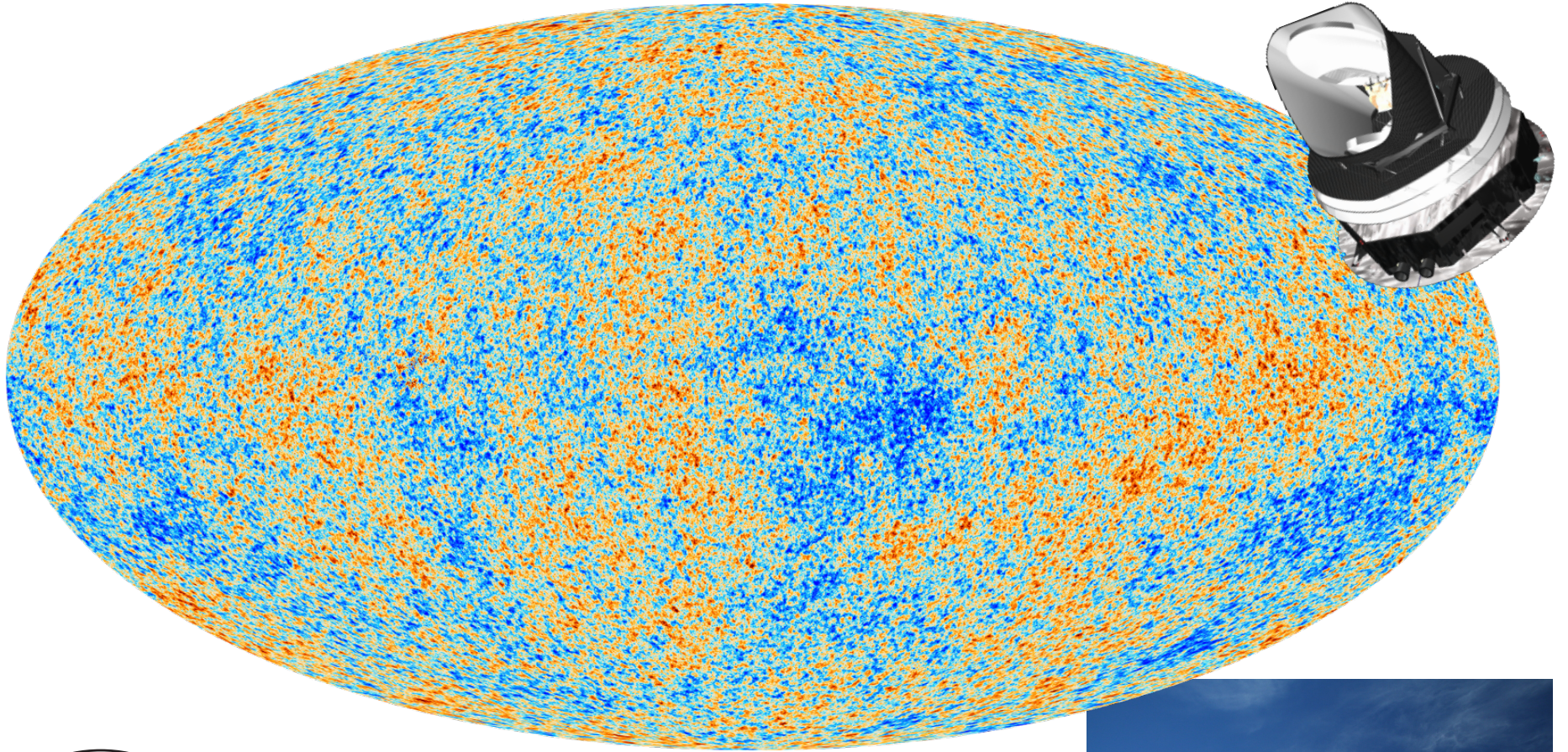
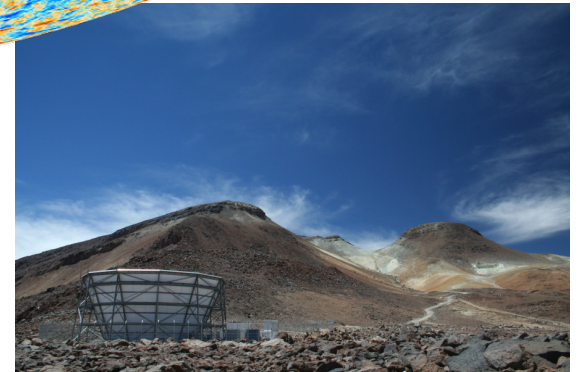


The Cosmic Microwave Background

Physics, Astrophysics, and Cosmology

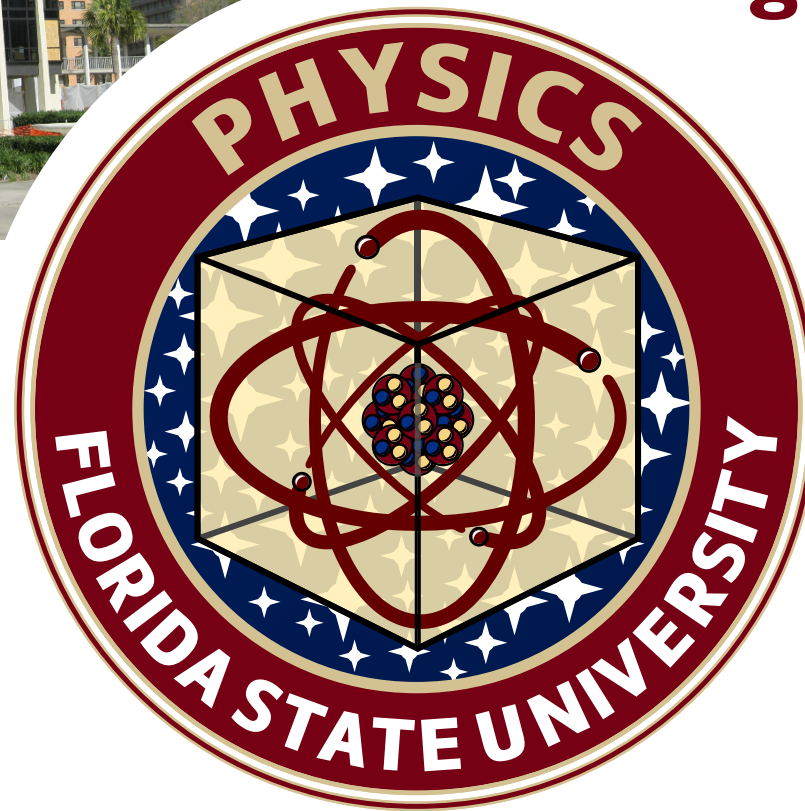


Kevin Huffenberger
Assoc. Prof., Dept. of Physics
Florida State University





Keen building
Ugrad Phys Lab
Nuclear Res. Bldg
Maglab



WIMSE
SPS

~45 Tenured / T. Track Faculty
~200 undergraduate majors
~150 graduate students

Astrophysics

**High Energy
Physics**

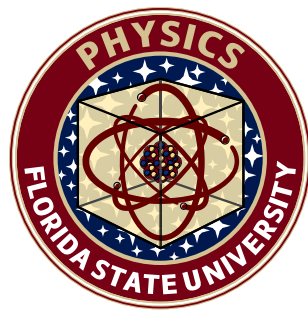


**Nuclear
Physics**

**Condensed
Matter/
Materials
Physics**

Astrophysics

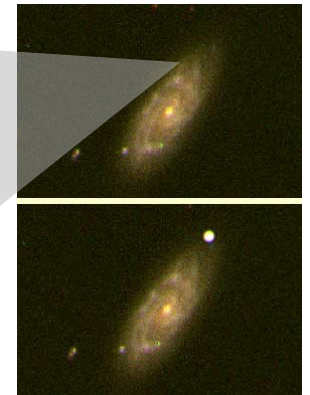
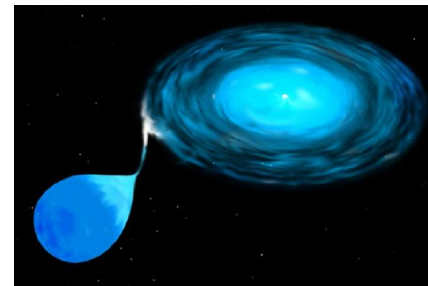
Founded 2007... 2 T / 3 TT Faculty



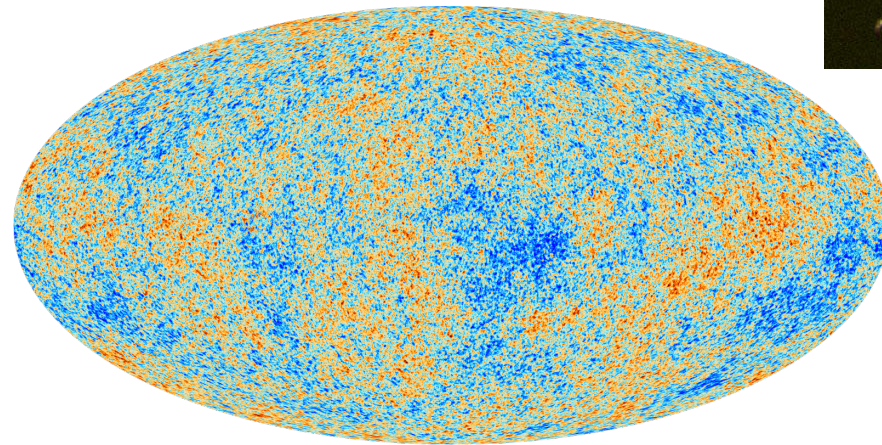
Star formation



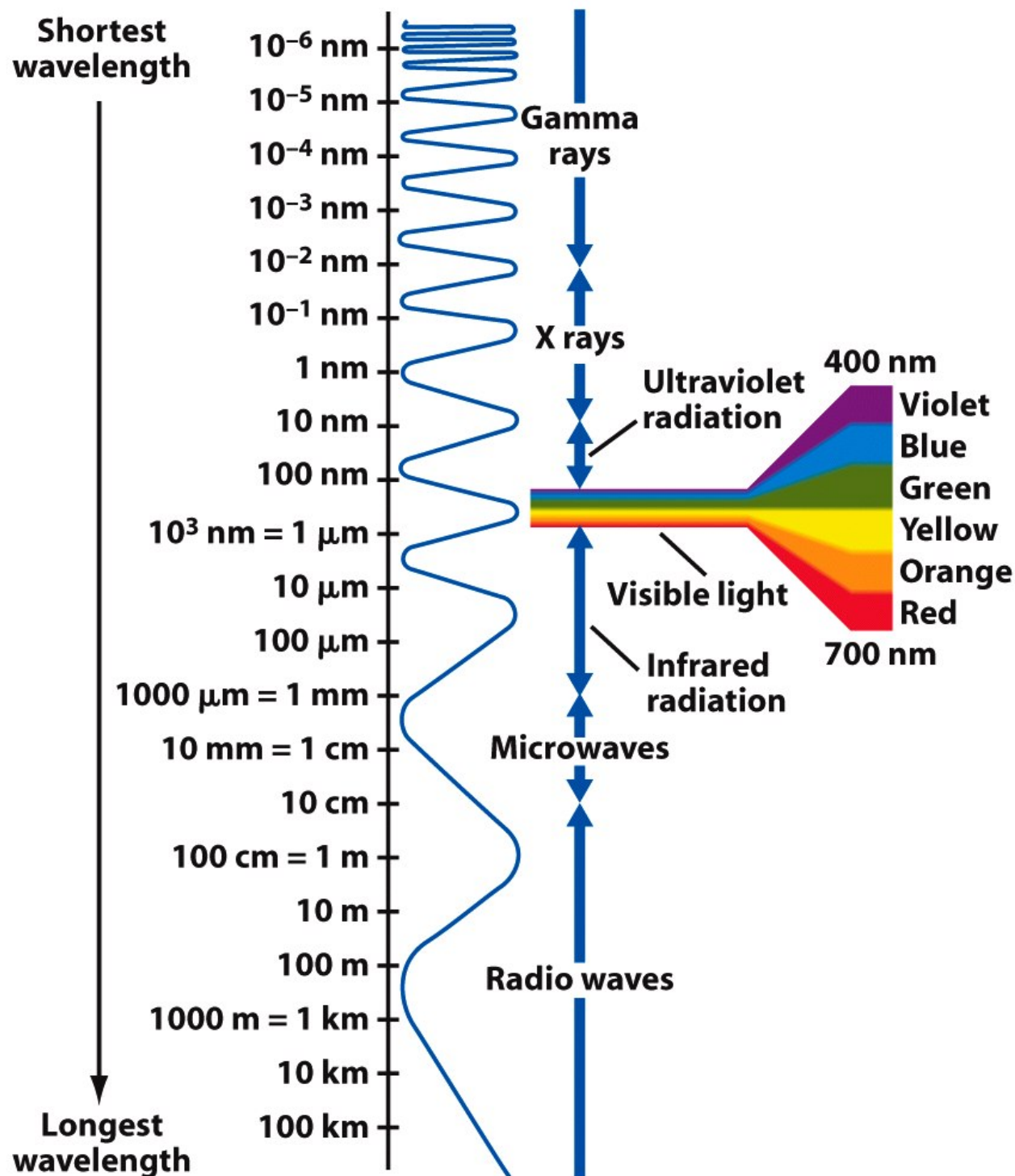
Stellar explosions



Cosmology



EM radiation characterized by wavelength



Practical uses of EM radiation



**(a) Mobile phone:
radio waves**



**(b) Microwave oven:
microwaves**



**(c) TV remote:
infrared light**



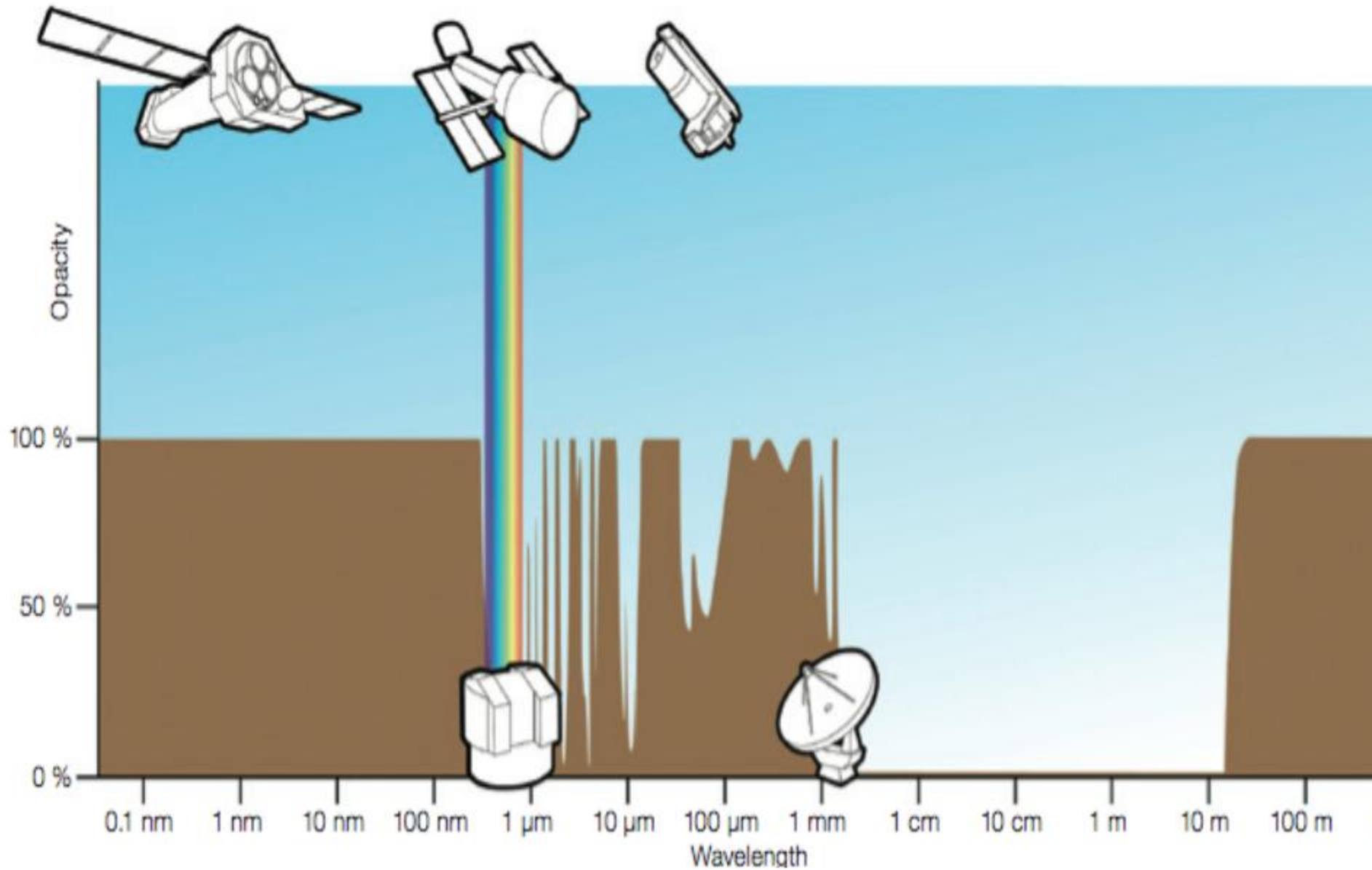
**(d) Tanning booth:
ultraviolet light**

