
Camera
Backshell / Sunshield
Secondary Mirror
(M2, actuated)
7 m
Cryostat Receiver
Elevation Drive
Cyro Electronics
& Readout
Ground Shields
Gondola & Flight
Electronics
Batteries
Science Instrument
Package (SIP)
Reaction Wheel



An Optimization Problem

Mapping Speed – a measure of telescope sensitivity

Units : $\frac{\text{deg}^2}{hr \cdot mJy^2}$

$$D_M = MS \times HT \times \epsilon_{obs}$$

Hold Time – How long can we fly the balloon. Depends on many factors but primarily how quickly we spend our cryogen reserves

Units : hr

Don’t be so sensitive.

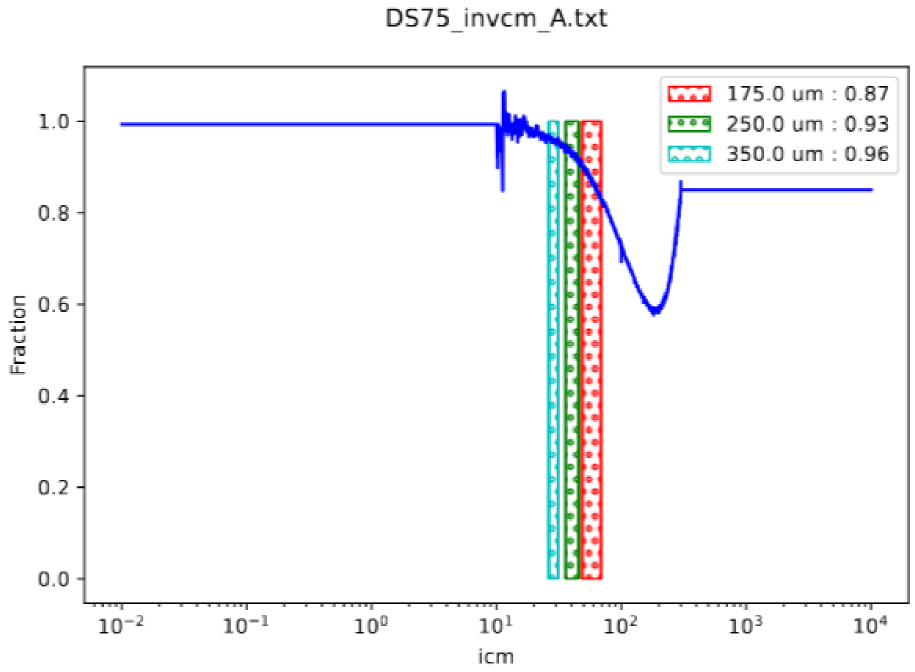
$$P_{opt} = \int_0^{\infty} W(\nu) \left[\sum_{i=0}^{N_{elem}} \left(\prod_{j=i+1}^{N_{elem}} \tau_j \right) \left(\sigma B_{S_i} \left(T_{S_i}, \nu \right) + \epsilon_i B_i \left(T_i, \nu \right) \right) \right] \mathrm{d}\nu$$

$$NEP^2_{\mathrm{phot}_{\mathrm{pixel}}} = 2 \int_0^{\infty} h\nu W(\nu) Q P_{\mathrm{opt}}(\nu) \mathrm{d}\nu + 2 \int_0^{\infty} Q^2 \left(P^{\mathrm{det}}_{\mathrm{opt}}(\nu) \right)^2 \mathrm{d}\nu \quad \left[W/\sqrt{Hz} \right]^2$$

$$NEFD^{sky}_{det} = NEP_{pix} \frac{2 \cdot 10^{26}}{\sqrt{2} \pi r^2 \eta \Delta\nu}$$

