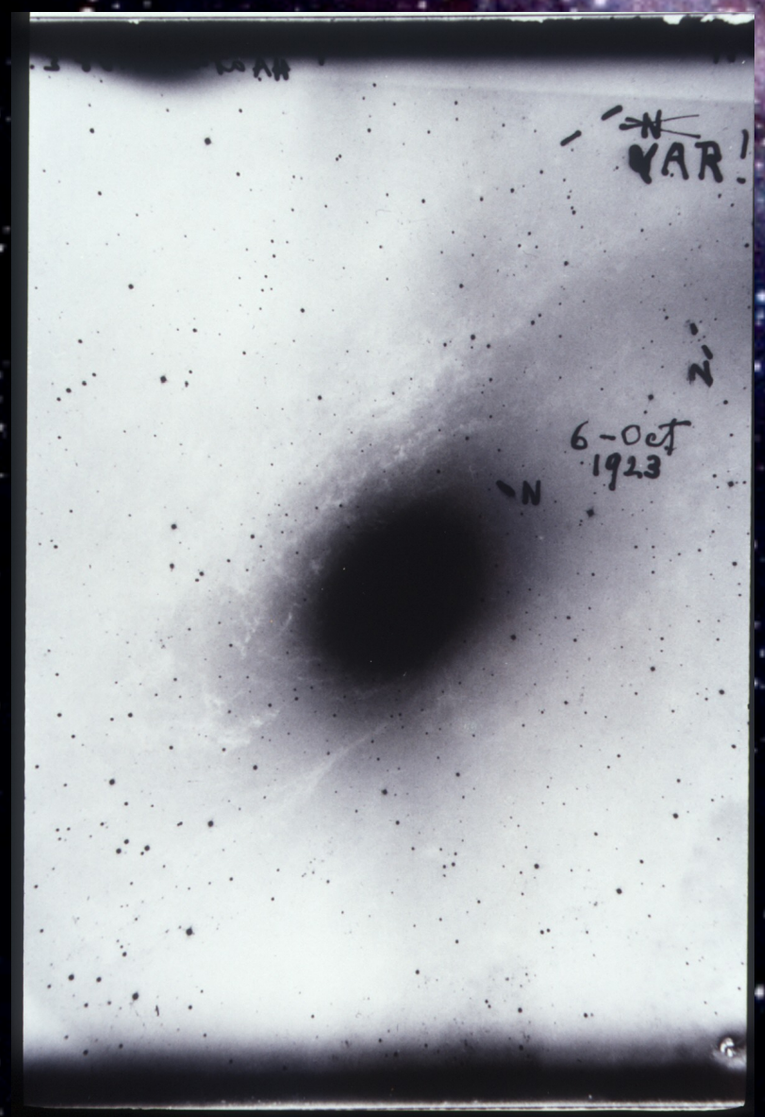
What Do Scientists Know About The Big Bang

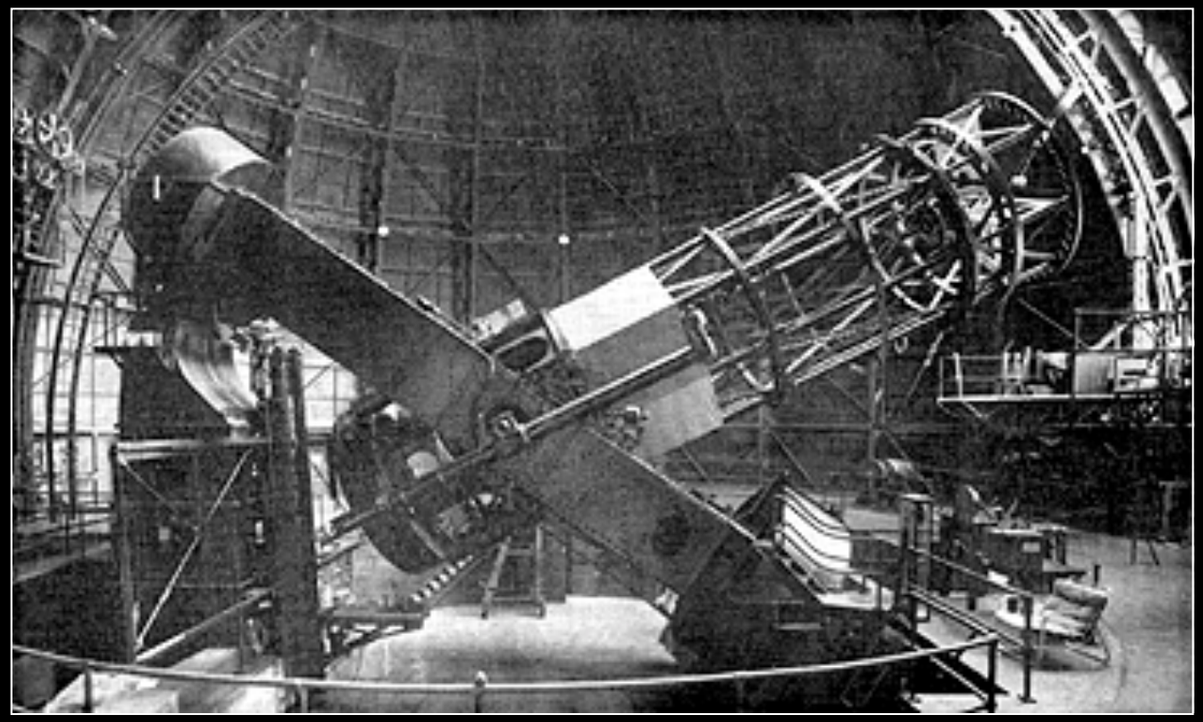
John Carlstrom

Kavli Institute for Cosmological Physics
at the University of Chicago

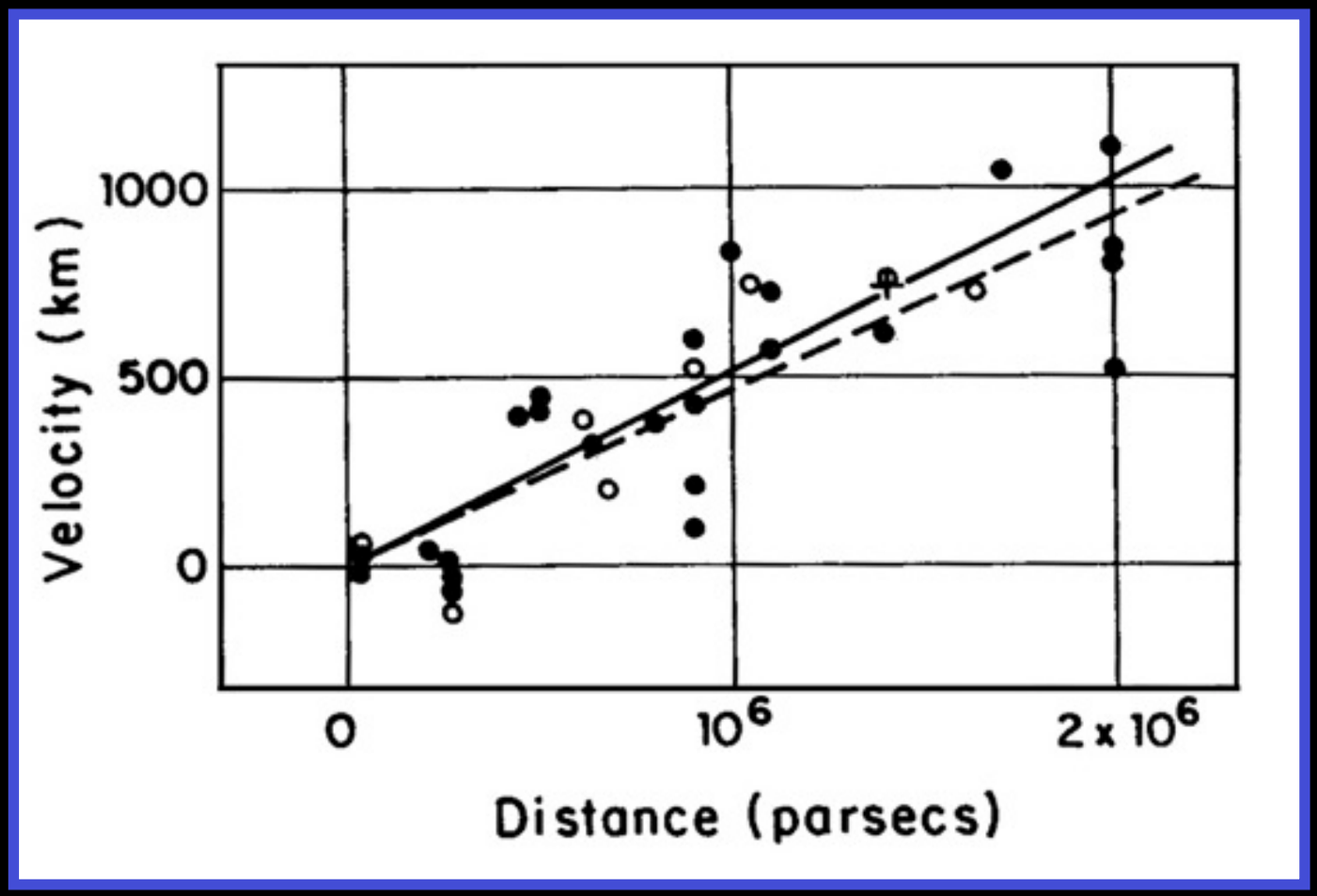
Nearby Galaxy M31 – The Andromeda Galaxy

Nearby Galaxy M31 – The Andromeda Galaxy

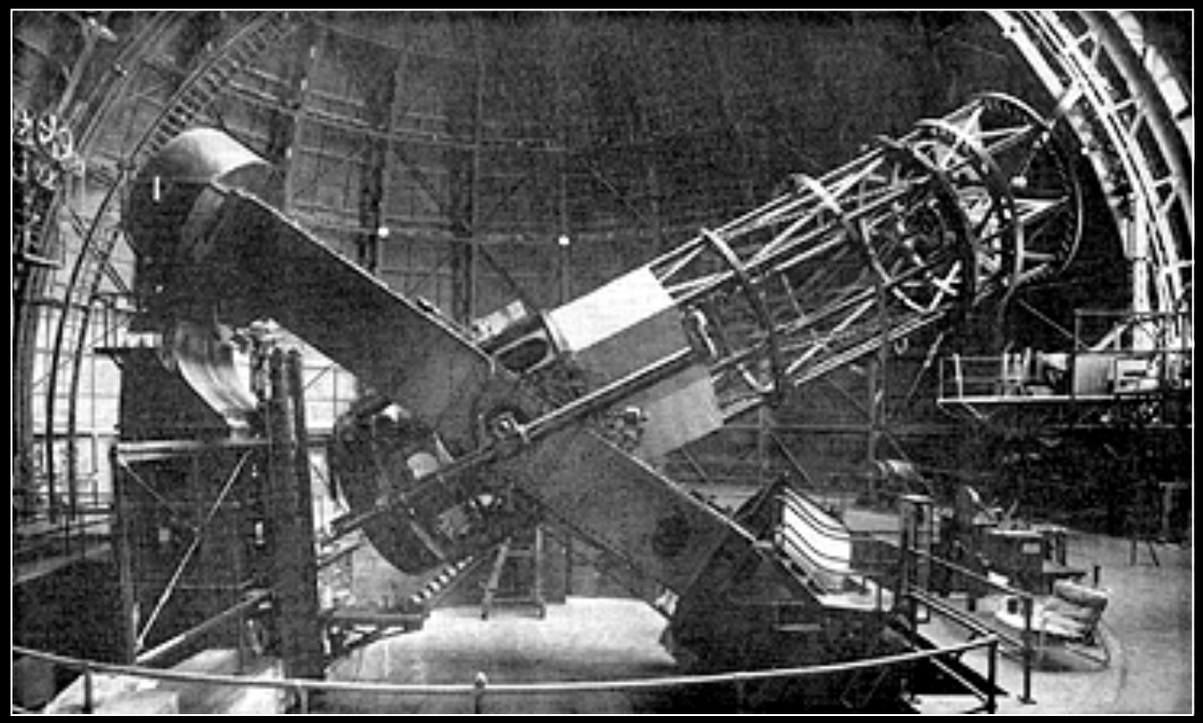




100-inch Hooker Telescope on Mt. Wilson



Hubble diagram of expanding universe (1930)



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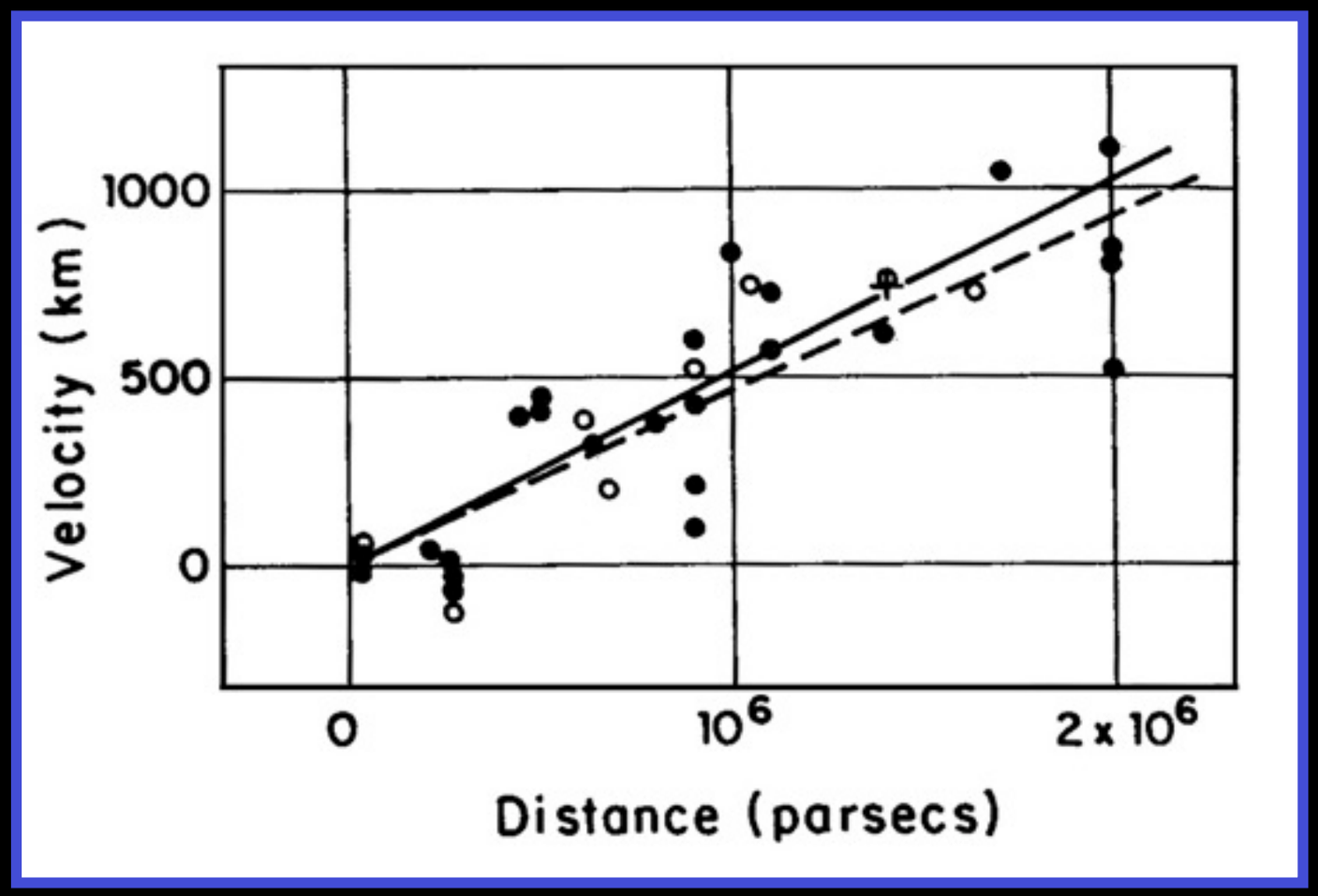
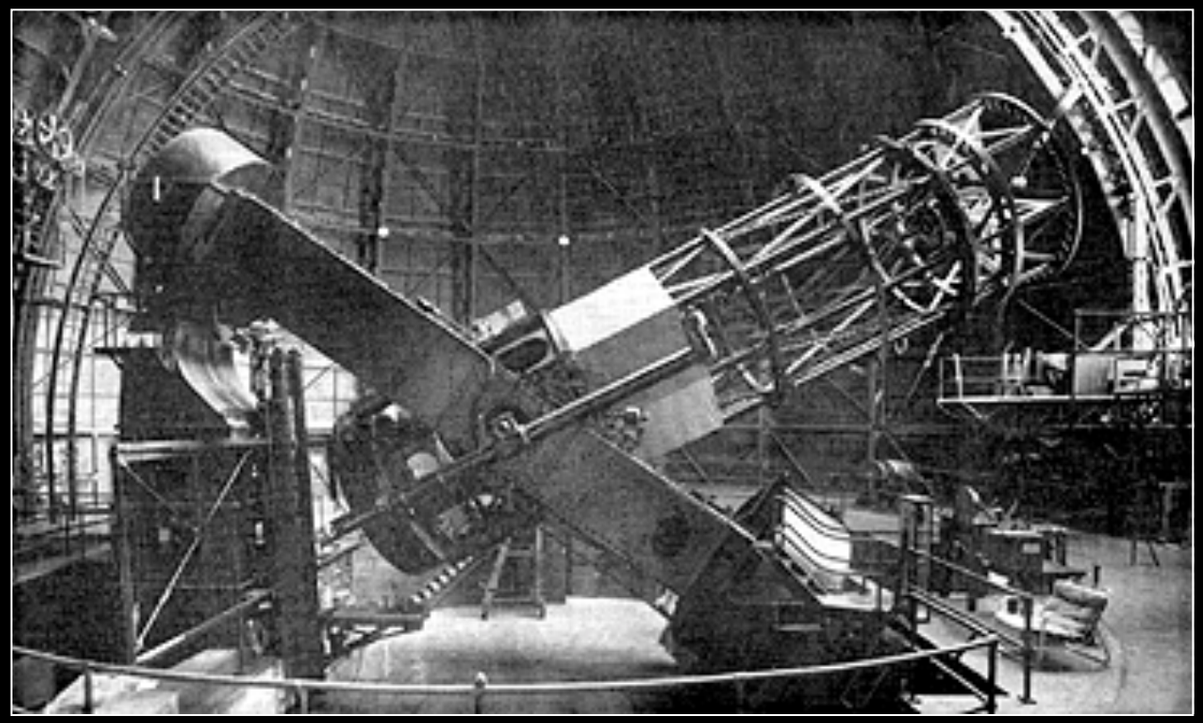


Hubble diagram of expanding universe (1930)



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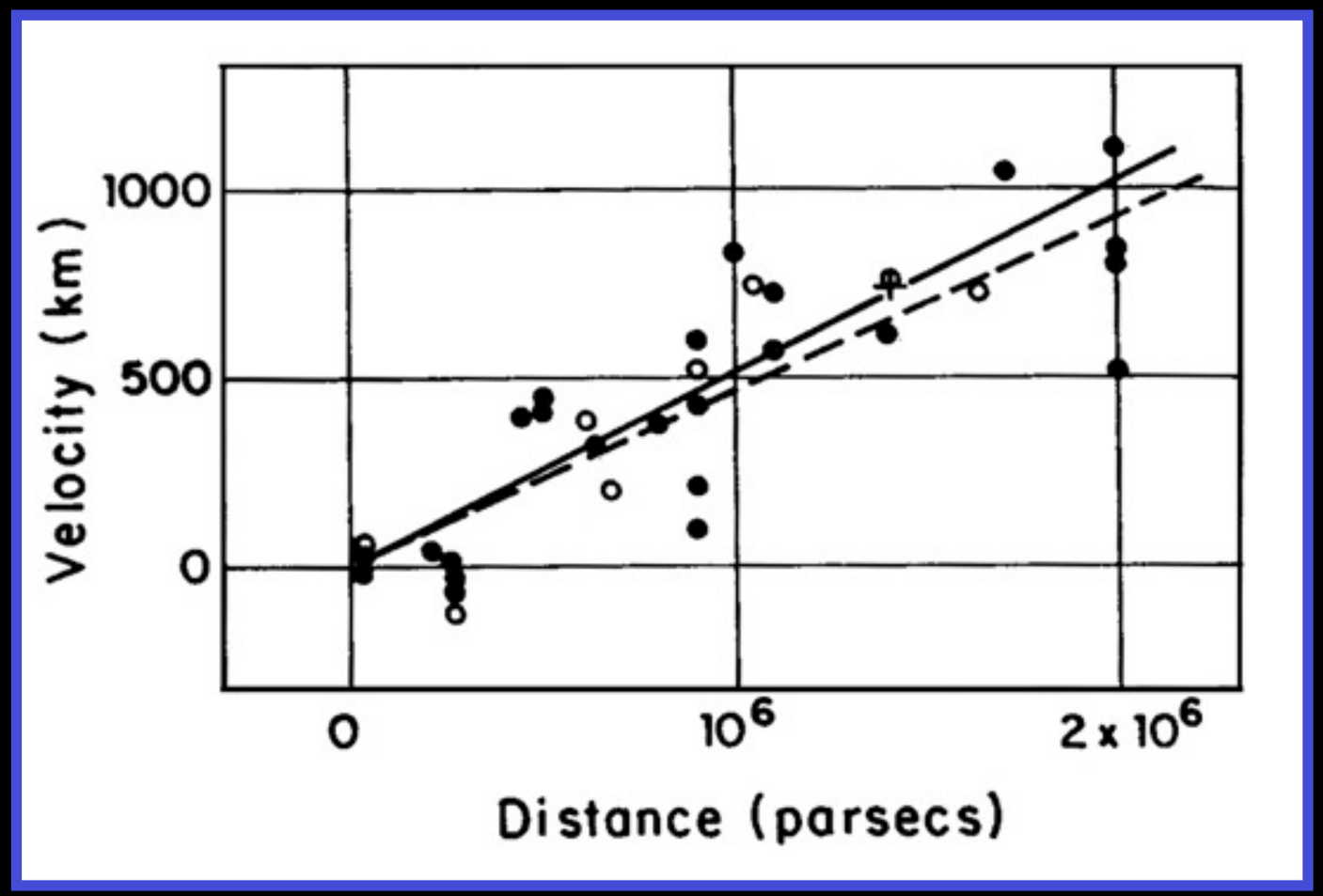
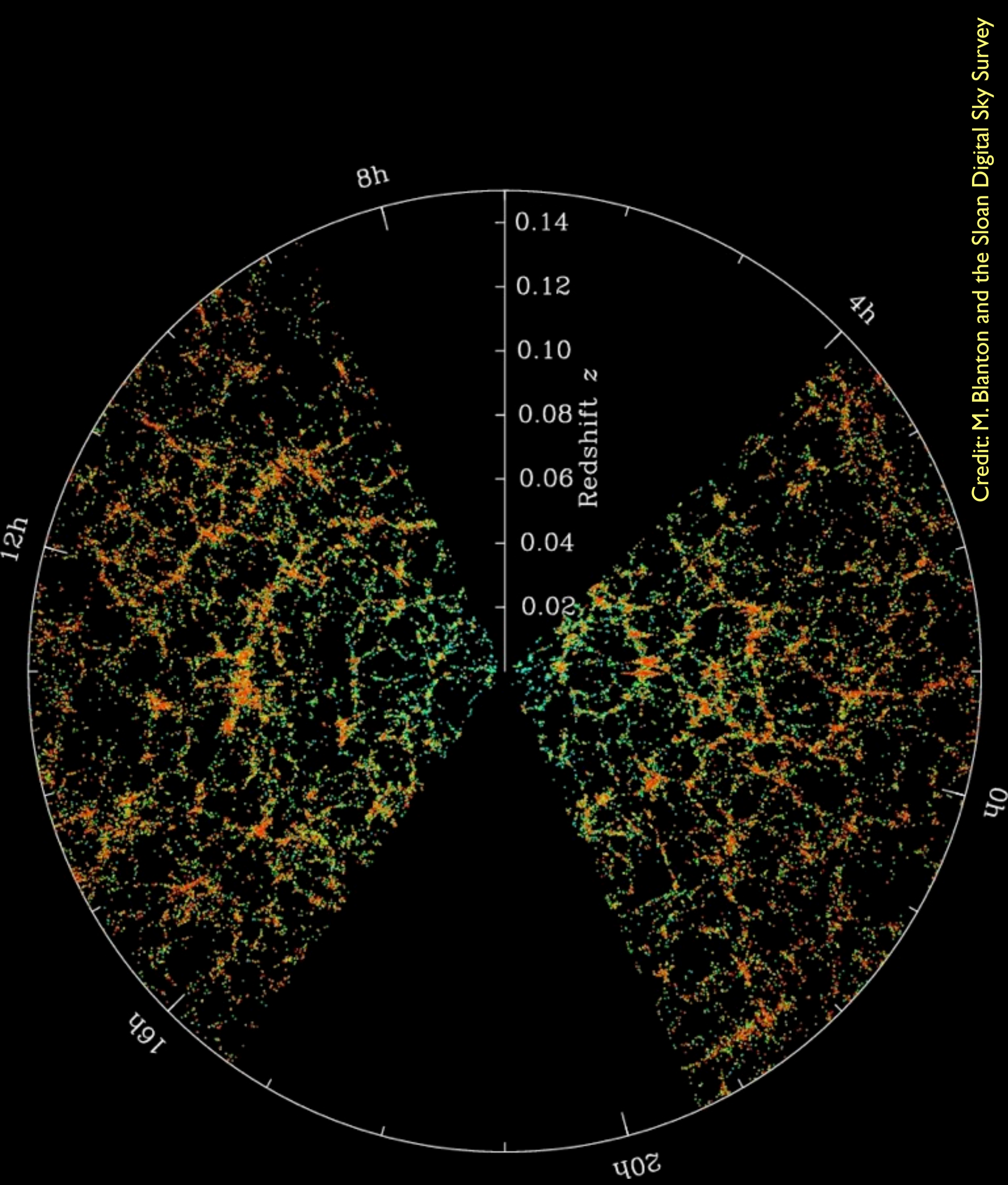


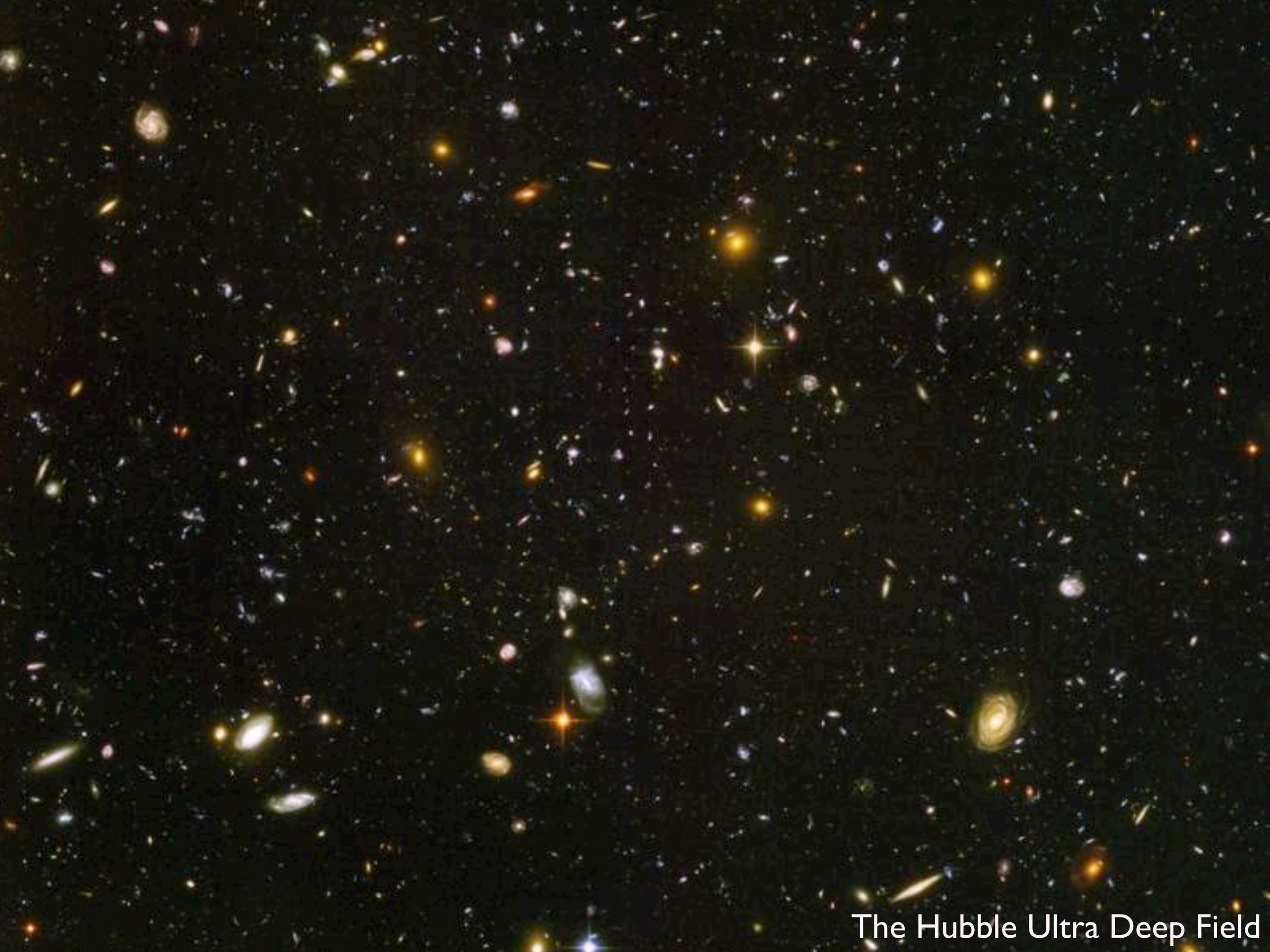
Hubble diagram of expanding universe (1930)

During the presentation, I showed a movie of a “fly through” the SDSS data made by Mark Subbarao at Adler Planetarium and Miguel Angel Aragon Calvo at John Hopkins University.

You can find similar version at
http://www.youtube.com/watch?v=08LBltePDZw



Credit: M. Blanton and the Sloan Digital Sky Survey



The Hubble Ultra Deep Field

An astronomical number to remember: **100 billion**

The Hubble Ultra Deep Field

An astronomical number to remember: **100 billion**

- Number of stars in the Milky Way
- Number of galaxies in the observable universe
- Age of the universe in dog years
- Apple's cash reserve

The Hubble Ultra Deep Field

Another interesting observation:
it's mostly black.

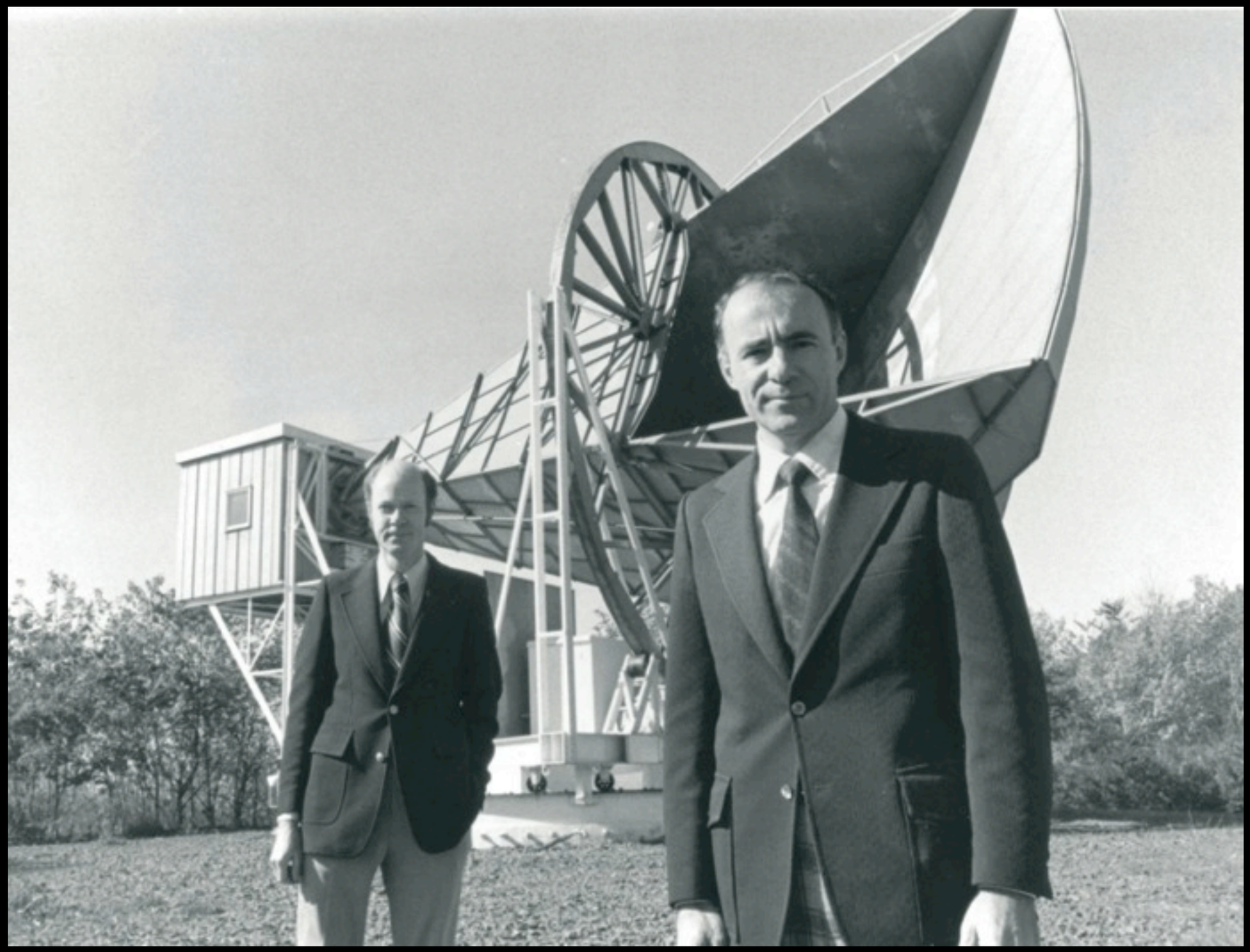
We are seeing past the galaxies…
… to a time before galaxies formed.