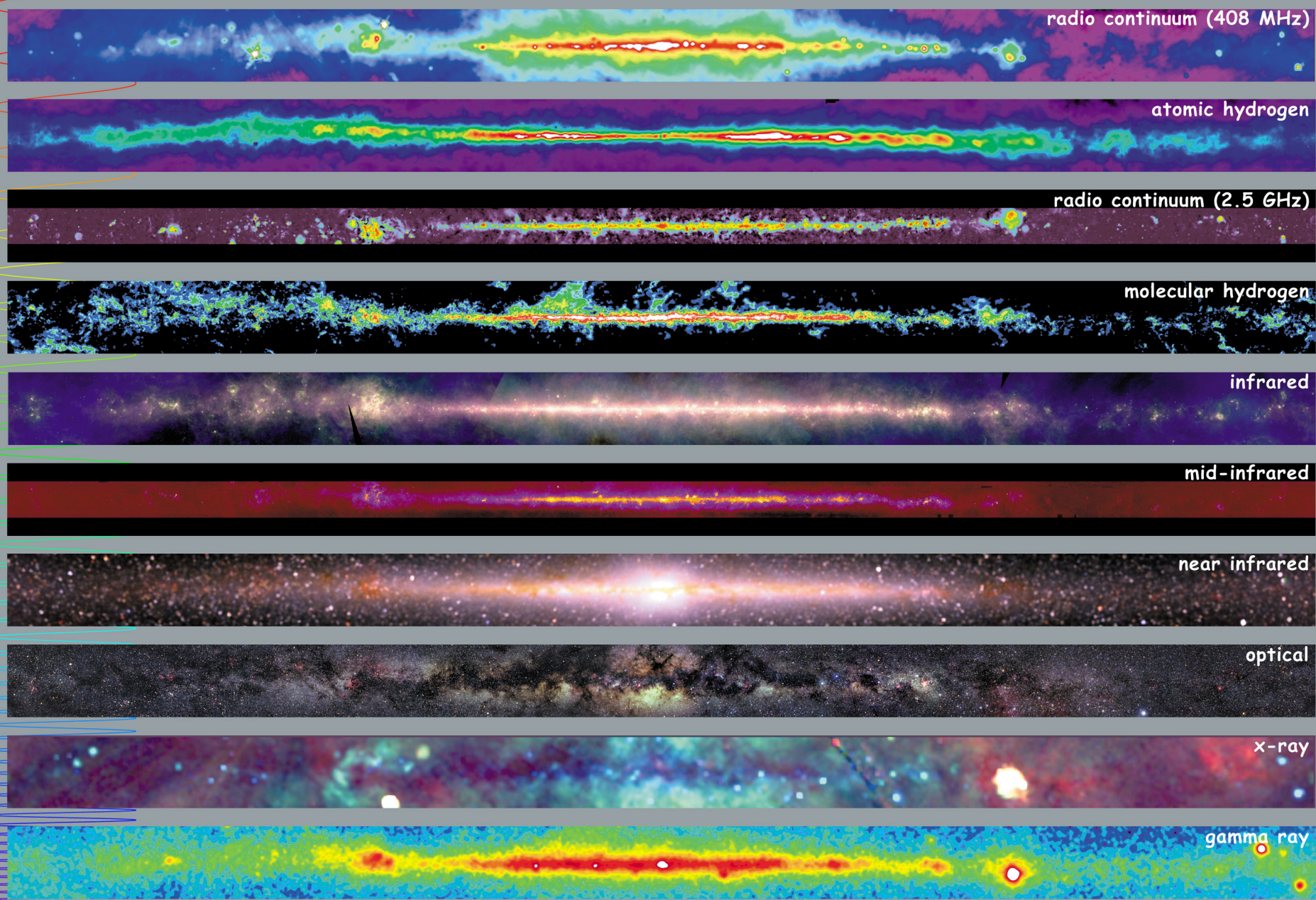


**(e) Medical imaging:
X rays.**

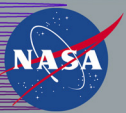


**(f) Cancer
radiotherapy:
gamma rays**

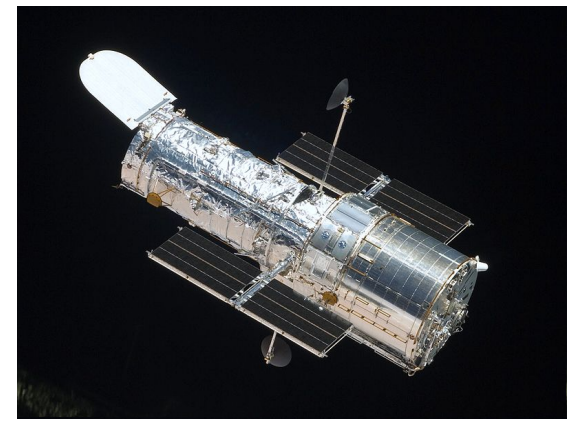
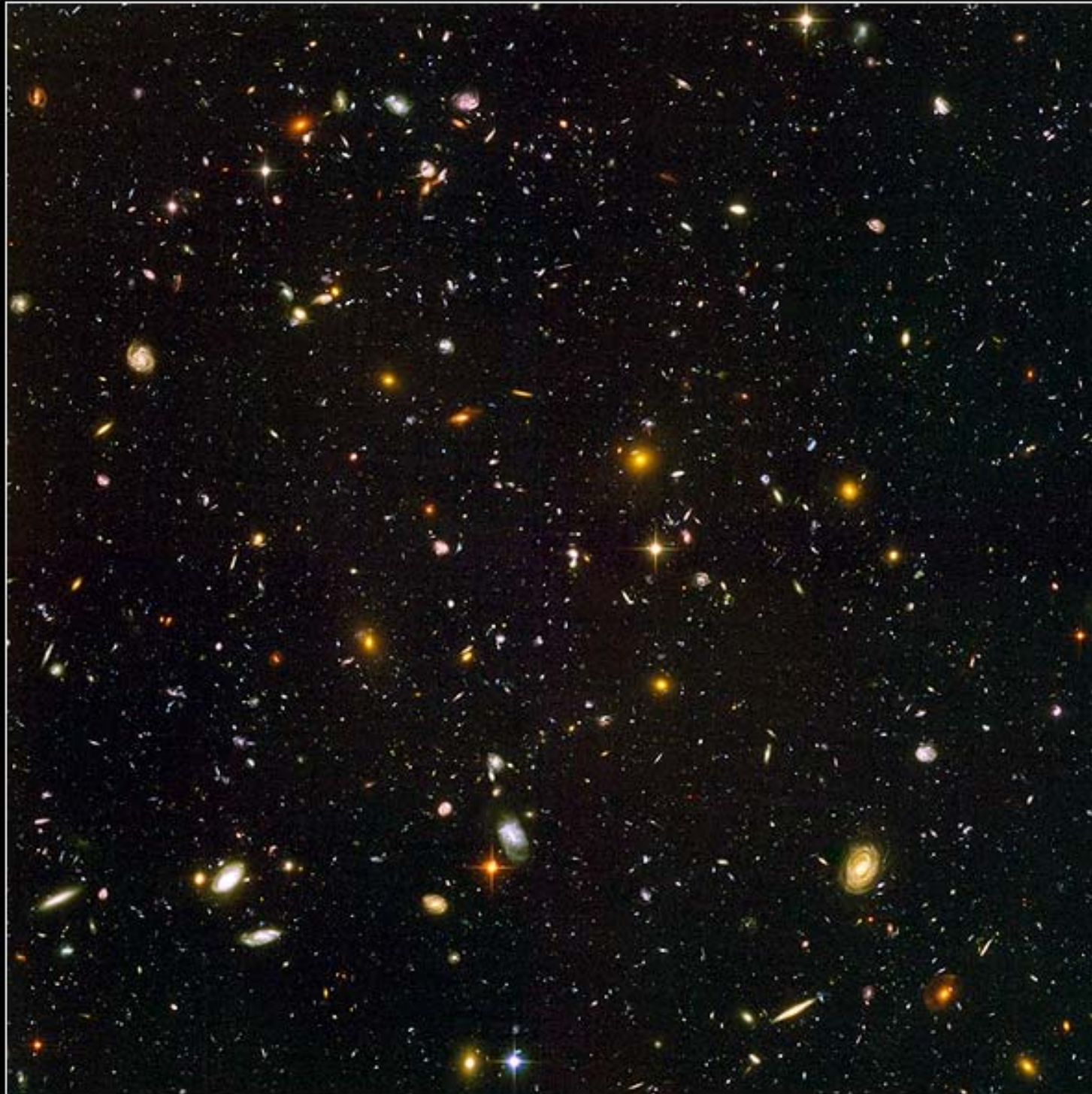




<http://adc.gsfc.nasa.gov/mw>



Multiwavelength Milky Way



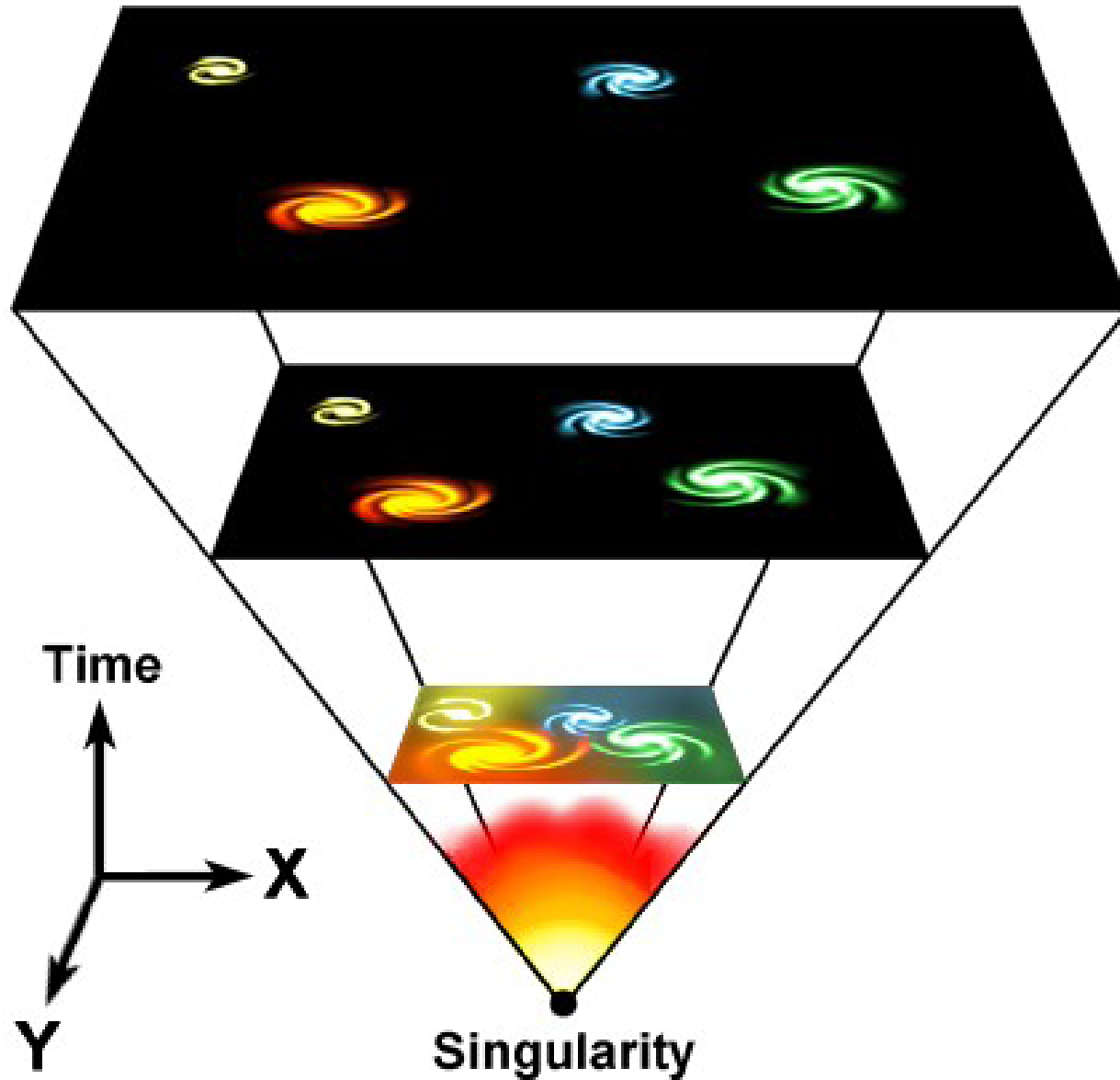
In Fornax,
11.0 arcmin²

1 mm² @ 1 m

13 million such
patches to cover
sky.