$$NEFD_{arr}^{sky} = \frac{NEFD_{det}^{sky}}{\sqrt{N_{det} Y}}$$

$$MS_{arr} = \frac{3600 \times N_{det} \mathbf{Y}}{N_{beams} NEFD^2_{sky_{arr}}} \quad [\mathrm{deg}^2/\mathrm{mJy}^2/\mathrm{hr}]$$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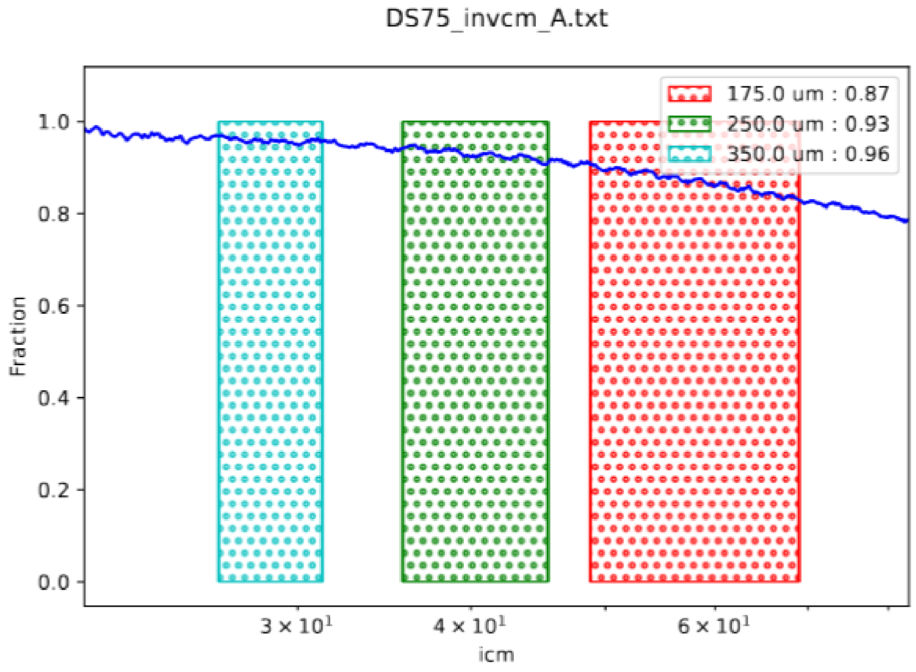
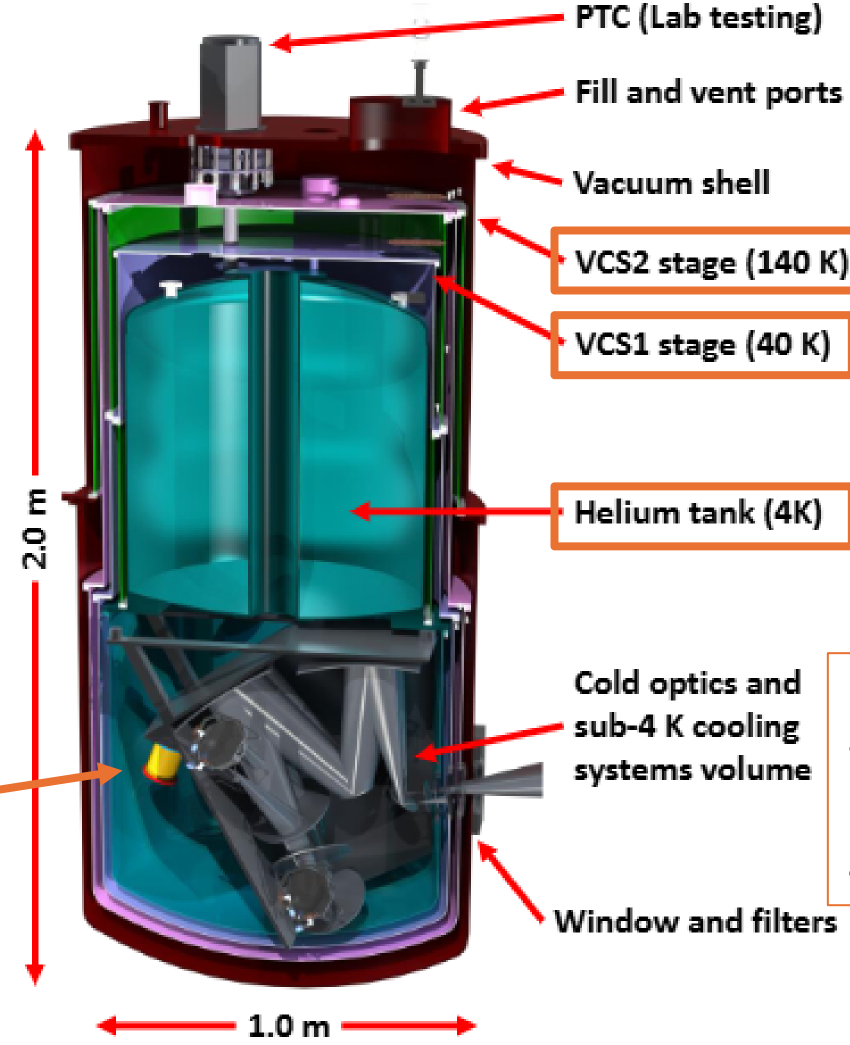
175.0 um : 0.87
250.0 um : 0.93
350.0 um : 0.96
Fraction
icm