The Hubble Ultra Deep Field

Actually the sky is very bright in every direction,
but with light at microwave wavelengths.

The Hubble Ultra Deep Field

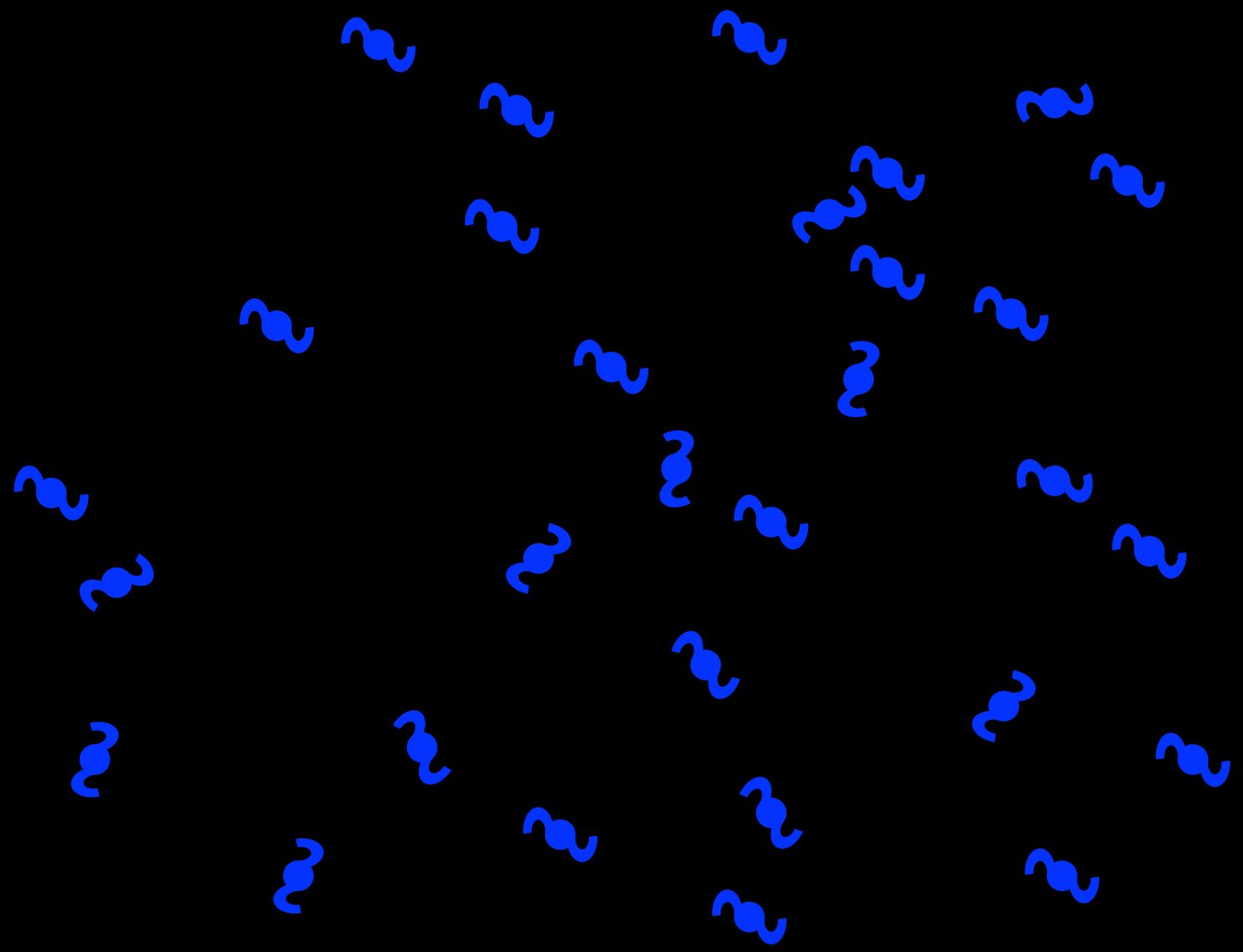
Discovery of the Cosmic Microwave Background

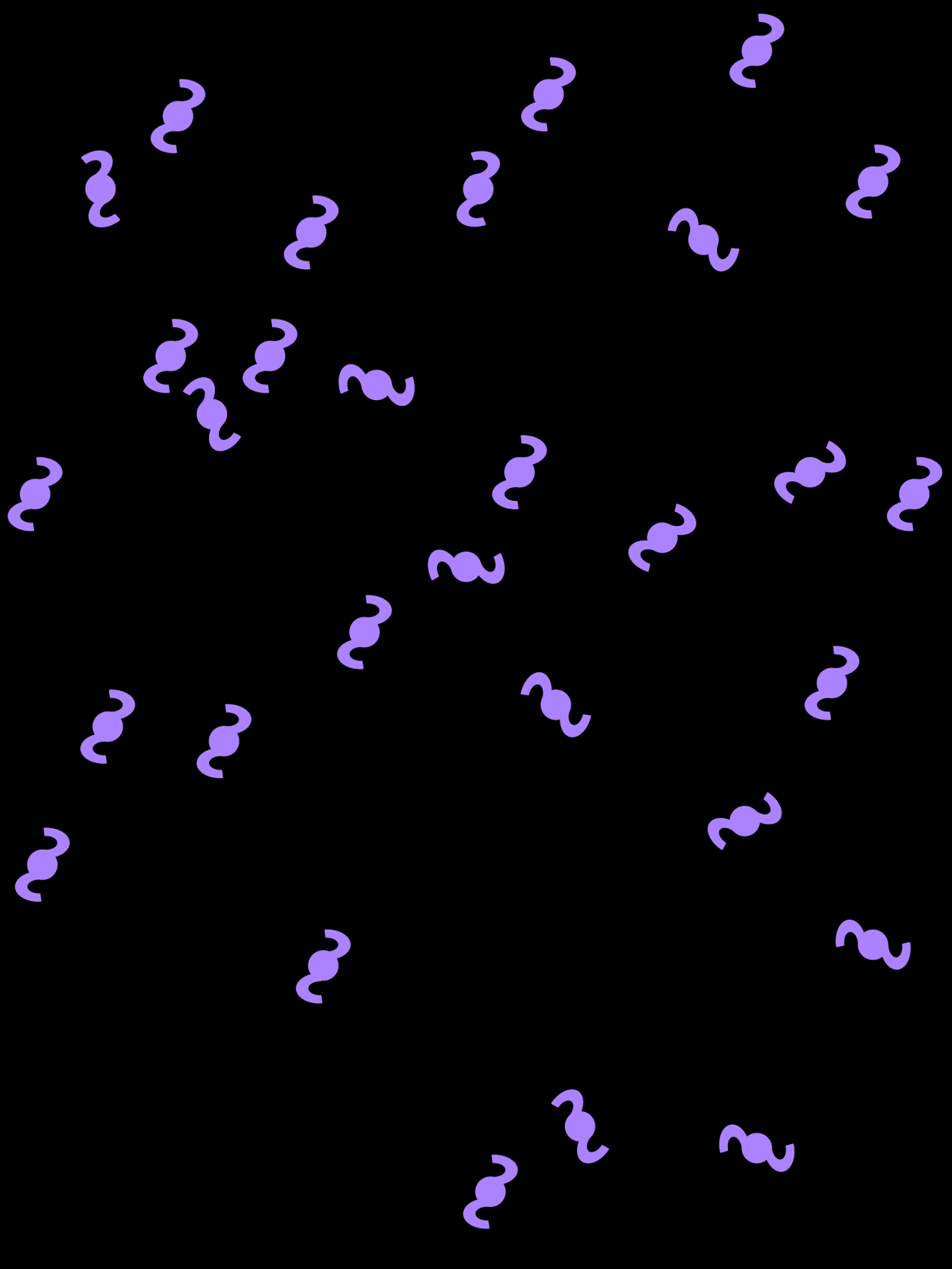


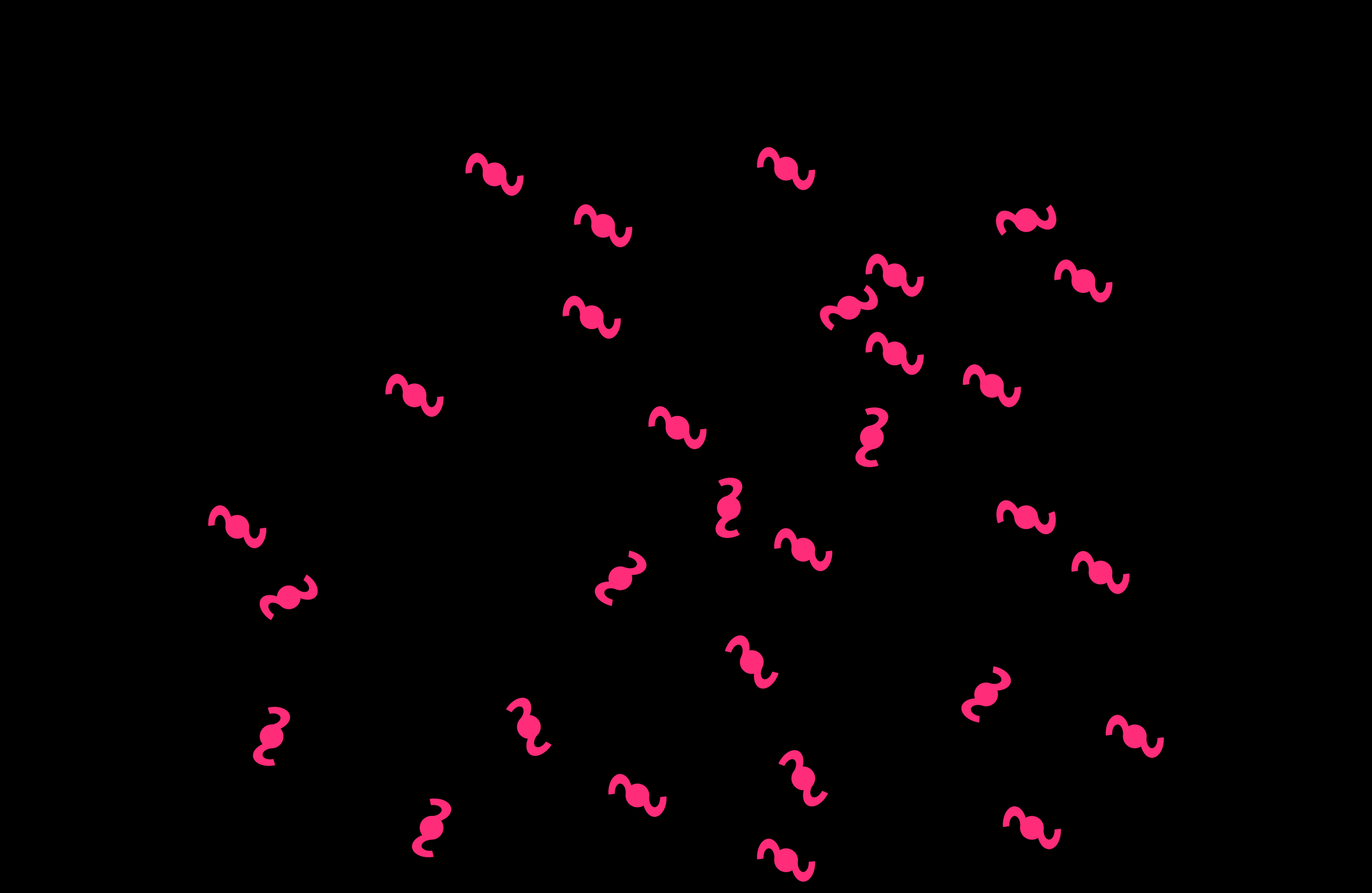
Arno Penzias & Robert Wilson in front of the 20ft Bell Labs antenna used to discover the microwave background in 1965

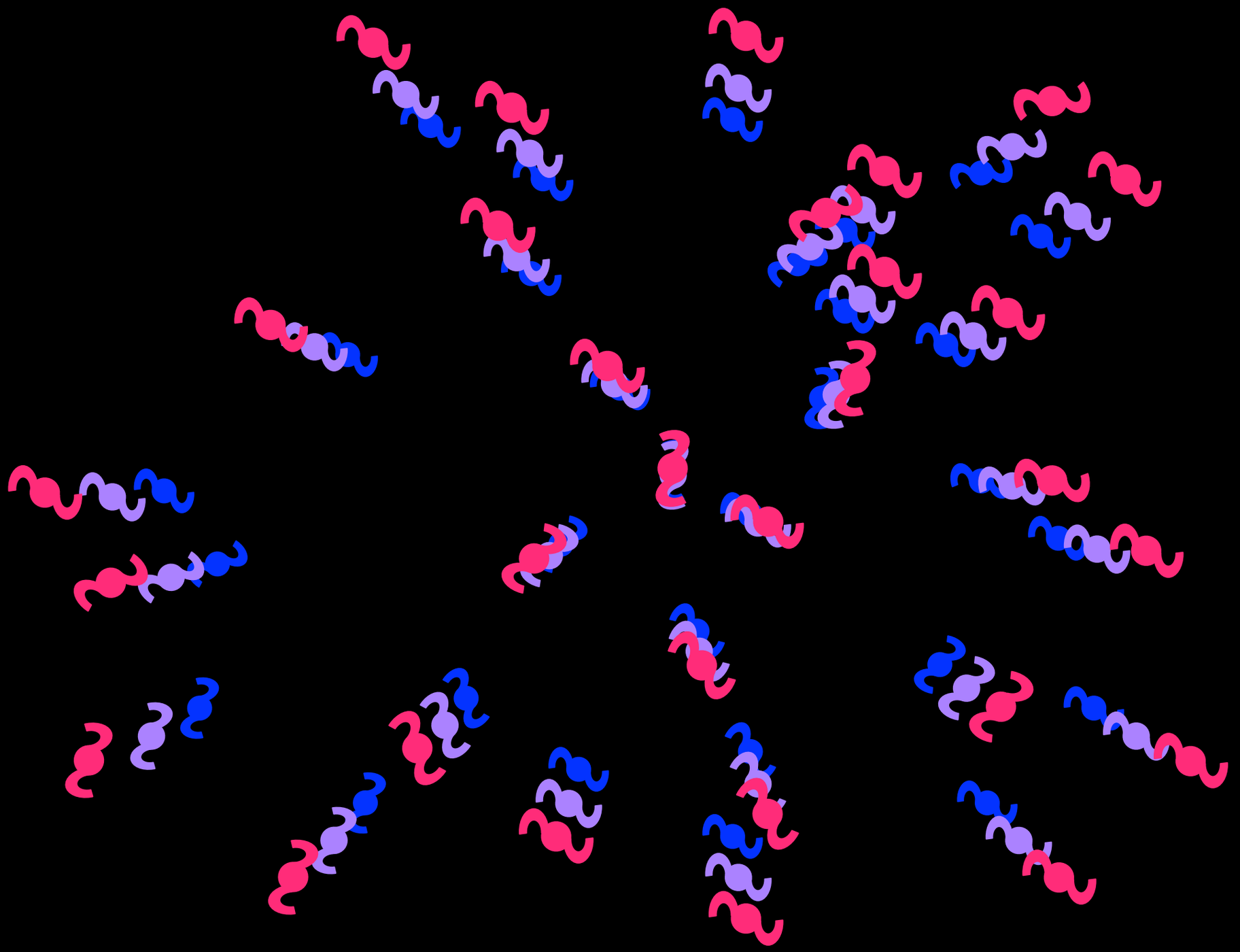
"smoking gun" evidence for a <u>Hot Big Bang</u>

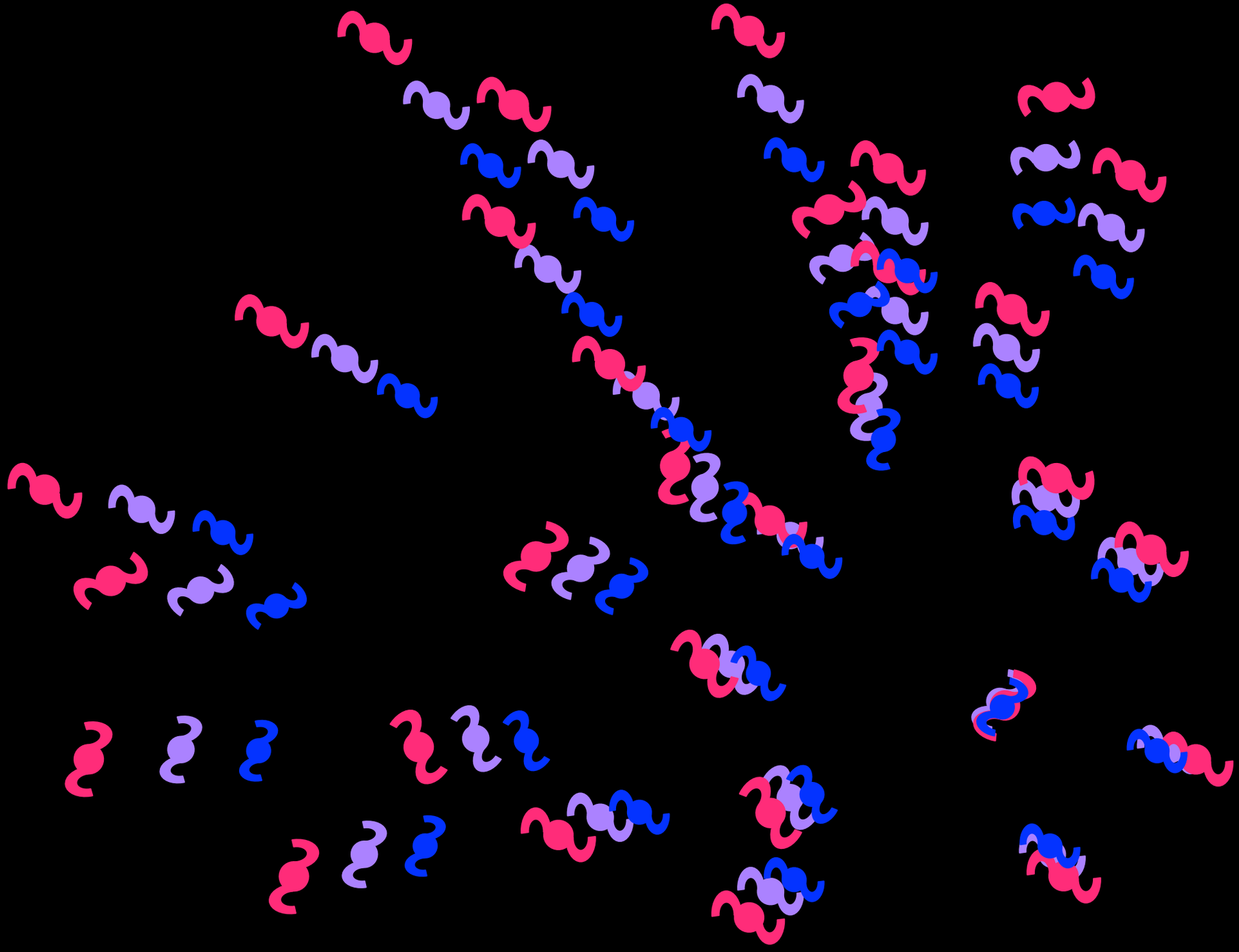
Received 1978 Nobel Prize

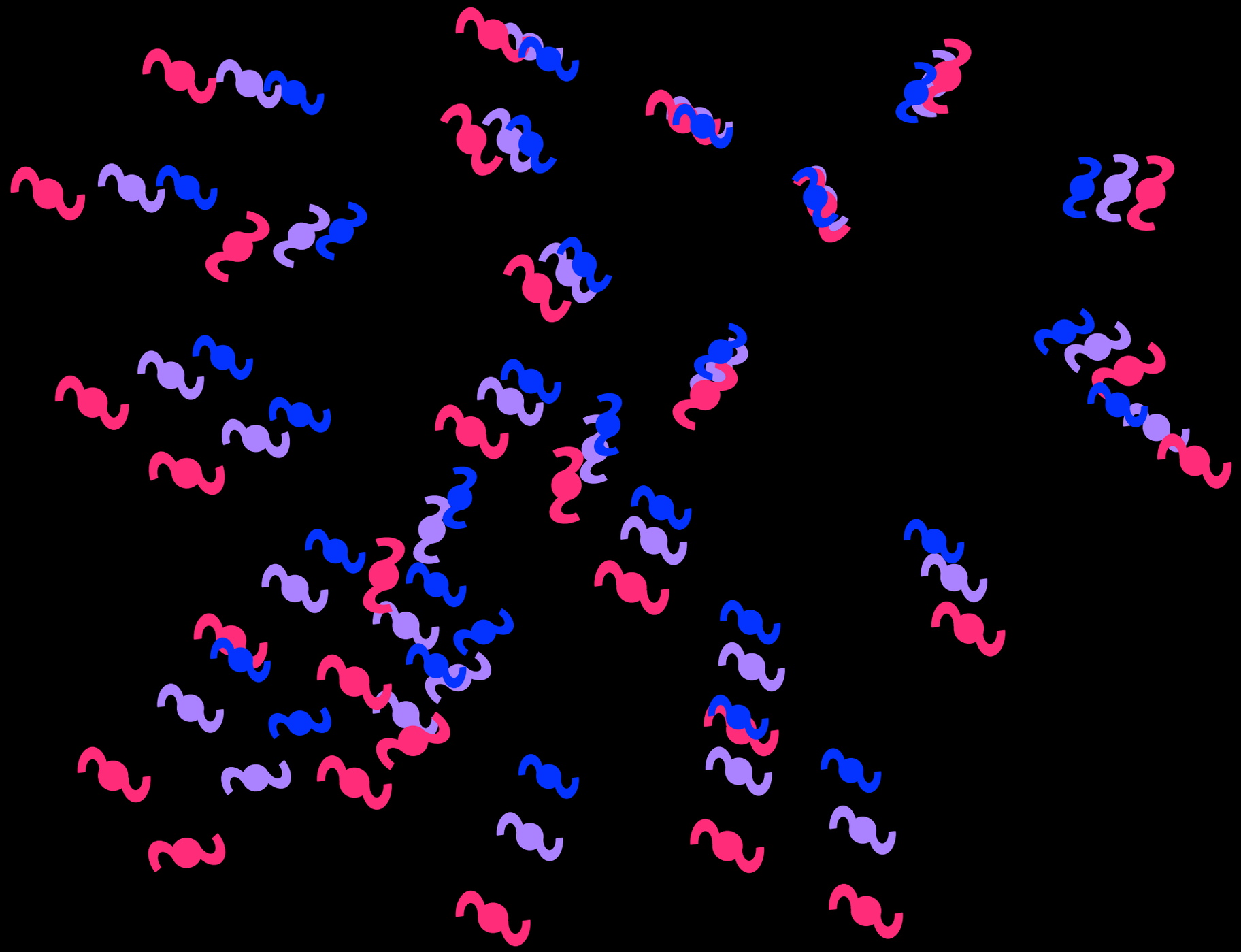




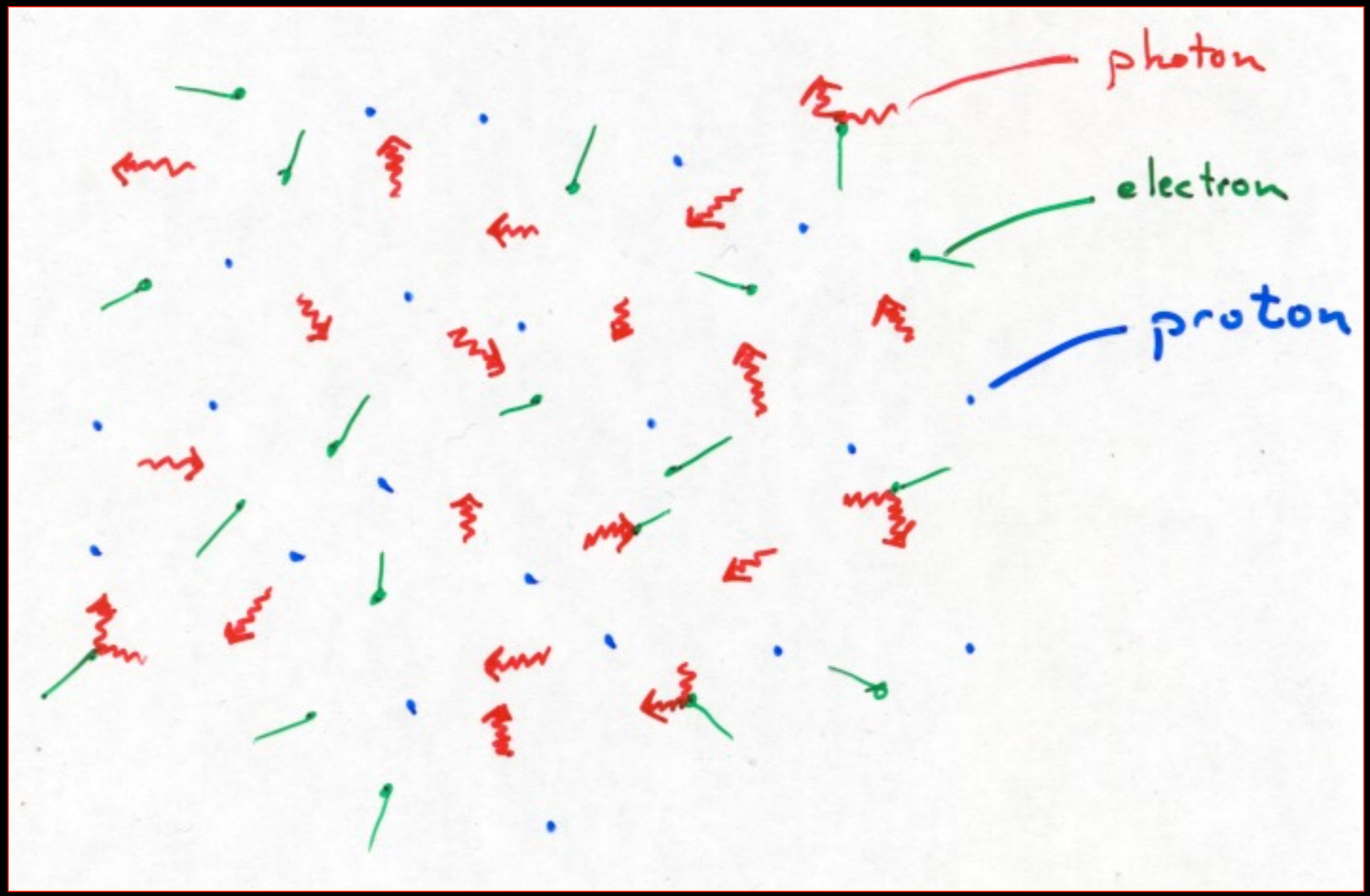




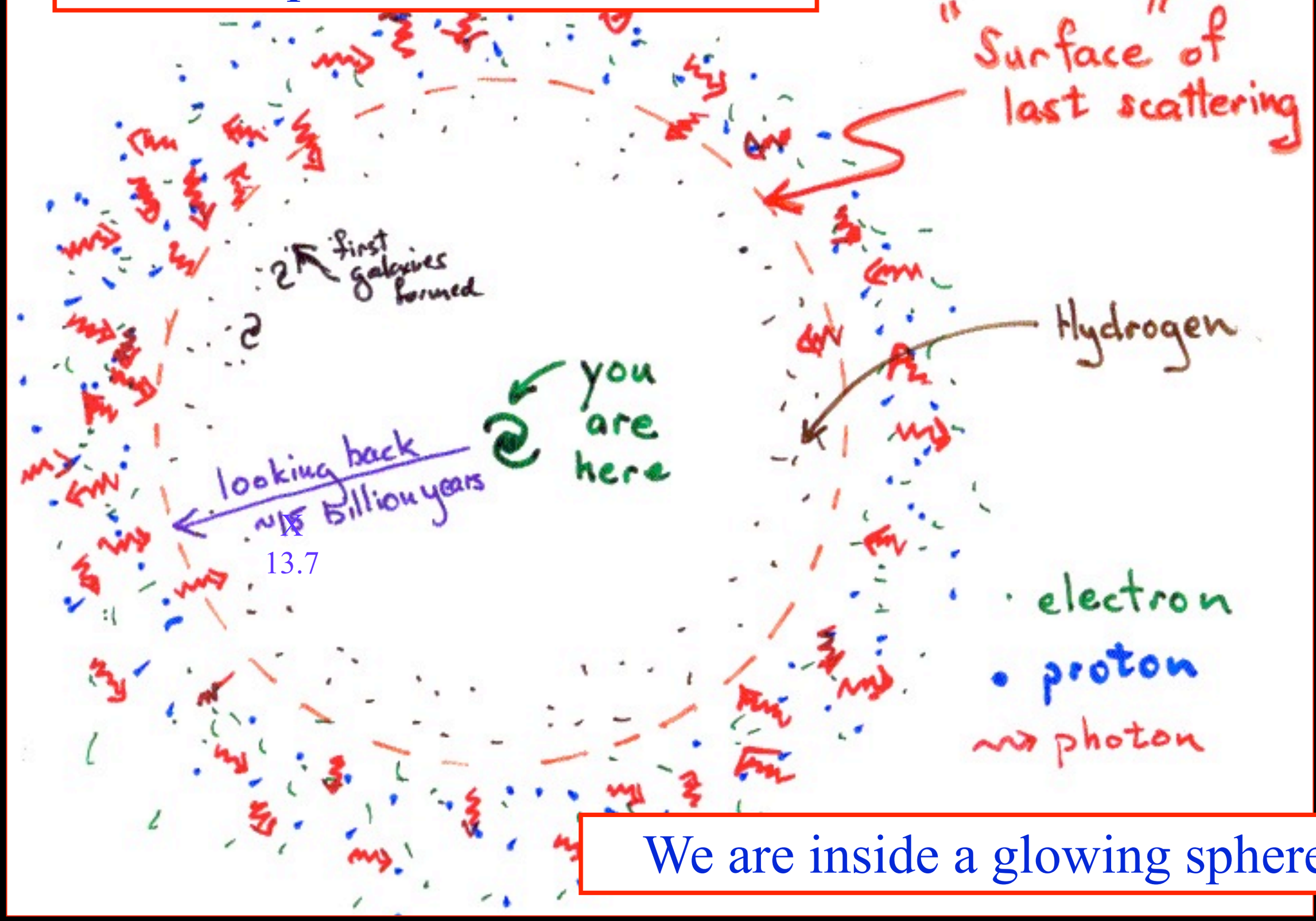




Physics is simple in the young universe –
It's just an ionized gas with sound waves

