The lecture slides are available at
https://wwwmpa.mpa-garching.mpg.de/~komatsu/lectures--reviews.html

Physics of the Cosmic Microwave Background

IMPRS Advanced Course

Eiichiro Komatsu (Max-Planck-Institut für Astrophysik), November 3–December 3, 2020

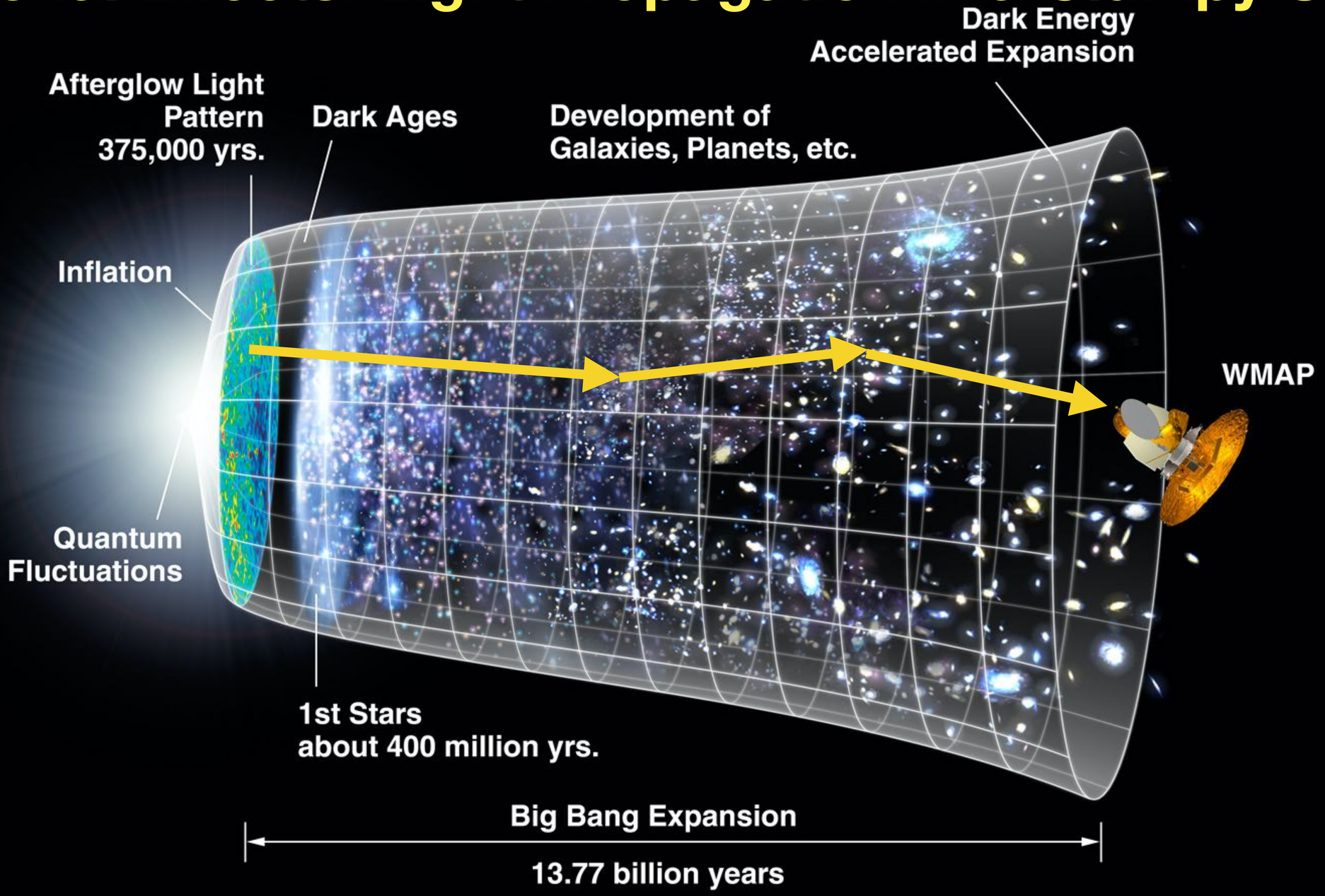
Basic information

- The lectures are given on Tuesdays and Thursdays, from 10:00–11:30 (90 minutes)
  - Starting on November 3, ending on December 3
- Except for today, the format is 40+10+40, i.e.,
  - 10:00–10:40, 10 minutes break, and 10:50–11:30
- Today is 60+10+20.