DS75_invcm_A.txt
175.0 um : 0.87
250.0 um : 0.93
350.0 um : 0.96
Fraction
icm

Hold Time

- Unlike ground-based telescopes BLAST (and other balloons) cannot fly forever. Some are limited by the gas in the balloon. We are limited by our cryogens.
- 300L of liquid helium + Helium-3 adsorption fridge + ADR to achieve 100mK for focal plane arrays.
- Helium boil off from cooling optical components provides vapor to cool warmer stages.
- Pumped-pot and adsorption fridge cycling require liquid helium fill.



ADR provides cooling from 270mK to 100mK

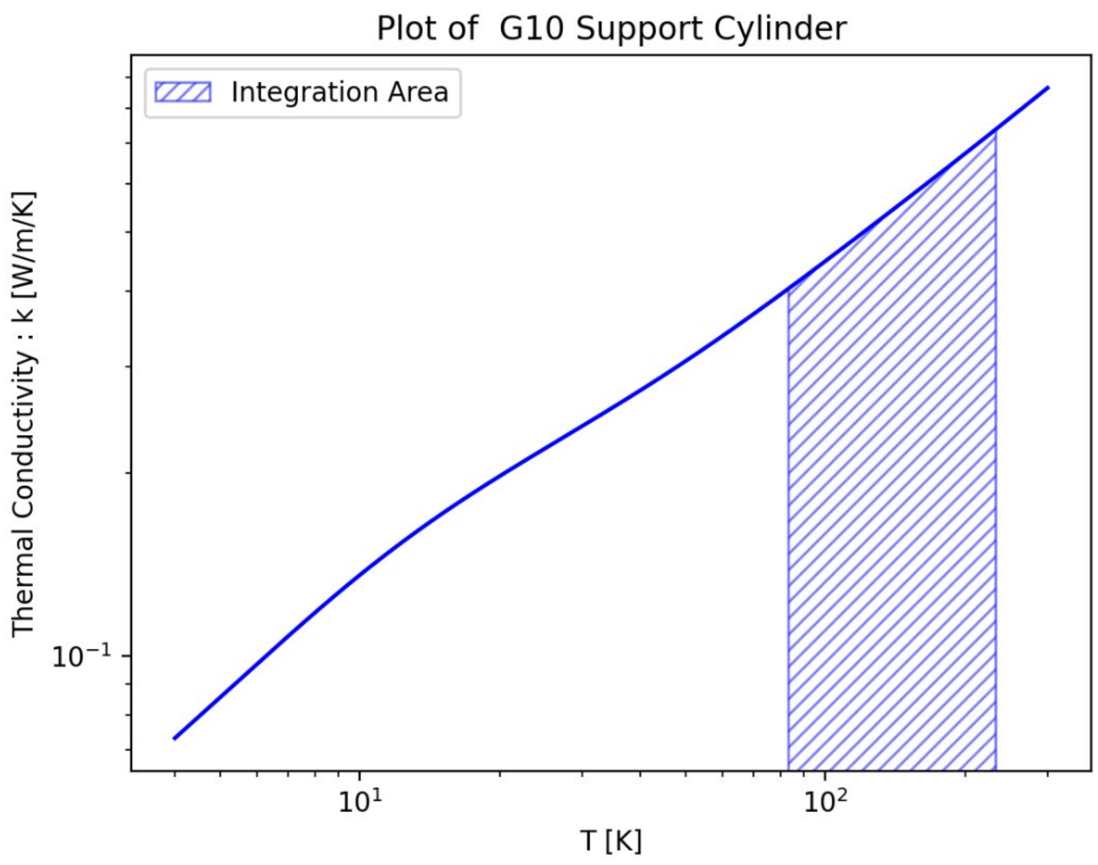
Not shown, He4 pumped-pot + He3 adsorption fridge will provide cooling from 4K to 2K and then 270mK