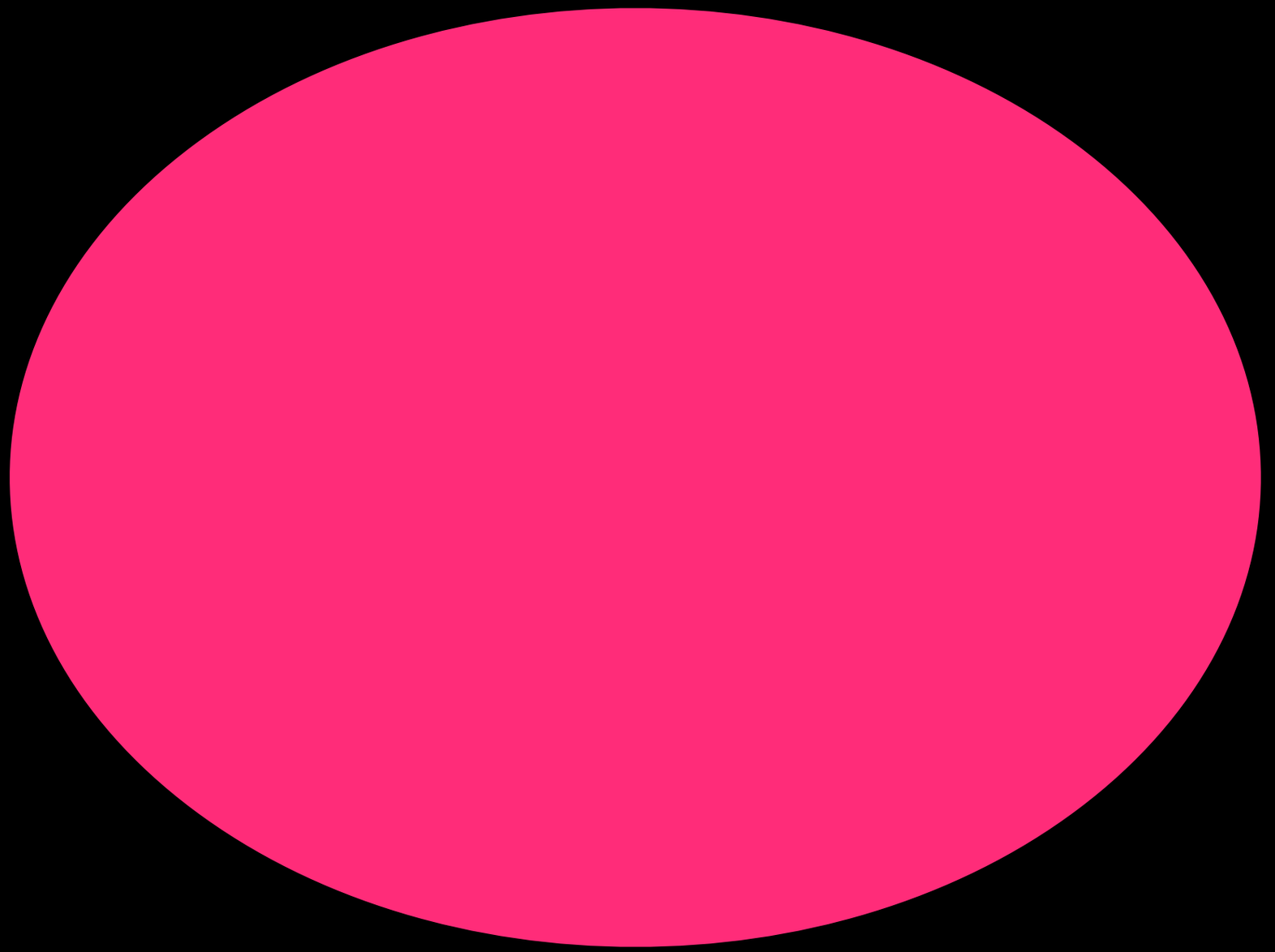


Cosmic Microwave Background Telescopes are *time machines*



We are inside a glowing sphere

Structure in background discovered in 1992

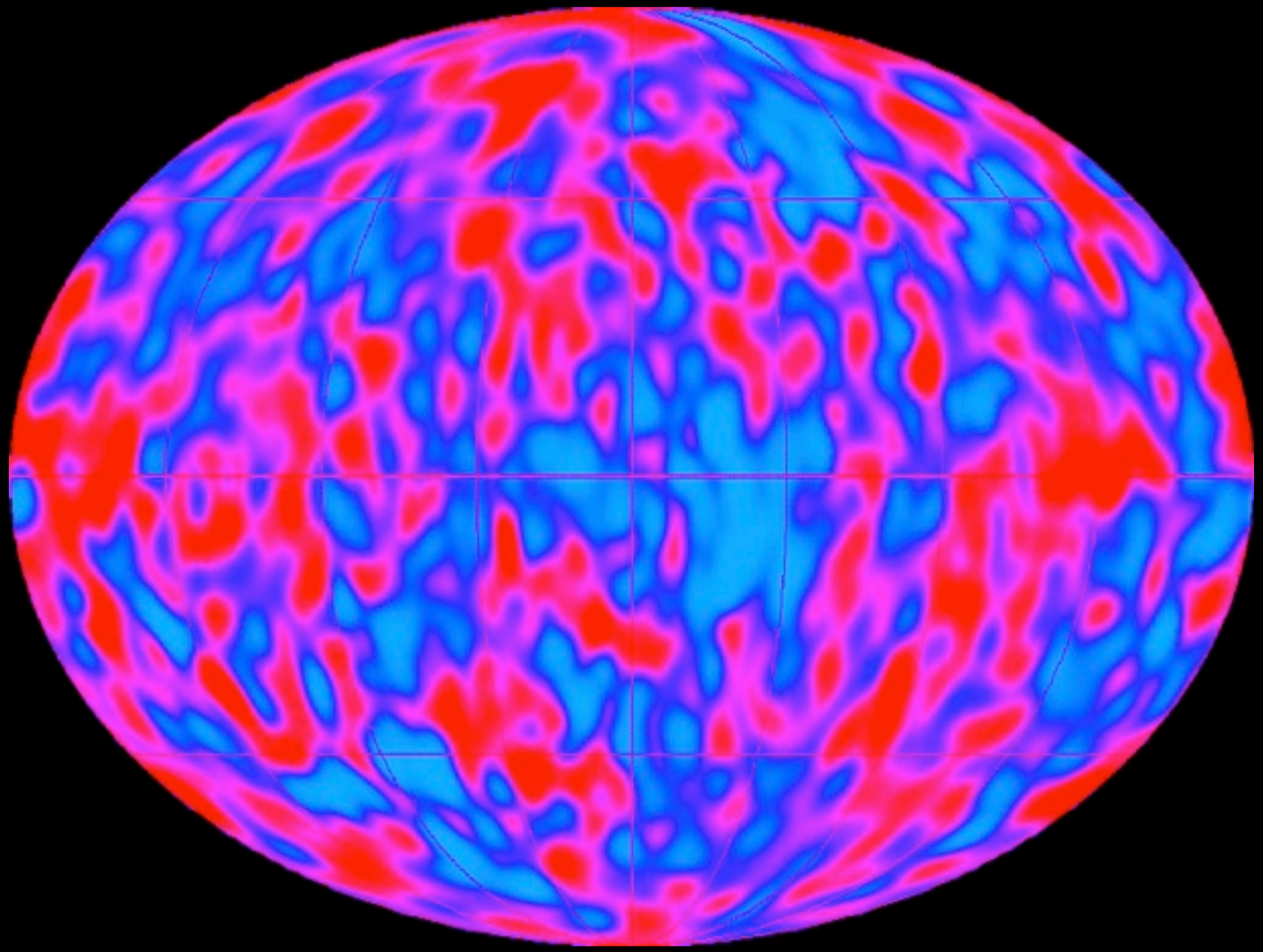


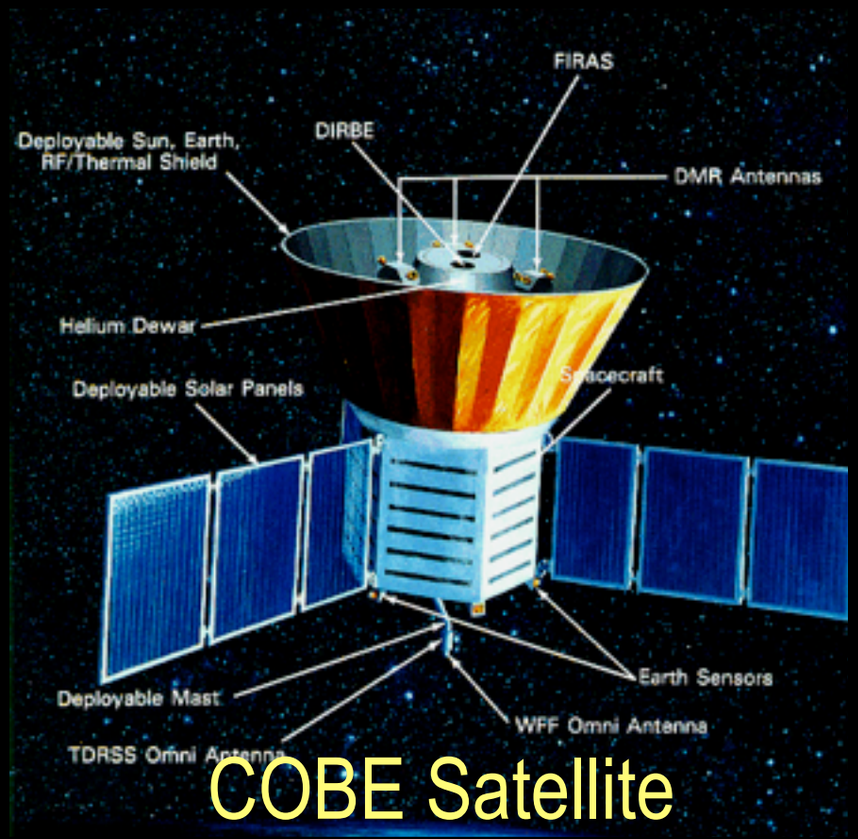
Smooth to a part in 100,000!

(the smoothness problem)

Structure in background discovered in 1992

COBE team leaders
John Mather & George Smoot
received 2006 Nobel Prize

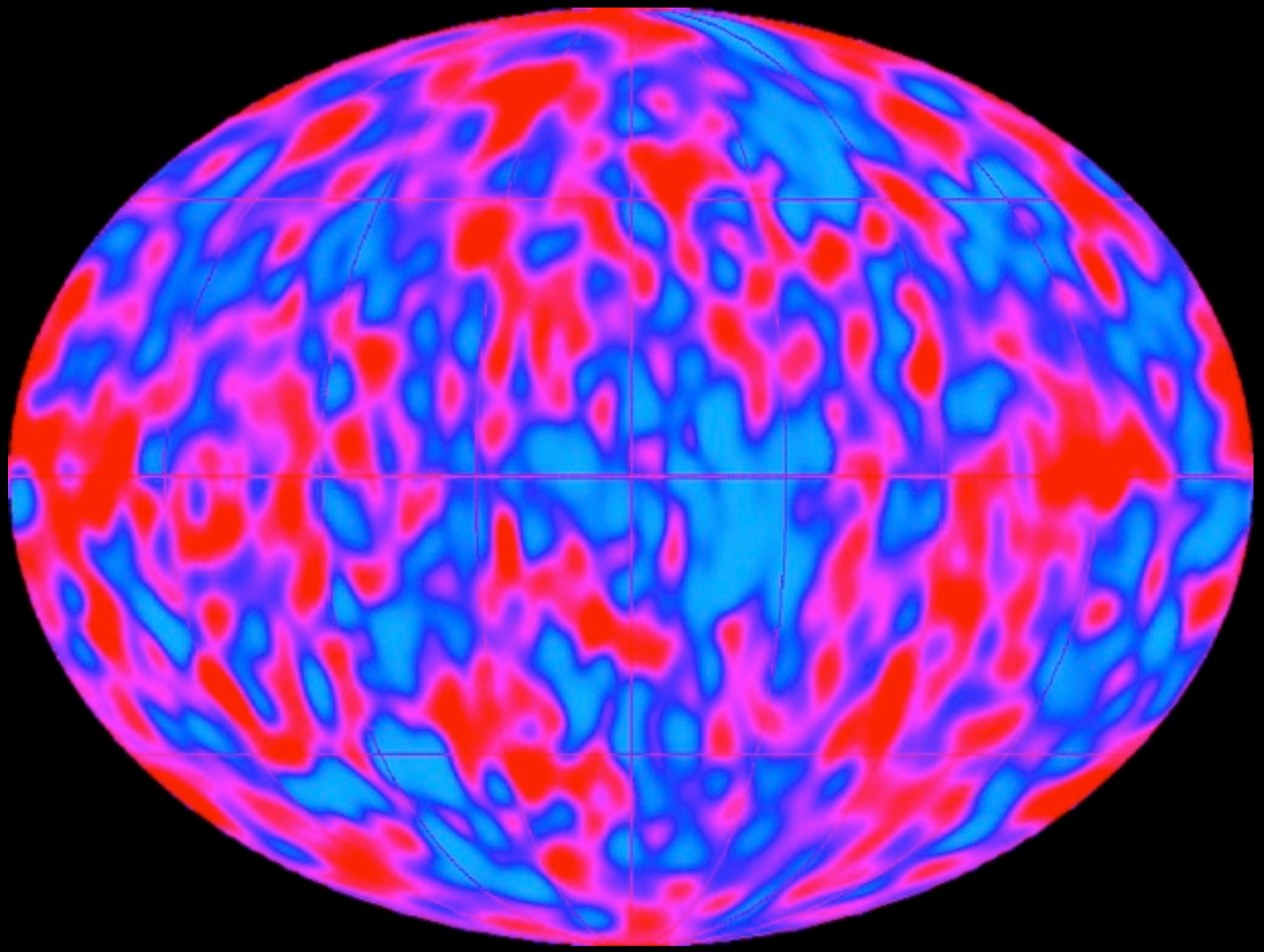




COBE Satellite

Smooth to a part in 100,000!
(the smoothness problem)

Solving the Smoothness Problem



Solving the Smoothness Problem

It’s easy, in the first

~0.00000000000000000000000000001 seconds

you simply stretch out space by at least

100,000,000,000,000,000,000,000,000,000 times

Solving the Smoothness Problem

It's easy, in the first

~0.00000000000000000000000000001 seconds

you simply stretch out space by at least

100,000,000,000,000,000,000,000,000,000 times

That's

INFLATION

Solving the Smoothness Problem

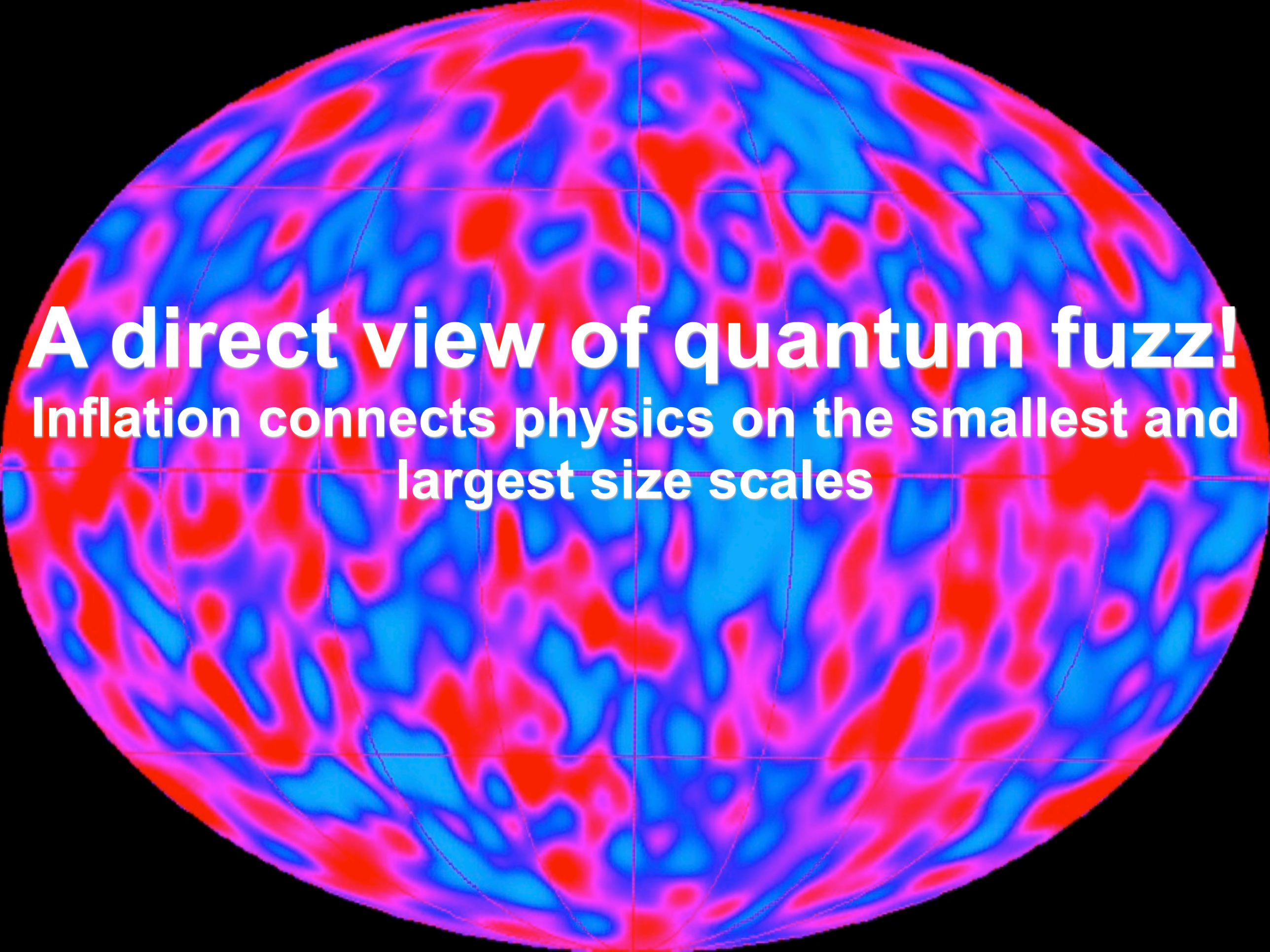
It's easy, in the first

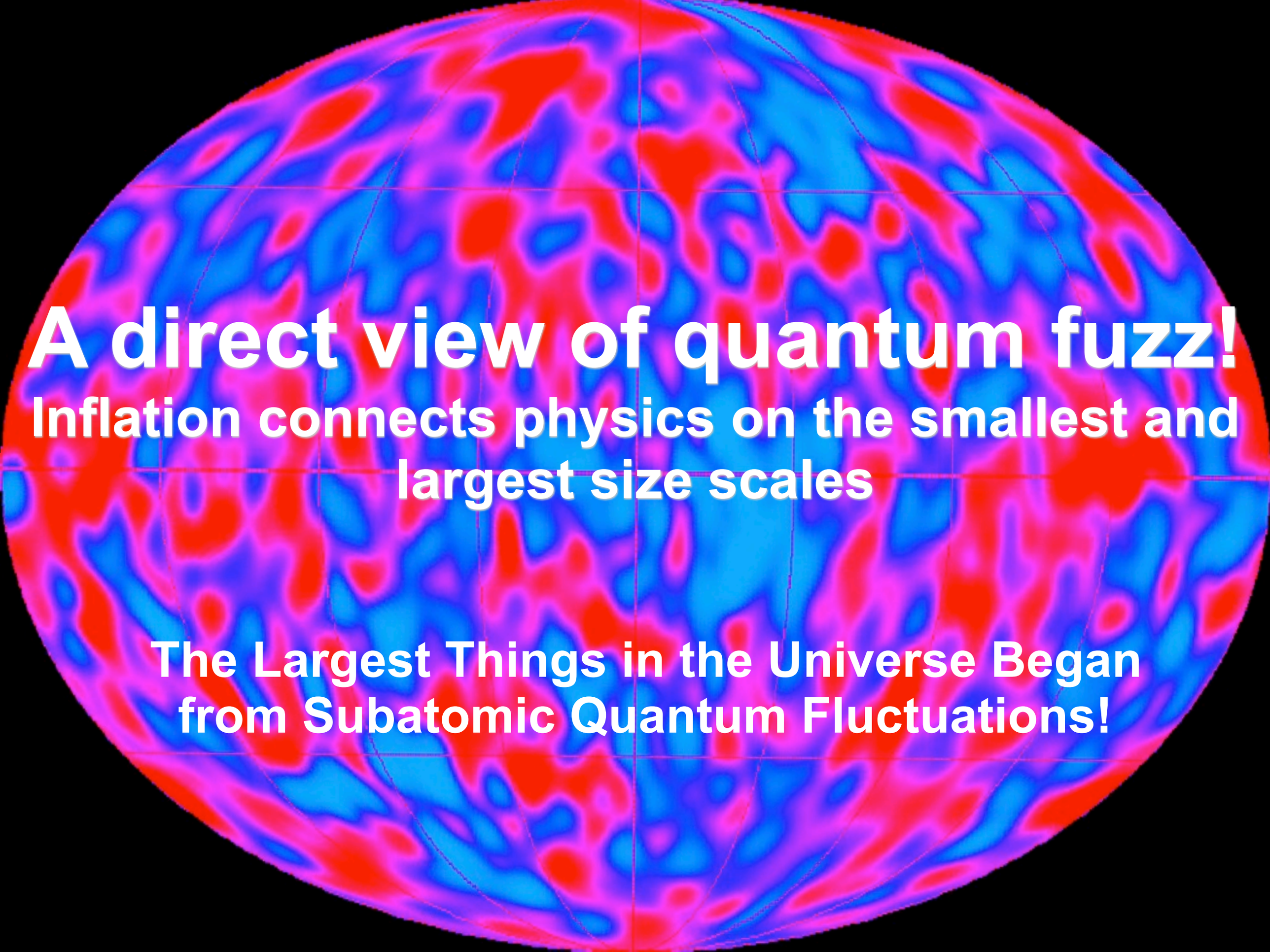
~0.00000000000000000000000000001 seconds

you simply stretch out space by at least

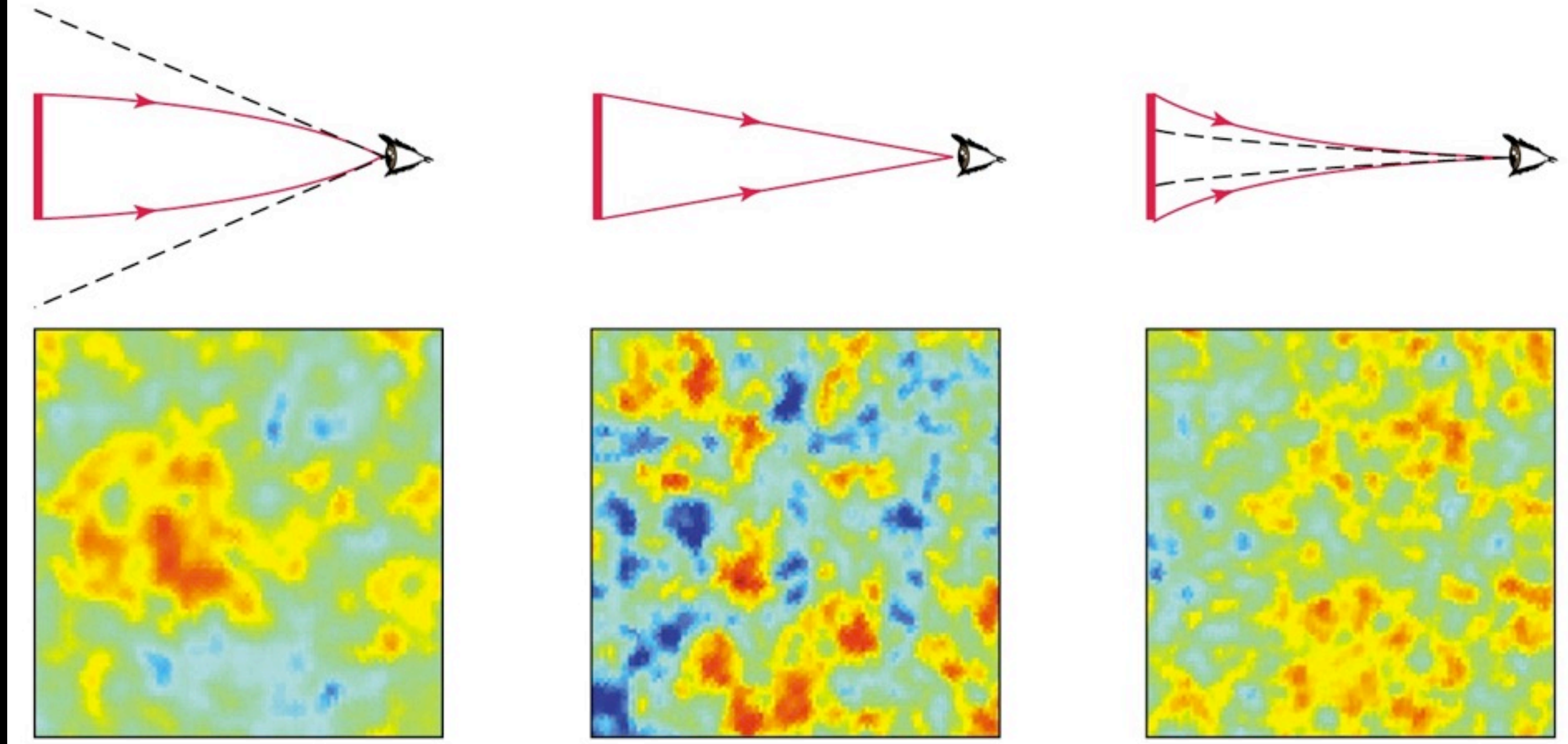
100,000,000,000,000,000,000,000,000,000 times

Inflation leads to flat (uncurved) space over the scales we can ever hope to measure.


A direct view of quantum fuzz!
Inflation connects physics on the smallest and
largest size scales


A direct view of quantum fuzz!
Inflation connects physics on the smallest and largest size scales
The Largest Things in the Universe Began from Subatomic Quantum Fluctuations!