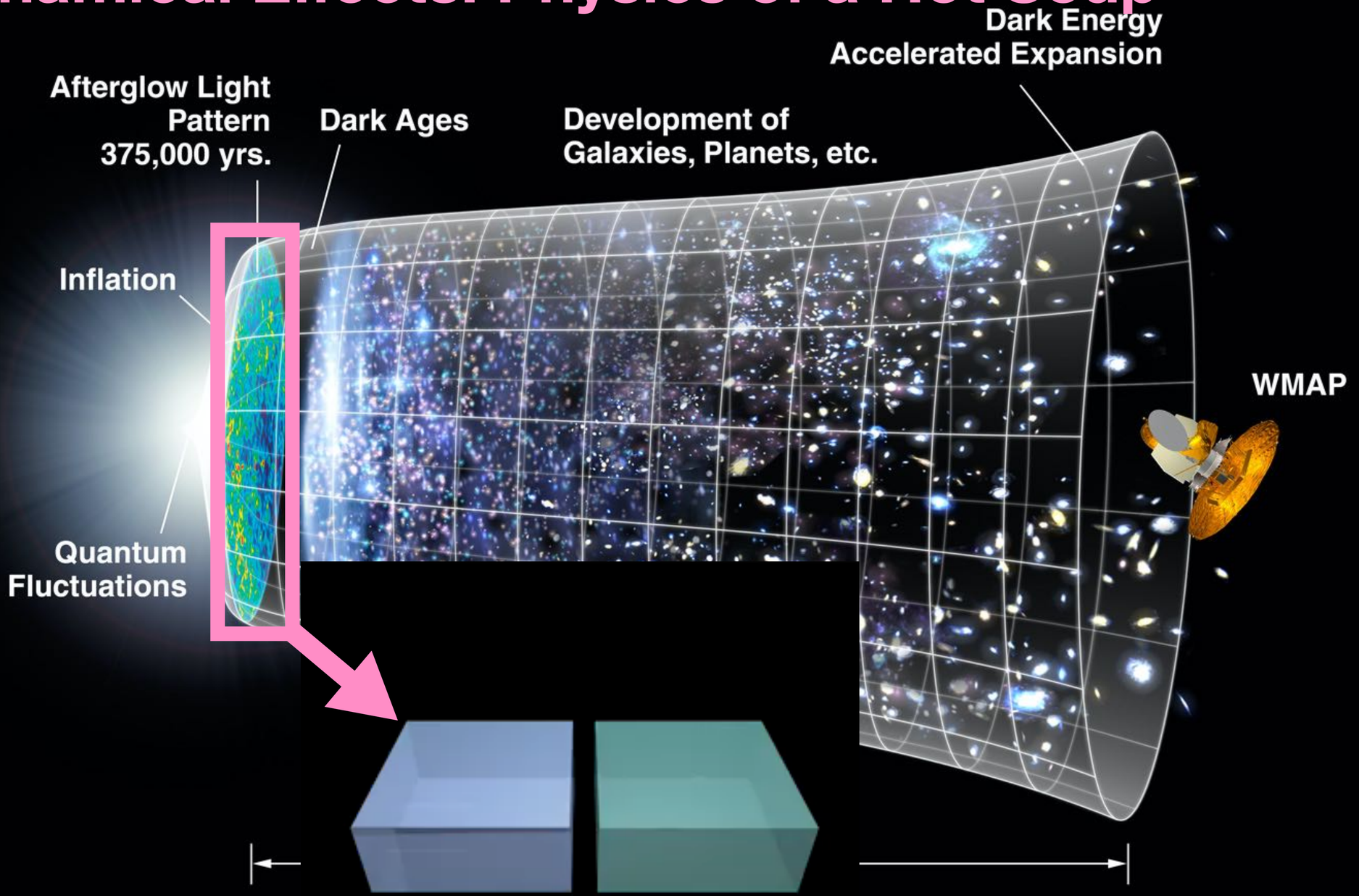
Syllabus

- This lecture covers all essential aspects of the physics of **primary anisotropies** (both temperature and polarisation) of the cosmic microwave background (CMB).
  - We do not cover the physics of recombination.
  - We also do not cover anisotropies generated in a late time Universe, such as the thermal and kinetic Sunyaev-Zeldovich effect.
- There will be equations; but the focus of the lecture is to **understand** the underlying physics. The goal: You will be able to explain all essential aspects of the physics of CMB **in words**.

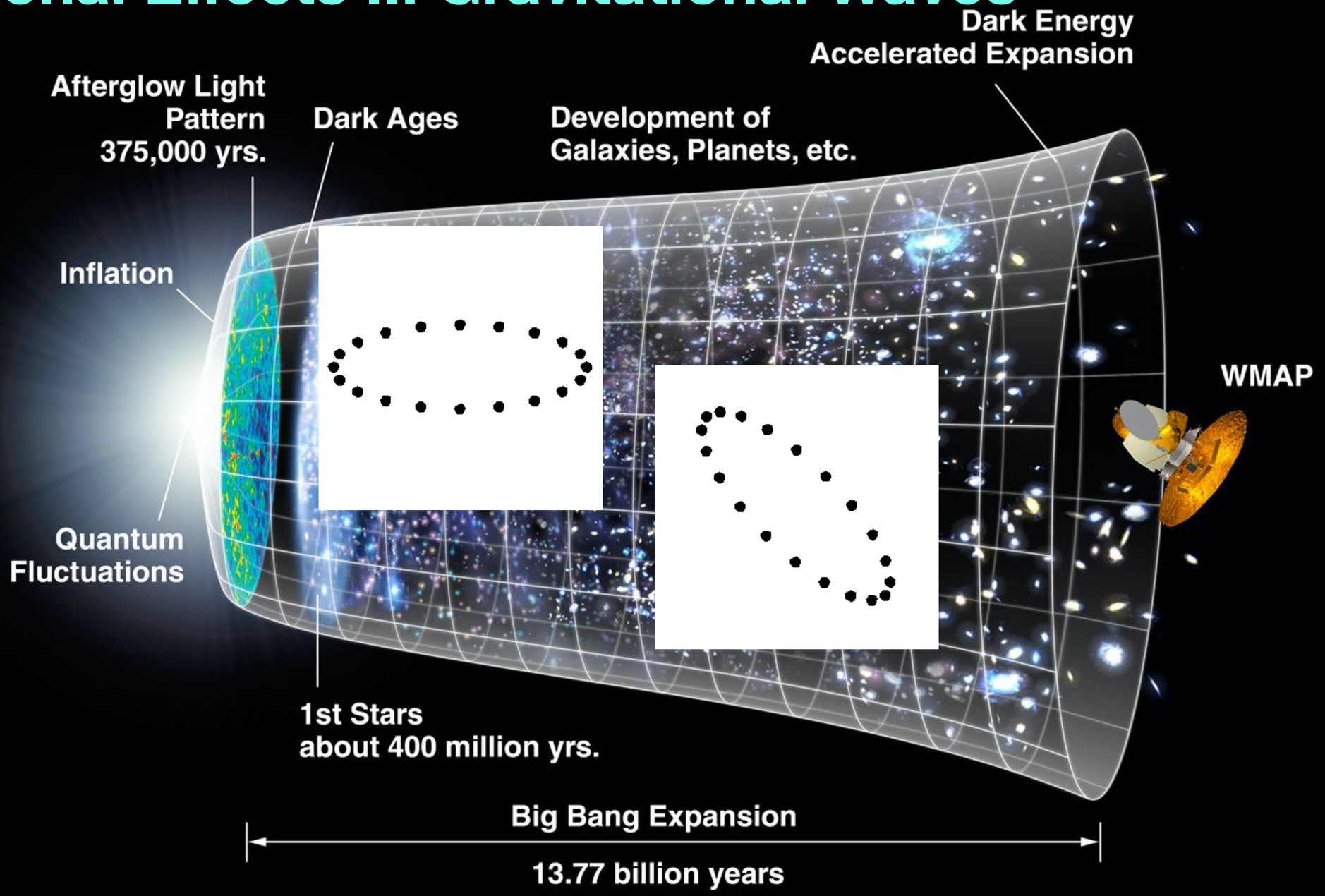
Gravitational Effects: Light Propagation in a Clumpy Universe



Hydrodynamical Effects: Physics of a Hot Soup



Gravitational Effects II: Gravitational Waves



Tip: Download lecture notes in advance

https://wwwmpa.mpa-garching.mpg.de/~komatsu/lectures--reviews.html

- It does not make sense to take notes when the complete lecture notes are available already.
  - Download the lecture notes before each lecture and have them ready.
  - Limit note taking to complementing the lecture notes, i.e., the things that I say but are not written in the notes.
- You certainly do not need to take notes of the equations. Focus on physics.

Tip: Ask Questions

- **You are most welcome to ask questions anytime during the lecture.**
- Asking questions is the easiest way to learn, but I know that you are too shy to ask…
  - “Is my question too simple?” “Is my question too naive?” The simple and naive questions are the **best** questions!
- The on-line lecture format makes it difficult to ask questions.
  - The best option is to write your questions in “*Public Chat*”.
  - I will answer questions in the order that I receive them.
  - But, you are also always welcome to ask questions directly without writing in Chat.