Thermal Load Calculations

$$P_{\text{comp}} = \frac{A}{L}\int_{T_1}^{T_2} \kappa(T)\mathrm{dT}$$

$$P_{\text{stage}} = \sum_{i}^{N} P_i$$

For example -



Details for G10 Support Cylinder

Property	Value
Type	Component
Material	G10_CR_Warp
OD (m)	0.904875
ID (m)	0.9017
Length (m)	0.508
Number	1.0
Power per Part (W)	0.7735123657401333
Power Total (W)	0.7735123657401333

Thermal model

Stages

VCS 2

	Property	Value
	High Temp	260
	Low Temp	233.3333
	Power	14.3663

G10 Support Cylinder

Edit G10 Support Cylinder

Property	Value
Type	Component
Material	Phosphorbronze
OD (m)	0.904875
ID (m)	0.9017
Length (m)	0.7366
Number	1.0
Power per Part (W)	12.553043734842932
Power Total (W)	12.553043734842932

He Fill Tube

Edit He Fill Tube

Property	Value
Type	A/L (m)
Material	Stainless_Steel
A/L (m)	8.584e-05
Number	1.0
Power per Part (W)	0.026647355507537843
Power Total (W)	0.026647355507537843

Radiation Vac Can

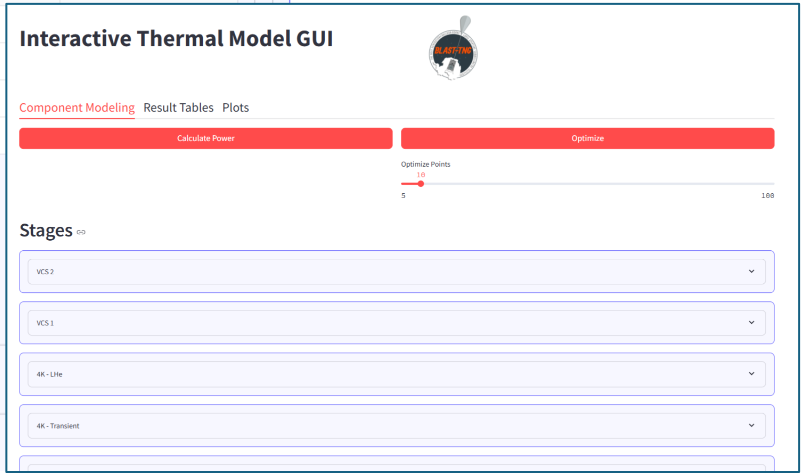
Edit Radiation Vac Can

Property	Value
Type	
Number	
Power per Part (W)	
Power Total (W)	