Checking the curvature of the Universe
with the biggest triangles possible



a If universe is closed, "hot spots" appear larger than actual size

b If universe is flat, "hot spots" appear actual size

c If universe is open, "hot spots" appear smaller than actual size

by using the structure in the microwave background

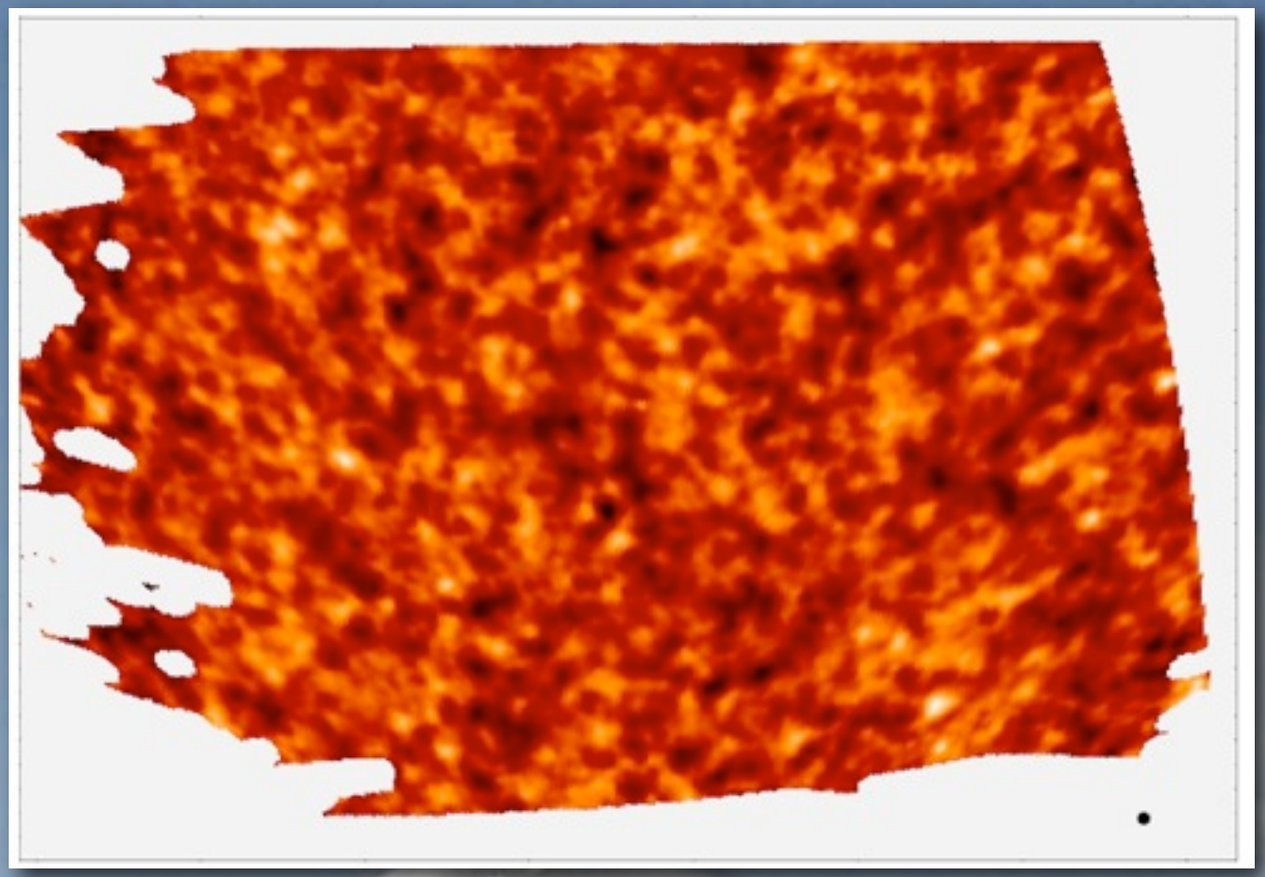
Freedman "Universe" textbook

Andrew Lange
1957-2010

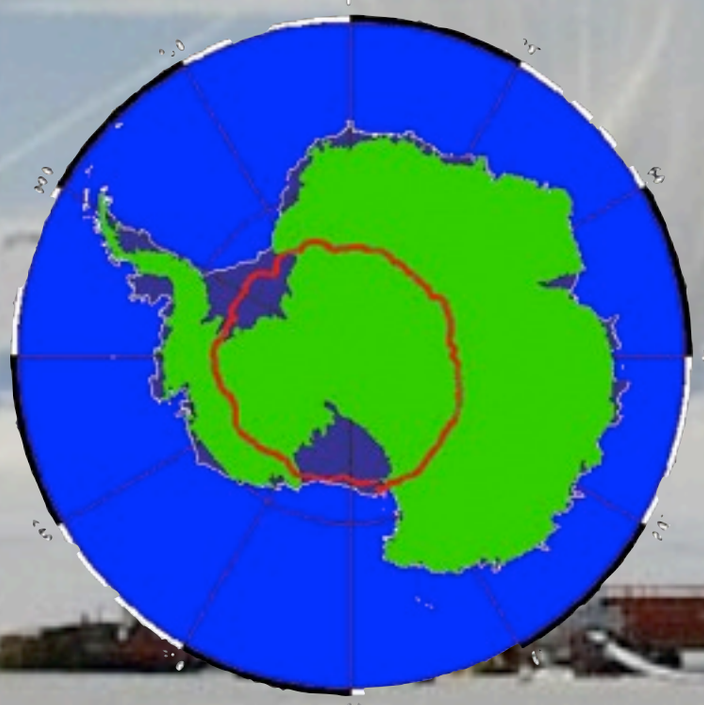
BOOMERANG

Williams Field, Antarctica

December 28, 1998



Andrew Lange
1957-2010



BOOMERANG

Williams Field, Antarctica

December 28, 1998

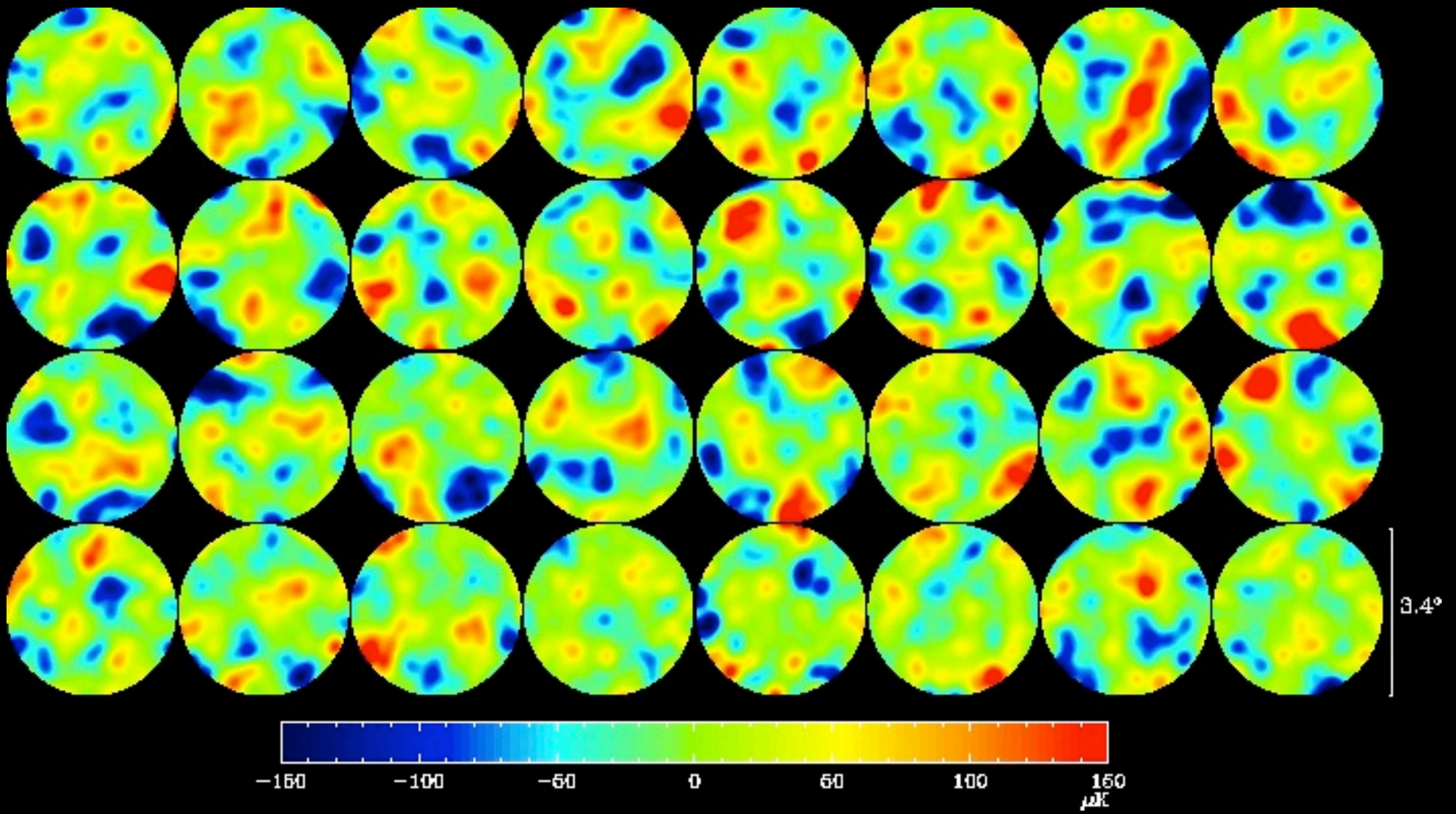
DASI

cosmic microwave background telescope

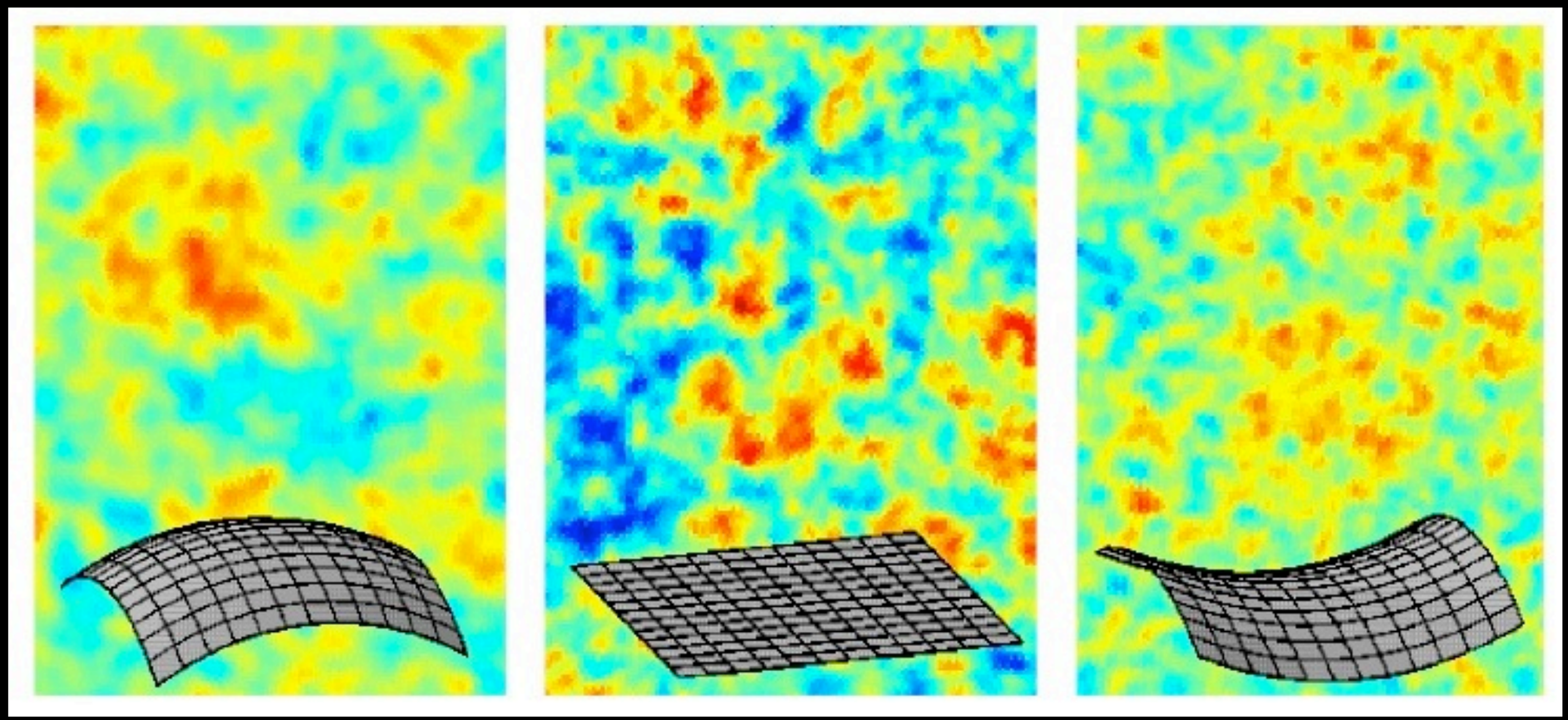
DASI

cosmic microwave background telescope

Sunset at the South Pole

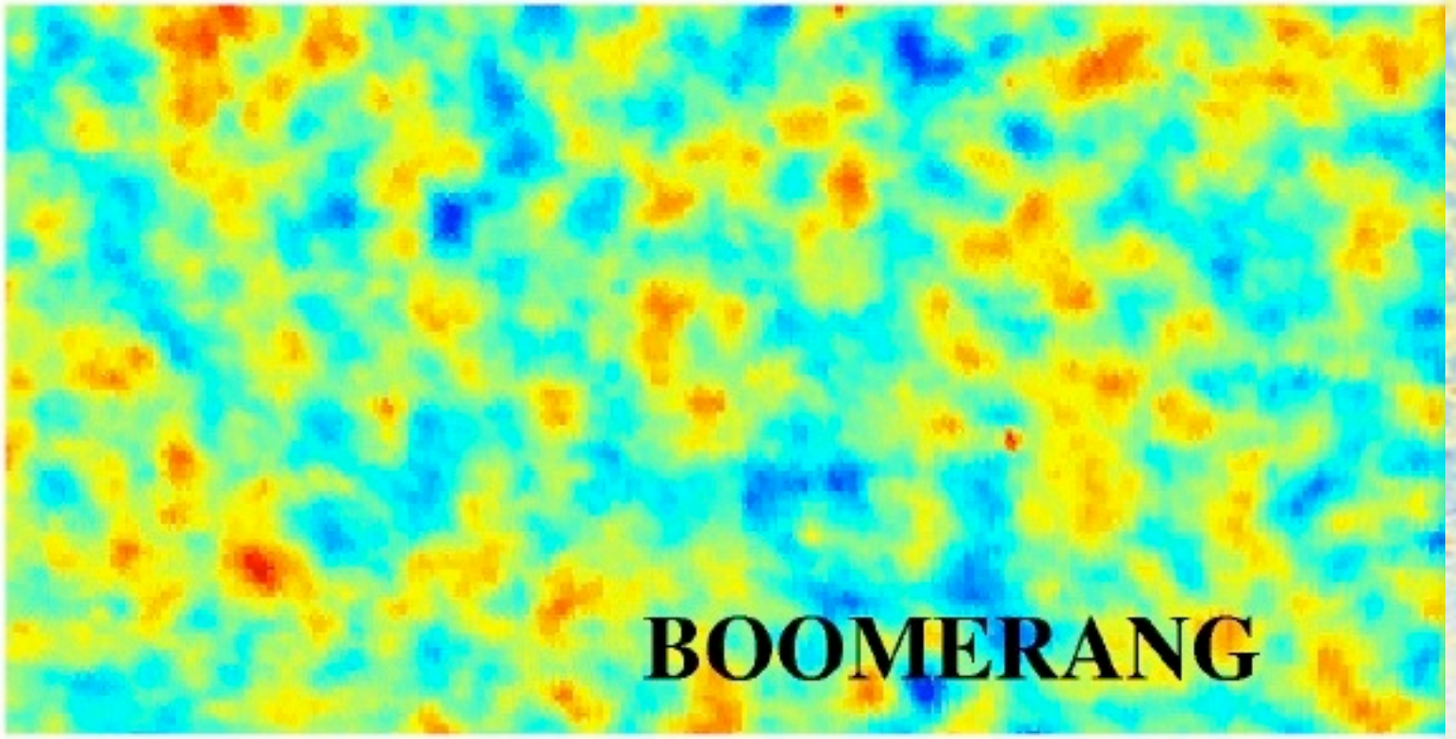

3.4°
−160
−100
−50
0
50
100
160
μK

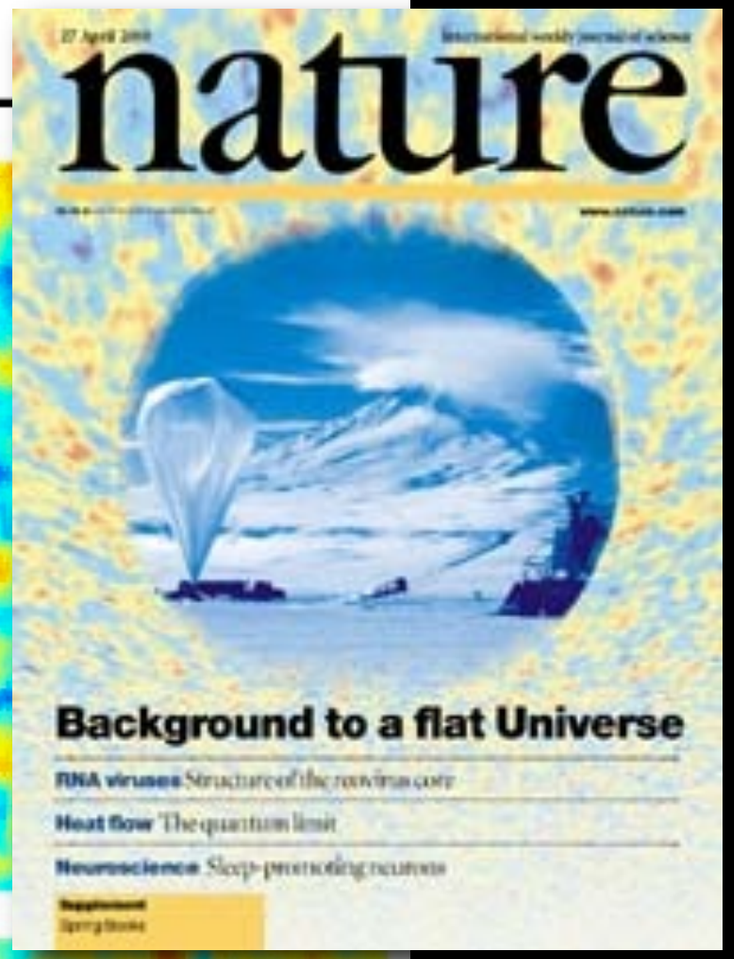
Which is the right one?

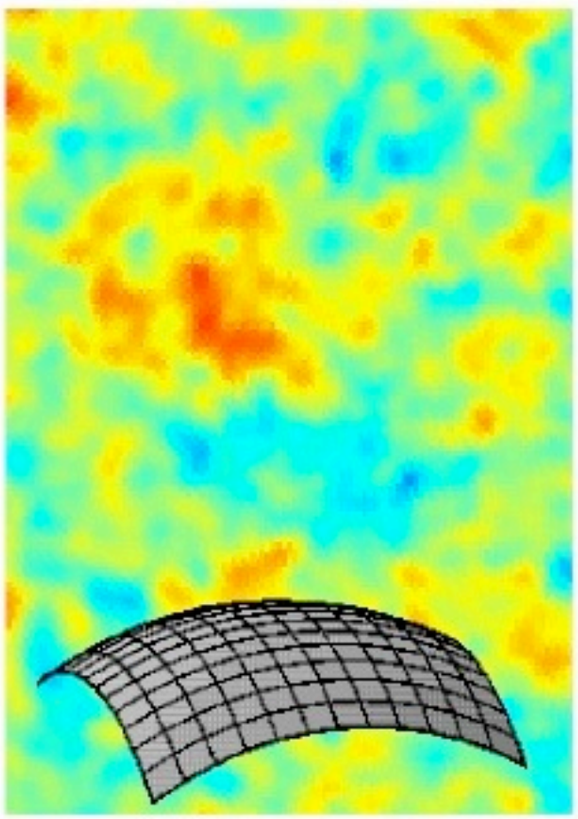


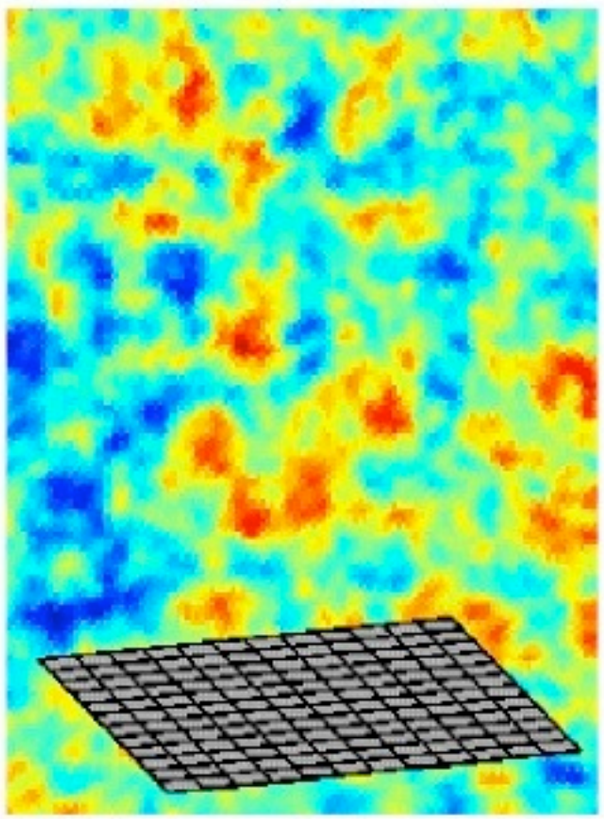
Freedman “Universe” textbook

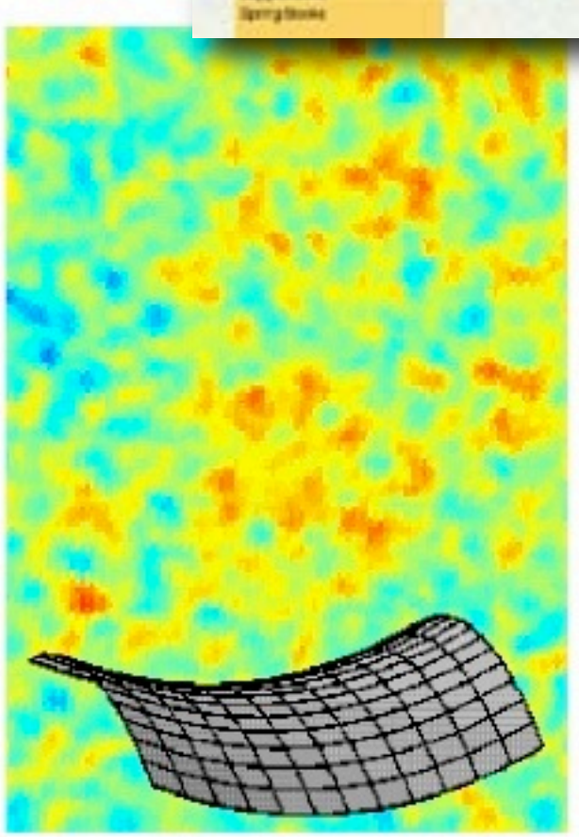
25°





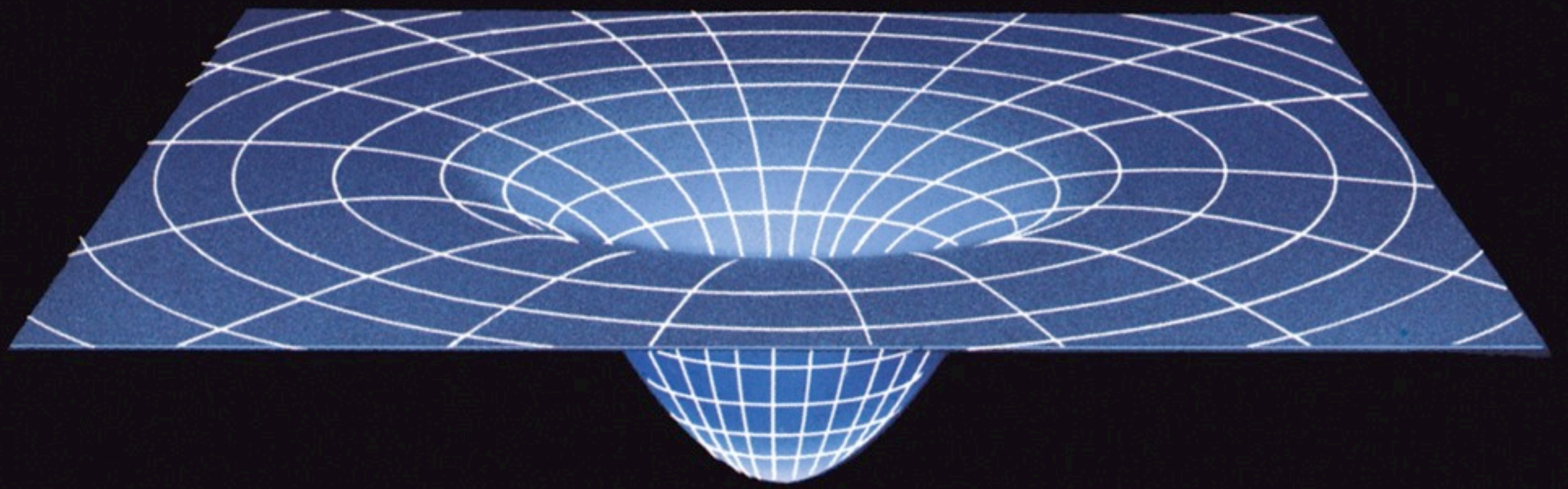






Freedman “Universe” textbook

Einstein:
Matter Curves Space



Since we measured the curvature of universe
→ *we can solve for its density*

Average density of the Universe

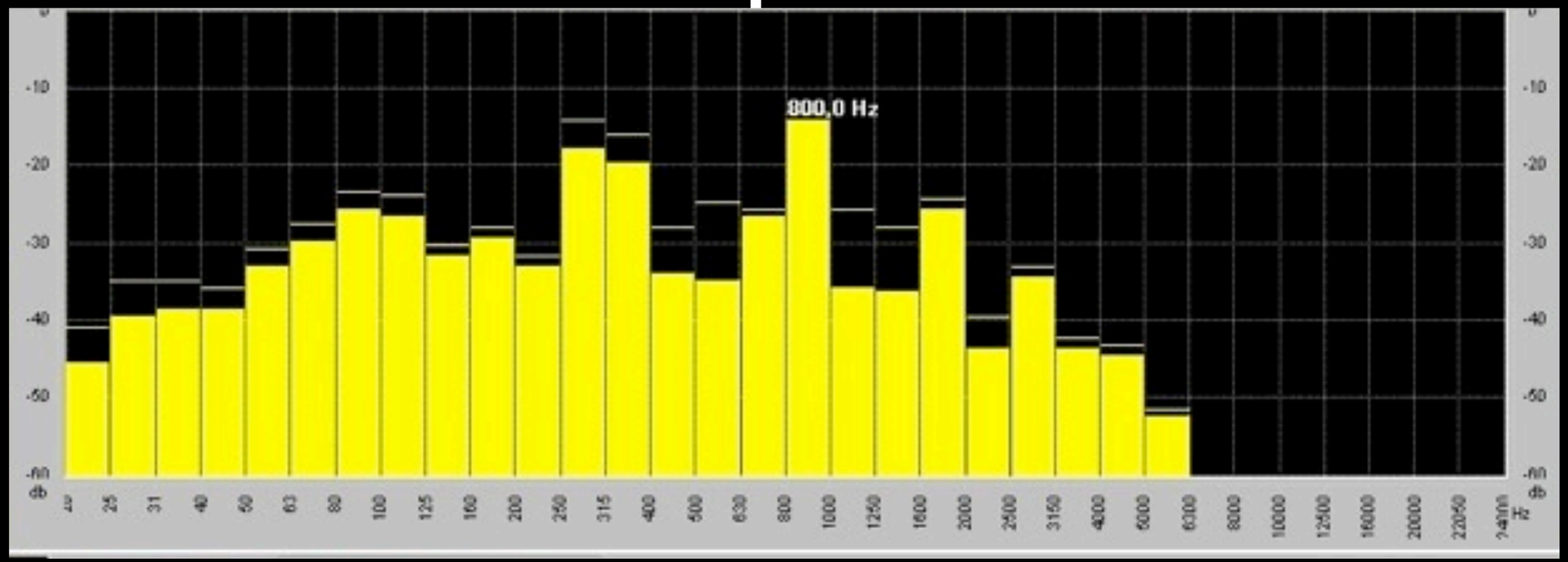
Universe: equivalent to that of roughly 3 hydrogen atoms per cubic meter

Average density of the Universe

Universe: equivalent to that of roughly 3 hydrogen atoms per cubic meter

Density of air in this room: equivalent to roughly 400,000,000,000,000,000,000,000,000 hydrogen atoms per cubic meter

A bit more quantitative…

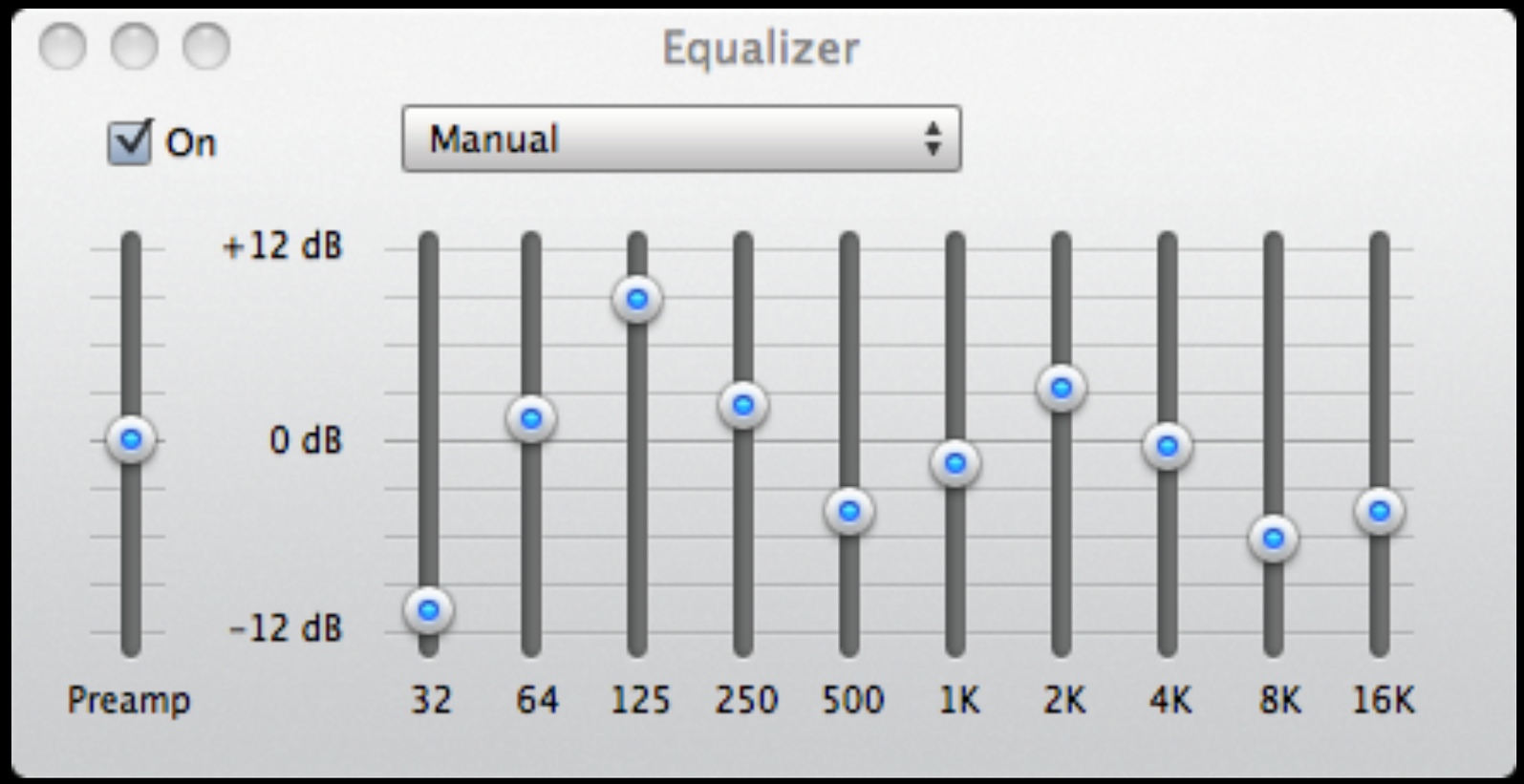


BASS TREBLE

Just like this characterizes the spectrum of sound,
we construct '**angular power spectrum**' to
characterize maps of the cosmic microwave background.

And, it actually reveals the spectrum of sound waves in the early universe.

you've used these before...



DASI & Boomerang results 2001

"All the News That's Fit to Print"

The New York Times

VOL. CL . . . . No. 51,739 Copyright © 2001 The New York Times MONDAY, APRIL 30, 2001

Listen Closely: From Tiny Hum Came Big Bang

By JAMES GLANZ

WASHINGTON, April 29 — Two detectors in Antarctica have discovered minute patterns in a glow from primordial gases, possible traces of the cosmic match that ignited the Big Bang and led to the creation of the universe 14 billion years ago, astronomers announced here today.

The patterns, astronomers said, were probably created by microscopic processes — energy fluctuations at the quantum scale — that were at work when the universe was a tiny fraction of a second old and smaller than a human fist.

The new observations do not see the quantum fluctuations directly, but instead have found traces of colossal waves, much like sound waves, that the fluctuations probably set in motion, rolling the young universe.

The results rest on the most detailed observations ever made of a glow from the hot gases of the early universe. That glow, called cosmic microwave background radiation, carried an imprint of those waves to the detectors on Earth.

The news comes as a relief for astronomers, some of whom started to worry last year that their basic picture of the origins of the universe might be flawed, after detailed observations failed to find the wave patterns.

"We see the structure of the universe in its infancy," said Dr. John Carlstrom, a University of Chicago astrophysicist who leads the team operating the Degree Angular Scale Interferometer, or DASI (pronounced daisy), a microwave detector at a South Pole research station operated by the National Science Foundation.

Dr. Michael Turner, a cosmologist

Continued on Page A8

Scientists Hear the Tiny Hum They Say Ignited the Big Bang

Continued From Page A1

at the University of Chicago who was not involved in the measurements, said that the precise time the fluctuations took place remained to be determined by future measurements, but that the process was likely to have taken place in a fraction of a second comparable to a decimal point followed by 32 zeros and a 1.

"We are living in the most exciting time ever in cosmology," he added.

Besides DASI, which also involved astronomers at the California Institute of Technology, the announcement today included the so-called Boomerang team. This group flew a balloon-borne detector around Antarctica, and includes astronomers from the United States, Italy, Canada and Britain. Antarctica is excellent for such observations because the air is thin and dry and does not strongly absorb microwave radiation.

Dr. John Ruhl of the University of California at Santa Barbara presented results today for the Boomerang team. The announcements took place at a meeting of the American Physical Society.

The Antarctica studies were buttressed today when another group of researchers reported that they had made less distinct observations of the wave patterns from the United States. That team, called Maxima, includes astronomers at the University of Minnesota and the University of California at Berkeley.

The leading theory of how the universe could have exploded out of the primordial nothingness, known as the theory of inflation, predicts that the quantum fluctuations should have rattled the universe in such a way that it resonated like a vast organ pipe, with one main tone, or wavelength, and a series of overtones or harmonics.

Last year, the Boomerang team detected the main tone but found no clear evidence for the overtones, raising the possibility that the inflation theory could be wrong. Since much of the information about the fluctuations, like their relative intensity and spectrum, would reside in the characteristics of the overtones, those results raised the prospect that few remnants of the initial spark might be found.

Today, the three teams announced that they had seen two of the overtones for the first time. In musical terms, the observations saw the first two harmonics above the main tone.

"We do see two more bumps and wiggles out there," Dr. Ruhl said. "We can move to the question of, 'What do these bumps and wiggles tell us?' "

Dr. Max Tegmark, a cosmologist at the University of Pennsylvania, said that while the new results were still far from absolute proof of the inflation theory, their agreement with the theory was uncanny and would cast doubt on alternative models. "It's even scary that things agree this well," he said. "This is a very bad day for the competition."

Some other scientists, including Dr. Andrew Lange of Caltech, a leader of the Boomerang group, said the results strikingly showed that cosmologists understood the composition and behavior of the universe in the first few hundred thousand years of its life. It was then that the sound waves were humming through the young cosmos; astronomers believe the microwave background radiation was emitted as the universe cooled below a critical temperature when it was about 400,000 years old.

"We've really been waiting for the other shoe to drop," Dr. Lange said in reference to the lengthy search for the overtones. "What we're confirming for the first time is a very generic prediction of modern cosmology."

Although astronomers said much more detailed observations, including the discovery of further overtones, would be required to define the quantum fluctuations and to verify inflation, the results are likely to be seen as major victories for two scientists in particular.

The first, Dr. Alan Guth of the Massachusetts Institute of Technology, developed the germ of the inflation model in 1980, a theory he has called "the ultimate free lunch" because it shows how the entire universe could have exploded out of nothing and impressed the quantum fluctuations on the cosmos.

The results also provide major support for ideas closely associated with Dr. David Schramm, a Chicago cosmologist who died in a plane crash late in 1997. Dr. Schramm and his colleagues worked out a theory, unrelated to inflation, using trace elements created in the Big Bang explosion to gauge the amount of ordinary matter in the universe.

Those values agree closely with the amounts deduced from the intensity of the sound wave overtones; that intensity is affected by the sloshing of matter in the sound waves' peaks and troughs.

On the other hand, the results also leave cosmologists with some deep and perhaps troubling questions.

For example, the new observations confirm that most of the cosmos seems to be made of so-called dark matter and dark energy, possibly particles or energy lurking somewhere in space but still never detected directly. Dr. Turner, of Chicago, said skeptics might well term that picture "the absurd universe, or the preposterous universe."

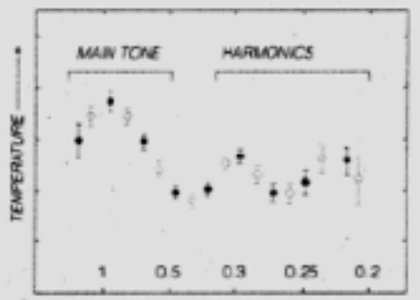
Sir Martin Rees, an astrophysicist at Cambridge University, said scientists were left with the question of whether fundamental physical laws would someday explain that strange mixture of ingredients, or whether the precise amounts were a sort of accident of how the universe came into being — something like snowflakes, each of which has a hexagonal symmetry but carries a pattern that is otherwise unique.

"It may well turn out that the underlying laws do not give us these numbers, any more than they give the detailed patters of a snowflake," Sir Martin said.

'Listening' to the Origin of the Universe

Measurements of a faint, pervasive radiation throughout space bolster a theory of the universe's origin.

THE MEASUREMENT



Tiny fluctuations in the temperature of wide stretches of sky carry the imprint of a wave of sound like one resonating from an organ pipe. The main tone is a tall peak, and the overtones, or harmonics, have smaller peaks. This "ringing" is predicted by the theory of inflation.

INFLATION THEORY AND THE BIG BANG

Intense, fluctuating energies fill a tiny point, setting it ringing.

It rapidly expands, stretching the fabric of space as well as the fluctuations....

...which ignites the Big Bang, creating a hot, dense soup of particles. The expanding universe continues to resonate as it cools.