Expanding universe & the Big Bang





Opaque

last scattering

Transparent

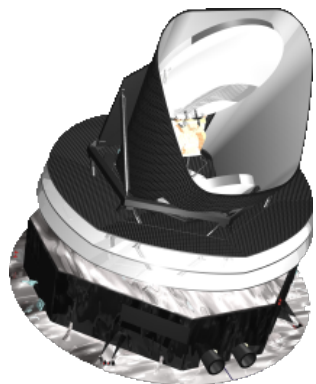
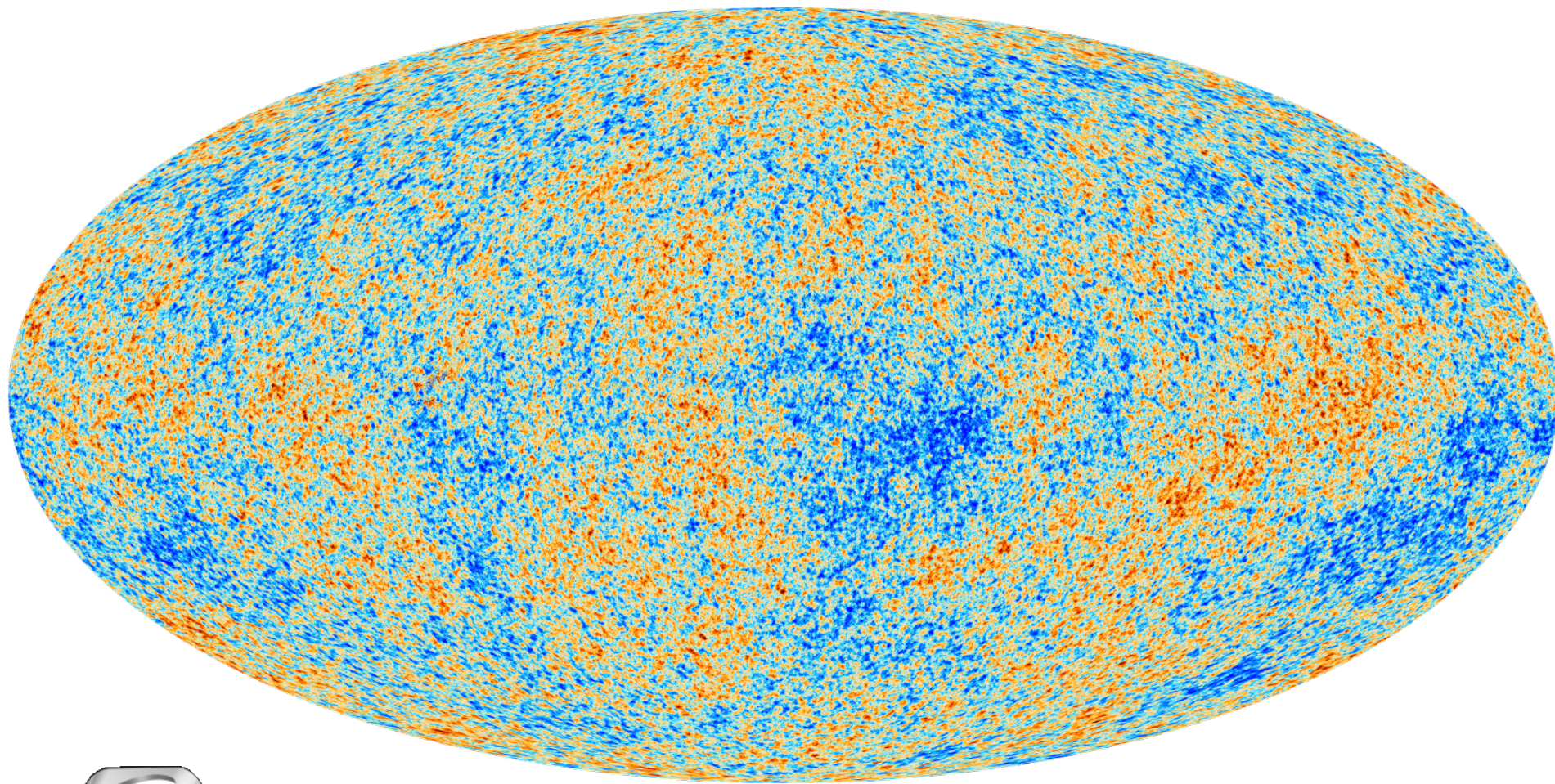
dark ages,
structure formation proceeds

Increasing distance,
lookback time,
mean density,
temperature

reionization,
1st stars



Cosmic Microwave Background



~ few hundred μK around mean T

"All the News
That's Fit to Print"

The New York Times

National Edition

Florida. A mix of sun and clouds. Afternoon showers. Highs 70s to near 80. Showers central and north tonight. Partly cloudy south. Lows 50s to 70s. Weather map, Page B10.

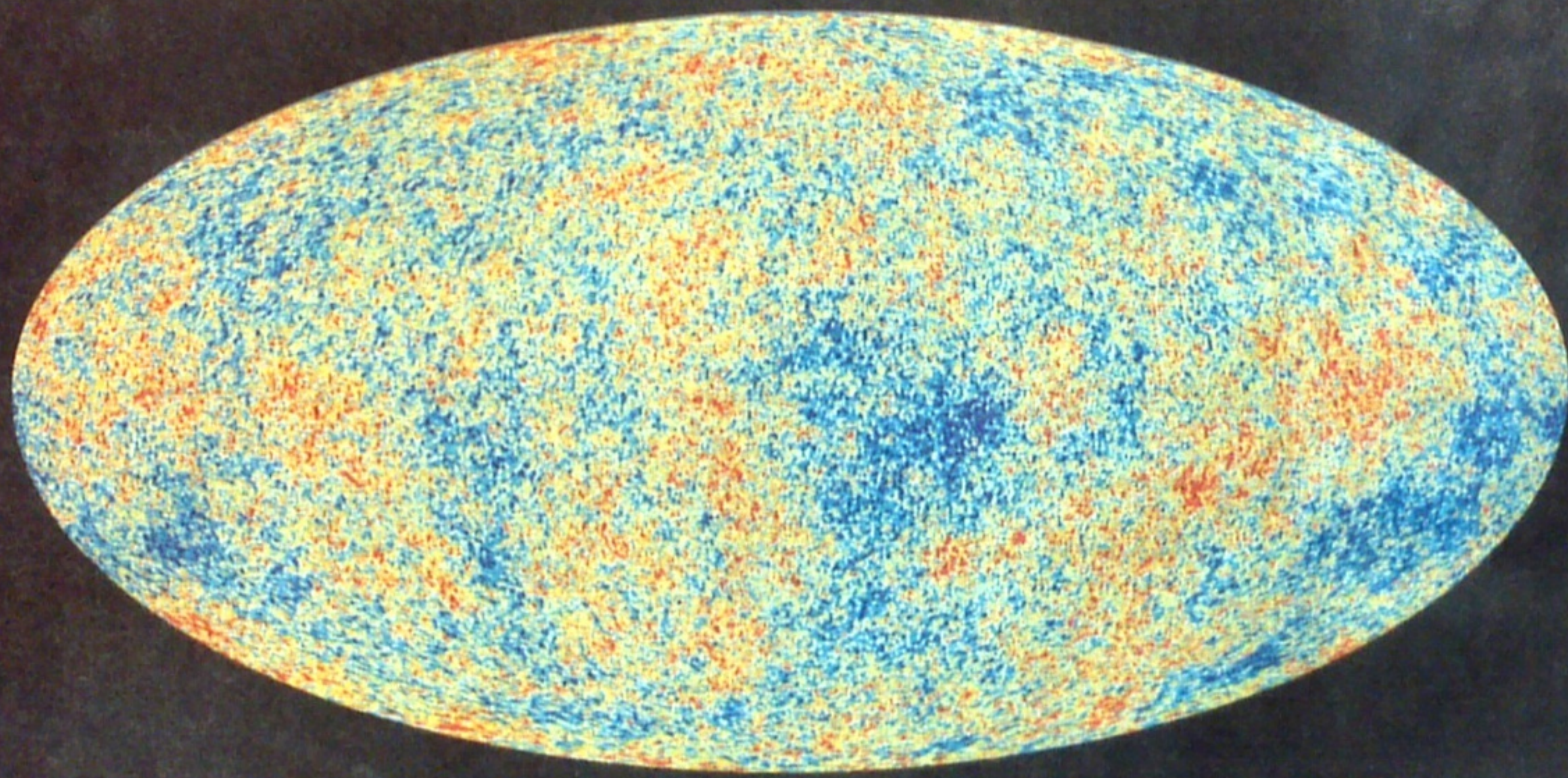
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\$2.50



ESA, PLANCK COLLABORATION VIA NASA, VIA ASSOCIATED PRESS

The Cosmos, Back in the Day

An image from data recorded by a European Space Agency satellite shows a heat map of the universe as it appeared 370,000 years after the Big Bang. Page A10.

As Pollution Worsens in China,

Once Few, Women Hold More Power in Senate

PRESIDENT URGES ISRAELIS TO PUSH EFFORT FOR PEACE

APPEAL AIMED AT YOUNG

In Jerusalem, He Eases
Stance on Settlement
Halt Before Talks

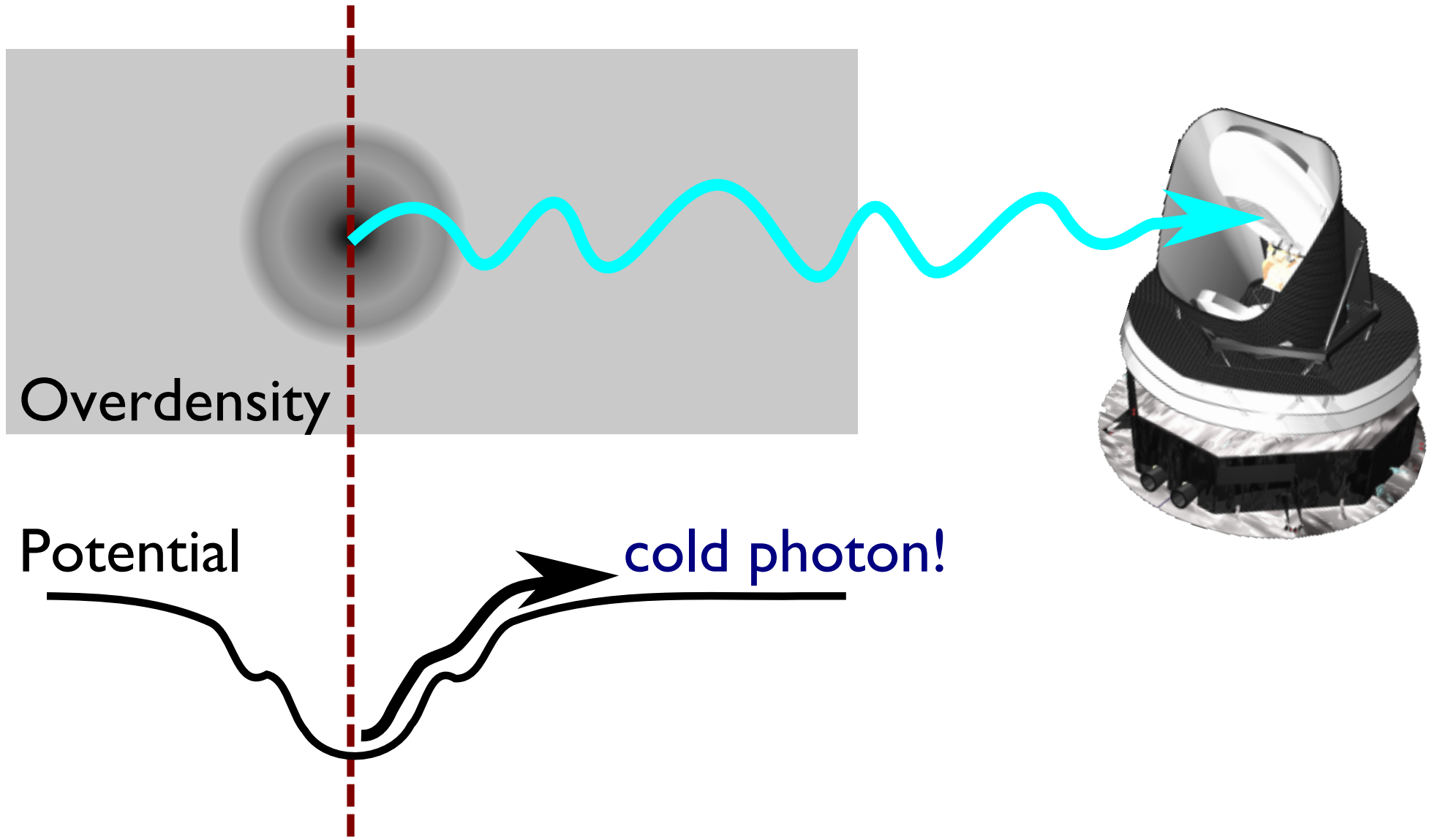
By MARK LANDLER

JERUSALEM — President Obama, appealing to very disparate audiences to solve one of the world's thorniest problems, moved closer on Thursday to the Israeli government's position on resuming long-stalled peace talks with the Palestinians, even as he passionately implored young Israelis to get ahead of their own leaders in the push for peace.

Addressing an enthusiastic crowd of more than 2,000, Mr. Obama offered a fervent, unsparing case for why a peace agreement was both morally just and in Israel's self-interest. Younger Israelis, Mr. Obama said, should empathize with their Palestinian neighbors living under occupation — or, as he put it, "look at the world through their eyes."

Probing gravitational potential

Recombination



Universe's contents

3 components cosmologically relevant:

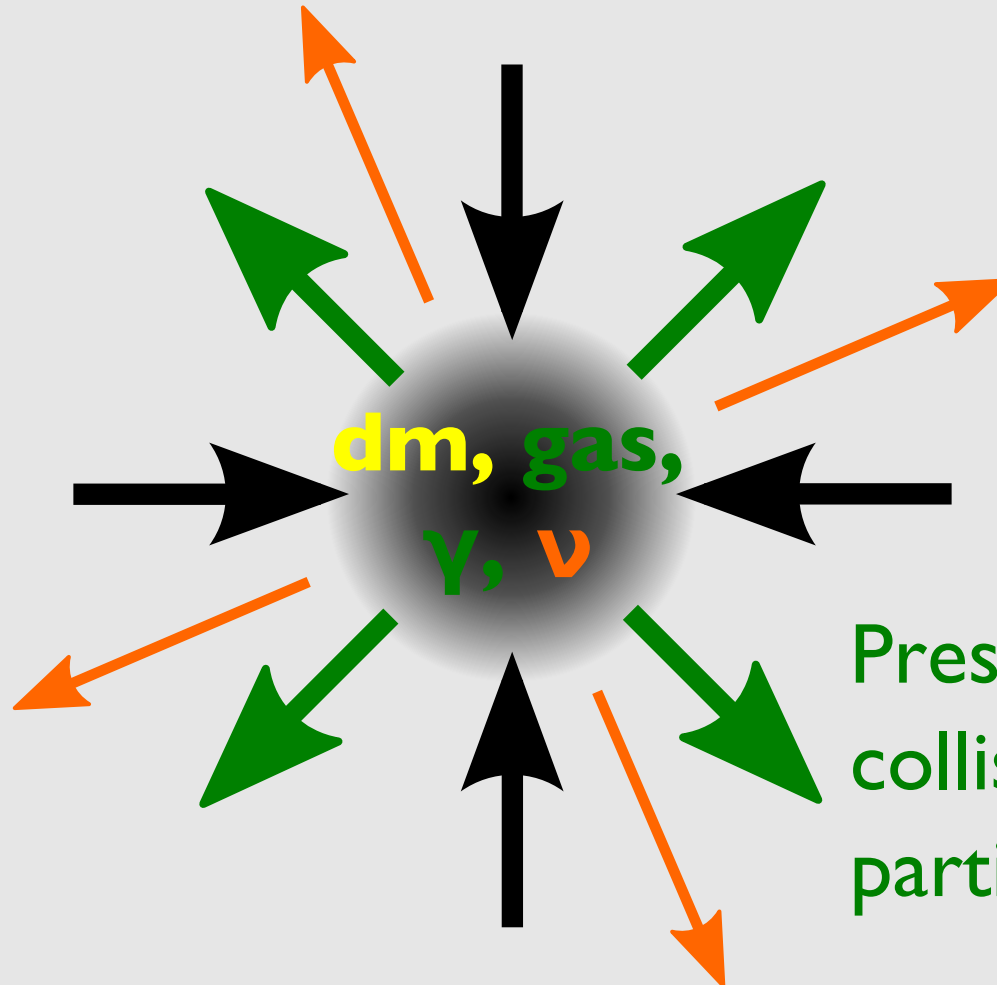
- 1. baryons, atoms, "normal matter".**
- 2. cold dark matter, normal gravity, no pressure, no interactions.**
- 3. dark "energy", $\Lambda = \text{Lambda}$, anti-gravity, cosmological constant, acceleration.**