He Pump Pot Tube

Housekeeping Cables

Radiation Window



Optimize VCS temperatures

- VCS2 and VCS1 are cooled via vapor
- ↑ thermal load = ↑ boil off (vapor) = ↓ stage temp = ↓ thermal load

- This is a weird and complex optimization problem
- Minimize ***sum variance*** – requires recalculating power per part for each component based on changes to the stage temperature.

$$\sigma = \left((\mathrm{VCS1}_{CC} + \mathrm{VCS2}_{CC}) - (W_{VCS1} + W_{VCS2})\right)^2$$

Calculate Hold Time

$$L/\text{cycle} = \frac{\text{AvgLoad} \times \text{He-3}_{HT}}{\ell_{\text{He}} \times \rho_{\text{He}}}$$

$$\text{AvgLoad} = \text{Load}_{\text{Active}} + \text{Load}_{\text{Passive}} + \frac{E_{\text{Recycle}}}{\text{He-3}_{HT}}$$

$$N_{\text{cycles}} = \frac{\text{He}_{Cap}}{L/\text{cycle}}$$

$$\text{He-3}_{HT} = \frac{\text{He3}_{Cap}}{\text{Load}_{\text{300mk}}}$$

$$\text{Hold Time} = N_{\text{cycles}} * \text{He-3}_{HT}$$

Stage	High Temperature (K)	Low Temperature (K)	Total Power (W)
VCS 2	260.00	233.33	1.44e+01
VCS 1	233.33	83.33	4.32e+00
4K - LHe	83.33	4.20	2.65e-01
4K - Transient	260.00	4.20	6.18e-02
1K	4.20	2.00	1.62e-03
300mK	2.00	0.30	2.65e-05
100mK	0.30	0.10	1.09e-06

	Value	Units
He3Cap	300	L
Total Average Load	0.3465	W
Load Providing Vapor	0.3234	W
VCS1 Cooling Capacity	6.3445	W
VCS2 Vapor Temp	79.0954	K
VCS2 Cooling Capacity	12.366	W
Fridge Hold Time	63.0015	hrs
Cryo Hold Time	26.304	days