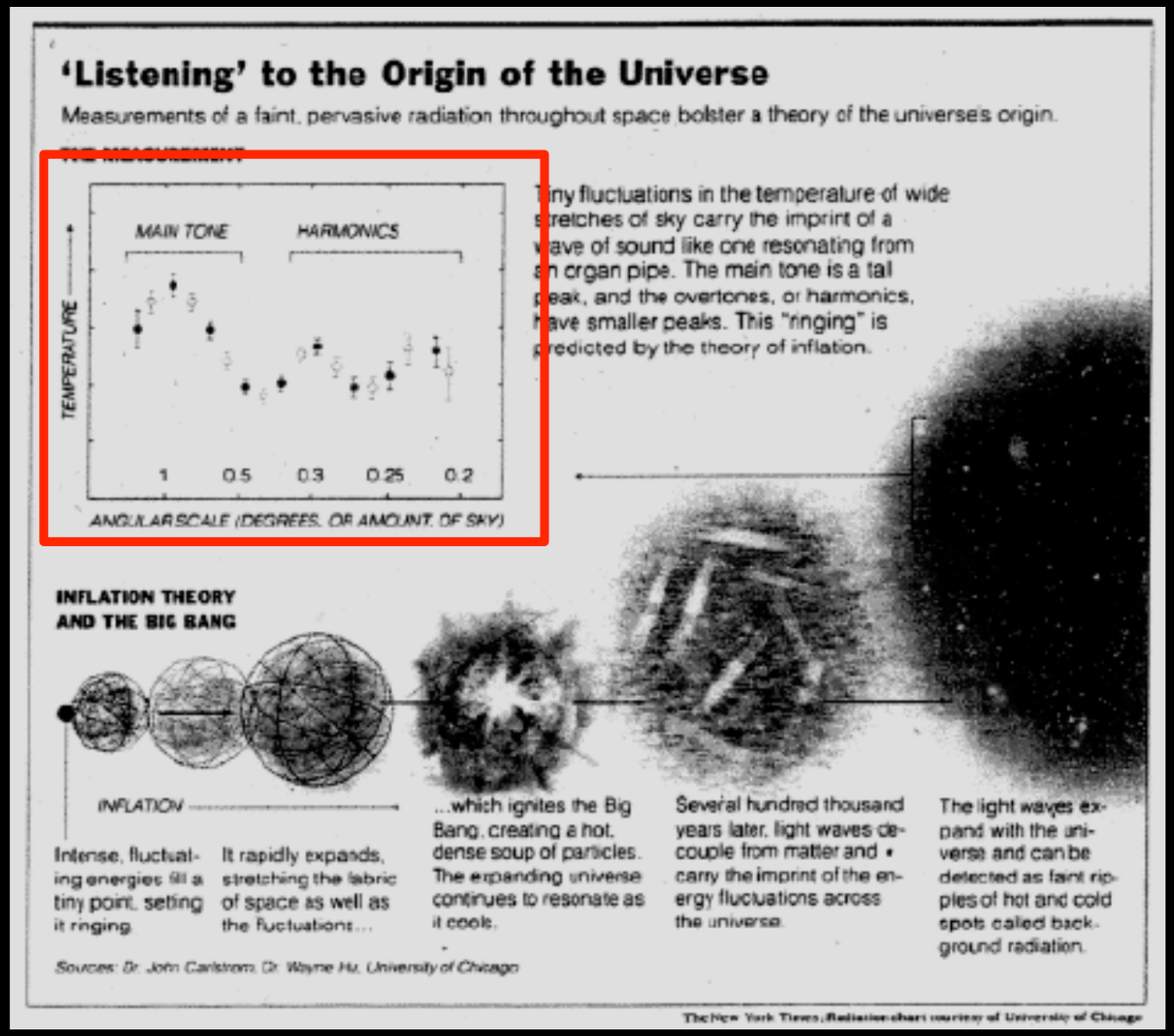
Several hundred thousand years later, light waves decouple from matter and carry the imprint of the energy fluctuations across the universe.

The light waves expand with the universe and can be detected as faint ripples of hot and cold spots called background radiation.

Sources: Dr. John Carlstrom, Dr. Wayne Hu, University of Chicago

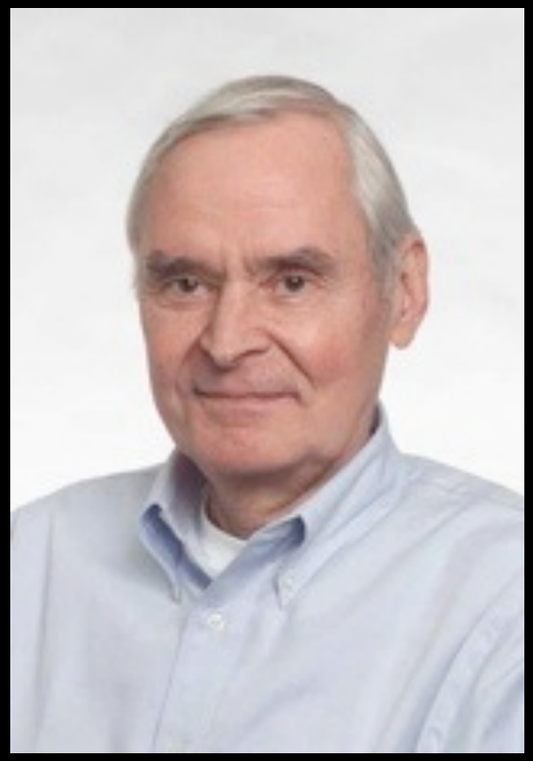
The New York Times, Reuters chart courtesy of University of Chicago

spectrum of the universe in the daily paper

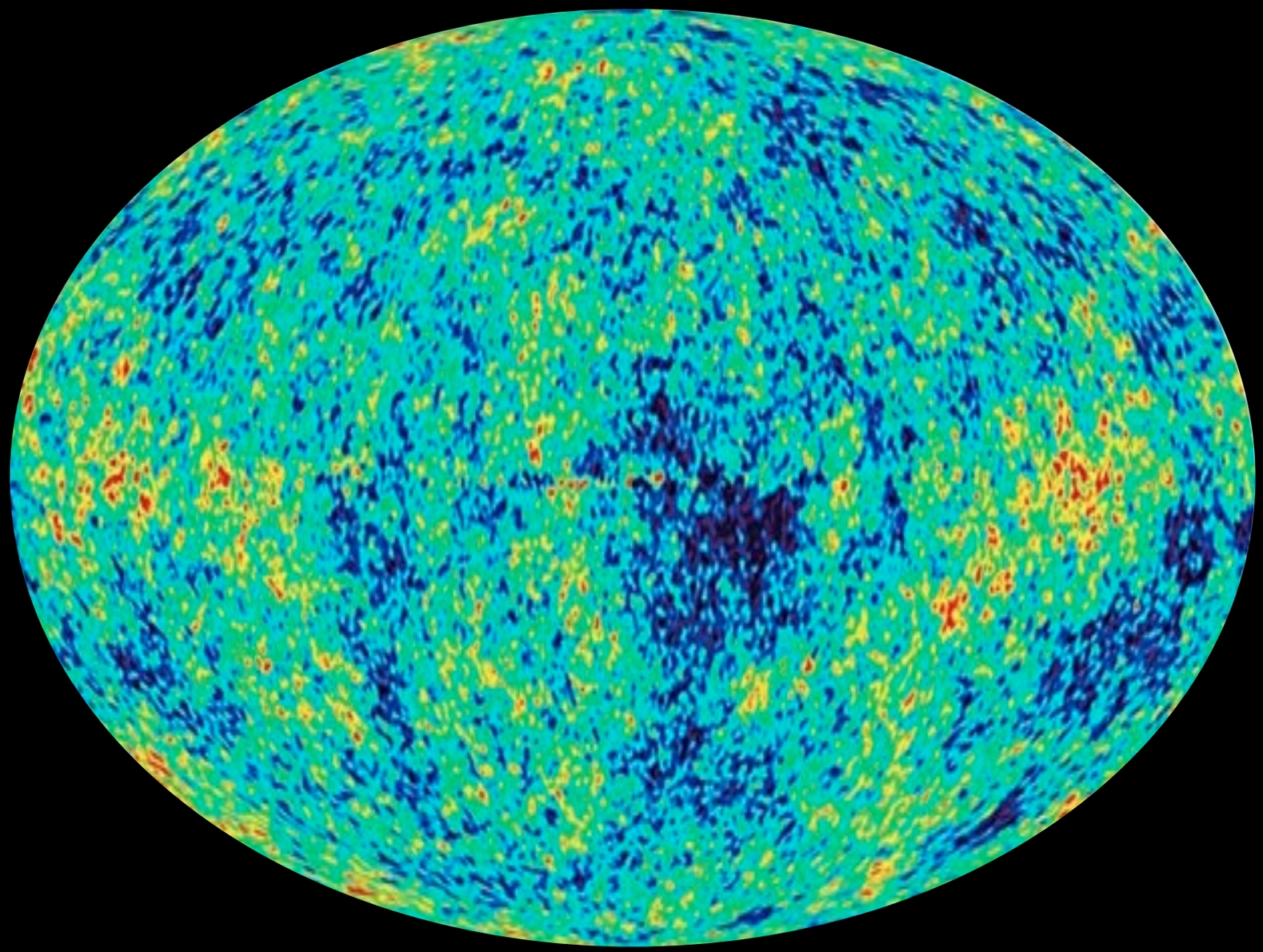


Analysis of the sounds waves in the early universe determines what stuff makes up the universe.

Wilkinson Microwave Anisotropy Probe (WMAP)



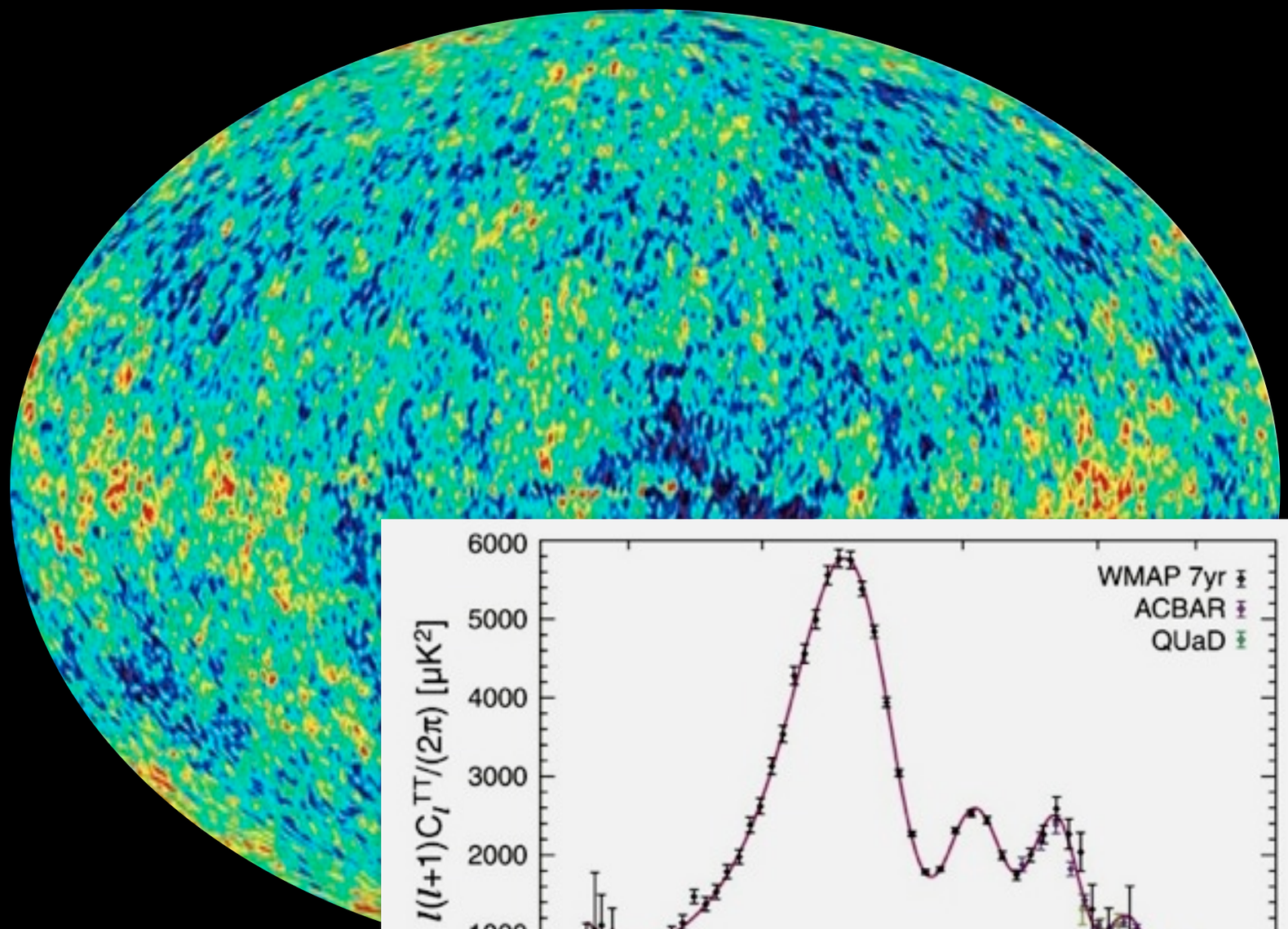
David Wilkinson
1935-2002



WMAP

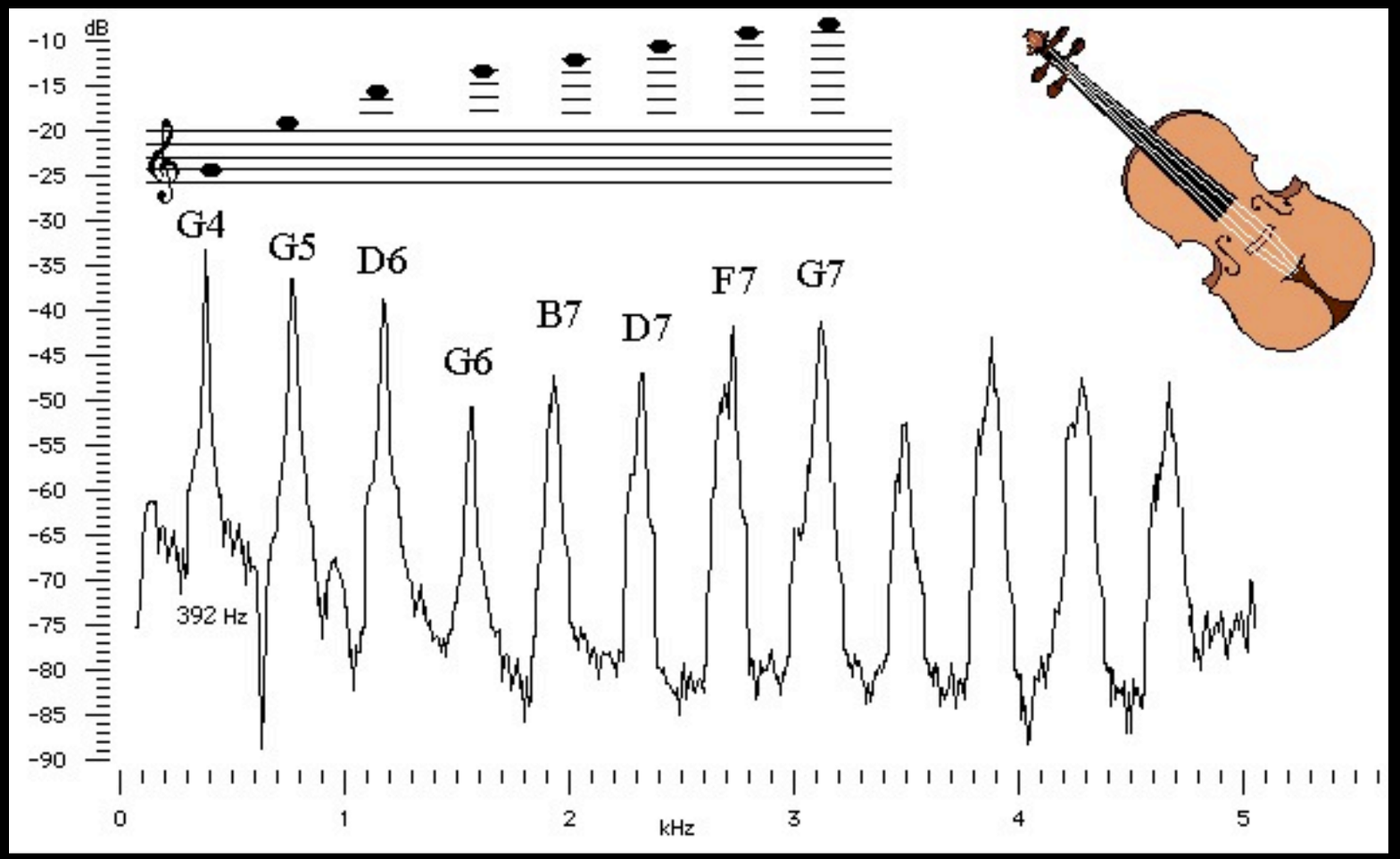
Wilkinson Microwave Anisotropy Probe (WMAP)

David Wilkinson
1935-2002



WMAP

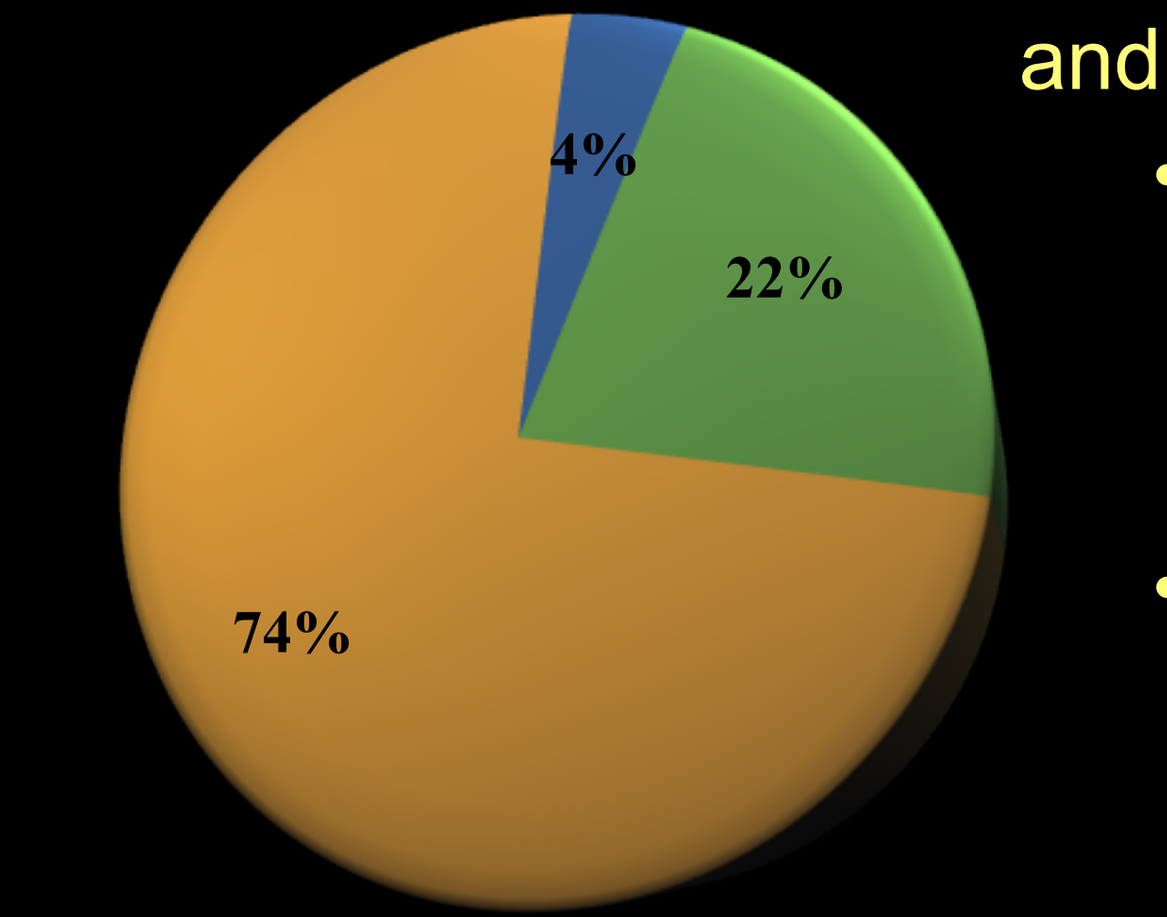
An instrument's tone depends on its harmonic content



Analysis of the sounds waves in the early universe determines what stuff makes up the universe.

From Murray Bourne at http://www.intmath.com/fourier-series/6-line-spectrum.php

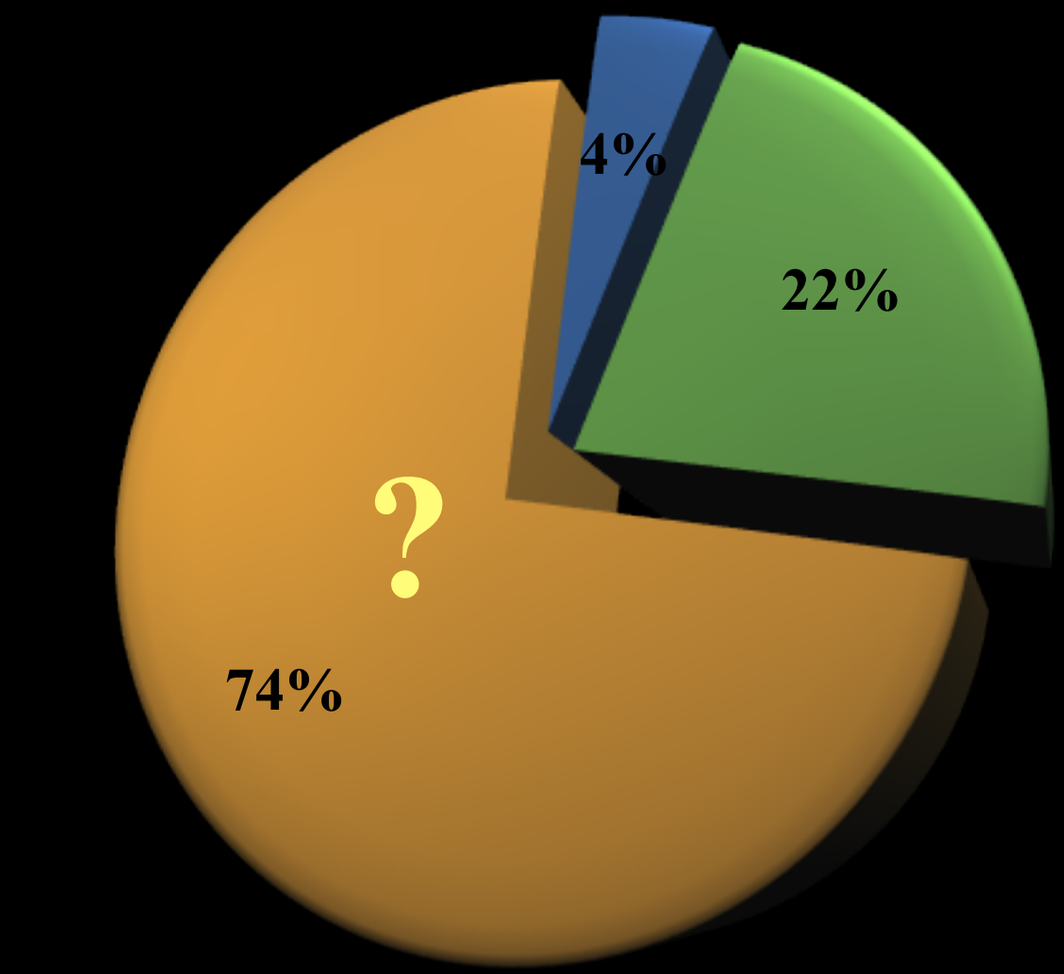
What stuff makes up the universe?



We solve for amount of ordinary and dark matter directly.

- **Ordinary matter**, the stuff we are made out of, all the stuff in your science books, is a measly 4.4%.
- **Dark Matter** dominates ordinary matter just as in galaxies. But, it still does not make up most of the universe!

What stuff makes up the universe?

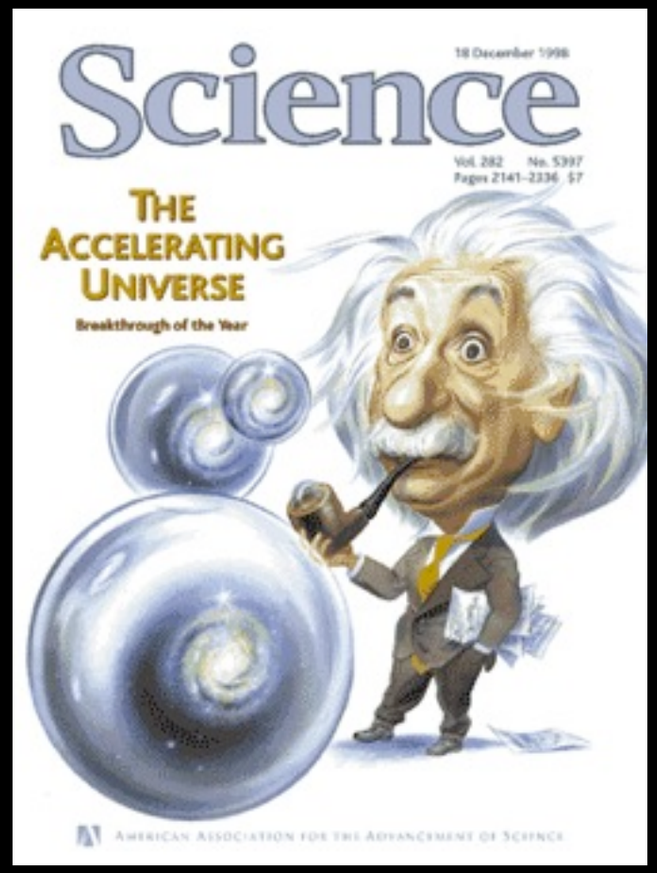


- We're left with **Dark Energy**, which we need to make the total come out right.

- The dark energy seems consistent with Einstein's cosmological constant, Λ !

ORDINARY MATTER
DARK MATTER
DARK ENERGY (!)

Cosmic Acceleration from Dark Energy?



Nobel Prize

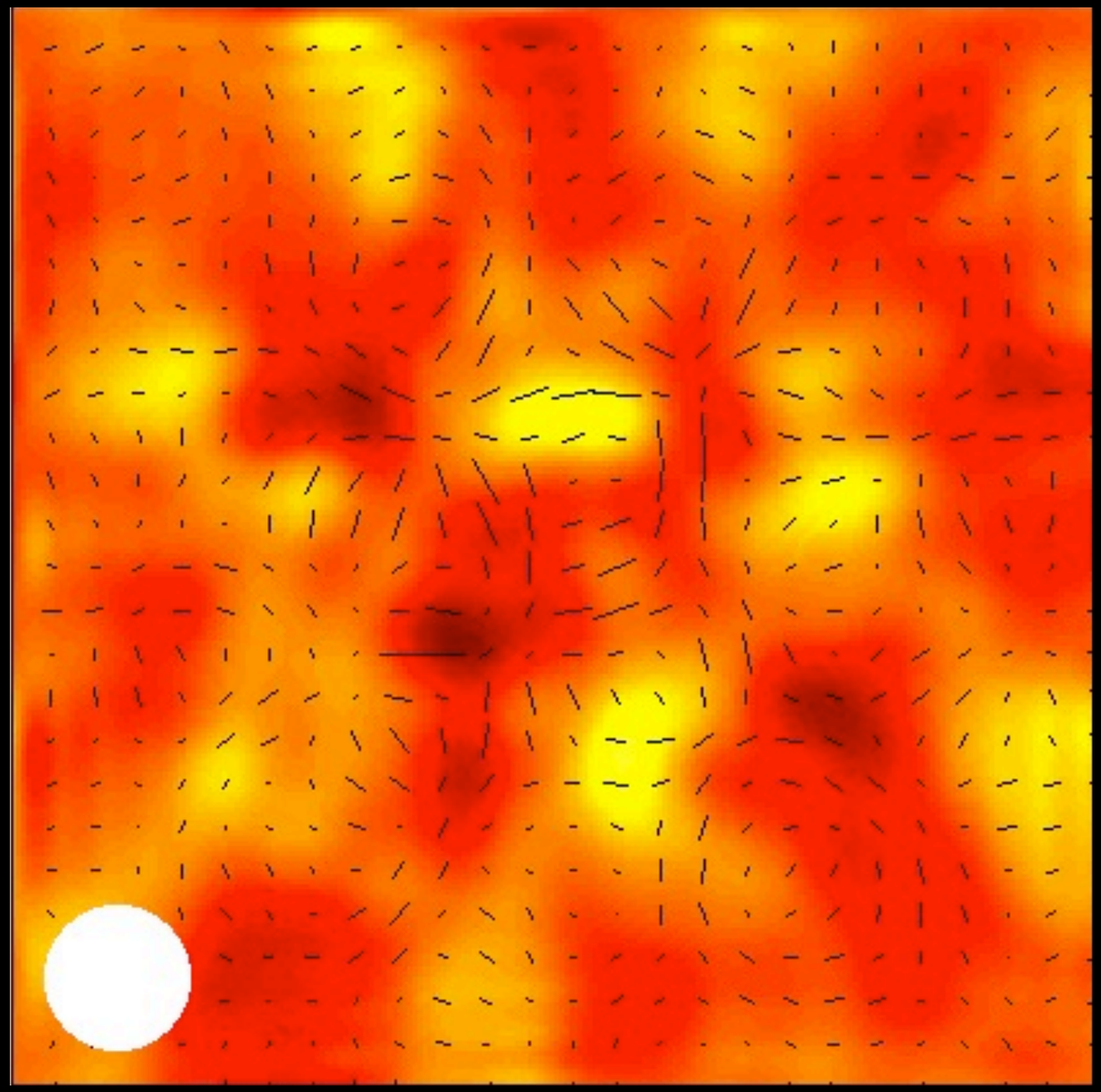
Physics 2011

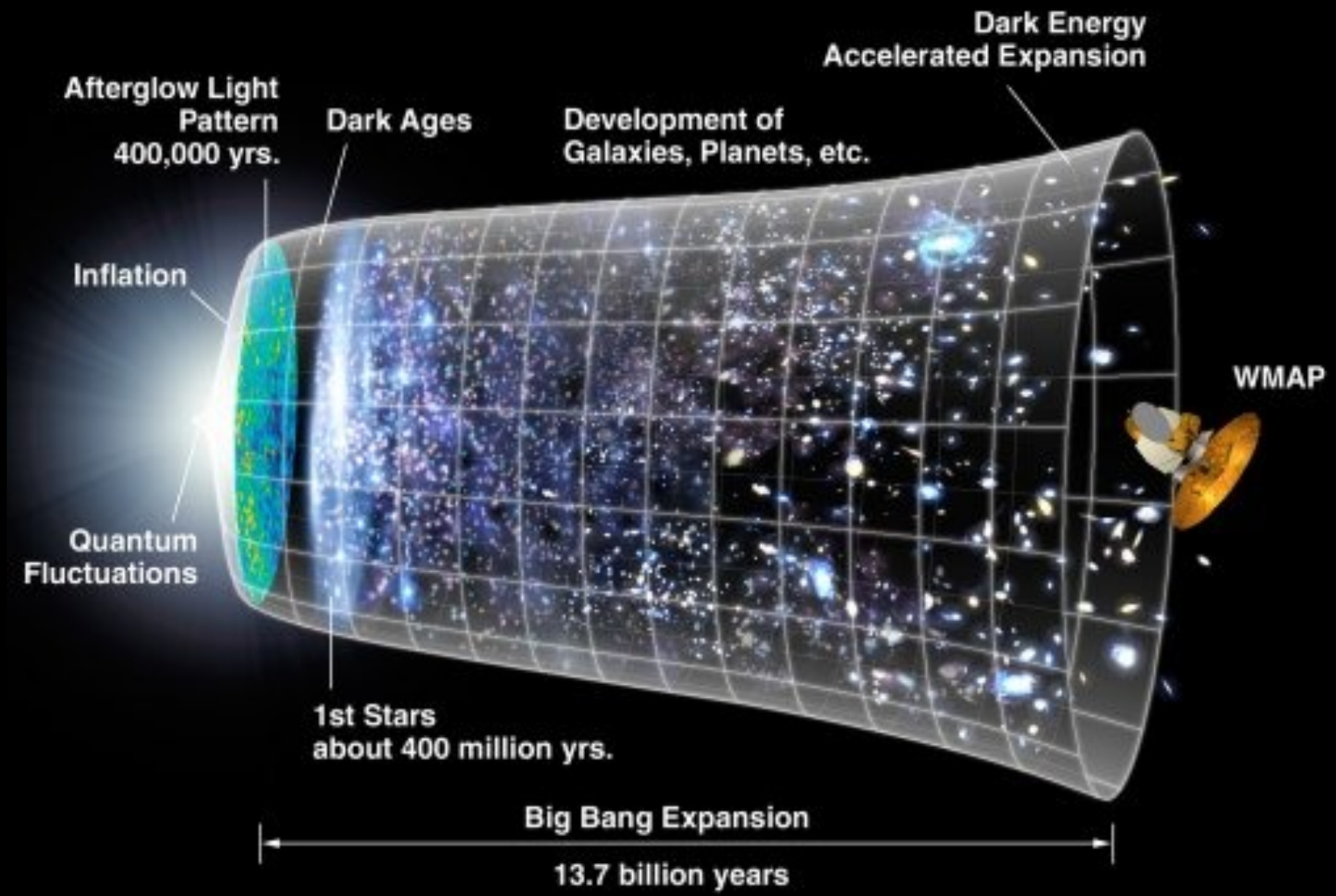
A test of the theoretical framework: Polarization of the CMB