Plan: Today

Movie! (41 minutes)

- After briefly introducing the CMB, we will watch the world's first movie on CMB, which was created for a full dome projection.
  - Title: "*HORIZON: Beyond the Edge of the Visible Universe*"
    - Director: Mr. Hiromitsu Kohsaka
    - Trailer: https://www.youtube.com/watch?v=CQbZi4wfoaw
    - Actors/actresses are humans, but the others are computer graphics. The music is original.

Plan: Your Work Today

While watching the movie…

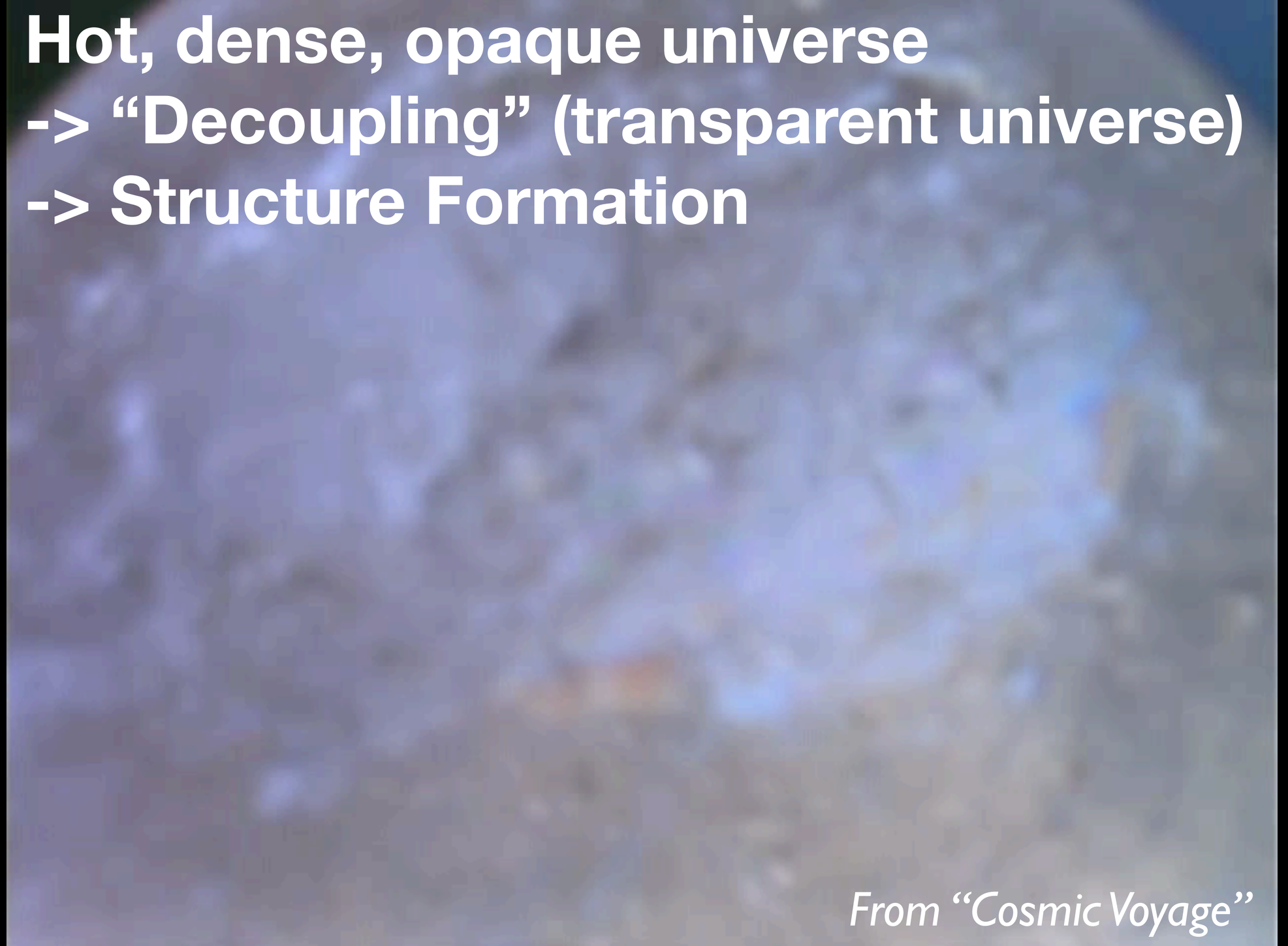
- You should watch the movie critically. The movie will show you:
  - The remarkable history of the Hubble-Lemaitre law and the CMB research
  - Intuitive explanation of the “power spectrum”, and how we used this to determine the composition of the Universe
- The target audience of the movie is the general public. While the movie is pretty accurate scientifically, many important details are dropped.
  - If you wondered anything about the contents of the movie (both scientific and otherwise), write them down. Pretend that you are a critique of the movie.
- We spend the rest of today’s lecture discussing your critique.

Lecture 1: Introduction

Hot, dense, opaque universe

-> “Decoupling” (transparent universe)

-> Structure Formation



From “Cosmic Voyage”

Sky in Optical (~0.5μm)