Evolution of overdensity

Expansion of
the universe

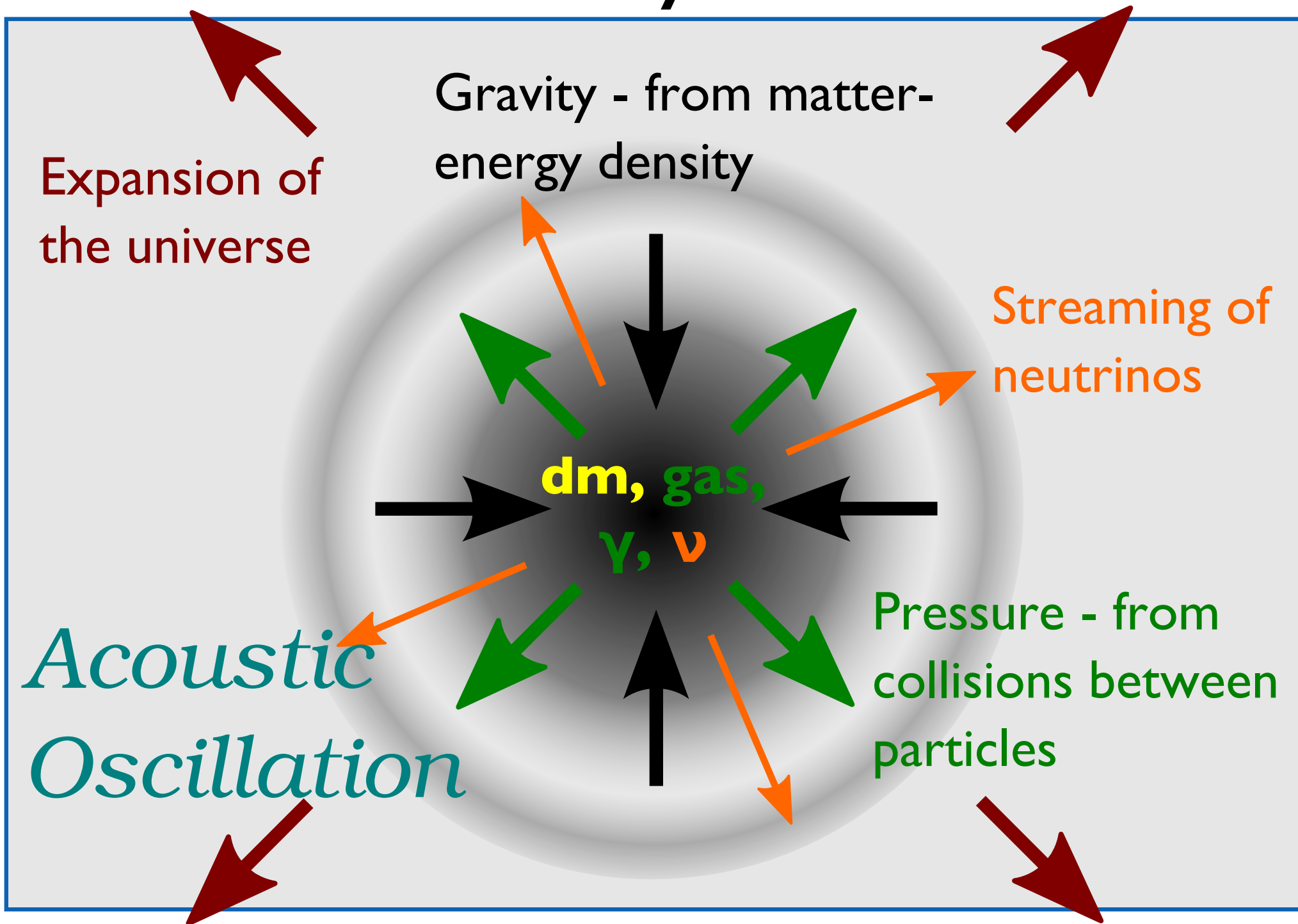
Gravity - from matter-
energy density

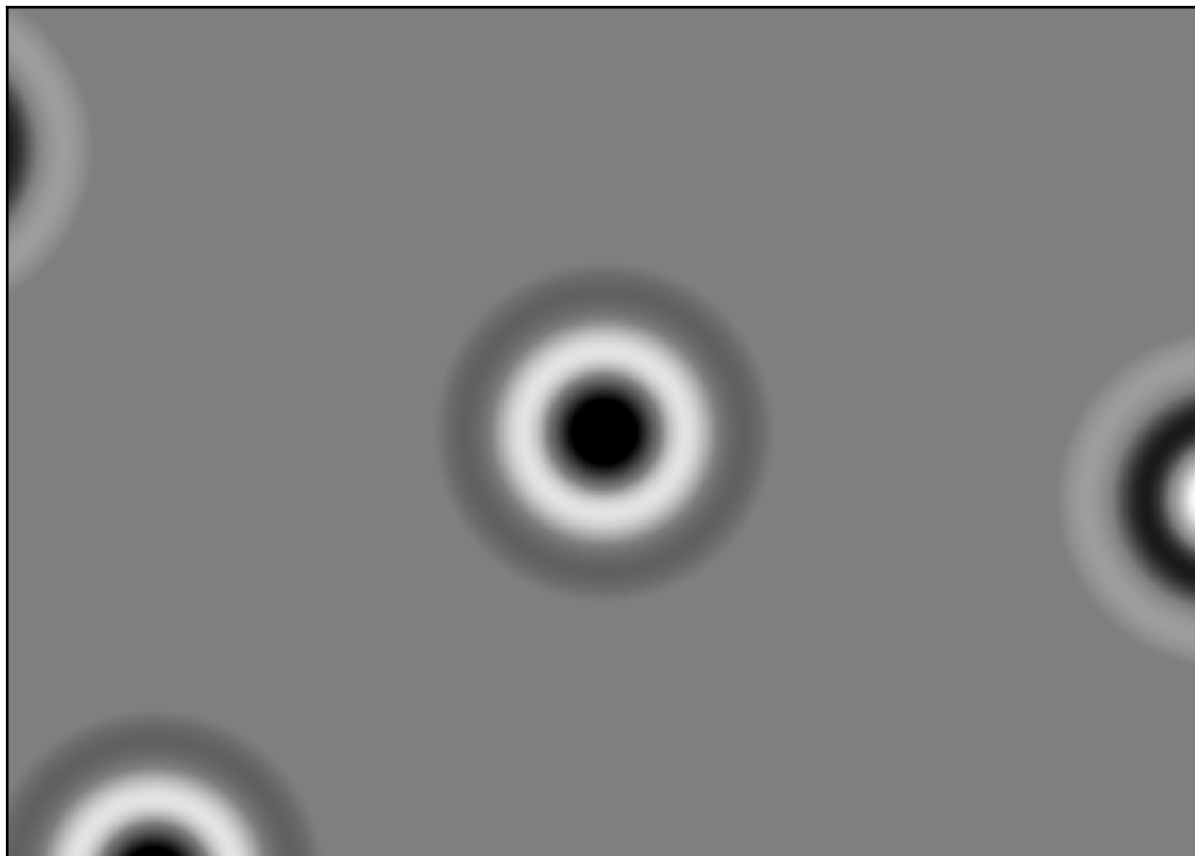
Streaming of
neutrinos

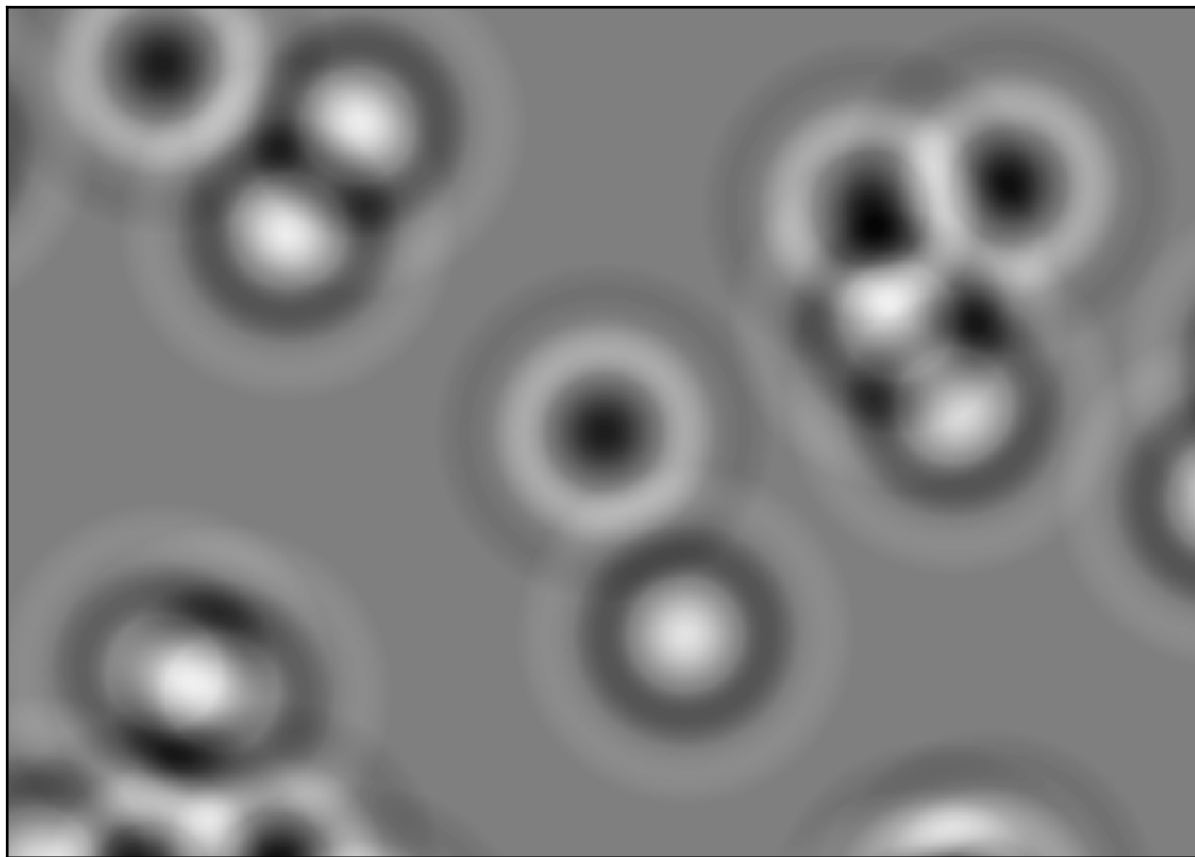


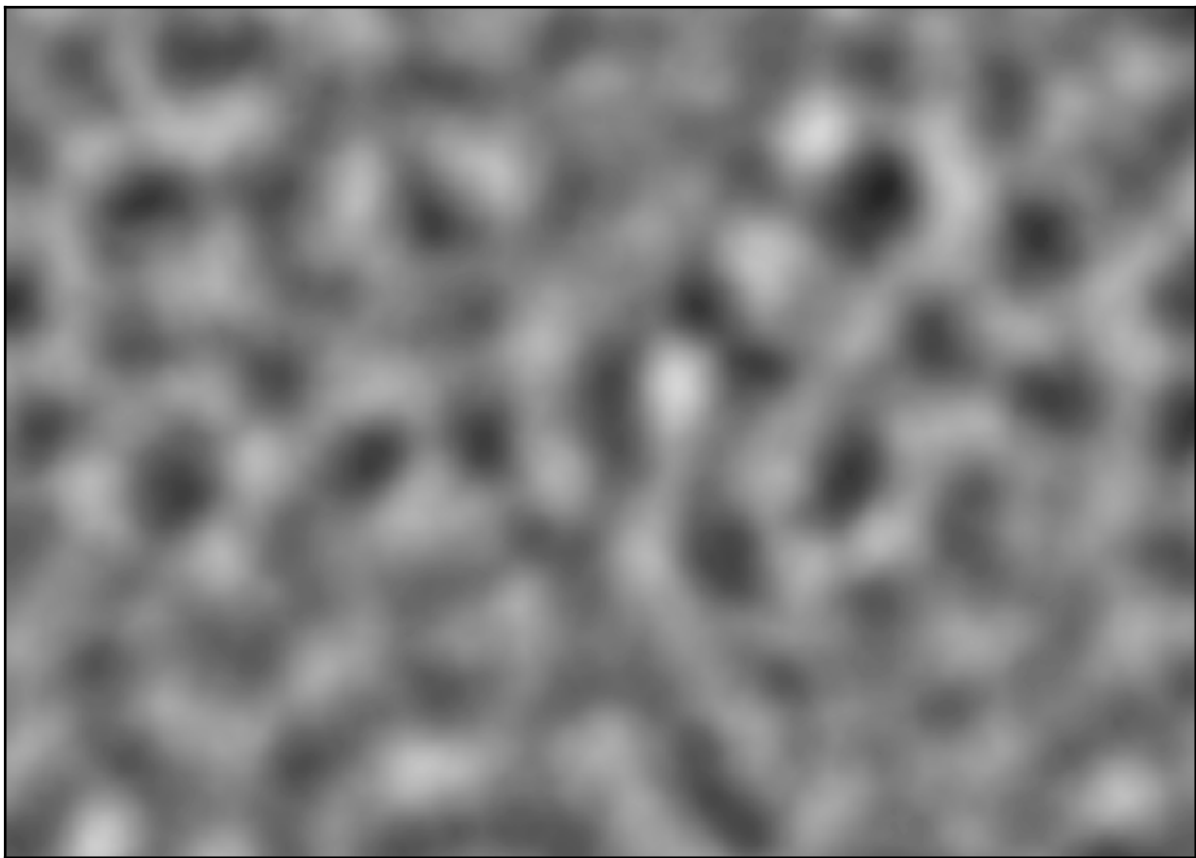
Pressure - from
collisions between
particles