Scattering leads to polarization - the CMB must be polarized

✓ It's polarized

2002 DASI measures CMB polarization

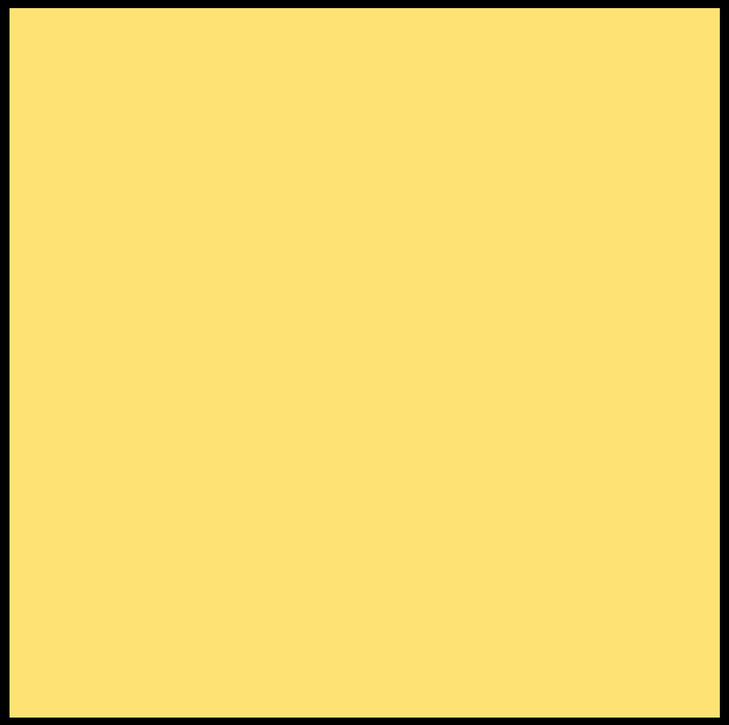



Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

NASA/WMAP

Evolution of the universe

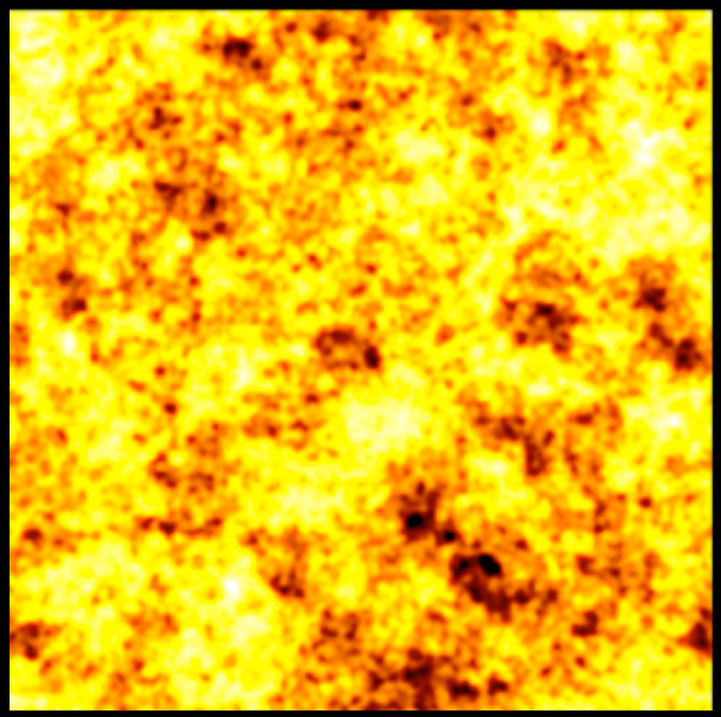
Cosmic Microwave Background



Slide courtesy Erik Leitch

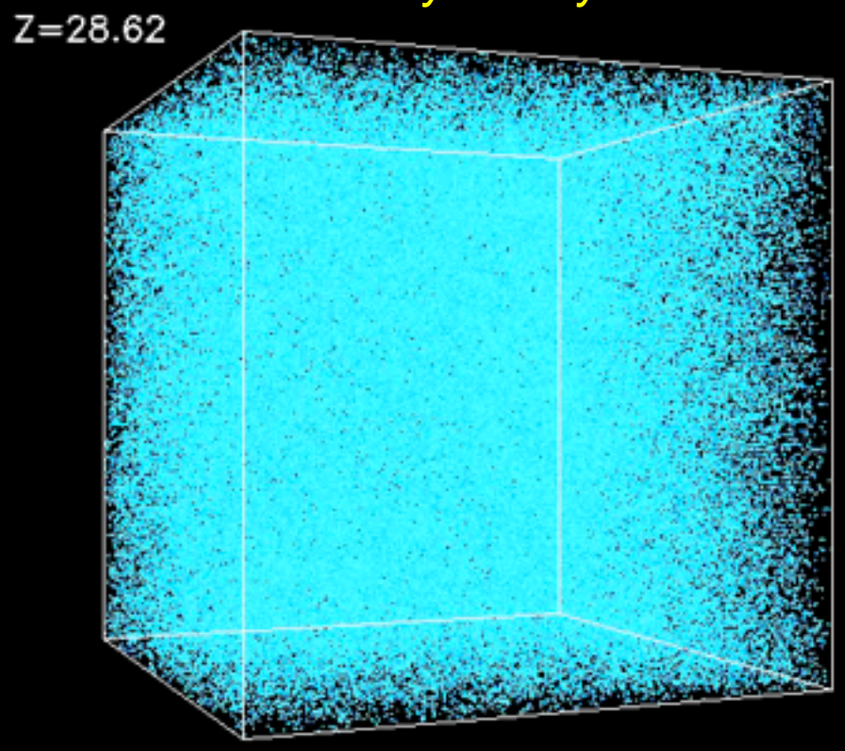
Evolution of the universe

Cosmic Microwave Background



Structure formation

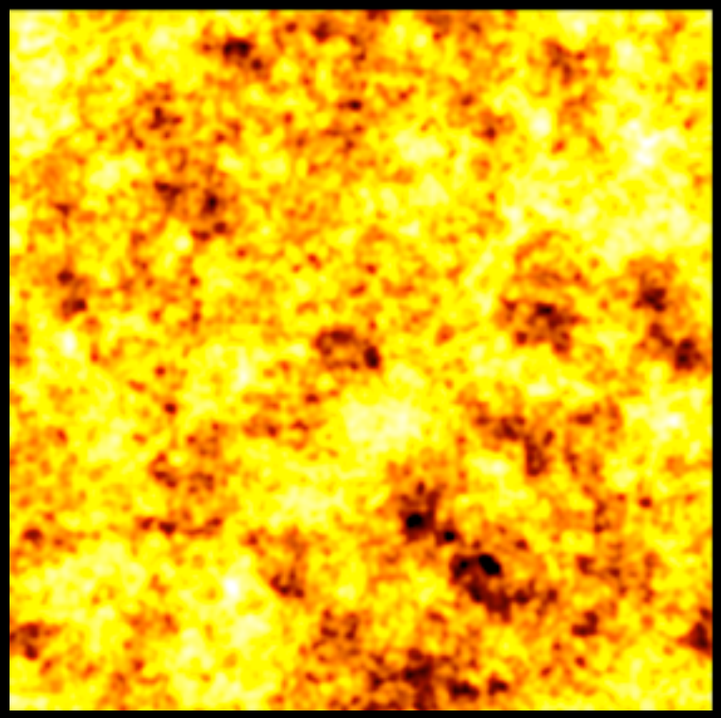
simulation by Andrey Kravstov



Slide courtesy Erik Leitch

Evolution of the universe

Cosmic Microwave Background



Structure formation

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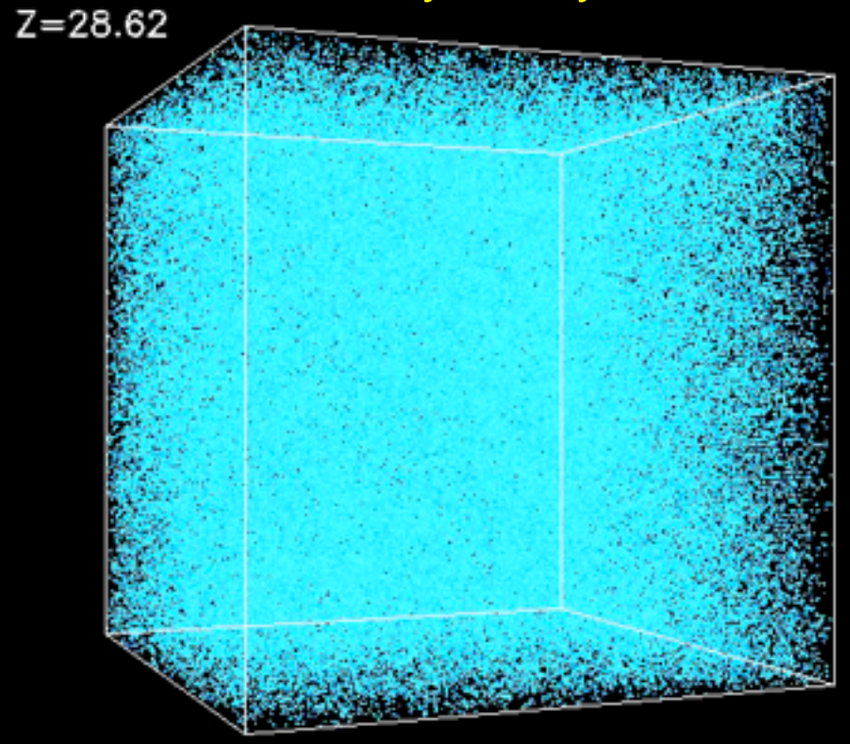
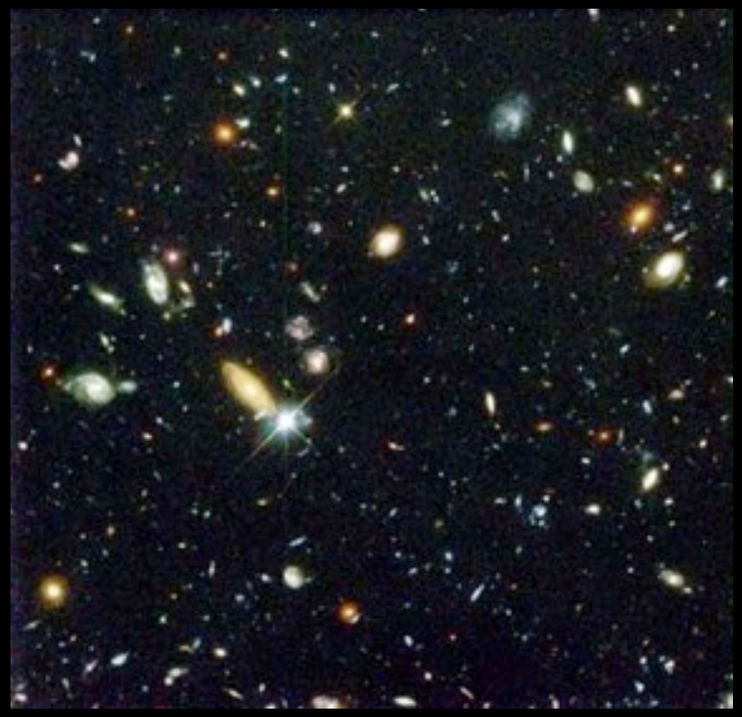


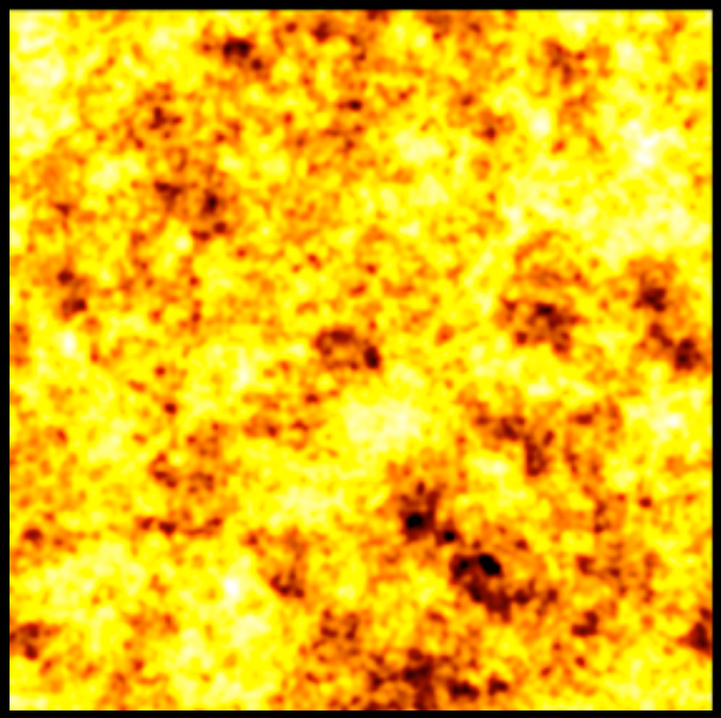
The "recent" universe



Slide courtesy Erik Leitch

Evolution of the universe

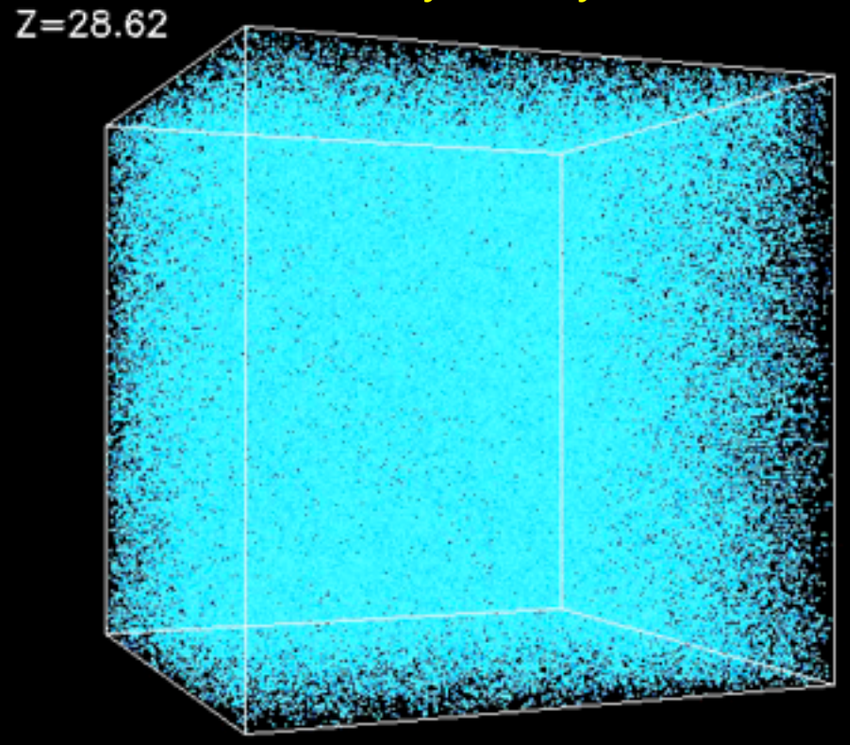
Cosmic Microwave Background



less than 1 day

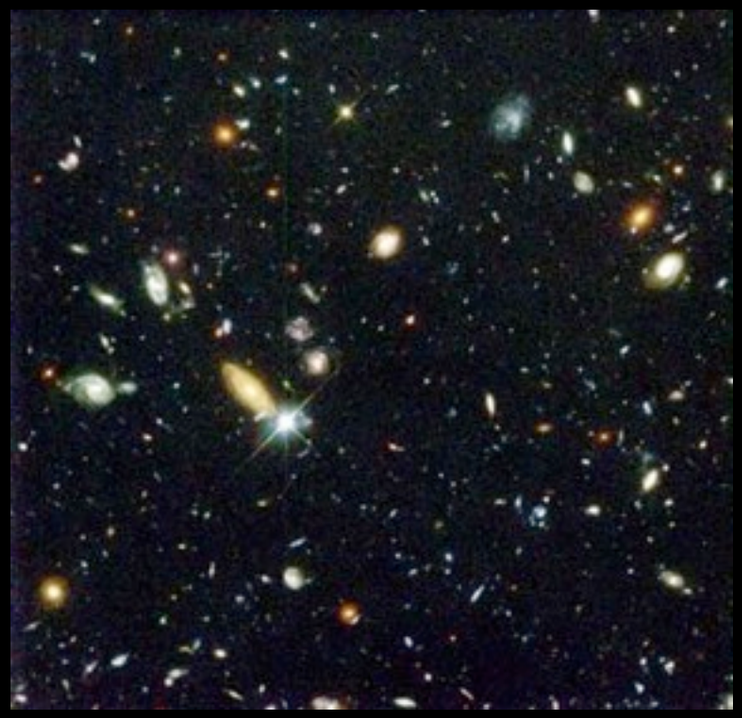
Structure formation

simulation by Andrey Kravstov



first few years

The "recent" universe



Just retired

People equivalent lifetimes

Slide courtesy Erik Leitch

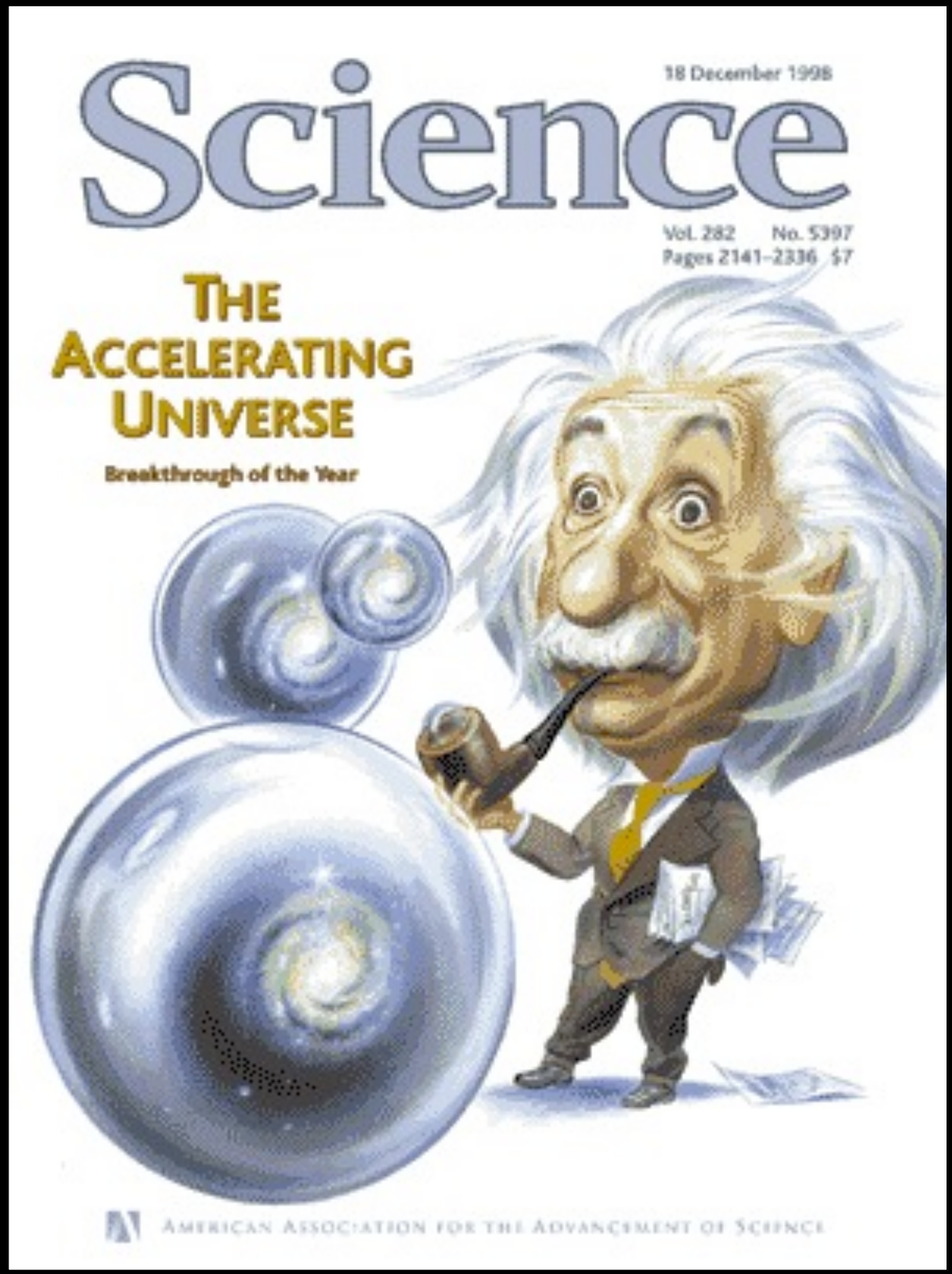
Standard model of Cosmology

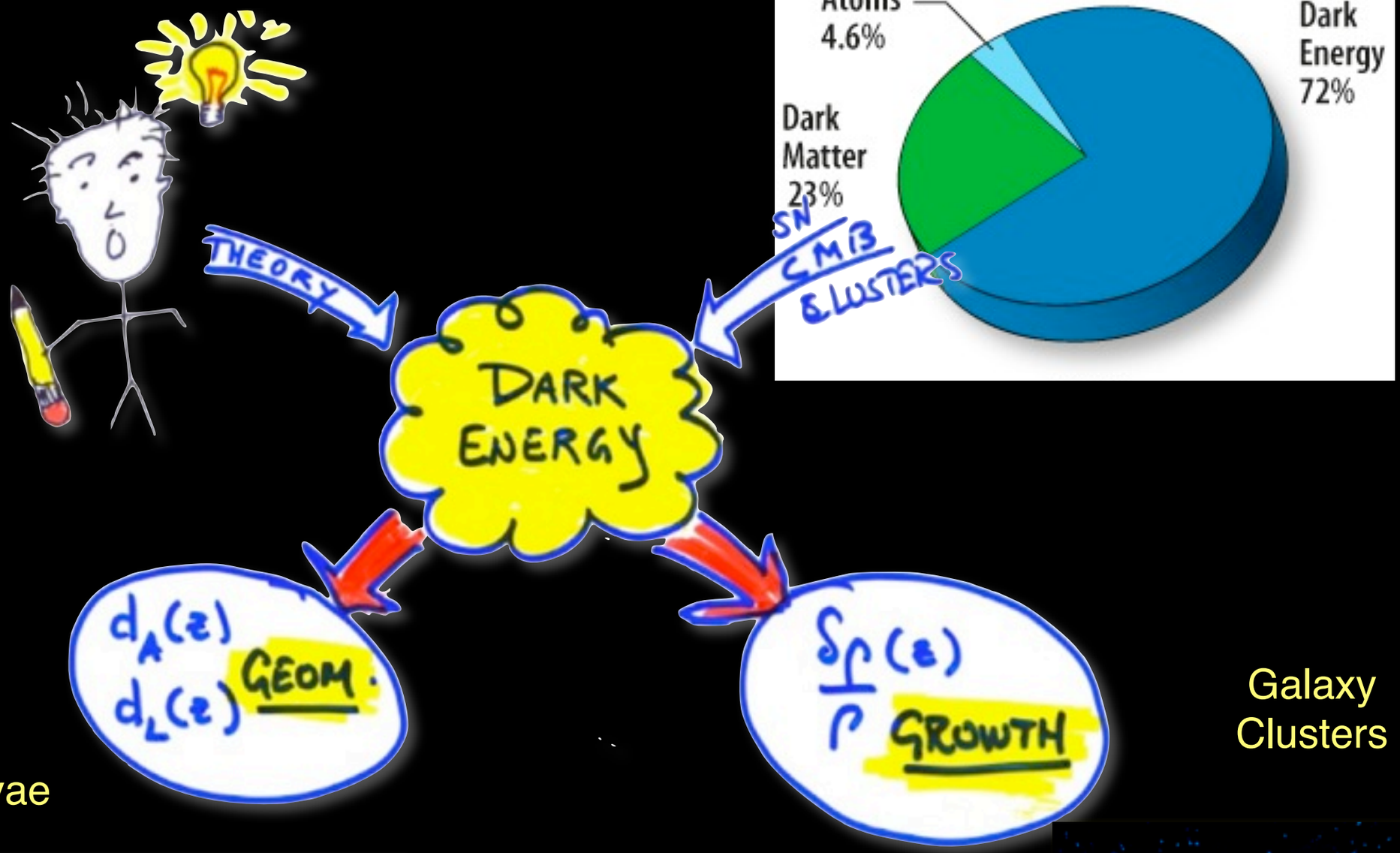
Rests upon three mysterious pillars

All implicate new fundamental physics!

Slide from M. Turner

... what is dark energy ?

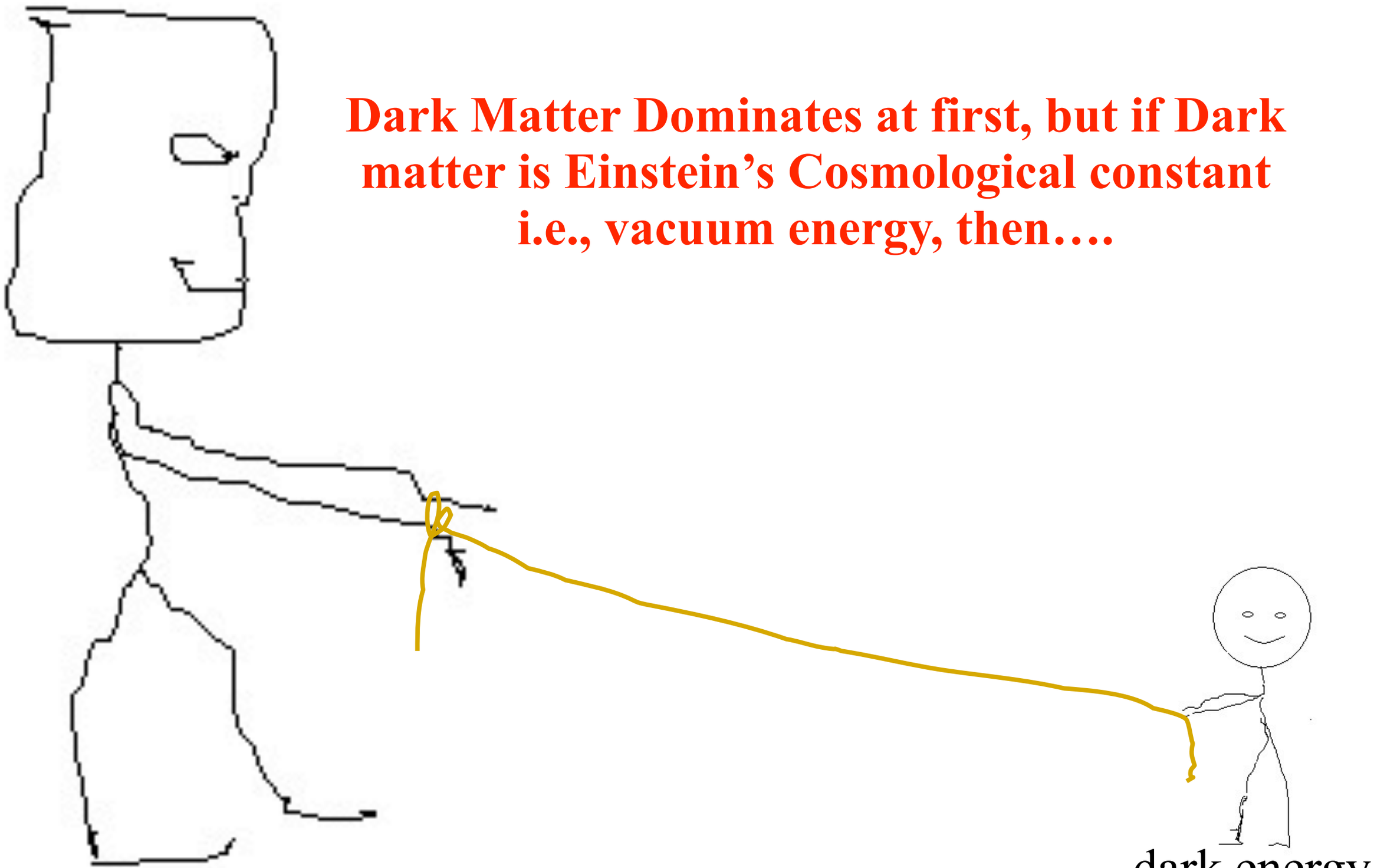




We need both geometrical and gravity tests

Dark Matter and Dark Energy Tug of War

Dark Matter Dominates at first, but if Dark matter is Einstein's Cosmological constant i.e., vacuum energy, then….



as the universe expands…

Dark Matter

dark energy

Today, Mr. Dark Energy dominates 2 to 1

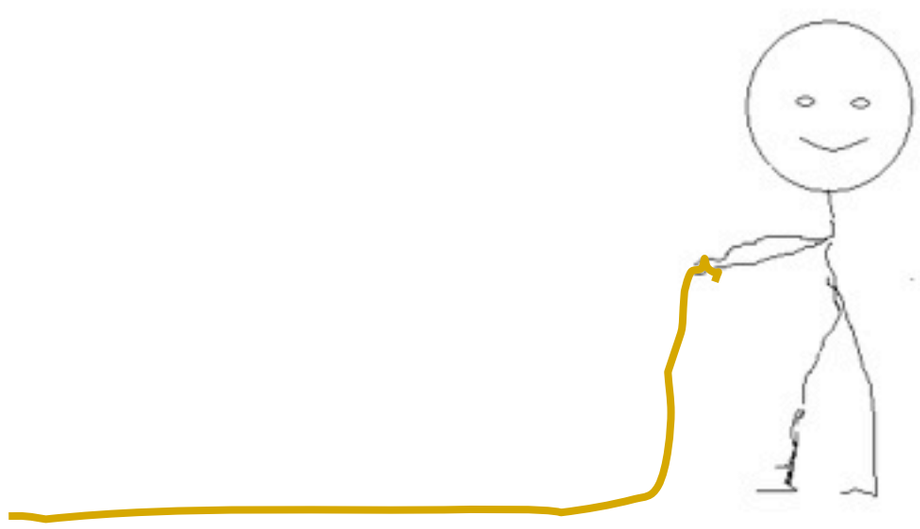
dark matter

Mr. Dark Energy

Soon, it's just Mr. Dark Energy's Universe

(vacuum is not diluted with expansion like matter)

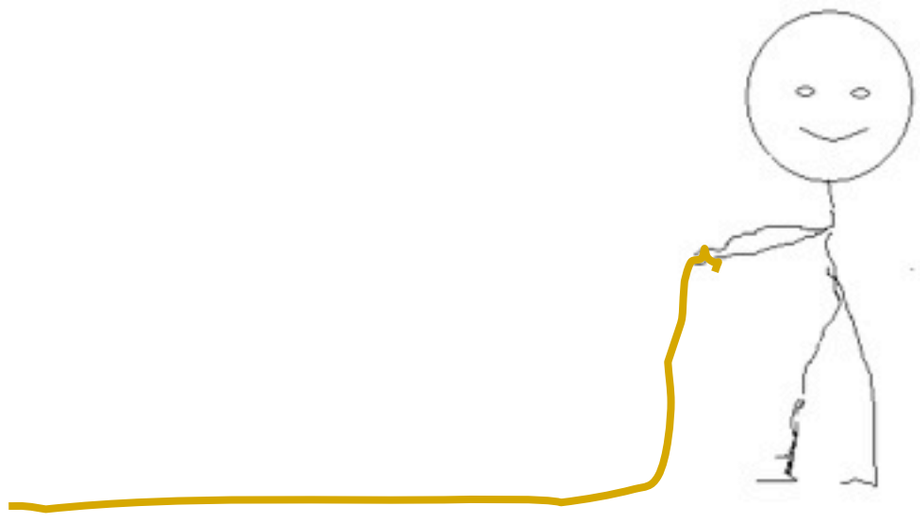
Mr. Dark Energy



Soon, it's just Mr. Dark Energy's Universe
(vacuum is not diluted with expansion like matter)

Seems crazy!