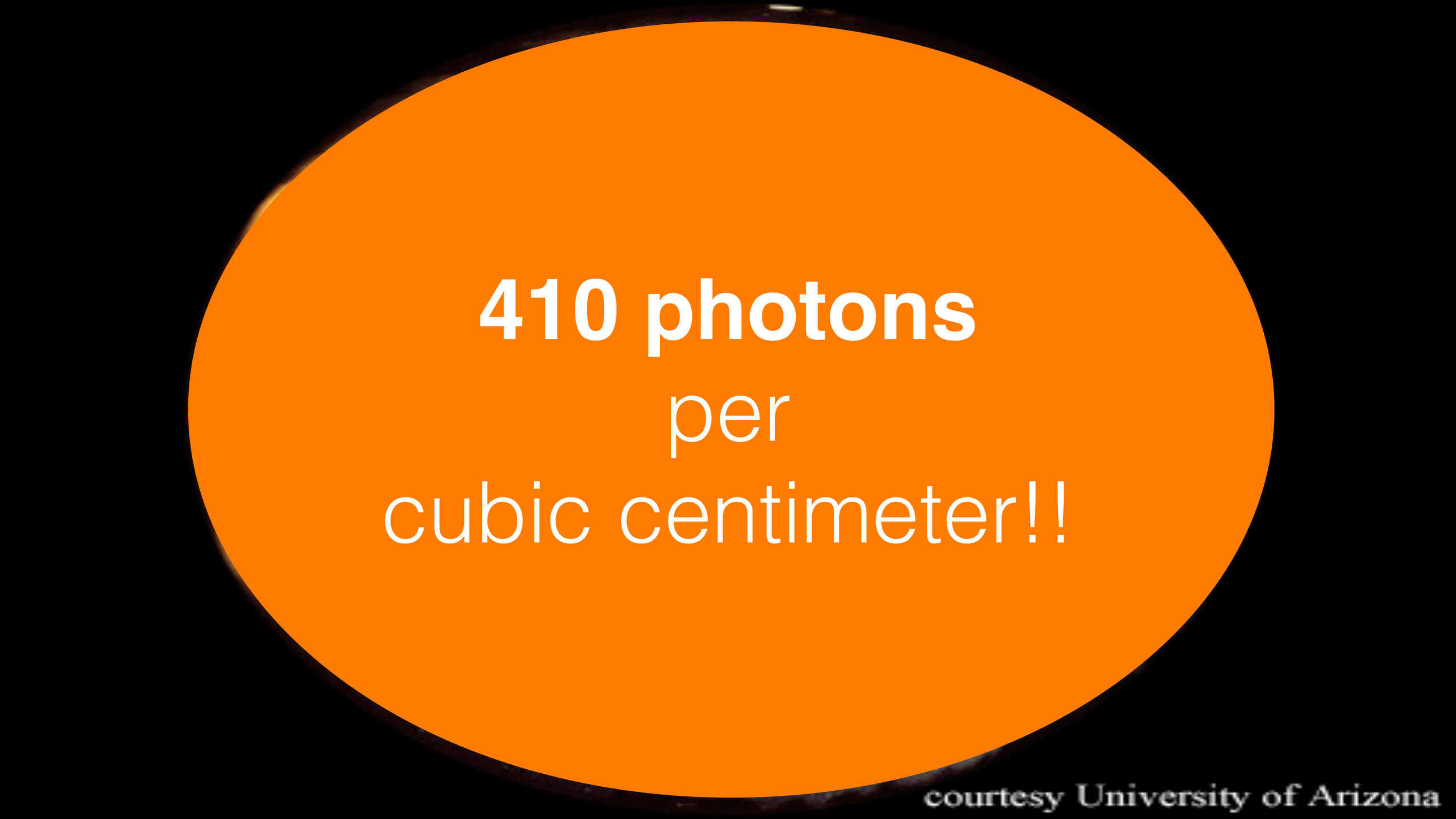
Sky in Microwave (~1mm)

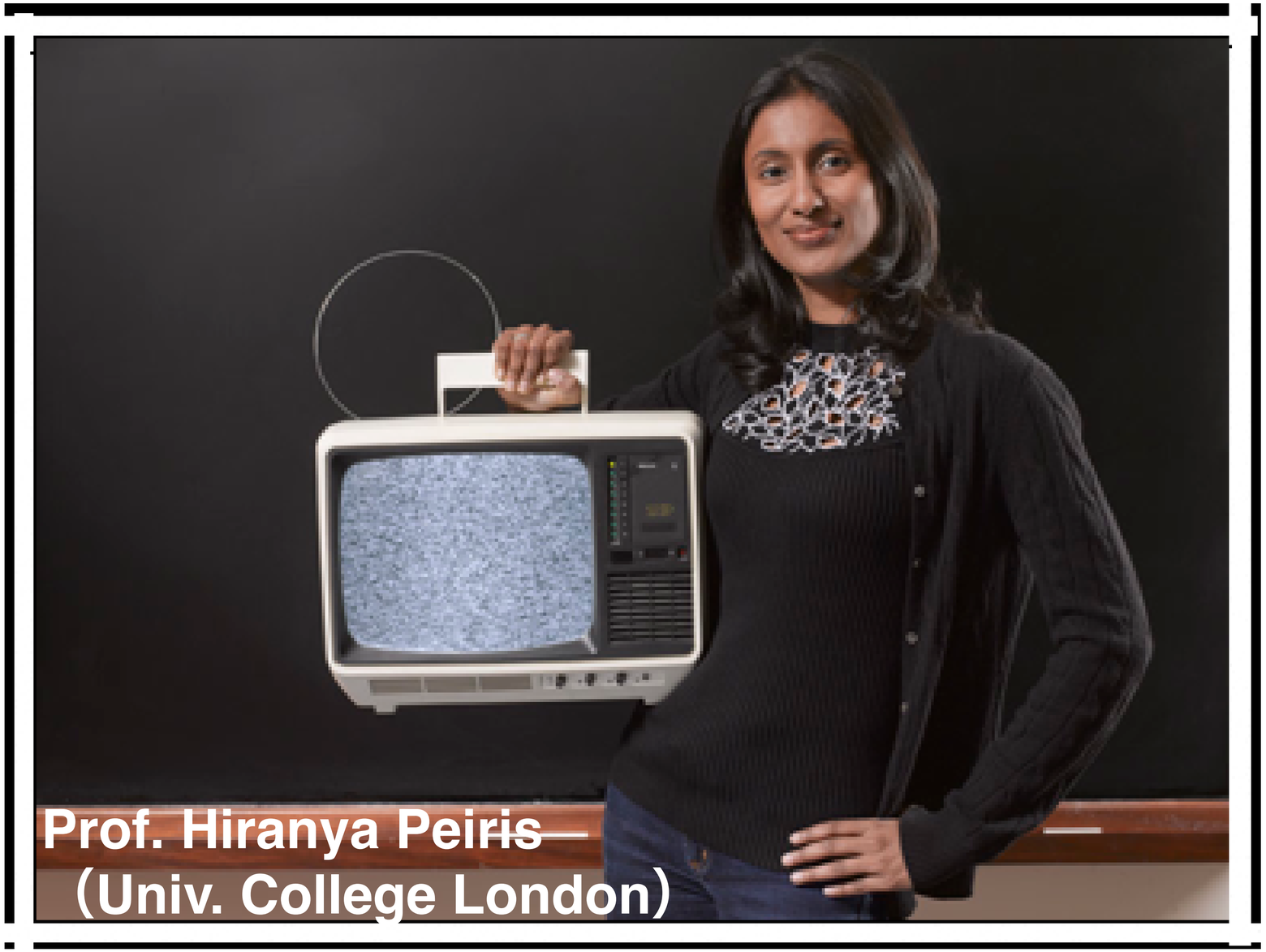
Sky in Microwave (~1mm)

Light from the fireball Universe, filling our sky (2.7K)

The Cosmic Microwave Background (CMB)