Further Optimization

$$D_M = MS \times HT \times \epsilon_{obs}$$

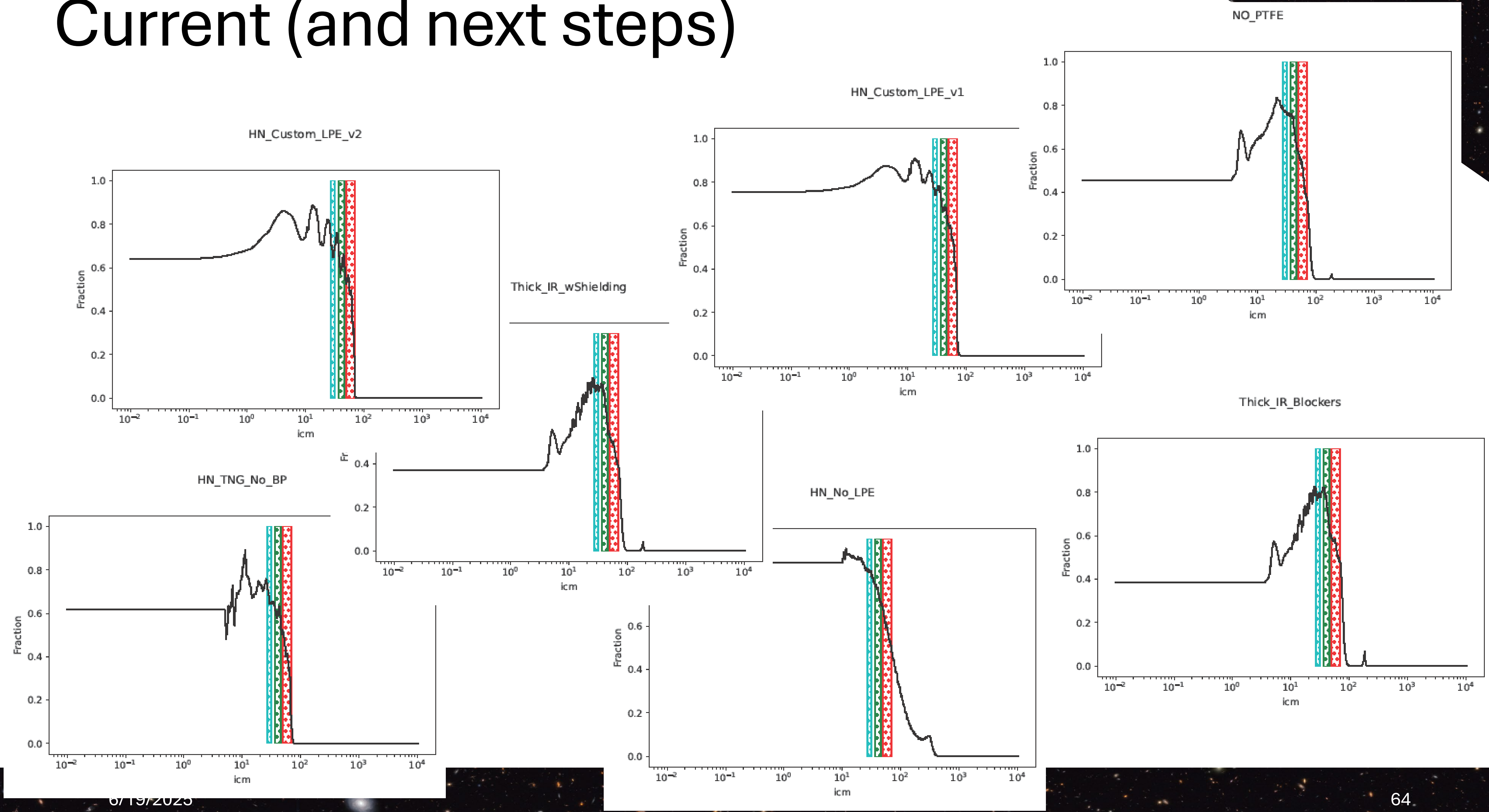
1. Optical components dictate mapping speed – how much optical power is incident on the detectors in each band.
2. Thermal components and ***radiative power*** dictate hold time.

↑ filtering = ↓ in-band optical efficiency = ↓ sensitivity = ↓ mapping speed

↑ filtering = ↓ out-band power = ↓ thermal load = ↑ hold time

- Changes in the filter stack can influence total degrees mapped in a complex manner.

Current (and next steps)



The Future

BLAST : Currently in NASA limbo – APRA 2024 decision should be released ~ July 2025.

PRIMA : Probe class mission ($1B) currently in Phase A - selection anticipated Fall 2025.

Simons Observatory : All telescopes (1 LAT and 3 SATs) on sky and taking data.