Evolution of overdensity

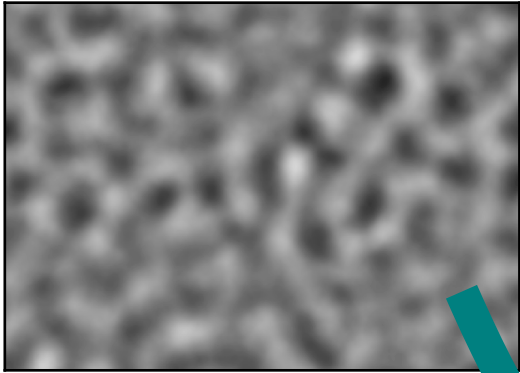




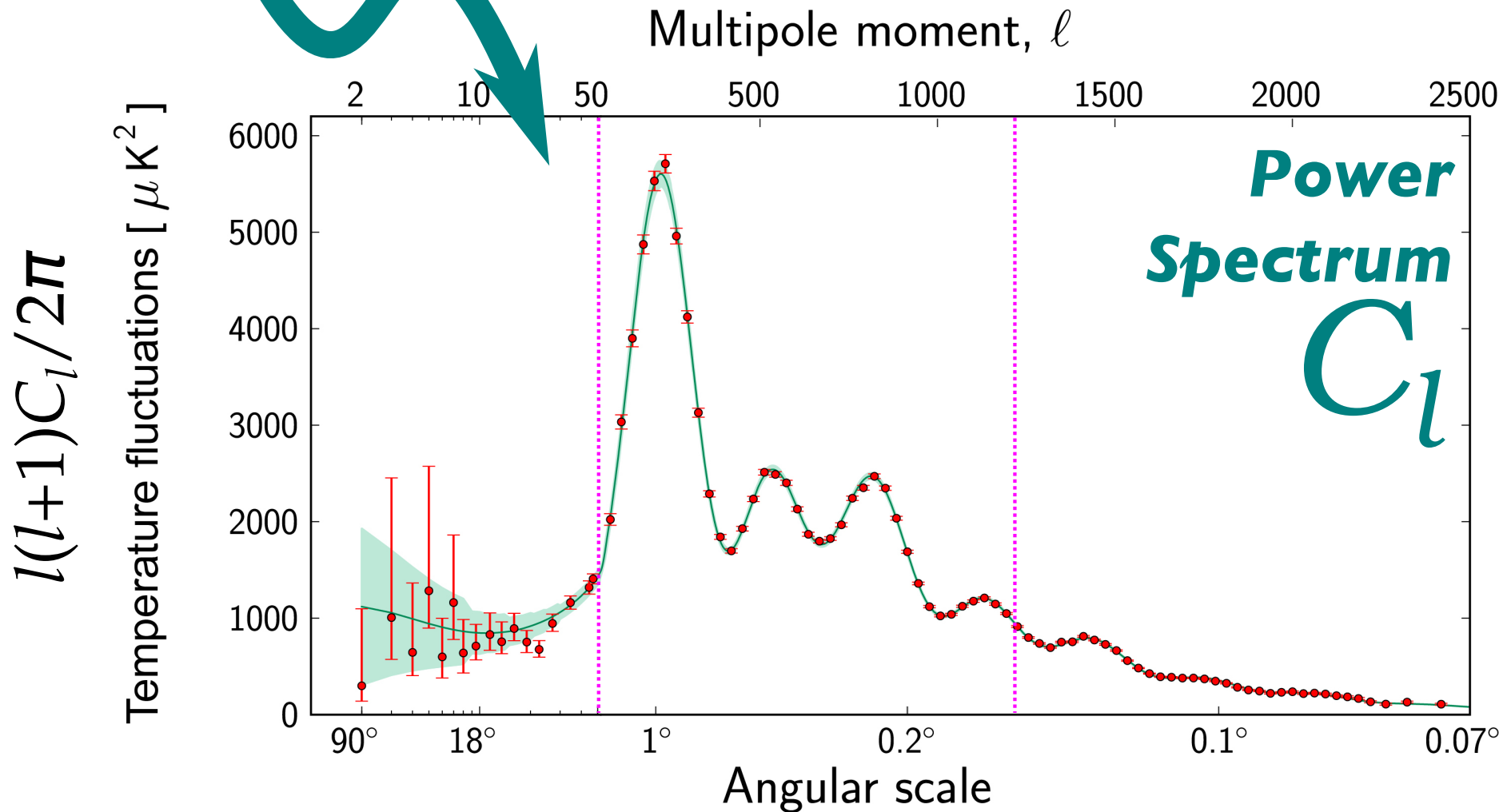


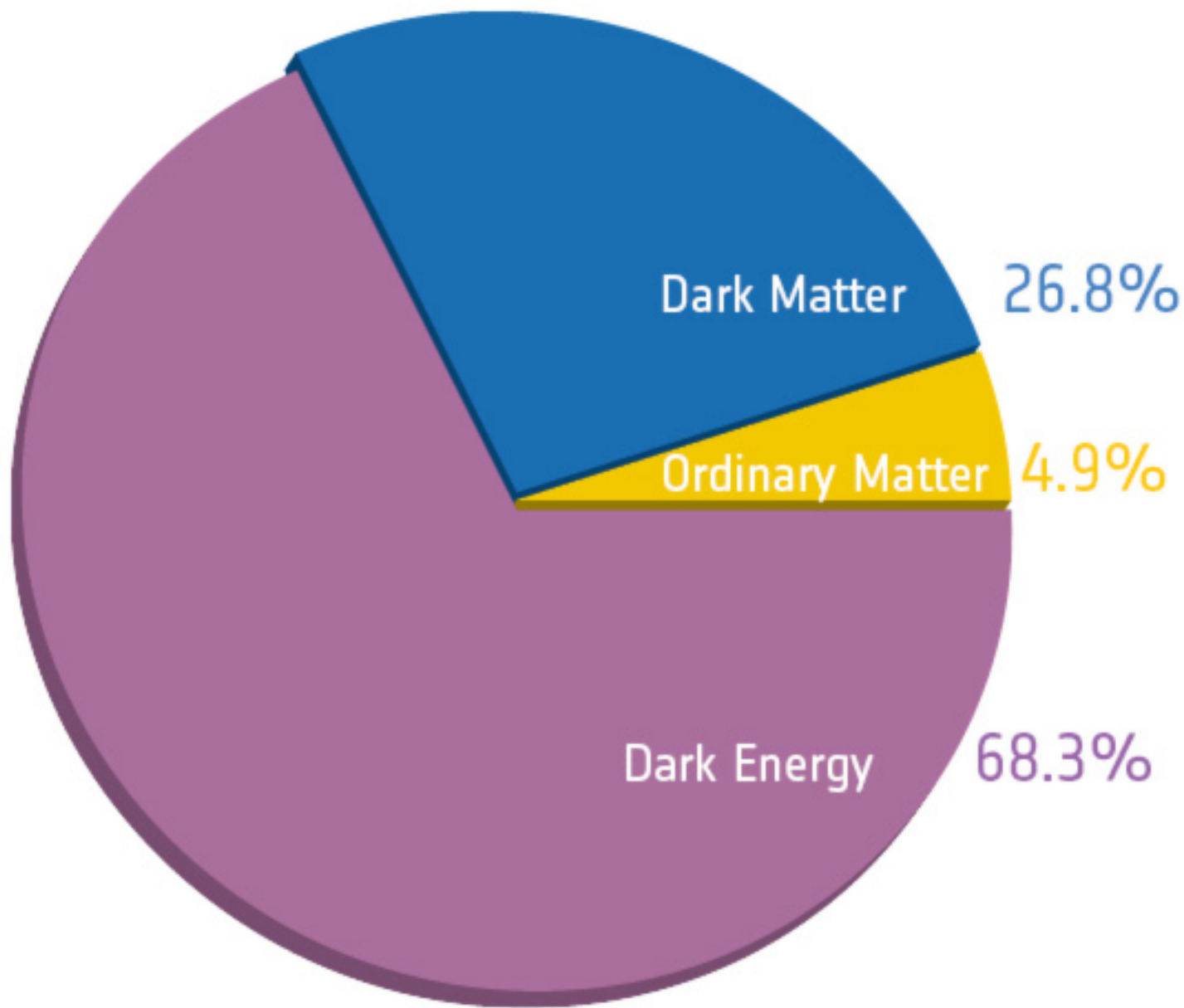


Correlations in harmonic space

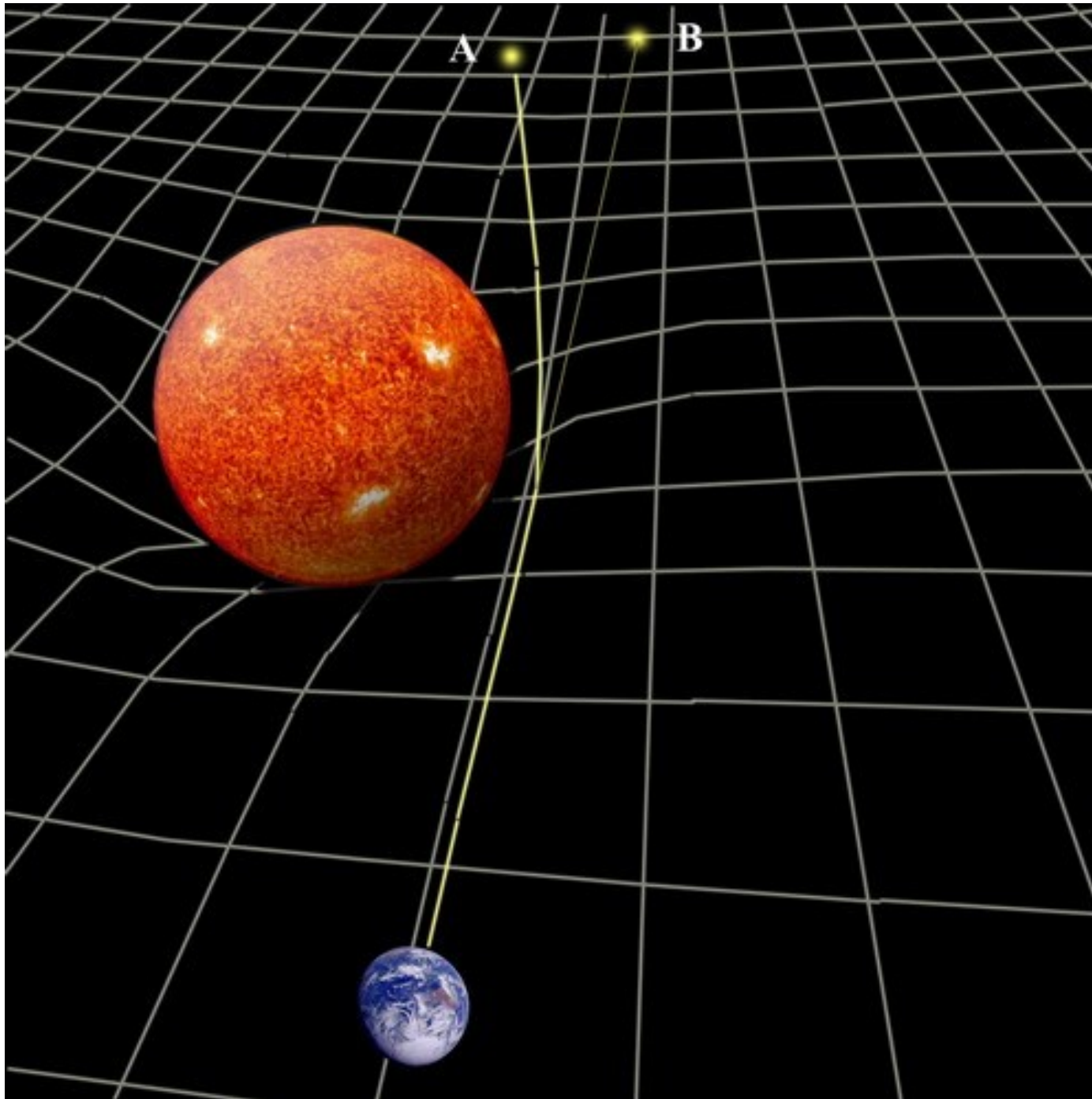


$$a_{lm} = \int d\Omega T(\theta, \phi) Y_{lm}^*(\theta, \phi)$$
$$\langle a_{lm} a_{l'm'}^* \rangle = C_l \delta_{ll'} \delta_{mm'}$$



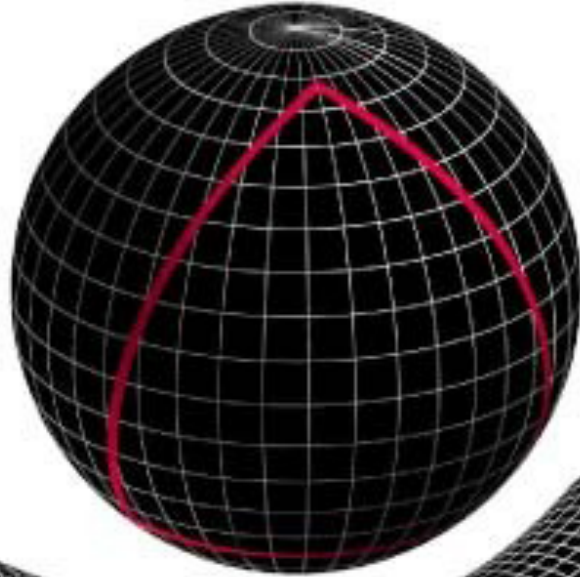


Gravity = curvature of spacetime.

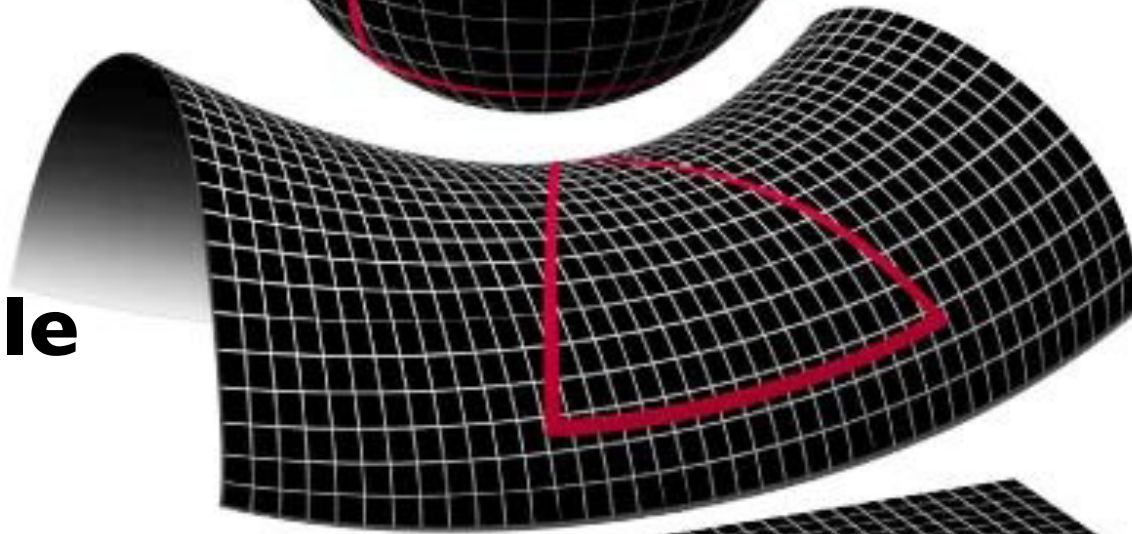


Gravity = curvature of spacetime.

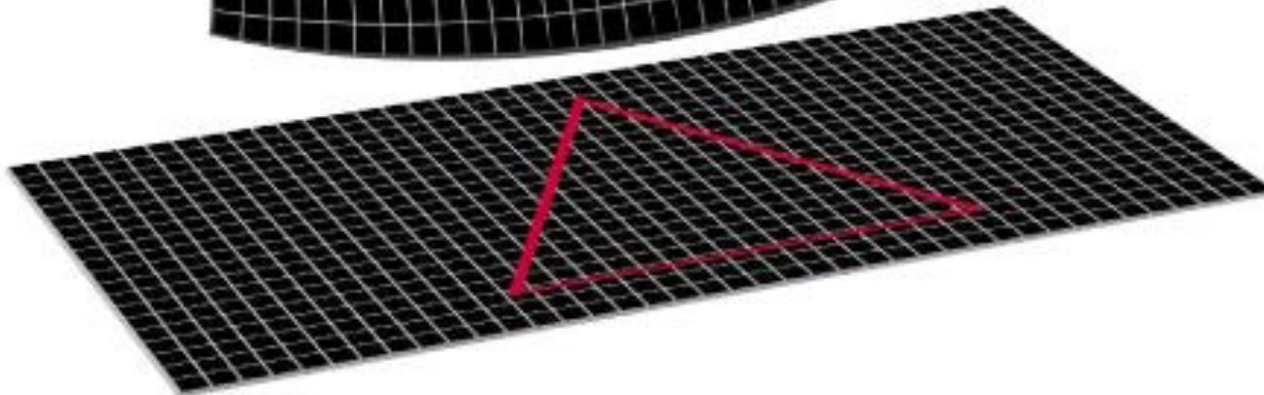
ball



saddle

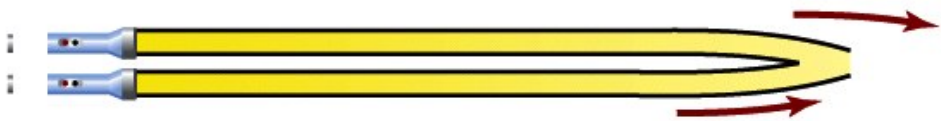
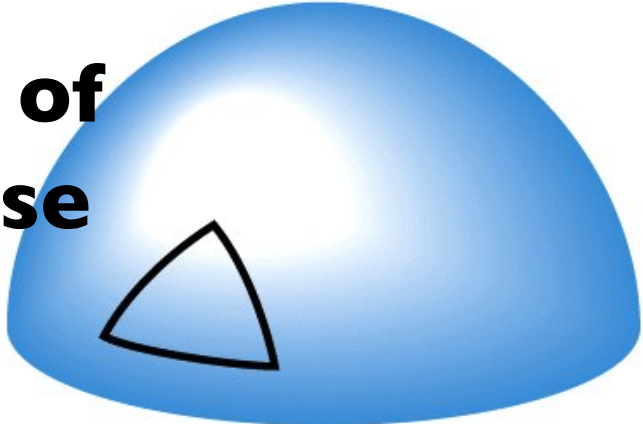


flat



**2-d analogs for
3-d curved spaces
we can't visualize.**

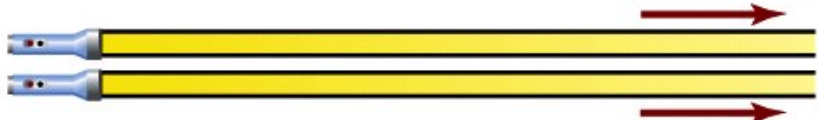
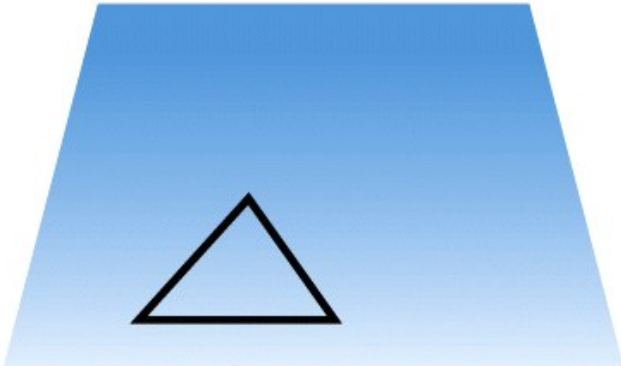
Geometry of the universe