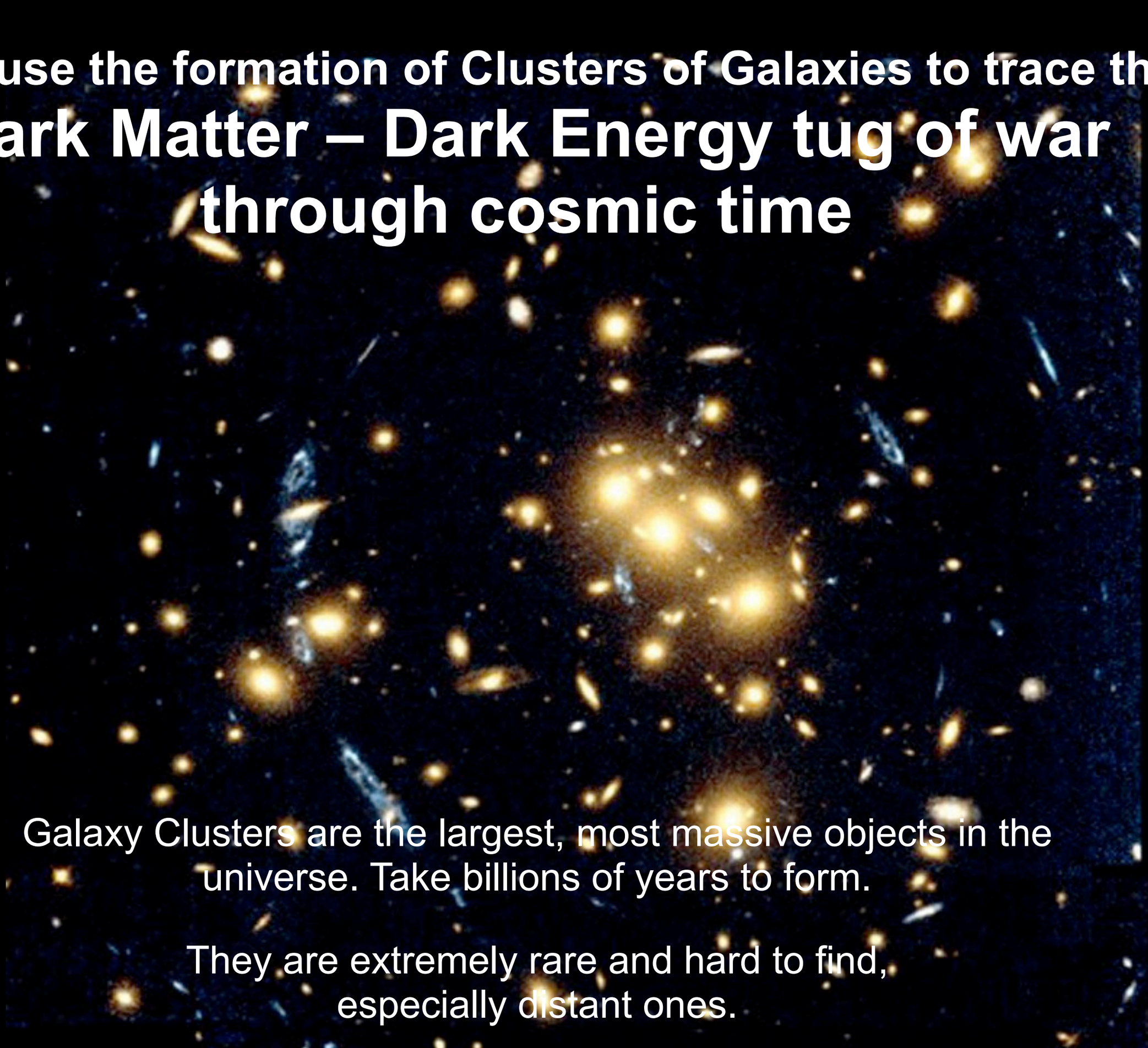
Mr. Dark Energy



We need to test this

We'll use the formation of Clusters of Galaxies to trace the

Dark Matter – Dark Energy tug of war through cosmic time



Galaxy Clusters are the largest, most massive objects in the universe. Take billions of years to form.

They are extremely rare and hard to find, especially distant ones.

Abell 1689 Hubble Space Telescope

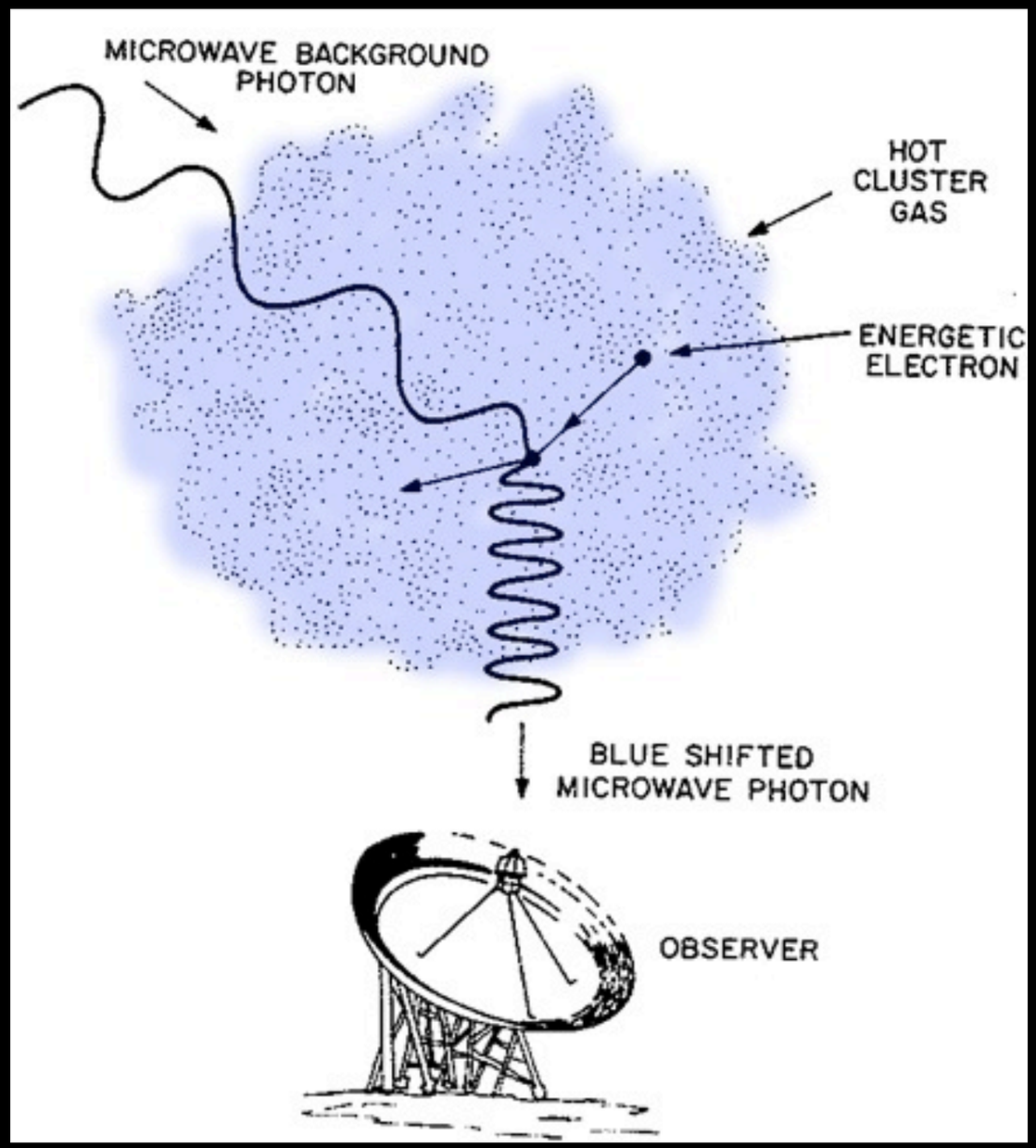
Clusters are mainly hot gas and dark matter

Abell 1689 X-ray (Chandra) and optical (HST) emission

Clusters are mainly hot gas and dark matter

Abell 1689 X-ray (Chandra satellite)

The Sunyaev-Zel'dovich (SZ) Effect: *Shadows against the cosmic background*

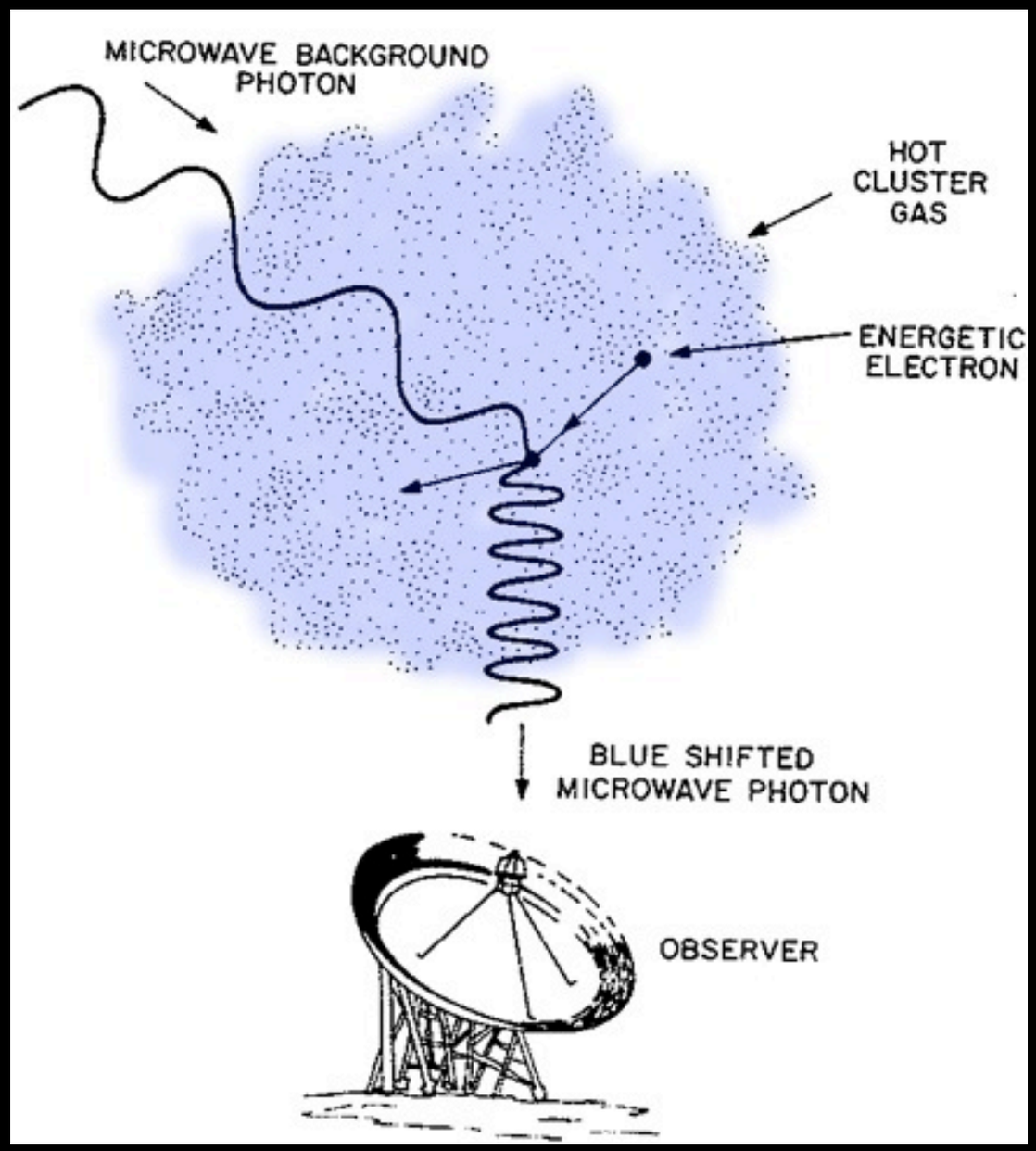


The SZ-effect provides a method to find ALL clusters, no matter how distant, so we can map out the growth of structure in the universe.

i.e., trace the Dark Energy - Dark Matter tug of war through cosmic time.

from L. Van Speybroeck

The Sunyaev-Zel'do
Shadows against the c



The S
metho
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Dark
throu

from L. Van Speybroeck

The 10 meter South Pole Telescope (SPT)

A 700,000 lb SZ machine:

- clean low-noise design
- BIG field of view for mapping large regions
- 10 meters gives 1 arcminute resolution to match cluster scales
  (about the resolution of your eye)

State of the art millimeter-wave camera:

- 960 ultra-sensitive superconducting detectors operating at 0.25 K (-459 F)

photo by Dana Hrubes


Argonne
NATIONAL LABORATORY
BERKELEY LAB
NIST
KICP
Kavli Institute
for Cosmological Physics
AT THE UNIVERSITY OF CHICAGO
Berkeley
University of California
THE UNIVERSITY OF
CHICAGO
LMU
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UNIVERSITÄT
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UC DAVIS
UNIVERSITY OF CALIFORNIA
CARDIFF
UNIVERSITY
PRIFYSGOL
CAERDYDD

the C17 Globemaster


C135 CNC


U.S. AIR FORCE
8203

the LC130 Hercules

South Pole Station


21094

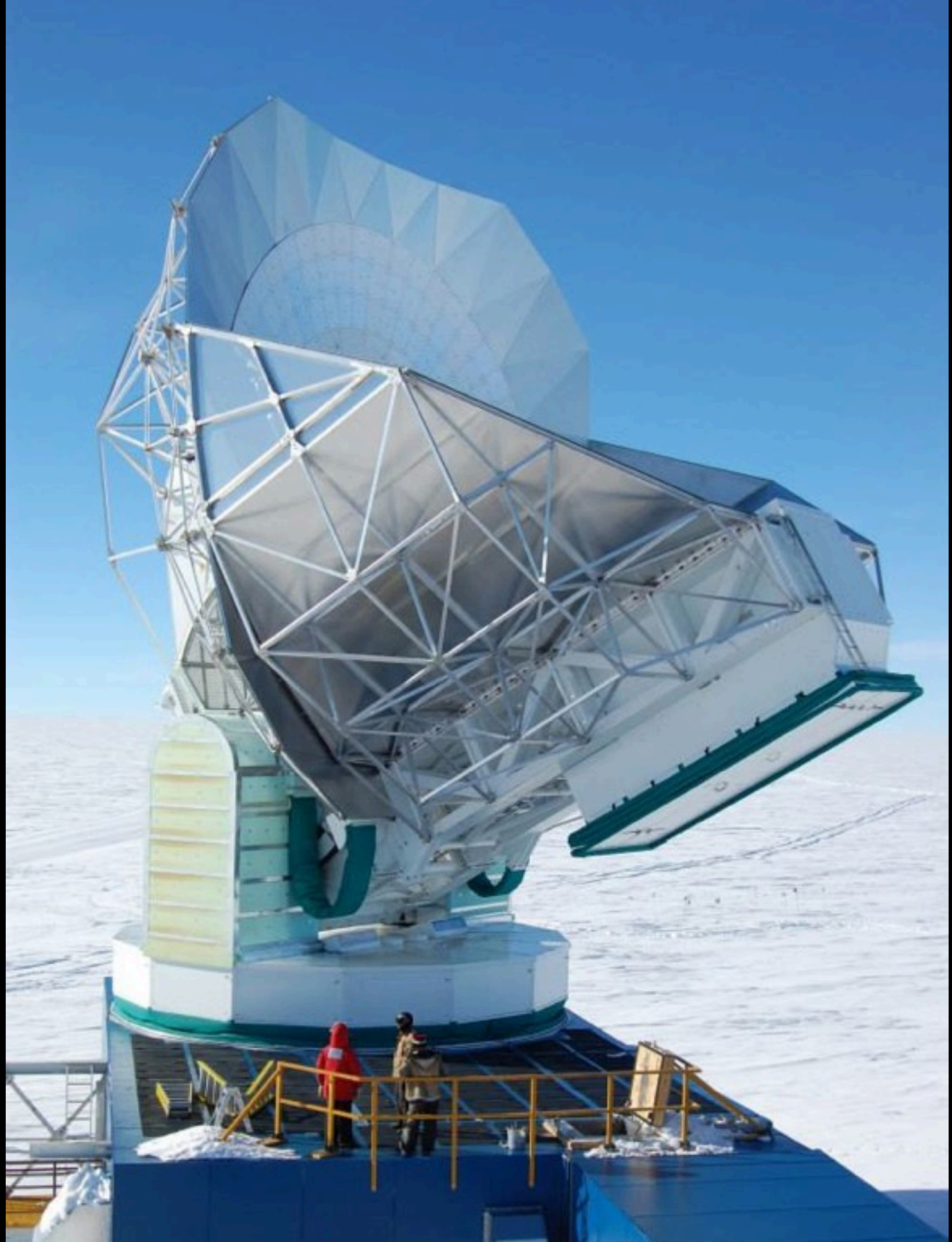

GEOGRAPHIC
SOUTH POLE
ROALD AMUNDSEN
ROBERT F. SCOTT
JANUARY 17, 1912

Preparing snow foundation for the SPT at South Pole


-60 -40 -20 0 20 40 60 80 100 120


DR THOMAS CRAWFO

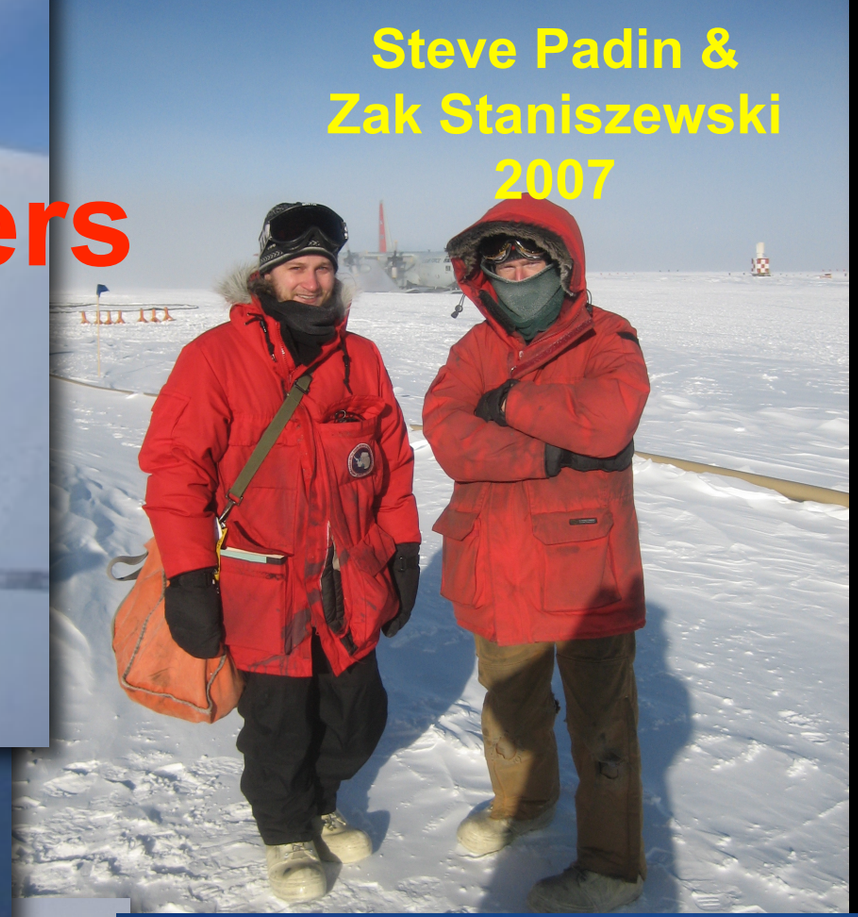

MANTIS
MANTIS
MANTIS
MANTIS
MANTIS



Our Heroes, the SPT Winterovers


Keith Vanderlinde 2008

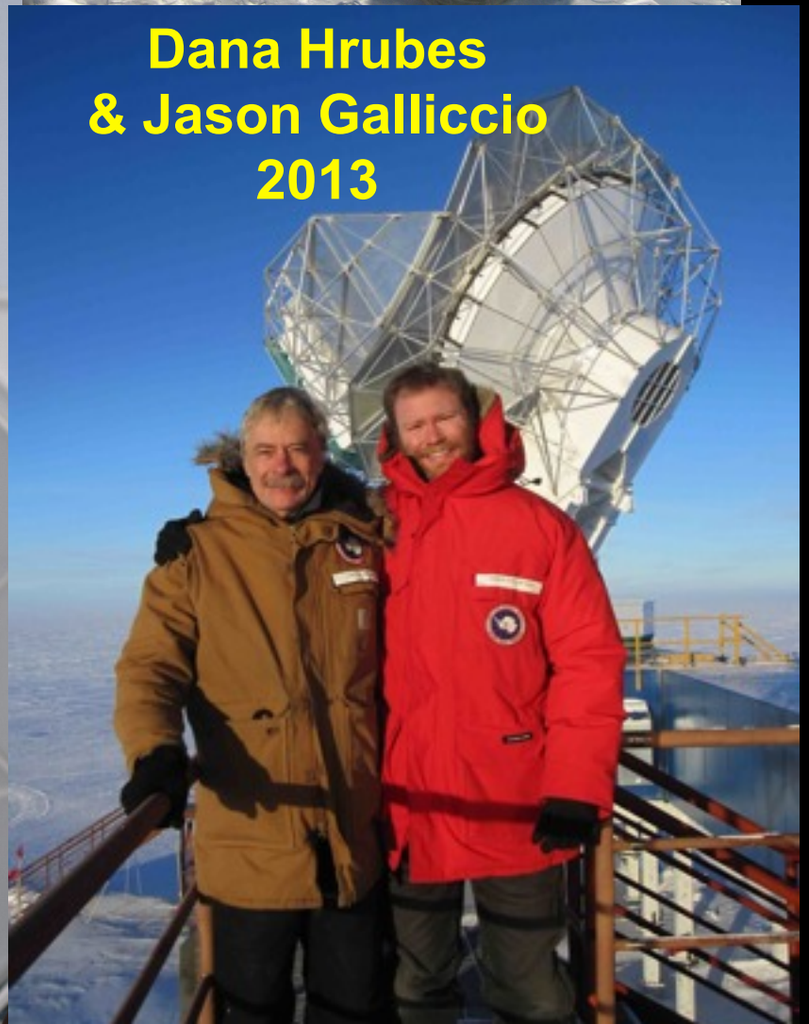

Dana Hrubes 2008


Steve Padin & Zak Staniszewski 2007


Dana Hrubes & Daniel Luong-van 2010 & 2011 !