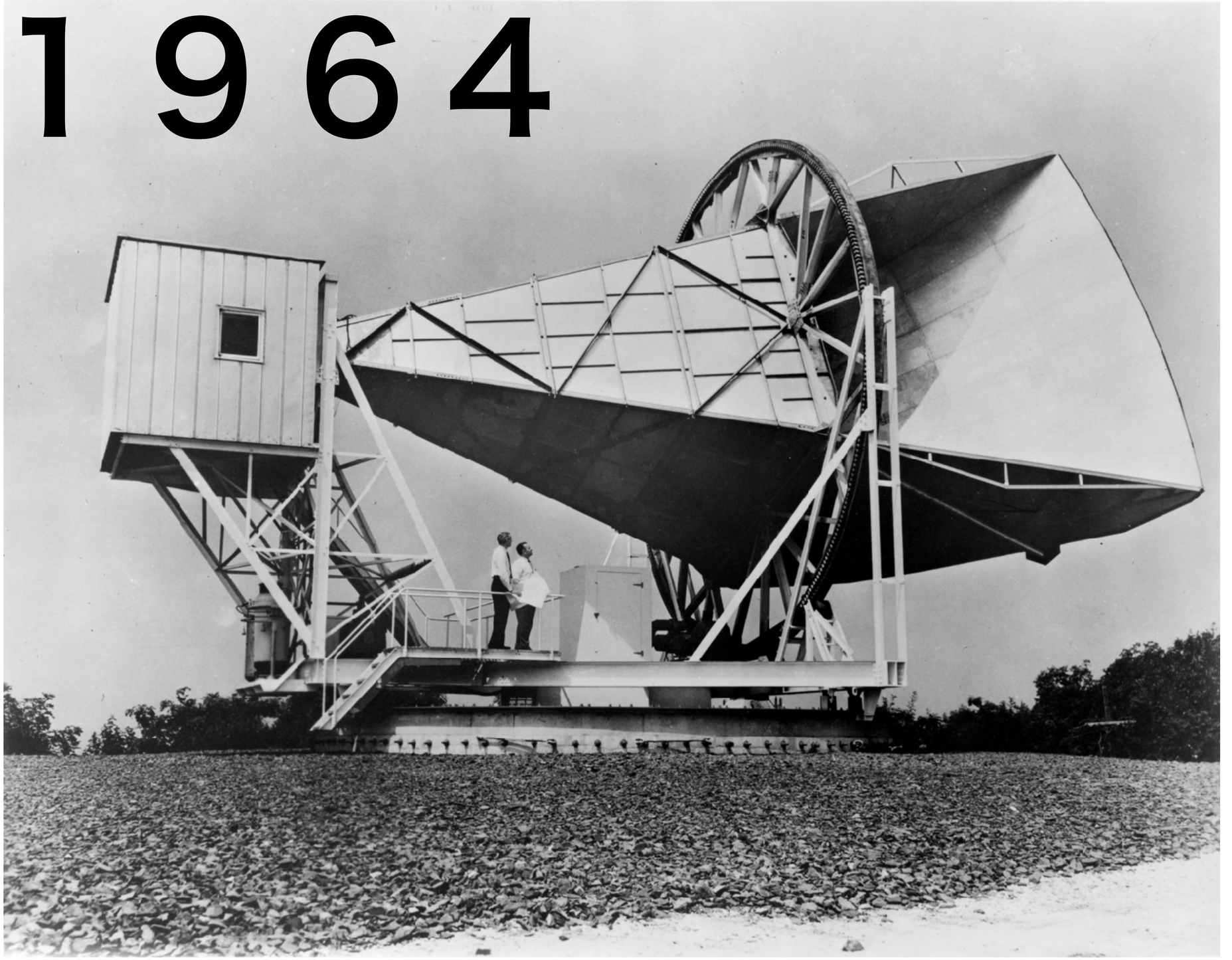
courtesy University of Arizona


410 photons
per
cubic centimeter!!
courtesy University of Arizona

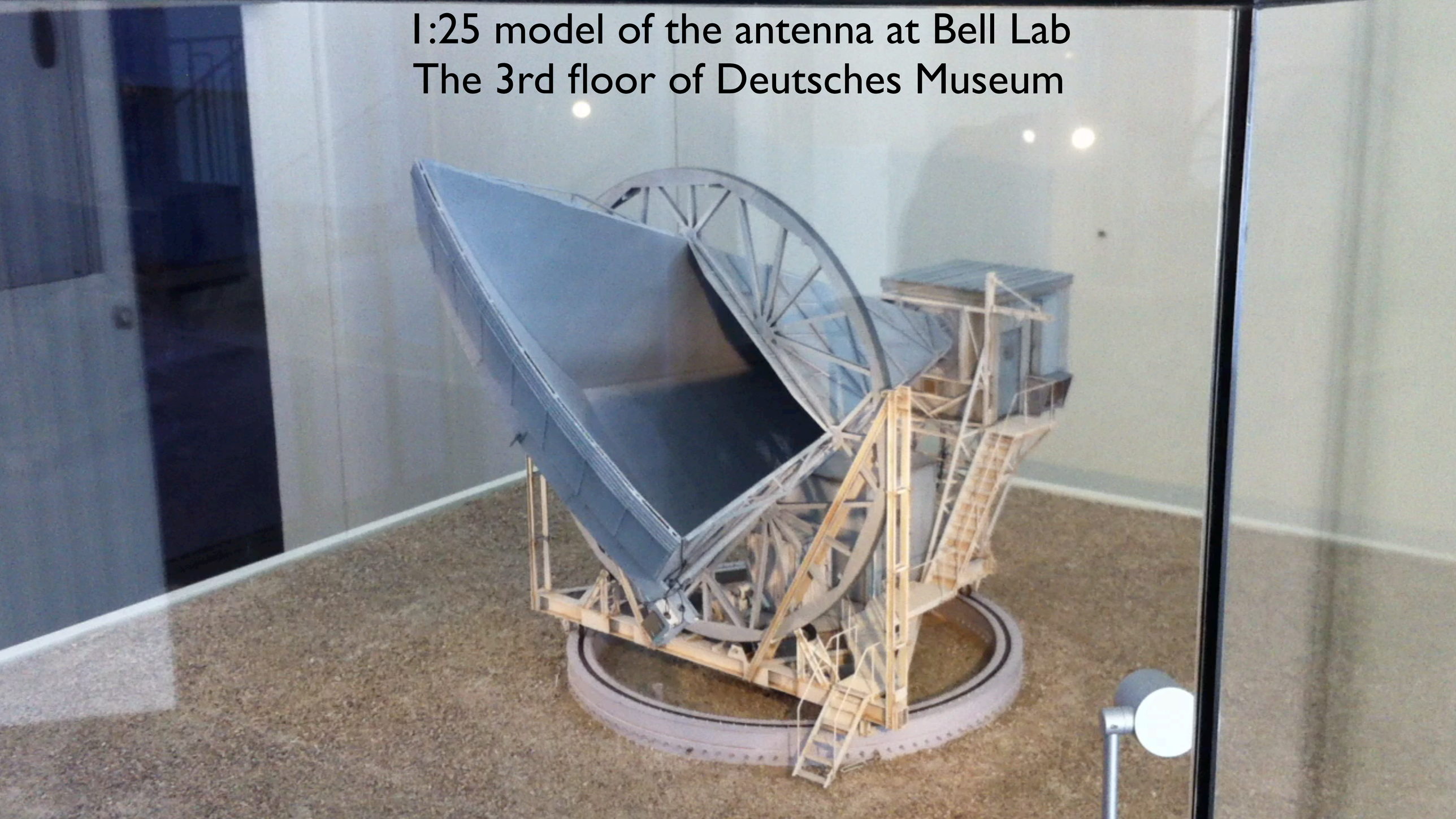


All you need to do is to detect radio waves. For example, 1% of noise on the TV is from the fireball Universe