Parallel light beams converge

(a) Spherical space

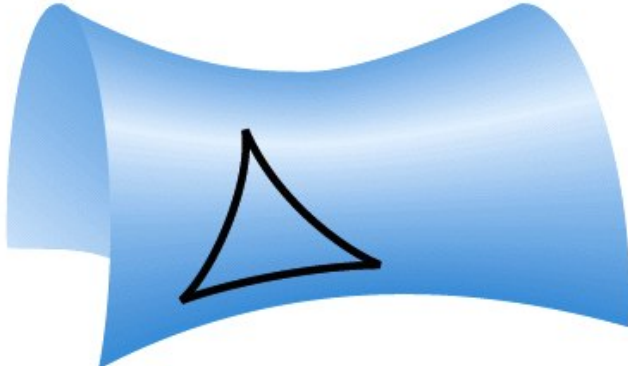
$$\rho_0 > \rho_c, \Omega_0 > 1$$



Parallel light beams remain parallel

(b) Flat space

$$\rho_0 = \rho_c, \Omega_0 = 1$$

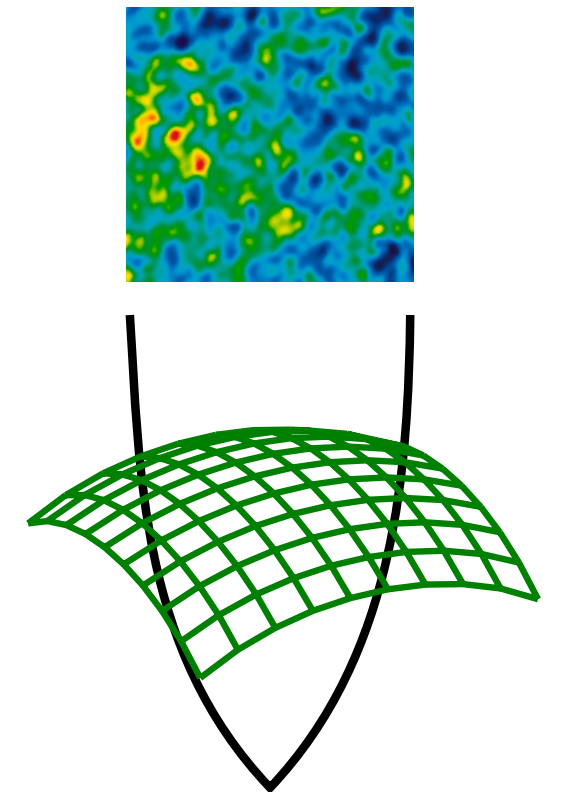
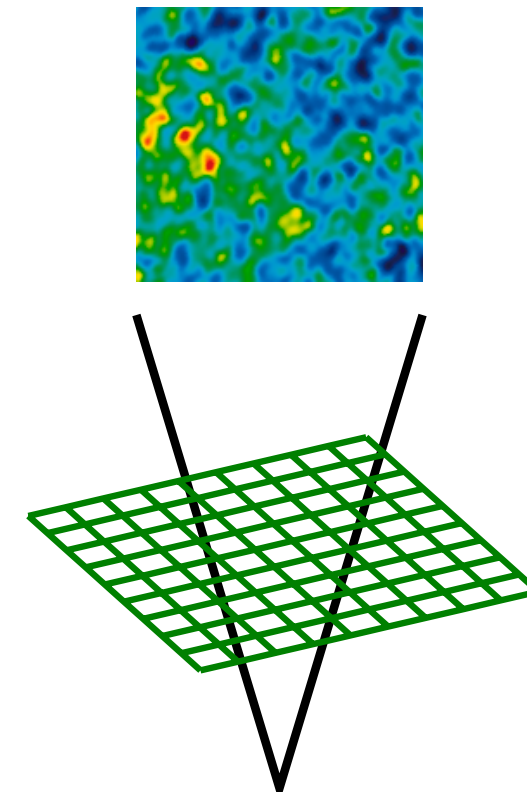
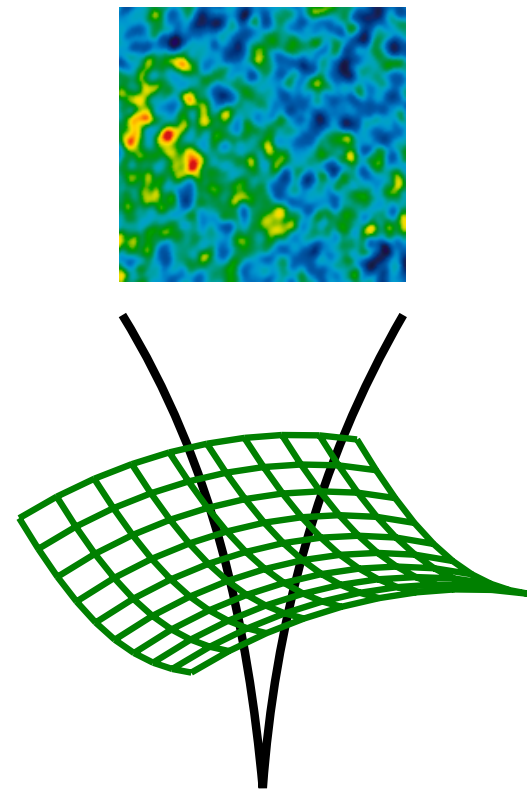


Parallel light beams diverge

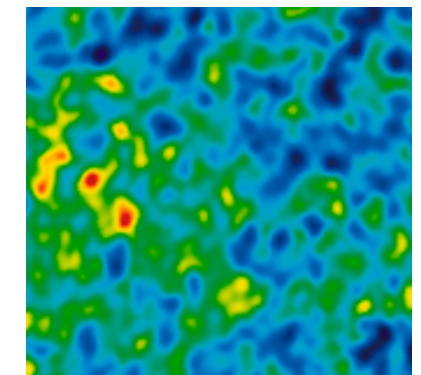
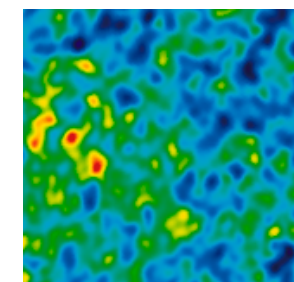
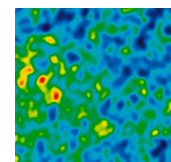
(c) Hyperbolic space

Measuring curvature

**CMB
surface**



**CMB
observed**

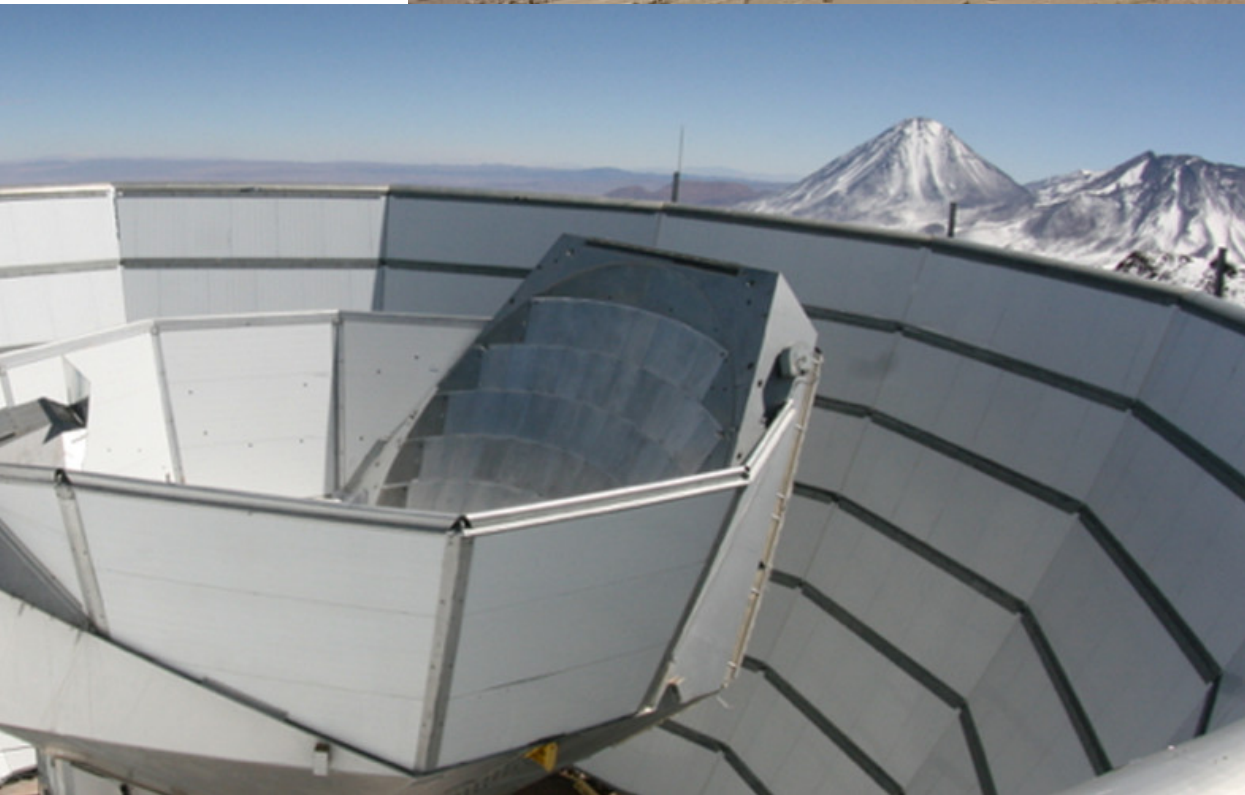


**Viewing standard ruler through
flat or curved spacetime.**

Atacama Cosmology Telescope and Simons Observatory

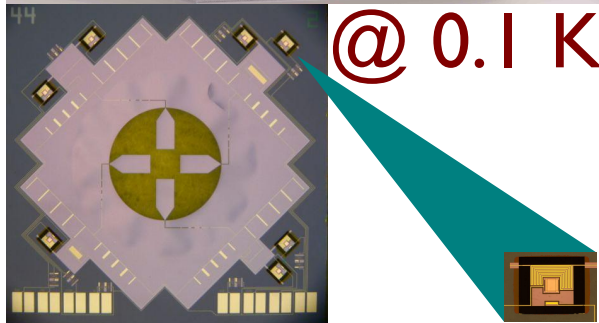
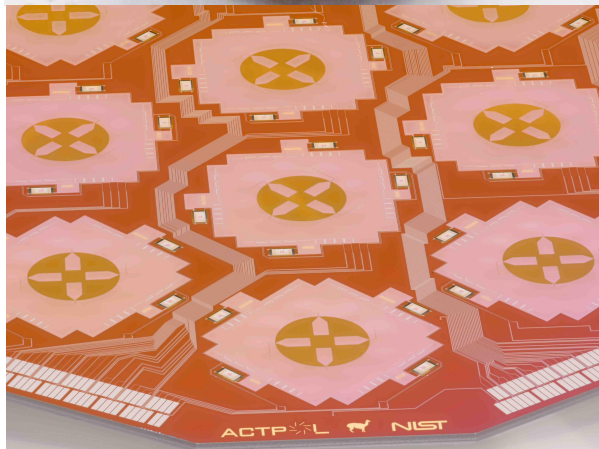
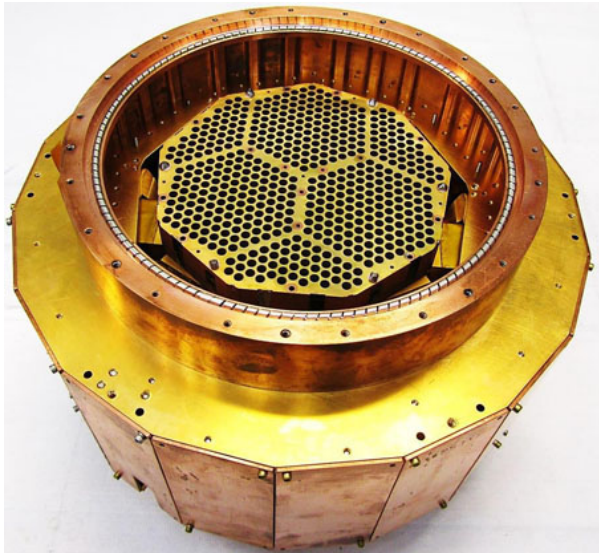


New observatory for CMB





CMB Detector Technology



@ 0.1 K

~ 7 mm

O Langley invented the **bolometer**,
Which is really a kind of thermometer.
You can measure the heat
Of a polar bear's seat
At a distance of half a kilometer.



ACT Map

4x4 Degrees (148 GHz Data)

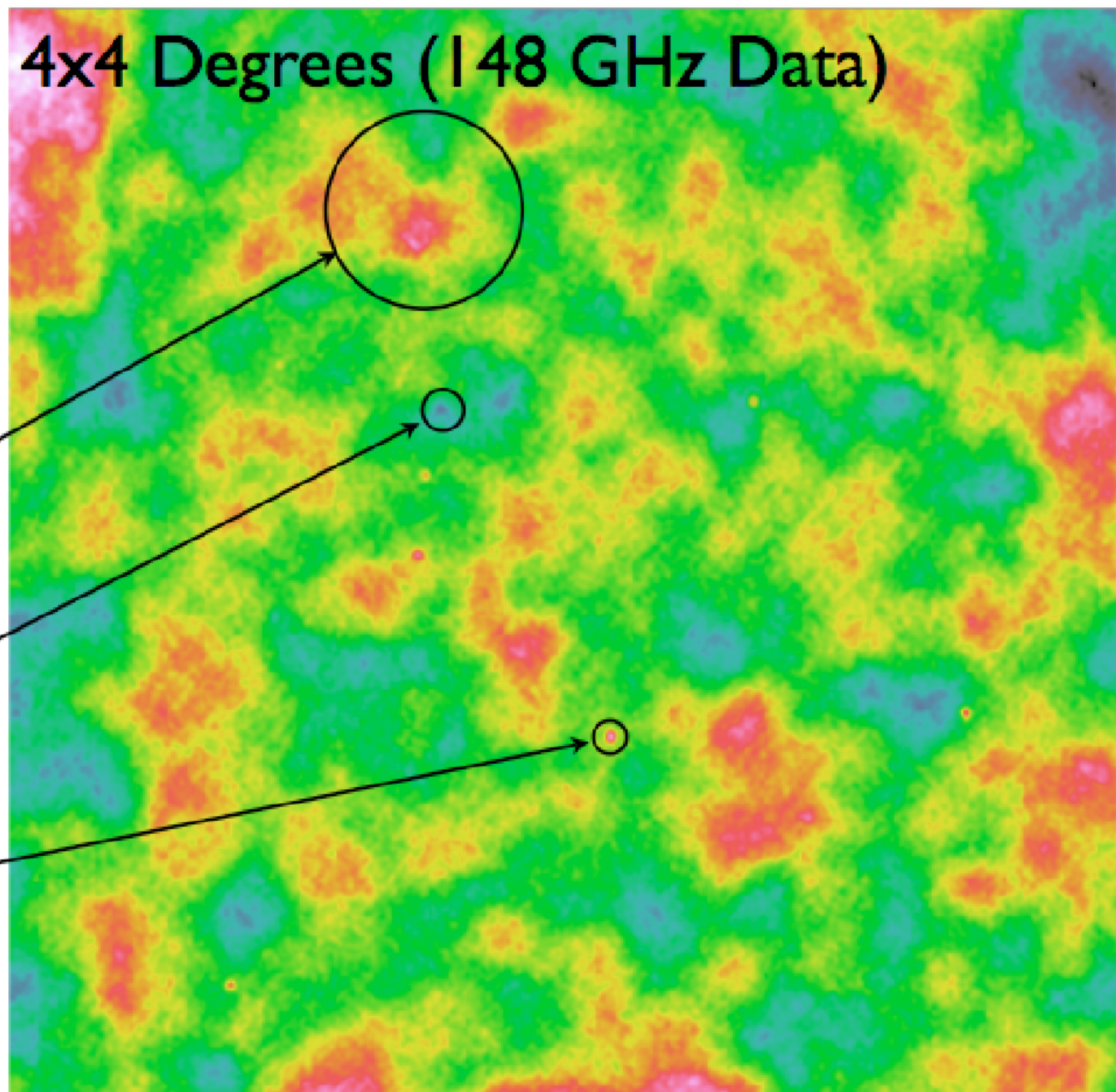
CMB fluctuation

Cluster

Active Galactic
Nucleus



δT_{CMB} [μK]





HOME

Research Group

Postdocs



Aditya Rotti

Research projects: Isotropy statistics of the CMB; B-mode foregrounds; clustering of large scale structure.

