Instrumentation for Cosmic Microwave Background (CMB) Telescopes

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AIMS Future of Science
Kigali, July 7 2019
• Cosmic Microwave Background (CMB)

• Ingredients for a CMB telescope
from $10^{14}$m to $10^{-8}$m

from $10^{-37}$s to $10^{-8}$s

from $10^{28}$K to 0.1K

primordial universe  CMB detectors
... SPANNING MANY ORDERS OF MAGNITUDE

from $10^{14}$m to $10^{-8}$m

from $10^{-37}$s to $10^{-8}$s

from $10^{28}$K to 0.1K

primordial universe CMB detectors

Working condition of a CMB instrumentalist:

0m to 5200m above sea level

-10°C to 30°C

$10^5$ part(>$0.5$um/min)@lab to 10 part(>$0.5$um/ft$^3$)@cleanroom
HISTORY OF THE UNIVERSE

1. expansion + cooling down
2. anisotropy

picture credit: nasa.gov
HISTORY OF THE UNIVERSE

1. Expansion + Cooling down
2. Anisotropy

- Big Bang
- Cosmic Inflation
- Origin of Fluctuations
- Particles form
  - Ordinary matter particles
  - Dark matter particles
- Dark ages
  - Ordinary matter particles decouple from light and dark matter
  - Background is released
- Recombination
  - Ordinary matter particles start building structures
- First stars & galaxies
- Ordinary structures created by dark matter
- Galaxy evolution
  - Clusters of galaxies and superclusters form

- Size of visible universe

Picture credit: nasa.gov
10^5K, 60eV
H+γ ↔ p+e, no Hydrogen formation
scattering Thomson γ +e ↔ γ +e
10^5 K, 60 eV
H + γ ↔ p + e, no Hydrogen formation
scattering Thomson: γ + e ↔ γ + e

THE OPAQUE UNIVERSE

the photon is scattered
THE OPAQUE AND THE TRANSPARENT UNIVERSE

$10^5 \text{K}, 60 \text{eV}$

$\text{H} + \gamma \leftrightarrow \text{p} + \text{e}$, no Hydrogen formation

scattering Thomson $\gamma + \text{e} \leftrightarrow \gamma + \text{e}$

the photon is scattered

$T = 380,000 \text{ years}, \ 3000 \text{K}, z = 1100$

Recombination (Hydrogen formation) + LAST SCATTERING
THE OPAQUE AND THE TRANSPARENT UNIVERSE

$10^5$K, 60eV

H$+\gamma \leftrightarrow p+e$, no Hydrogen formation

scattering Thomson $\gamma +e \leftrightarrow \gamma +e$

the photon is scattered

$T=380,000$ years, 3000K, $z=1100$

Recombination (Hydrogen formation) + LAST SCATTERING

the photon is NO MORE scattered
COSMIC MICROWAVE BACKGROUND related to Universe
THE CMB

COSMIC related to Universe

MICROWAVE

expansion of the Universe

past (optical) today (microwave) future (radio)

BACKGROUND
THE CMB

COSMIC related to Universe

MICROWAVE

past (optical) today (microwave) future (radio)

expansion of the Universe

BACKGROUND is everywhere!

411 CMB photons/cm$^3$
THE CMB IS A BLACK BODY AT 2.725 K

John Mather and George Smoot Nobel Prize 2006

Guess who is John Mather ...

OUR UNIVERSE WHEN IT WAS 380,000 YEARS OLD

Planck satellite

red spots -> warmer/denser regions
blue spots -> colder/less dense regions

SEEDS ->>> BOTH EVOLVED WITH GRAVITY ORIGINATING THE STRUCTURES WE OBSERVE TODAY

CMB ANISOTROPIES
Imagine to be a FREE electron surrounded by an **ISOTROPIC** distribution of CMB photons.

What you would do?

FREE= not bounded inside an atom
Imagine to be a FREE electron surrounded by an ANISOTROPIC distribution of CMB photons.

What you would do?

FREE= not bounded inside an atom
LINEAR POLARIZATION BY THOMSON SCATTERING

A electron

B $e^-$ $e^-$ $e^-$

C Hotter Colder

D Scattering of colder photons

E Scattering of hotter photons

F Net scattering = polarized photons

G

ANISOTROPY SCATTERING
Now imagine an isotropic distribution ...

How it could become anisotropic?
Inflation
High-energy physics \( \rightarrow \) GUT

\[
r = \frac{T}{S} = 0.0043\left(\frac{E_i}{10^{16}\text{ GeV}}\right)^4
\]
Black Body at 2.725K continuum spectrum

0.5°
linearly polarized <0.3μK

CMB-S4 Science Book
SEVEN INGREDIENTS
FOR
A
CMB TELESCOPE
CMB = Black Body at

\[ T = (2.72548 \pm 0.00057) \text{K} \]

\[ \lambda_{\text{max}} T = 2.9 \times 10^{-3} \text{ m*K} \]

Wien’s Displacement law

1. FREQUENCY

Max emission at 150GHz

Fixsen et al., 1996
EVERYTHING ABOVE 0K EMITS RADIATION...