1964

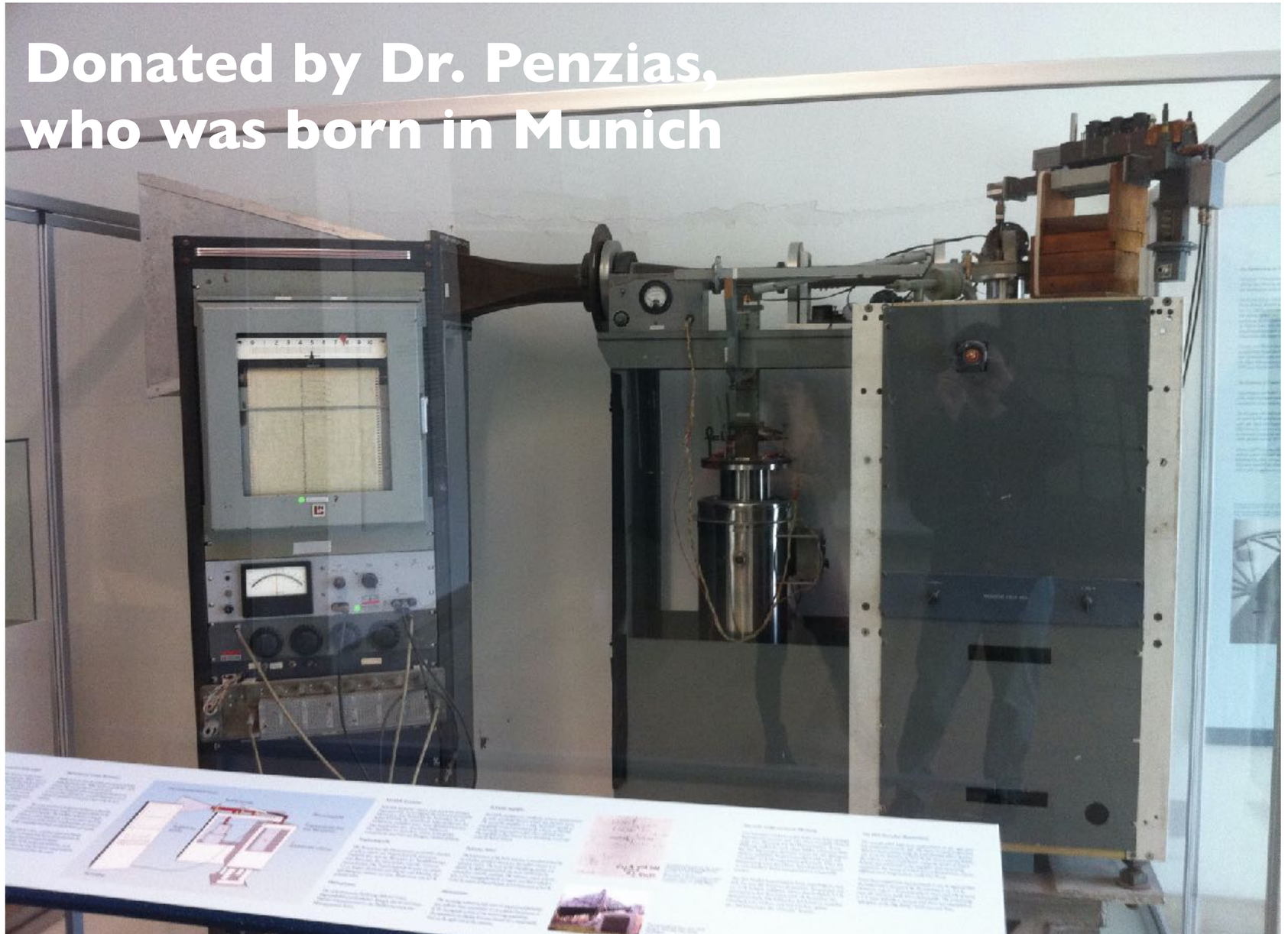


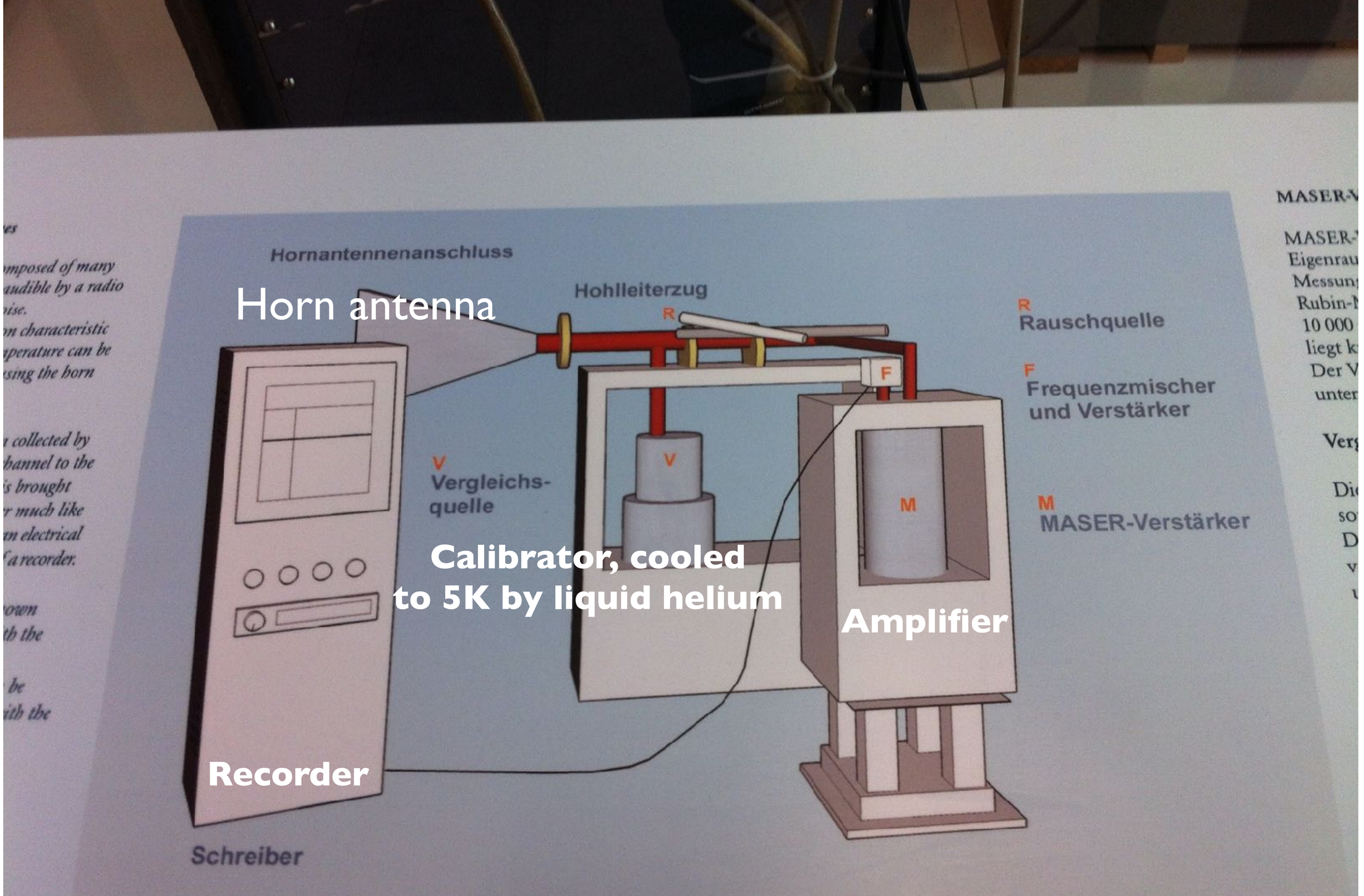
1:25 model of the antenna at Bell Lab
The 3rd floor of Deutsches Museum