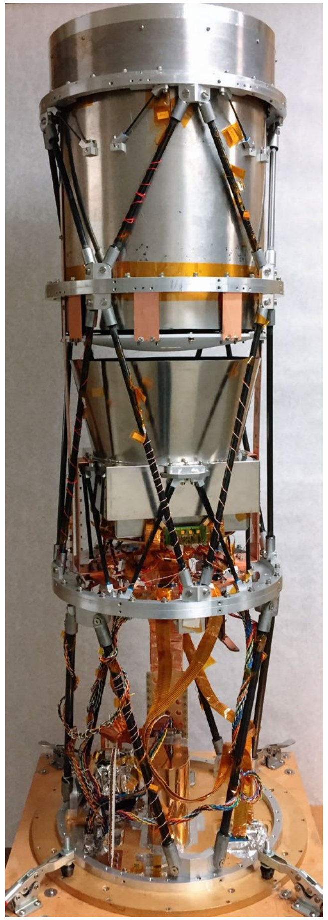
CMBS4 : 🙃

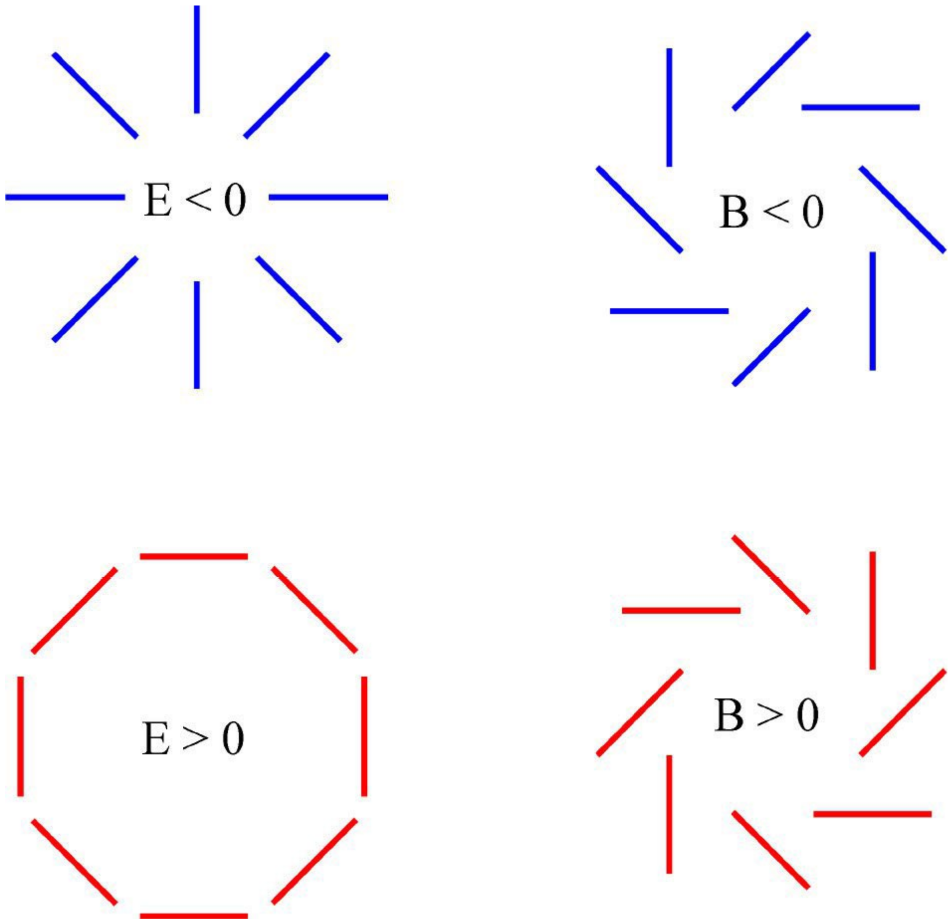
Thanks!

References (where not mentioned)

- https://www.balloonrevolution.com/en/montgolfiere/histoire-montgolfiere
- https://www.pbs.org/wgbh/aso/databank/entries/dp65co.html
- Dodelson and Schmidt – Modern Cosmology