Graduate students



Brittany Fuzia

Research projects: Stacking analysis of SZ clusters.



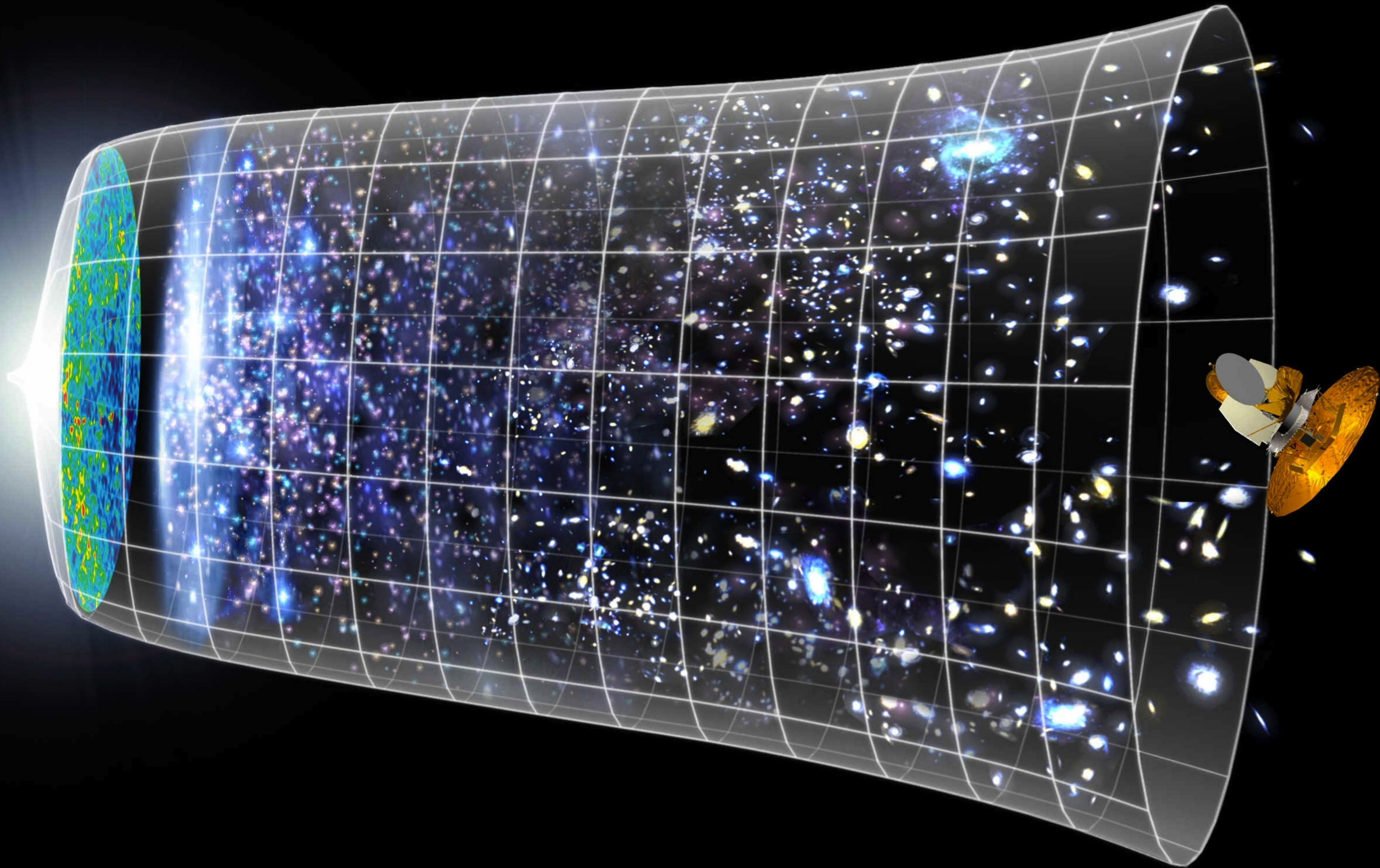
Vincent Lakey

Research projects: CMB/X-ray background cross-correlations.



Felipe Maldonado

Research projects: Joint analysis of CMB lensing and large scale structure.





**THE
HUNT
FOR
B-MODES**

**POLARIZATION
SIGNATURE OF
GRAVITY WAVES**

**DISTINCTIVE OF
INFLATION IN EARLY
UNIVERSE**

**PHYSICS AT GRAND-UNIFIED-
SCALE ENERGIES**

ACT, SIMONS OBSERVATORY, CMB-S4, MANY OTHERS

The Simons Observatory

United States

- Arizona State University
 - Carnegie Mellon University
 - Columbia University
 - Cornell University
 - Florida State
 - Haverford College
 - Johns Hopkins University
 - Lawrence Berkeley National Laboratory
 - NASA/GSFC
 - NIST
 - Princeton University
 - Rutgers University
 - Stanford University/SLAC
 - Stony Brook
 - University of California - Berkeley
 - University of California – San Diego
 - University of Illinois at Urbana-Champaign
 - University of Michigan
 - University of Pennsylvania
 - University of Pittsburgh
 - University of Southern California
 - West Chester University
- 8 Countries
 - 35+ Institutions
 - 160+ Researchers

Canada

- CITA/Toronto
- Dalhousie University
- Dunlap Institute/Toronto
- McGill University
- University of British Columbia

Chile

- Pontificia Universidad Catolica
- University of Chile

Europe

- APC - France
- Cardiff University
- Imperial College
- Manchester University
- Oxford University
- SISSA – Italy

Japan

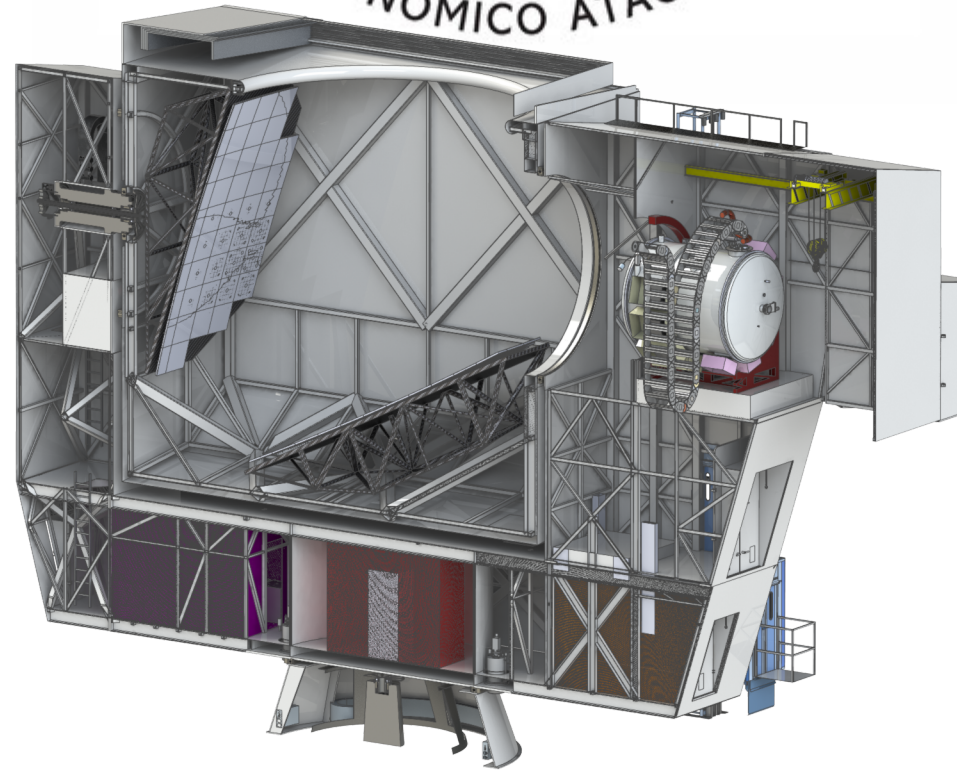
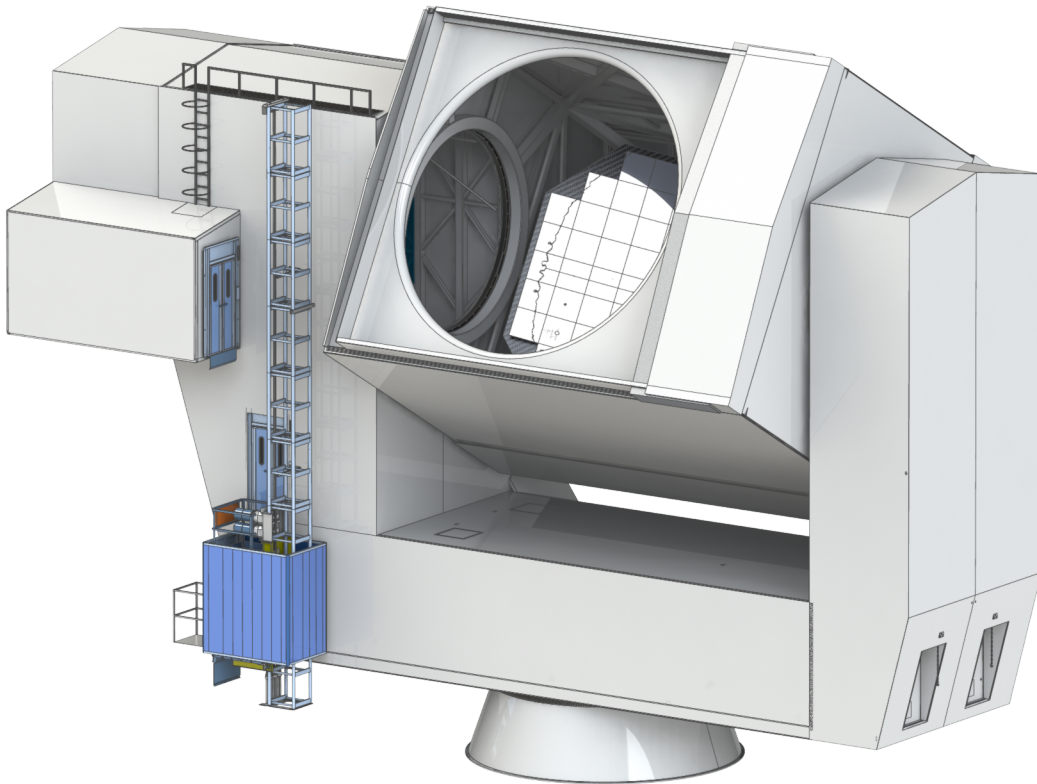
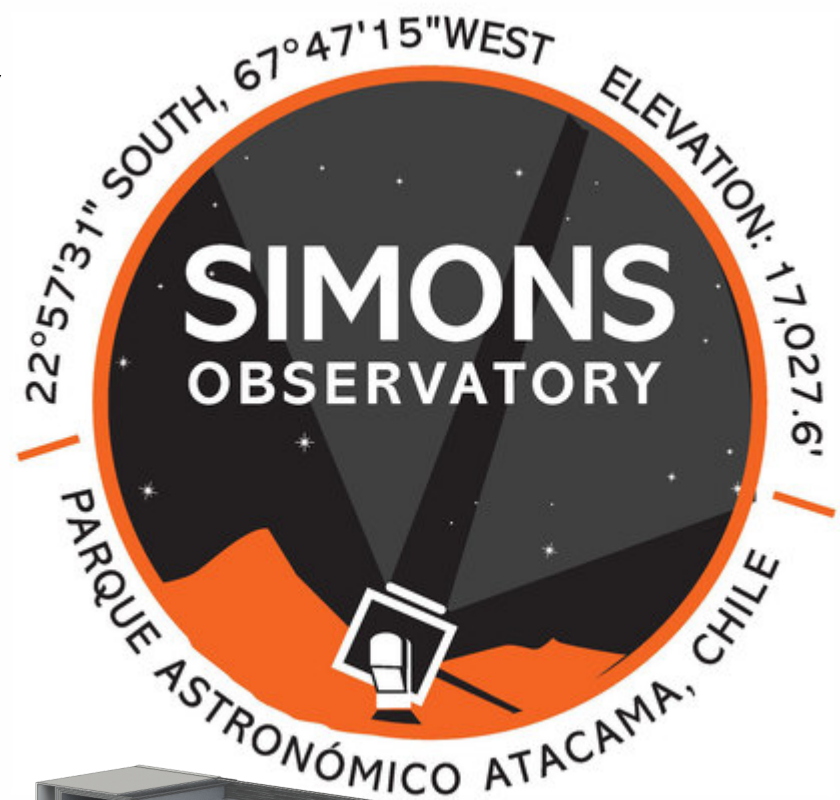
- KEK
- IPMU

South Africa

- Kwazulu-Natal, SA

Simons Observatory

First light 2020



Conclusions

What are the contents?

Mostly dark energy, with some dark matter, and a small fraction of normal atoms.

But what *are* dark energy and dark matter?

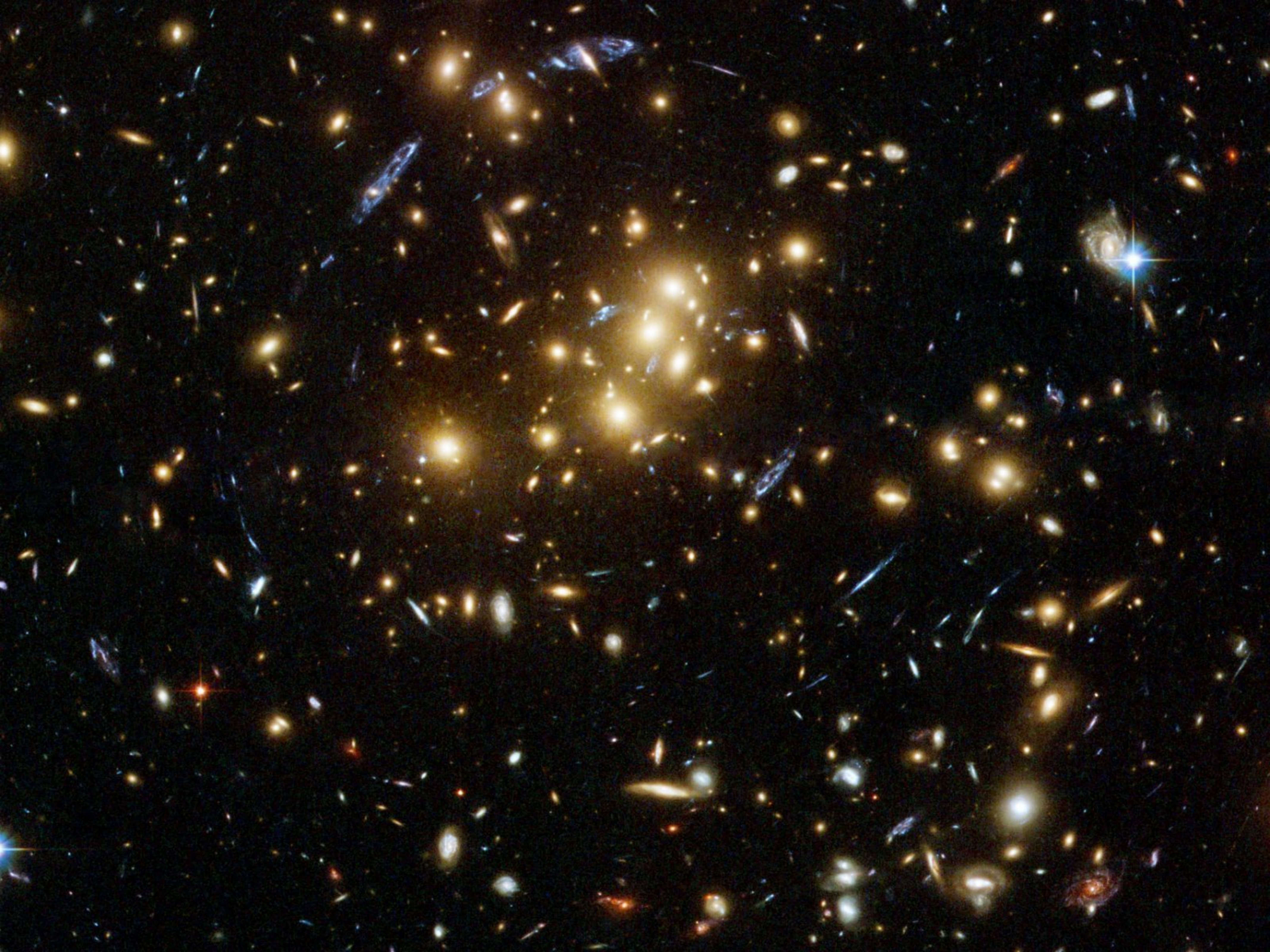
What's the space-time like?