2. CRYOGENIC TEMPERATURES (0.1, 2K, 77K)

MINIMIZE:
RADIATIVE LOAD -> COOLING TELESCOPE (e.g. MIRRORS, FILTERS)

CONVECTION -> HIGH VACUUM 10e-6 mbar

CONDUCTION -> REDUCE NUMBER OF ELECTRICAL WIRES (MULTIPLEXING)
**ATACAMA COSMOLOGY TELESCOPE (ACT)**

1.5m

Atacama desert - 5,200 m above sea level

**ACT CRYOSTAT**

3. DETECTOR

- The CMB spectrum is continuum
- Wide band detectors
- High sensitivity

Slide adapted from P. de Bernardis
3. DETECTOR R(T)

CMB photon -> power deposited on the Au meander -> delta T -> delta R

we measure delta Current

Transition Edge-Sensor (TES)
Irwin K. and G. Hilton, 2005

$\Delta P \rightarrow \Delta T \rightarrow \Delta R \rightarrow \Delta I$

Li D. et al, JLPT 184,66, 2016

Diagram: Transition from superconducting to normal state with temperature, normalized resistance, and transition edge sensor schematic.
A typical cleanroom laboratory

Chalmers MC2 Göteborg
1. DETS COOLED DOWN AT 0.1K
   (-> this maximize their sensitivity)

NOISE from DETS itself (since T>0K)

2. Also the CMB radiation is noisy itself
   CMB= photons \(\rightarrow\) fluctuations in their time of arrival  -> Delta N
   N=number of photons

3. Current dets technology
   DETS are PHOTON-NOISE LIMITED
    
    -> they are so good that their sensitivity
    is limited by the noise in your target radiation

    To detect your target radiation we need more sensitivity....
    What we can do?

4. DETS.... How...?
4. KILOPIXEL DETECTOR ARRAY

Henderson S. et al., SPIE 9914, 99141G, 2016
FEEDHORN ARRAY

Coupling incoming radiation to detector array

4. KILOPIXEL DETECTOR ARRAY

Advanced ACTPol HF

Henderson S. et al., SPIE 9914, 99141G, 2016
components for the readout electronics

printed circuit board
Cu support

detector array
flex

Advanced ACTPol HF

1 cm
• 15μm thick polyimide
• one line:
• Al 50 μm wide, 70 μm pitch

Pappas C. et al., JLT 184,476, 2016

• 2012 TESes
• 20,000 wire bonds
• 300 readout chips
• 4,056 flex traces
Can we observe the CMB from NYC - Times Square?
roto-vibrational emission lines of O2 (60 and 119 GHz) and H2O (at 22 and 183 GHz)

5. SITE DRY & HIGH ALTITUDE

ACTPol bandpasses
Thorton R.J. et al,
ApJSS 227, 21, 2016
IMPORTANCE OF LOW SIDELOBES

Sidelobes:
like yourself
(view capability away from direction of view)

Planck’s law $T^4$

Necessity of shields

\[
W = A \left[ \int_{\text{main lobe}} B_{\text{sky}} (\theta, \varphi) R A (\theta, \varphi) d\Omega + \int_{\text{side lobes}} B_{\text{Ground}} (\theta, \varphi) R A (\theta, \varphi) d\Omega \right]
\]

\[
(2.7K)^4 \quad 1 \quad << \quad 1 \text{sr} \quad (300K)^4 \quad 10^{\text{-}7} \quad 2\pi \text{sr} \]

slide from P. de Bernardis

BICEP3

South Pole Telescope

BICEP3

Reflecting ground shield Flexible boot Absorbing forebaffle

DSL roof Electronics MCE

Deck angle

Azimuth

Indoor environment (20° C) Outdoor environment (-50° C)

What do you do, Maria?
ALICPT-1

- **ALI CMB Polarization Telescope-1**
- First CMB experiment on the Tibetan plateau, 5250m a.s.l.
- Northern hemisphere
- O(4) AlMn TESes, 4 modules late 2020, umux readout
CURRENT STATUS OF ALICPT-1

- Site construction finished by IHEP & NAO
- Control system\DAQ by IHEP & Stanford
- System integration\Calibration by IHEP & NTU
- Telescope mount under test in Beijing
- Cryostat receiver designed at Stanford fab is starting ~mid July
- Detector array design at NIST
- Readout design at ASU
# SEVEN INGREDIENTS FOR A CMB TELESCOPE

Target:
Measure a very small polarized signal, <0.3μK

<table>
<thead>
<tr>
<th>Reason/origin</th>
<th>Ingredient kind</th>
<th>Ingredient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Thermal history/expansion universe</td>
<td>Frequency</td>
<td>150GHz</td>
</tr>
<tr>
<td>2. Thermal history/continuum spectrum</td>
<td>Wide band</td>
<td>33% 150GHz</td>
</tr>
<tr>
<td>3. Small signal</td>
<td>Large number detector arrays</td>
<td>2,000 TESes</td>
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<tr>
<td>4. Thermal noise</td>
<td>Cryogenics</td>
<td>cryostat, multiplexing readout</td>
</tr>
<tr>
<td>5. Atm transmission</td>
<td>Dry site</td>
<td>Atacama, South Pole, Tibet</td>
</tr>
<tr>
<td>6. Angular dimension CMB anisotropies</td>
<td>Angular Resolution</td>
<td>0.5m diameter</td>
</tr>
<tr>
<td>7. Inflation theory</td>
<td>Polarized CMB</td>
<td>OMT/polarizer</td>
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Remember to look up at the stars and not down at your feet. Try to make sense of what you see and wonder about what makes the Universe exist. Be curious.

Stephen Hawking

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ACT – pic: J. Ward