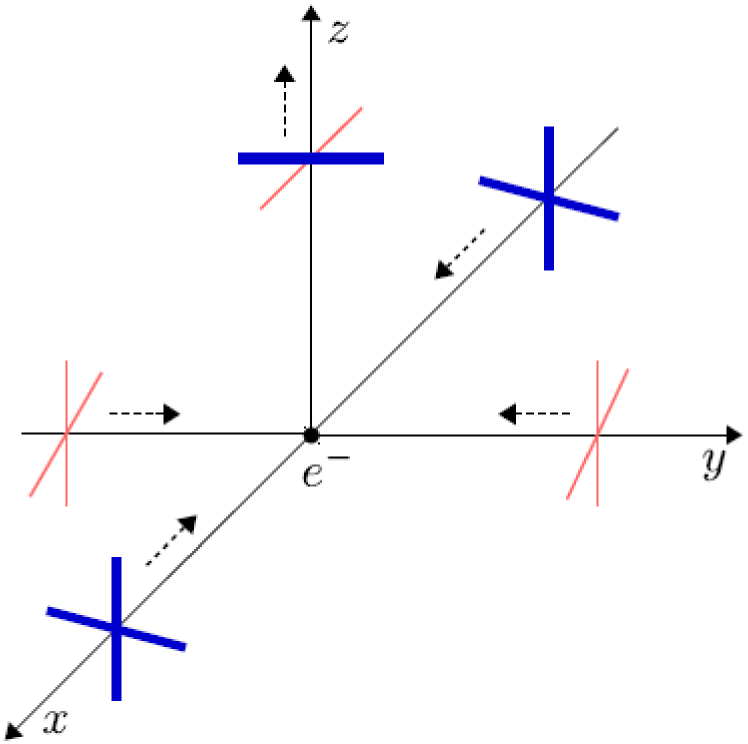
SPIDER-2 280 GHz receiver - ECS

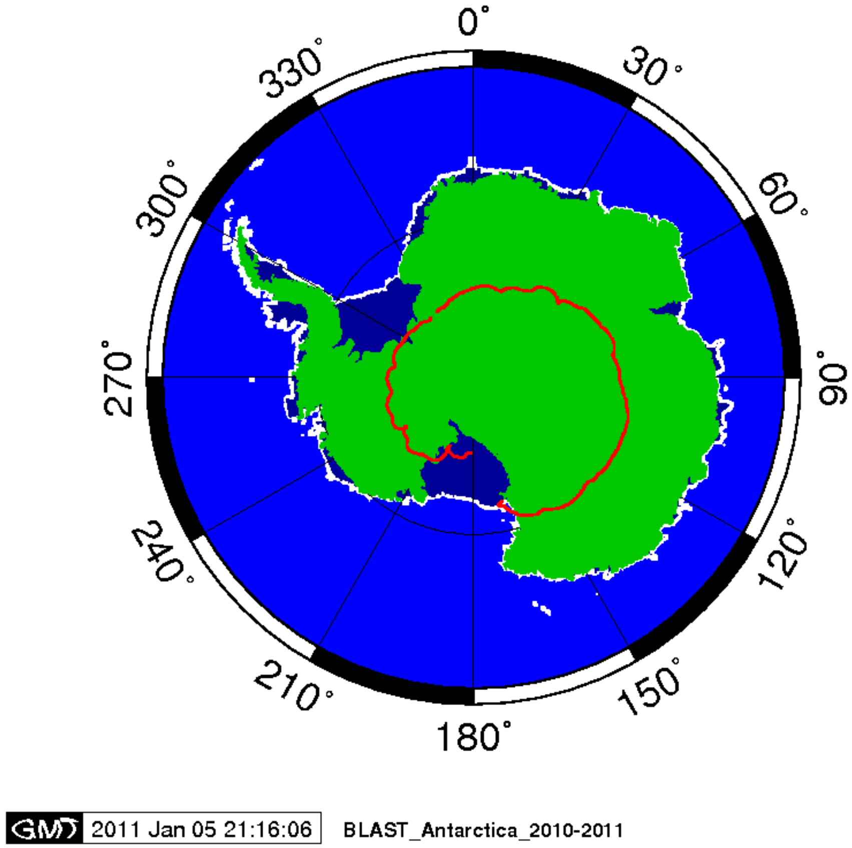



E < 0
B < 0
E > 0
B > 0

How to recover polarization signal and modulation

Scattering of quadrupole




0°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
GMT 2011 Jan 05 21:16:06
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