Measurements are consistent with flat.

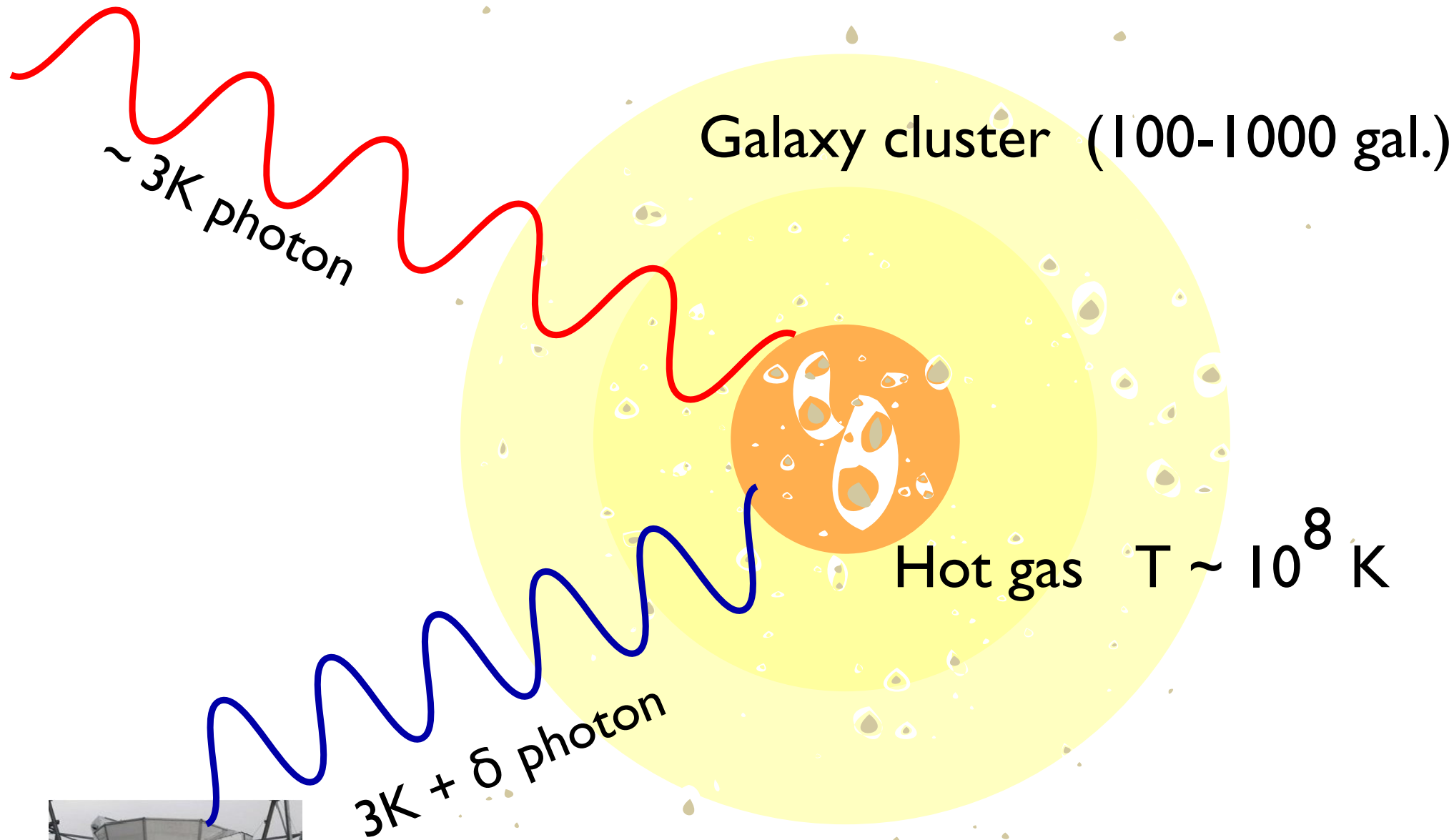
What happened at the very beginning?

Many exciting efforts!

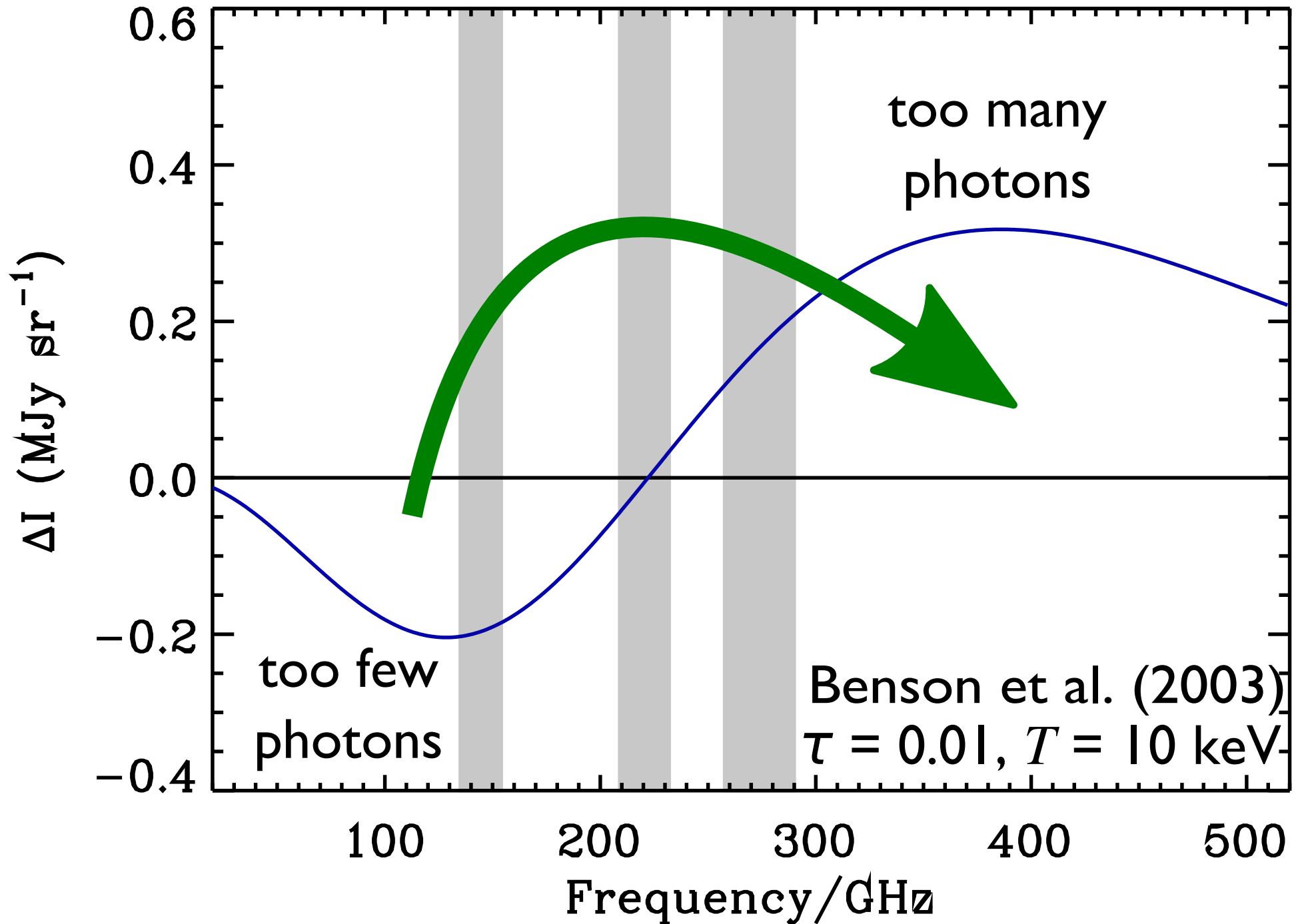
It will all our skills in advanced engineering, microwave detector development, software design, image processing, etc. to find out!

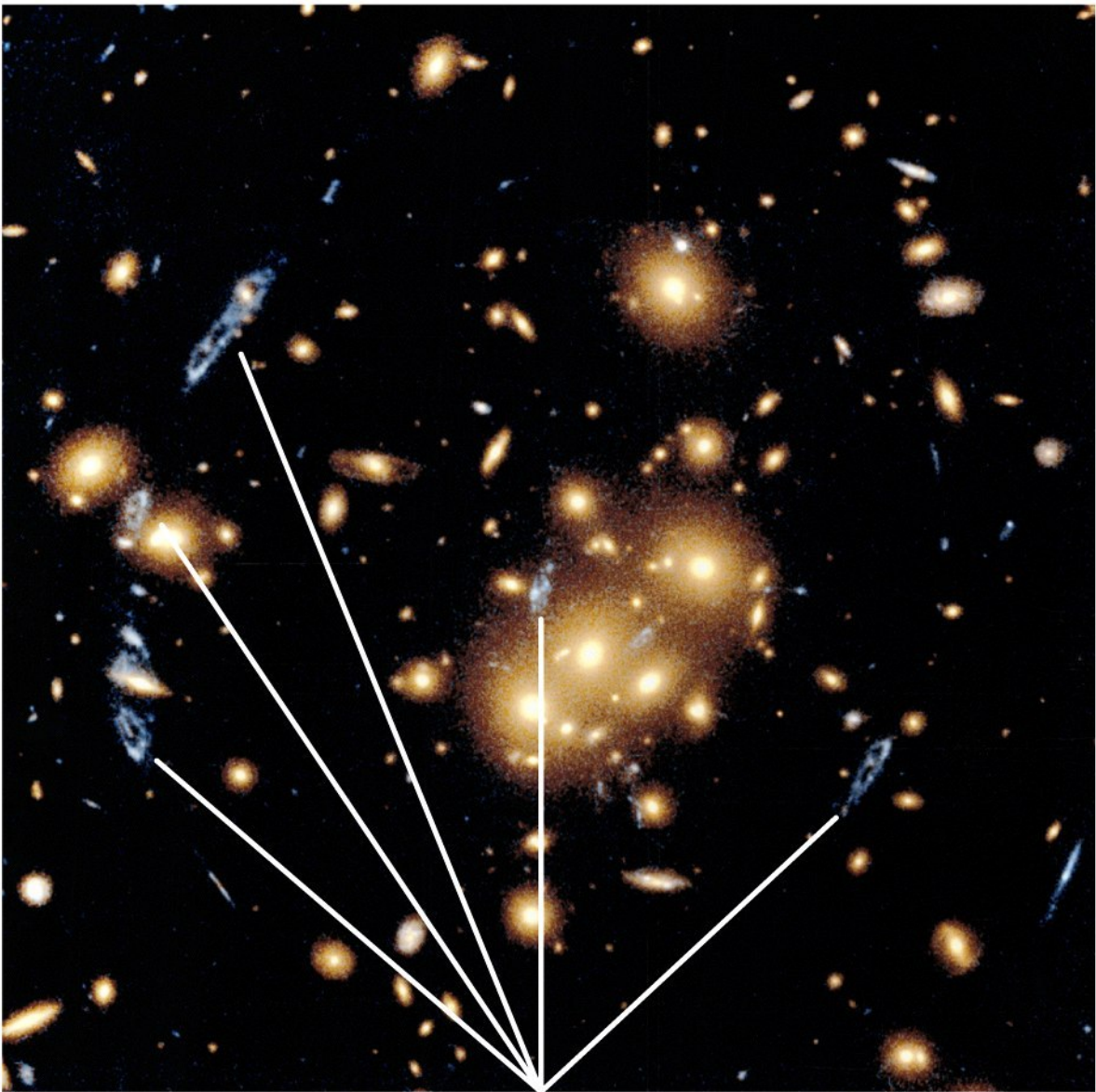


Sunyaev-Zeldovich effect

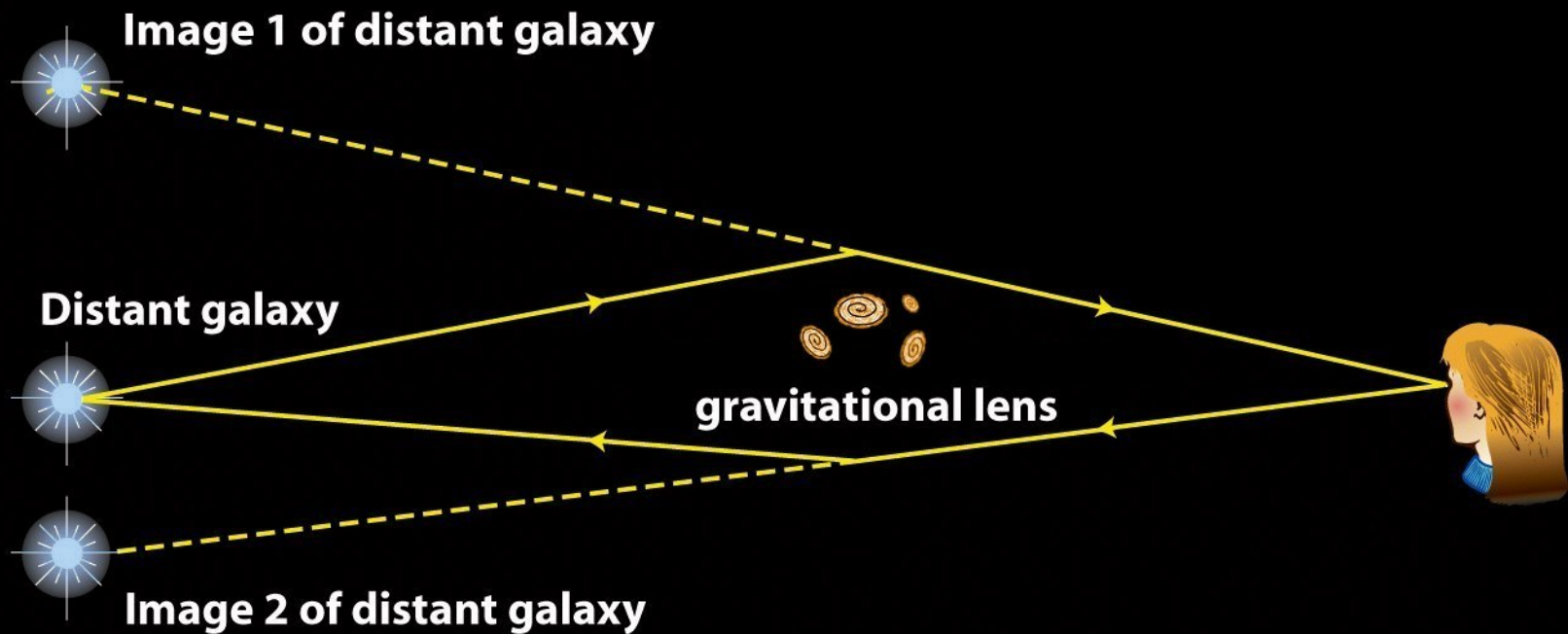


SZ distorts CMB blackbody





All of these blue arcs are images of the same distant galaxy.



How gravitational lensing happens