The real detector system used by Penzias & Wilson
The 3rd floor of Deutsches Museum

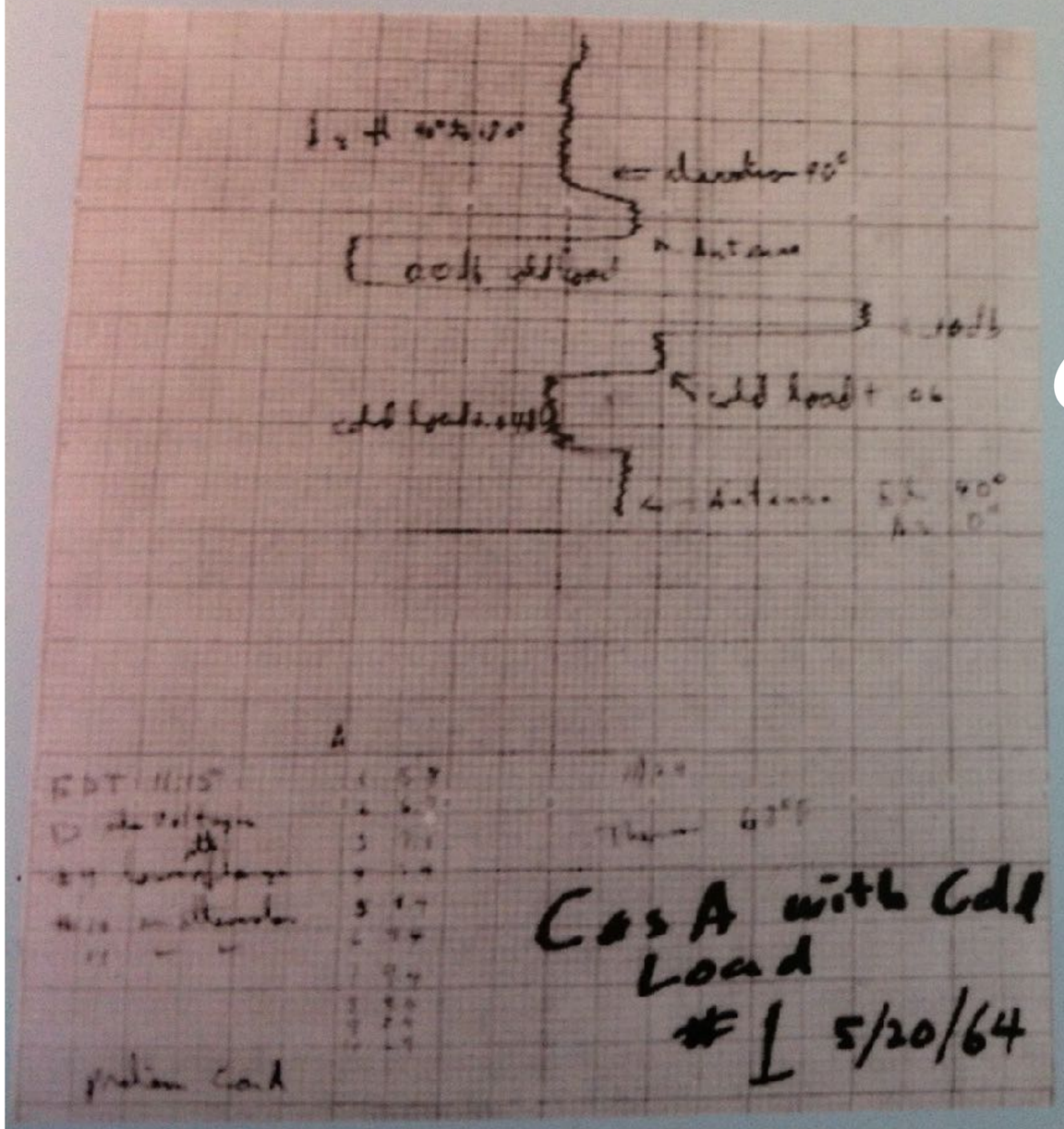
Arno Penzias




Hornantennenanschluss
Horn antenna
Hohlleiterzug
R
Rauschquelle
F
Frequenzmischer
und Verstärker
M
MASER-Verstärker
V
Vergleichs-
quelle
Calibrator, cooled
to 5K by liquid helium
Amplifier
Recorder
Schreiber

May 20, 1964
CMB
Discovered

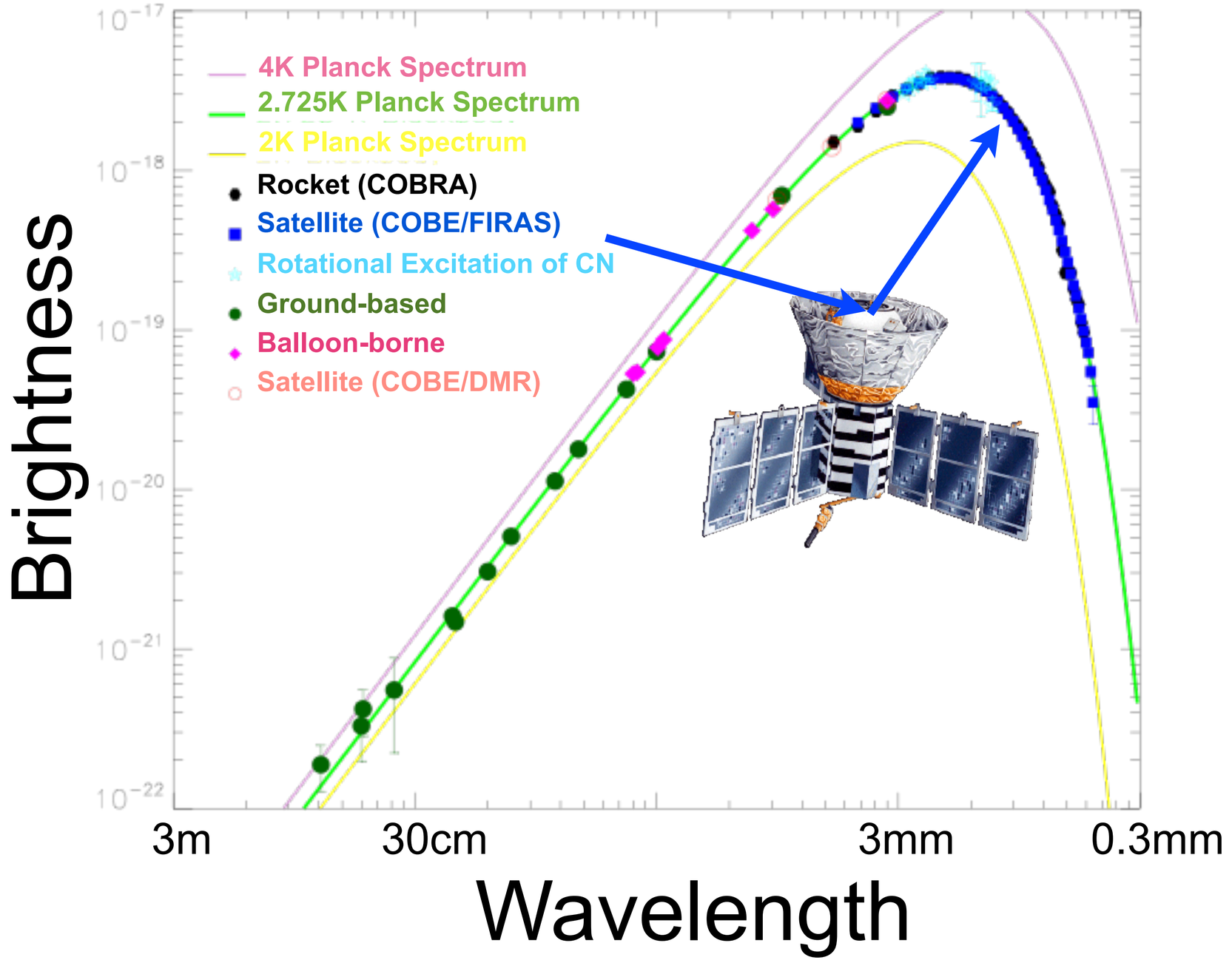
6.7–2.3–0.8–0.1
= 3.5±1.0 K

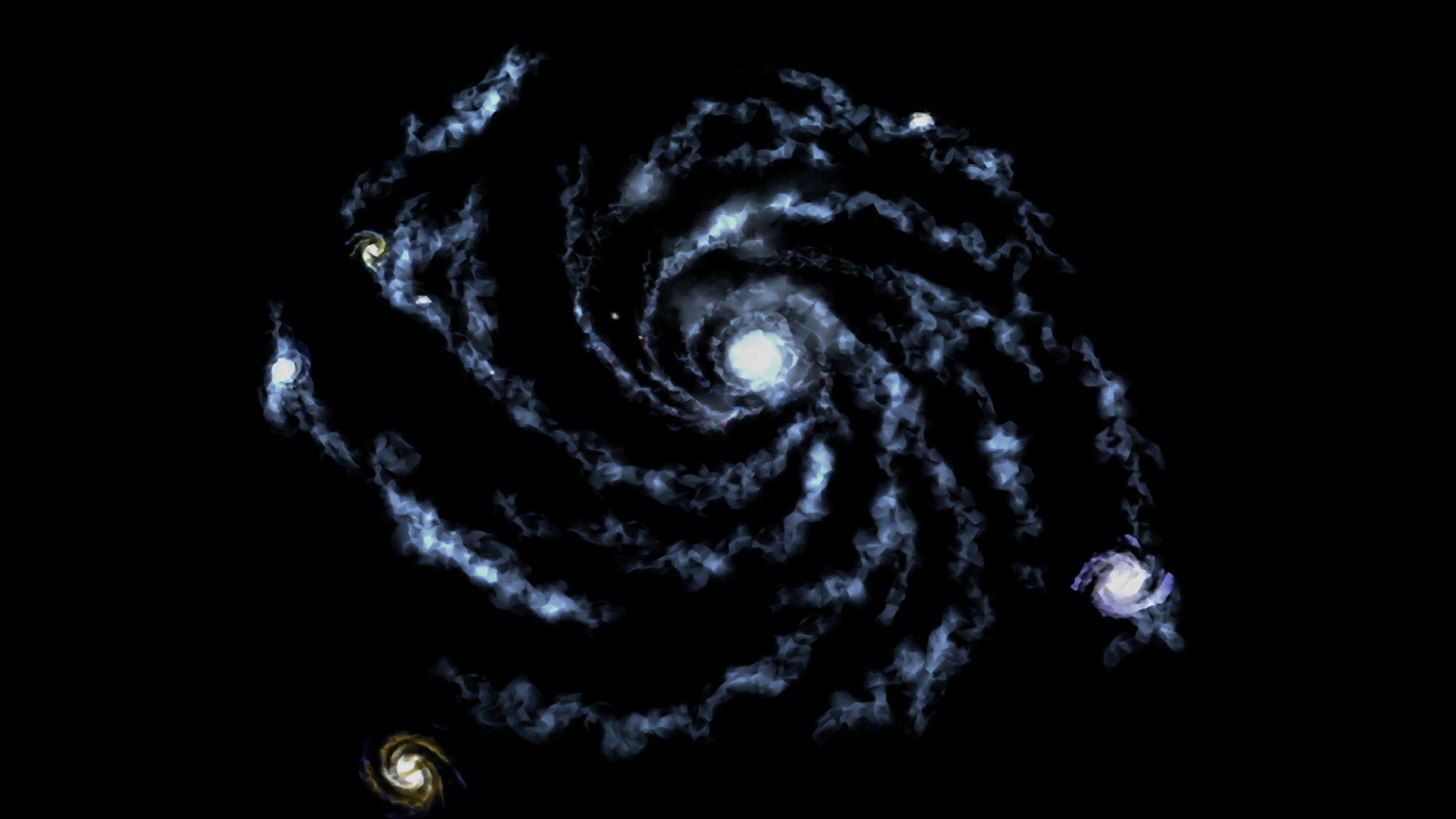


Schreiberaufzeichnung der ersten Messung des Mikrowellenhintergrundes am 20.5.1964

Recording of the first measurement of cosmic microwave background radiation taken on 5/20/1964.

Spectrum of CMB = Planck Spectrum





WMAP Science Team
Princeton, July 19, 2002

- WMAP was launched on June 30, 2001
- The WMAP mission ended after 9 years of operation

Let’s watch

“*HORIZON: Beyond the Edge of the Visible Universe*”

Reminder: Your Work Today

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