Cynthia Chiang & Nicholas Huang 2012

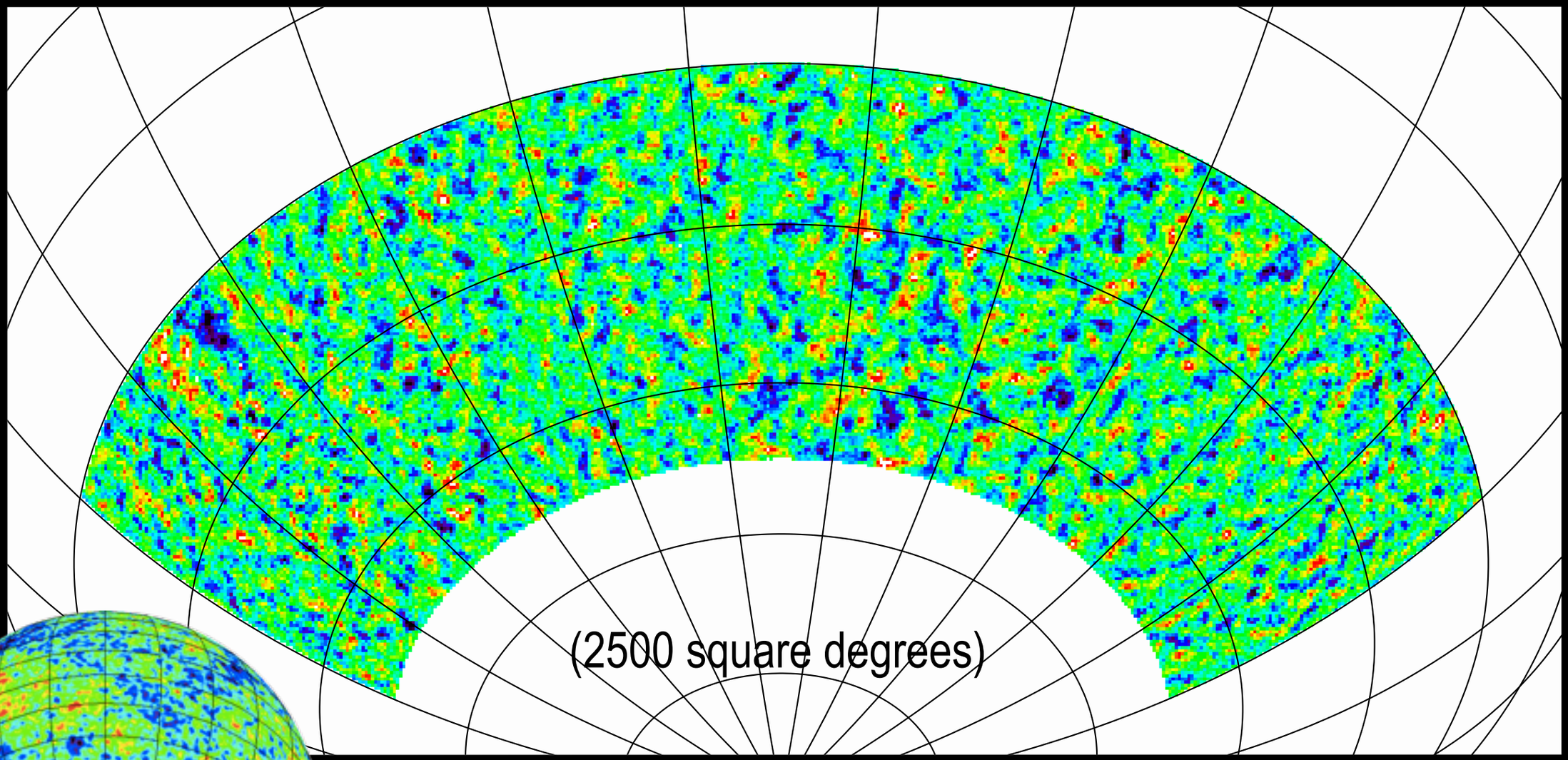

Ross Williamson & Erik Shirokoff 2009

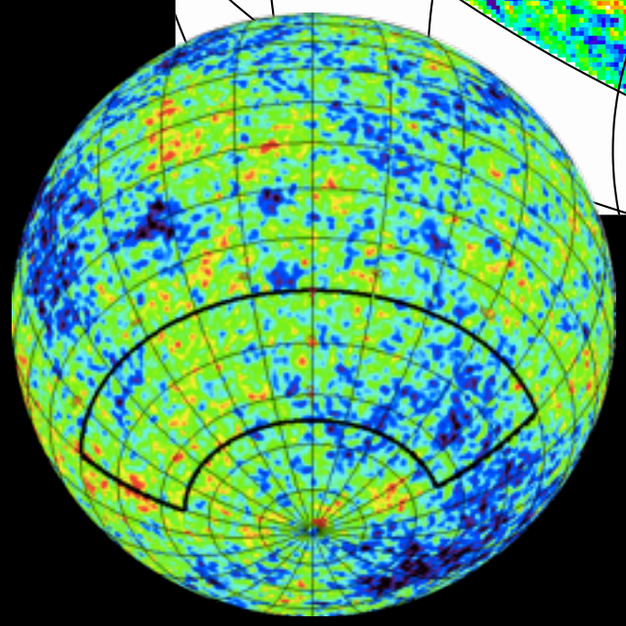

Dana Hrubes & Jason Gallicio 2013

SPT has produced the

highest resolution and sensitivity map of the CMB

covering 1/16 of the sky





WMAP lower resolution full sky map with SPT area marked

WMAP

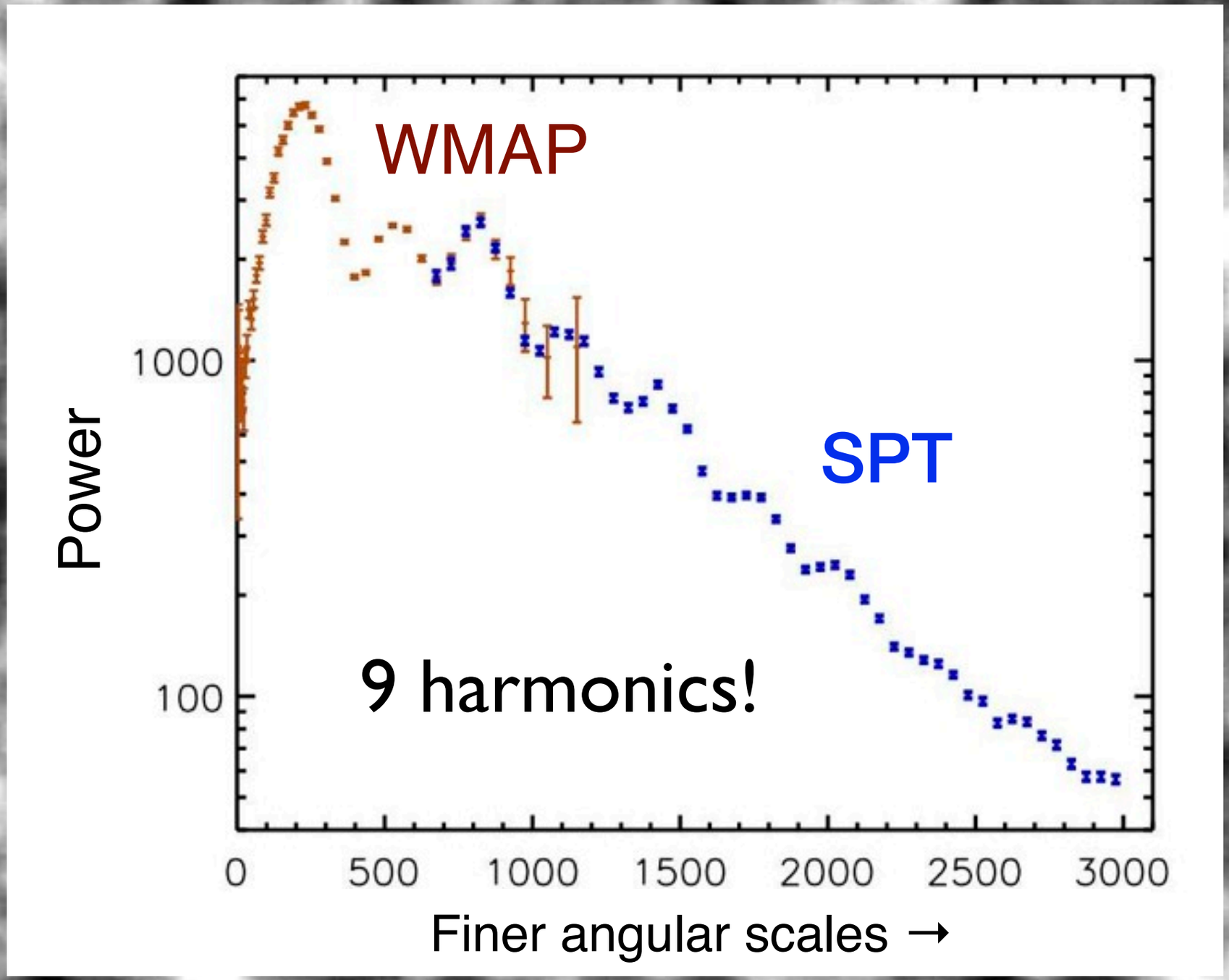
~70 deg^2

Planck 143 GHz

~70 deg^2

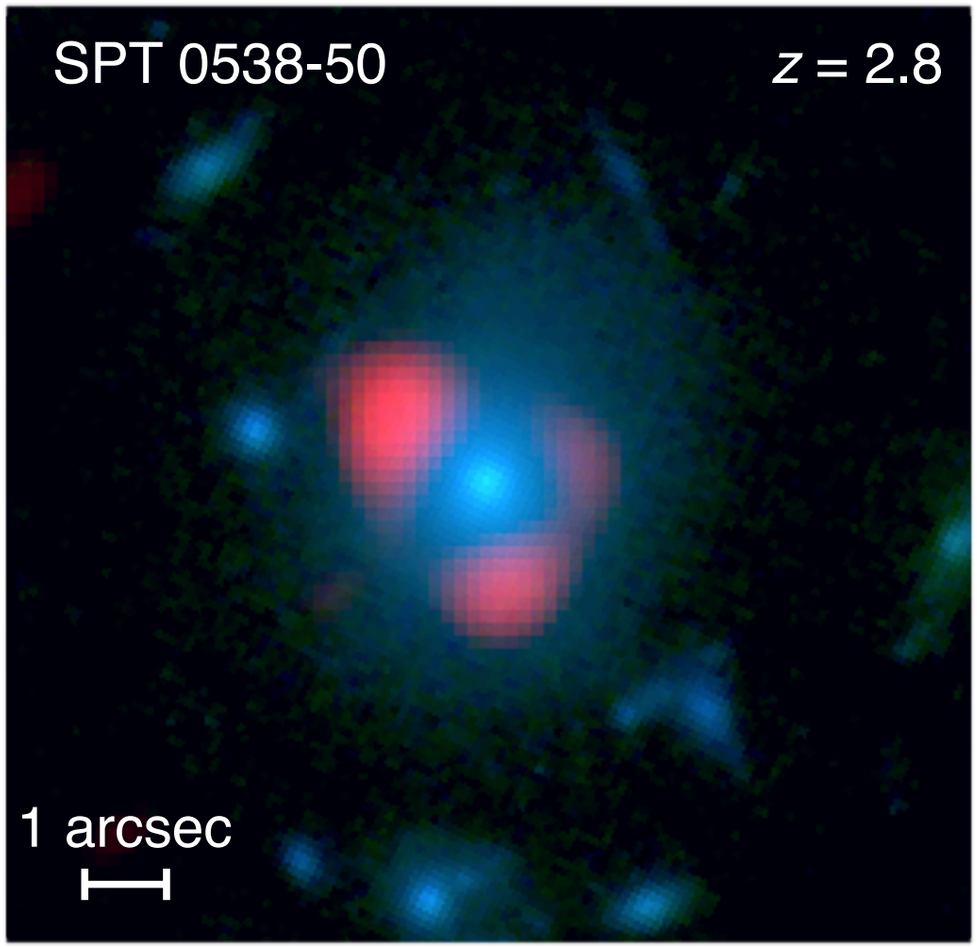
South Pole Telescope

~70 deg^2

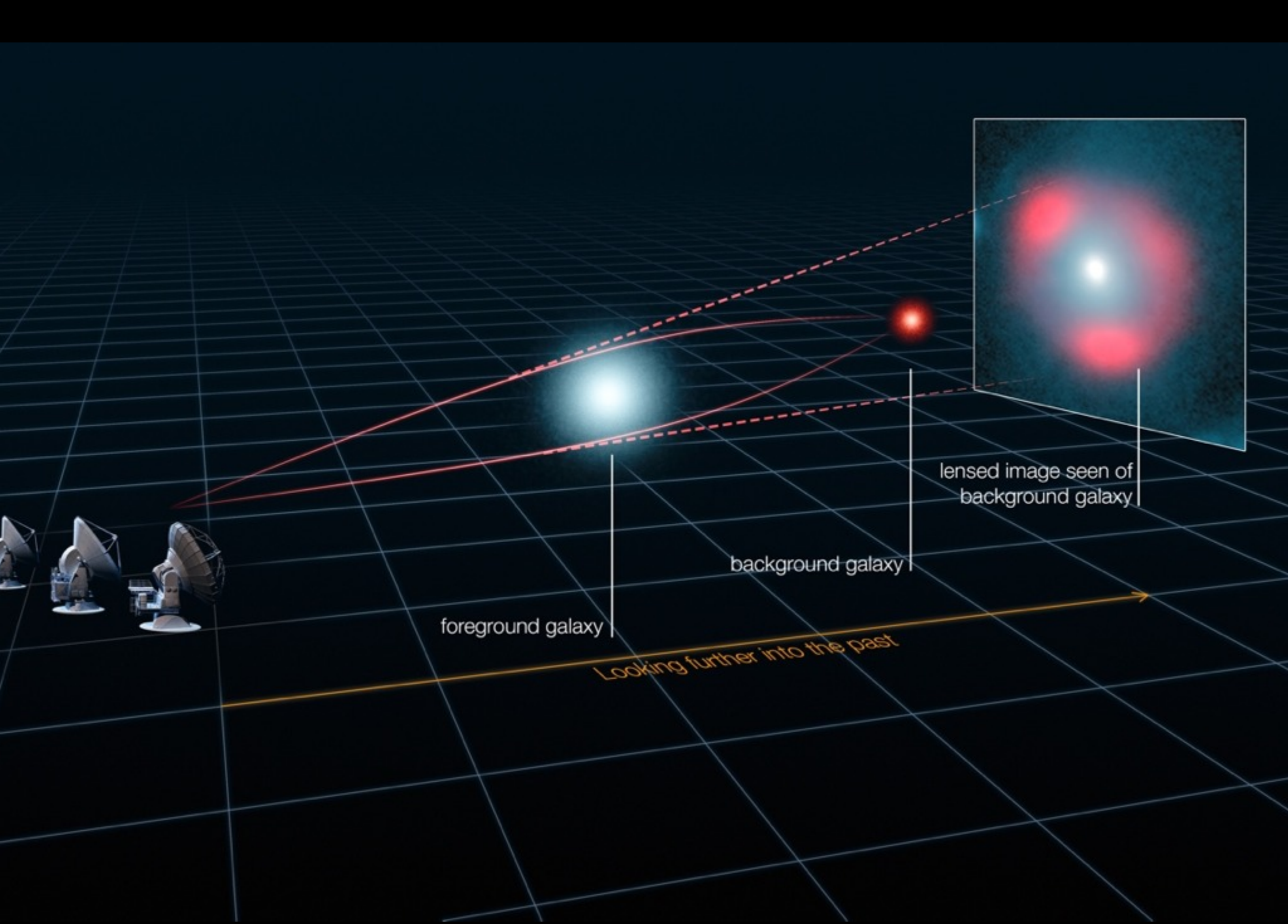


So precise that we are now measuring the impact of the cosmic neutrino background!

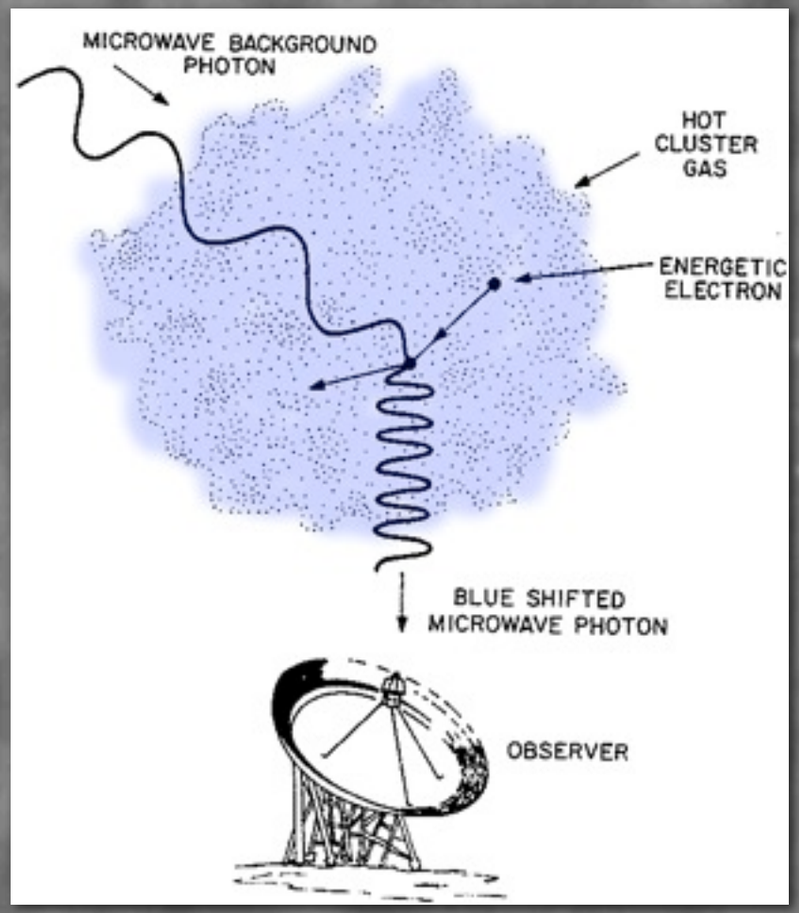
Zoom in on an SPT map
and filter the large stuff out



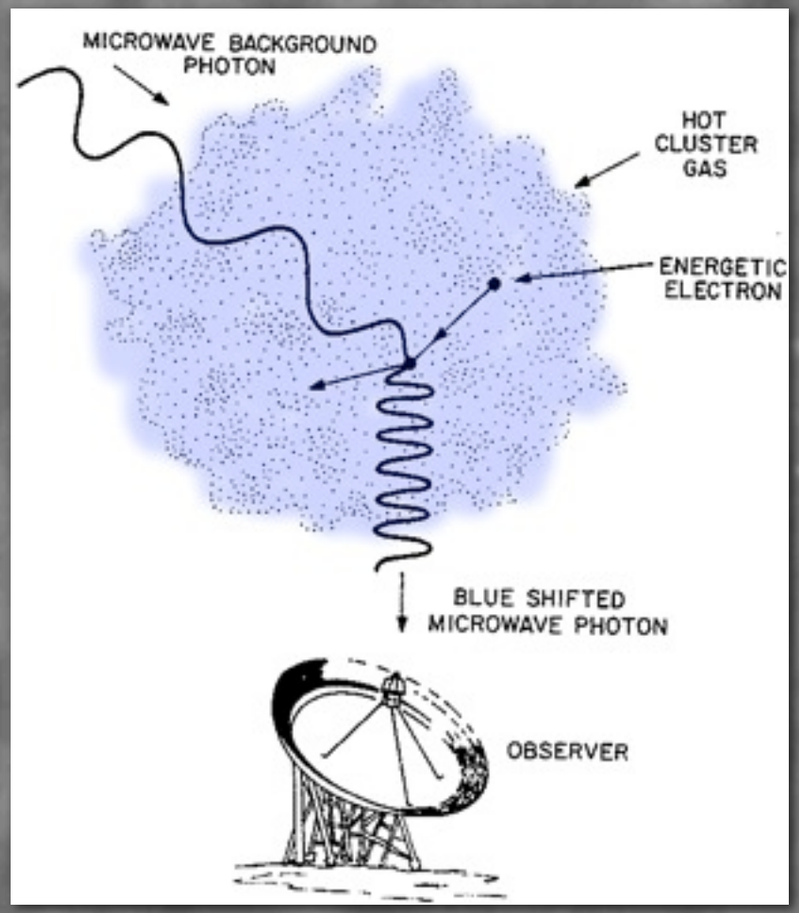
Bright radio galaxies, AGN, and the discovery of very rare, distant dusty star forming galaxies.


lensed image seen of
background galaxy
background galaxy
foreground galaxy
Looking further into the past

What about galaxy clusters and the Sunyaev Zel'dovich effect?

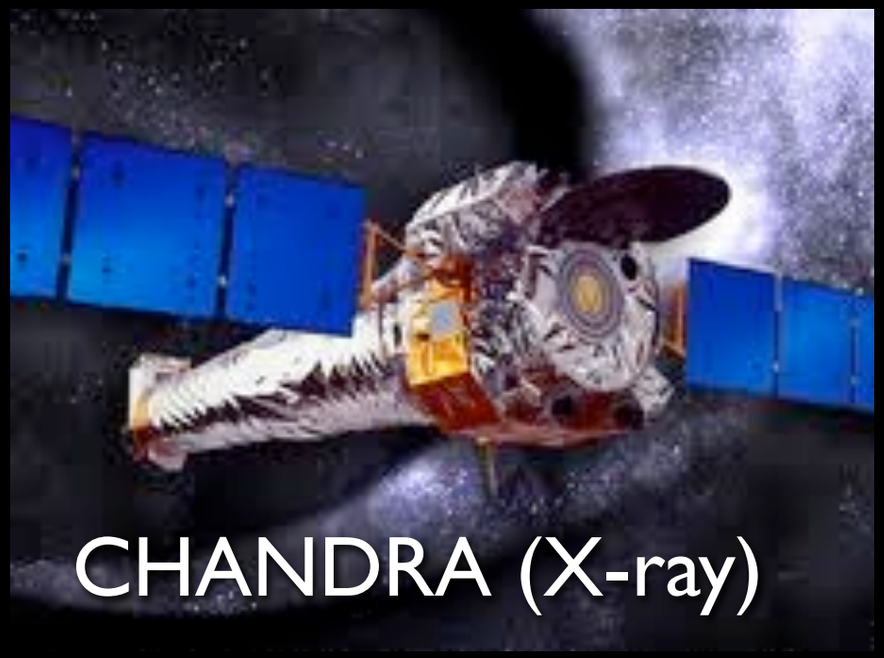


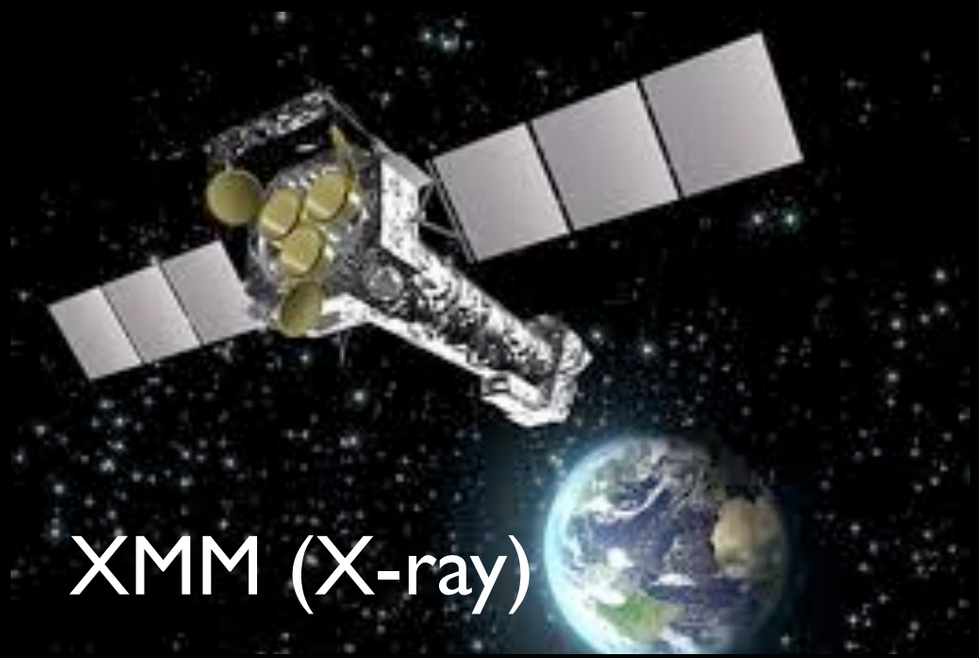
What about galaxy clusters and the Sunyaev Zel'dovich effect?



Shadows against the background made reveal clusters of galaxies, the largest objects in the universe.

Optical image of cluster of galaxies from the Hubble Space Telescope


CHANDRA (X-ray)

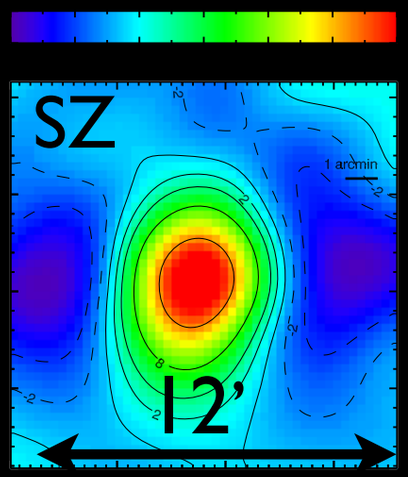

XMM (X-ray)

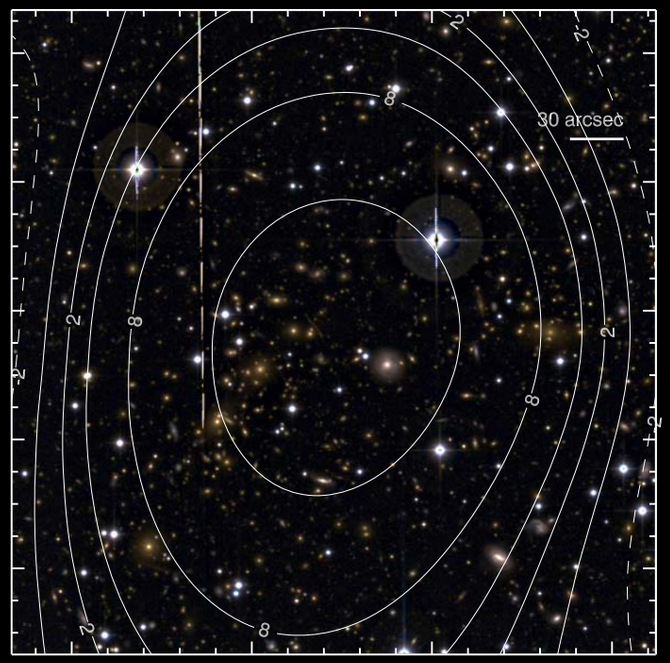

Hubble (Optical)


Magellan (Optical)

Optical and infrared images of discovered clusters

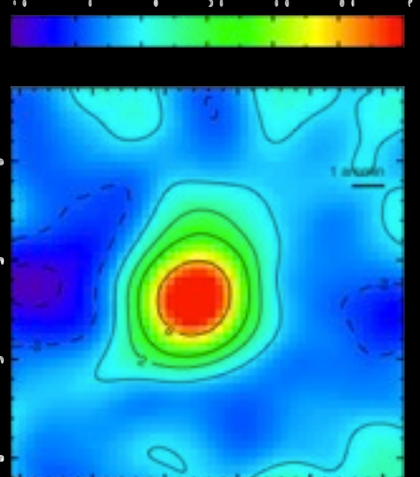
0658-5358 (z=0.30) (Bullet)





2344-4243 (z=0.60)

Most X-ray luminous cluster known!



"Phoenix" Cluster

Optical and infrared images of discovered clusters

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Galaxy cluster's 'starburst' surprises astronomers

Astronomers have seen a huge galaxy cluster doing what until now was only theorised to happen: making new stars.

Most galaxy clusters - the largest structures in the Universe - are "red and dead", having long since produced all the stars they can make.

But cluster formation should, according to theory, include a cooling phase, resulting in blue light from new stars.

Writing in Nature, researchers say they have seen evidence that the enormous Phoenix cluster makes 740 stars a year.

In our own Milky Way, only one or two new stars are made each year.

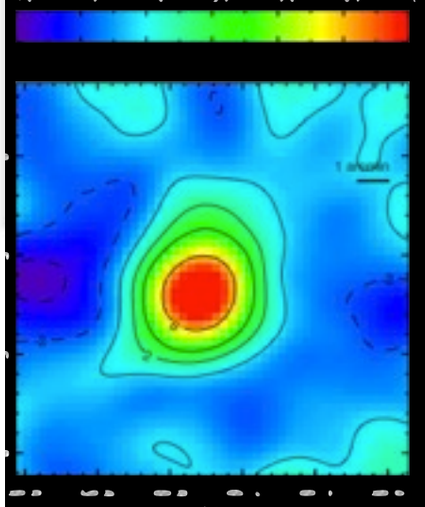
The cluster, some seven billion light-years away, is formally called SPT-CLJ2344-4243 but the researchers have renamed it for the constellation in which it lies.

Microwave, visible and ultraviolet studies sum to show a bright core of the cluster

Related Stories

2344-4243 (z=0.60)

Most X-ray luminous cluster known!



Optical and infrared images of discovered clusters

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seen evidence that
cluster makes 740

In our own Milky W
are made each yea

The cluster, some s
is formally called SI
for the constellation

SZ-Optical

GAWKER TOP STORIES

SPACE

'Cosmic Supermom' Galaxy Is Having Over Two Star Babies a Day

Taylor Berman

A galaxy 5.7 billion light years away from Earth has been having so many star babies that the Associated Press deemed it a 'cosmic supermom.' This space mom galaxy, which

AUG 15, 2012 7:35 PM 8,282 46

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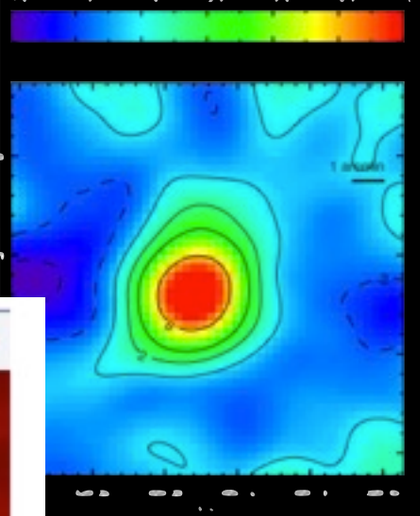
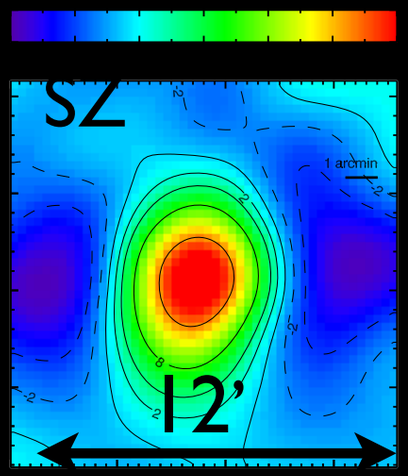
Most X-ray luminous cluster known!

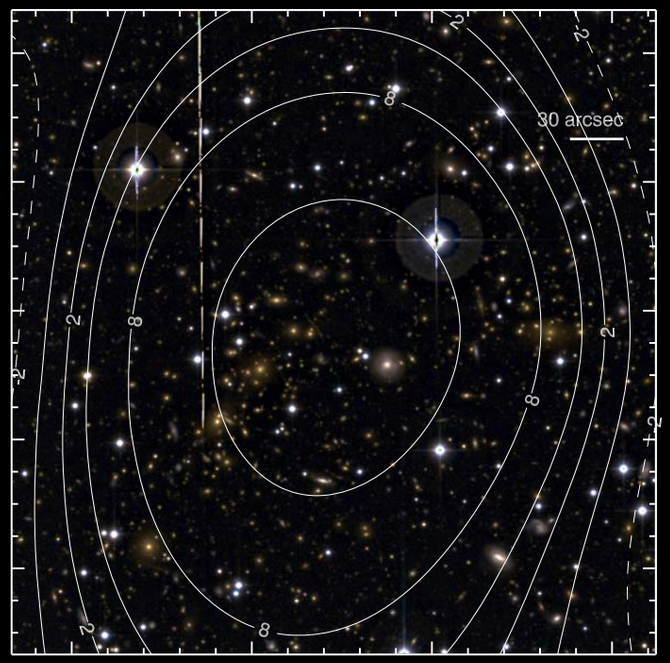


"Phoenix" Cluster

Optical and infrared images of discovered clusters

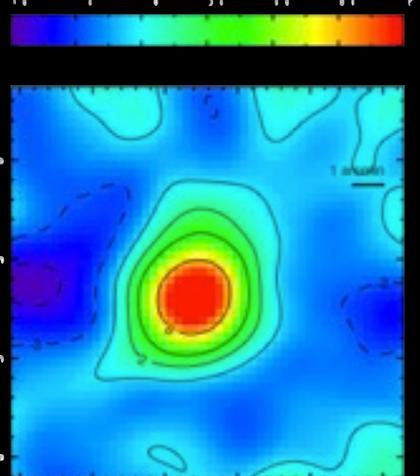
0658-5358 (z=0.30) (Bullet)



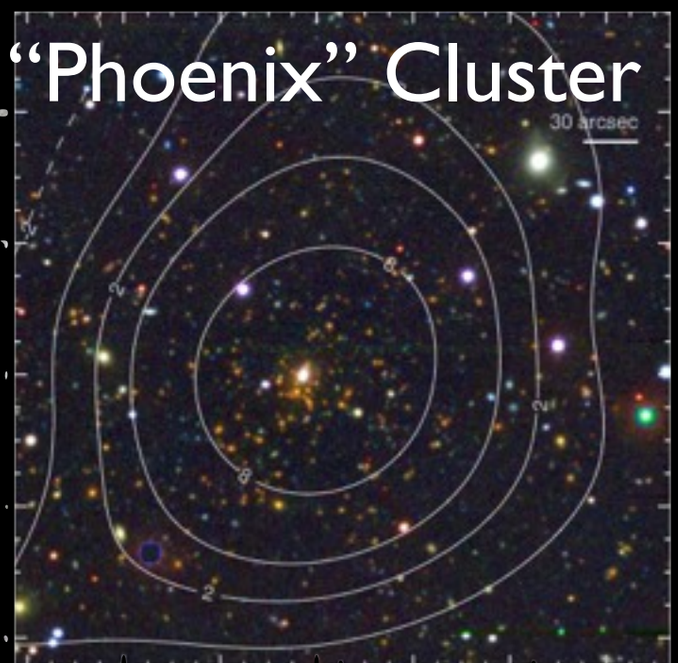


2344-4243 (z=0.60)

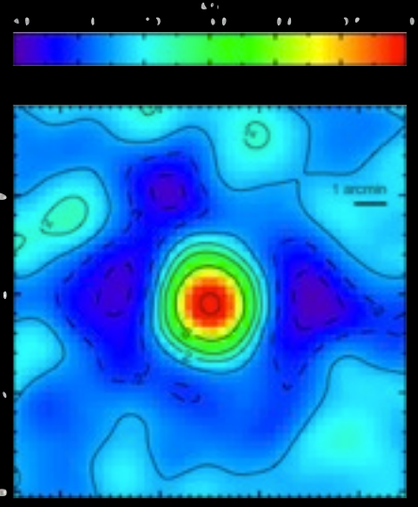
Most X-ray luminous cluster known!

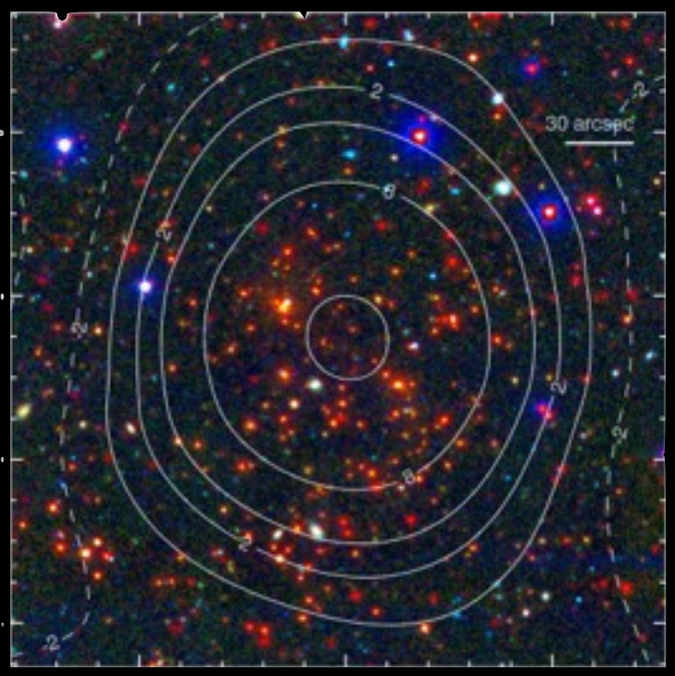


"Phoenix" Cluster



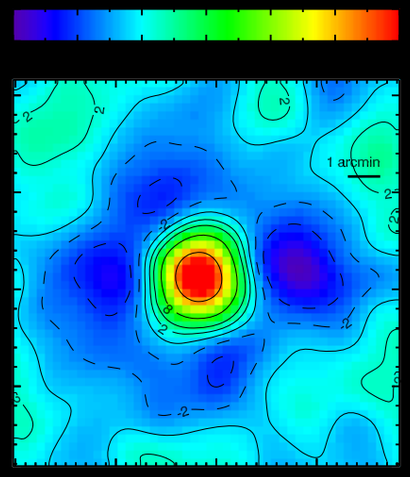
2337-5942 (z=0.78)

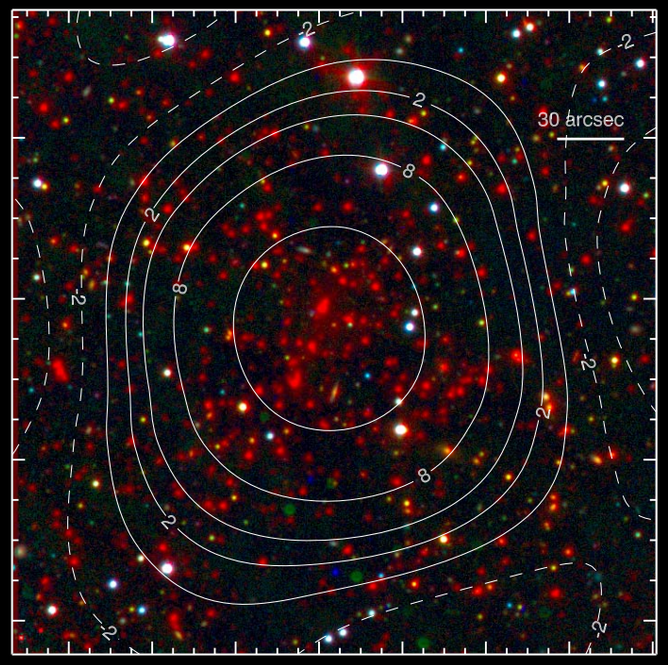




2106-5844 (z=1.13)

Most massive distant cluster known!





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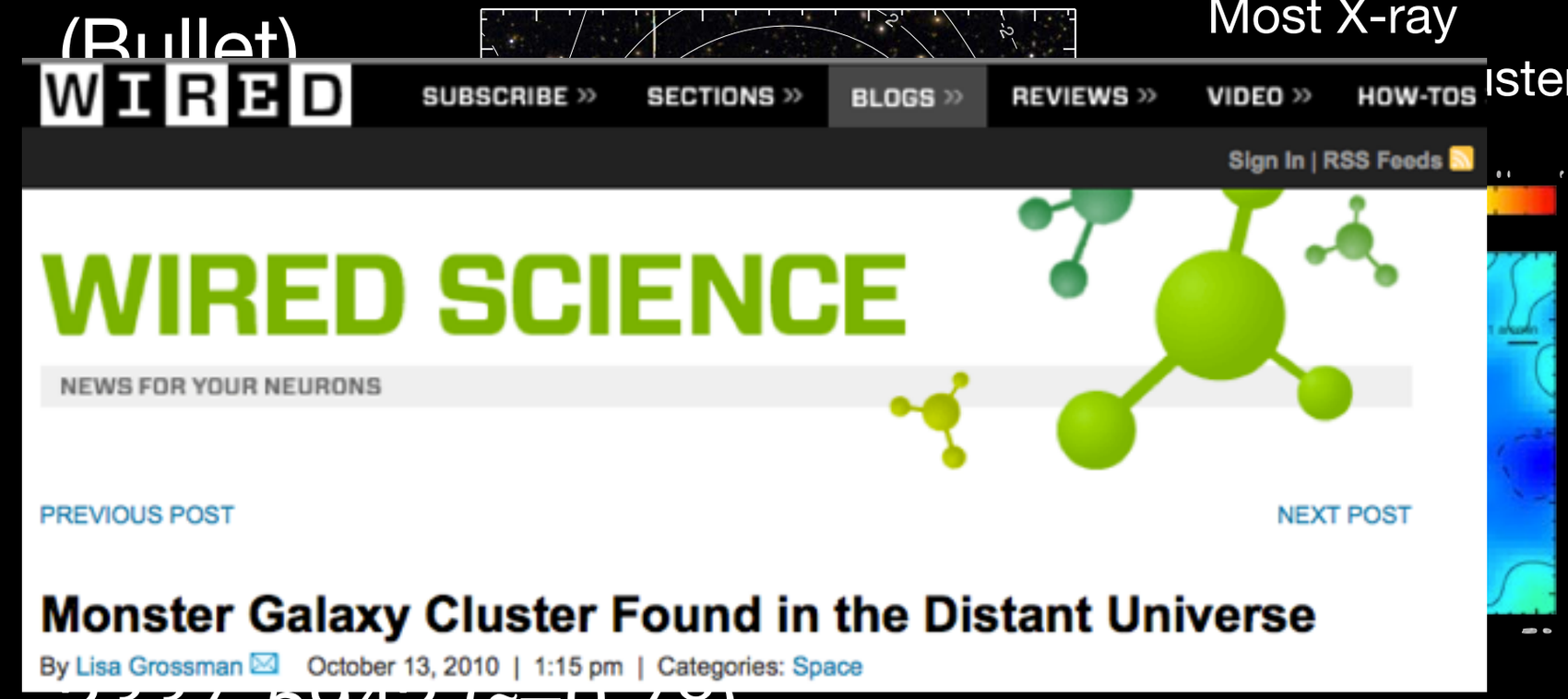

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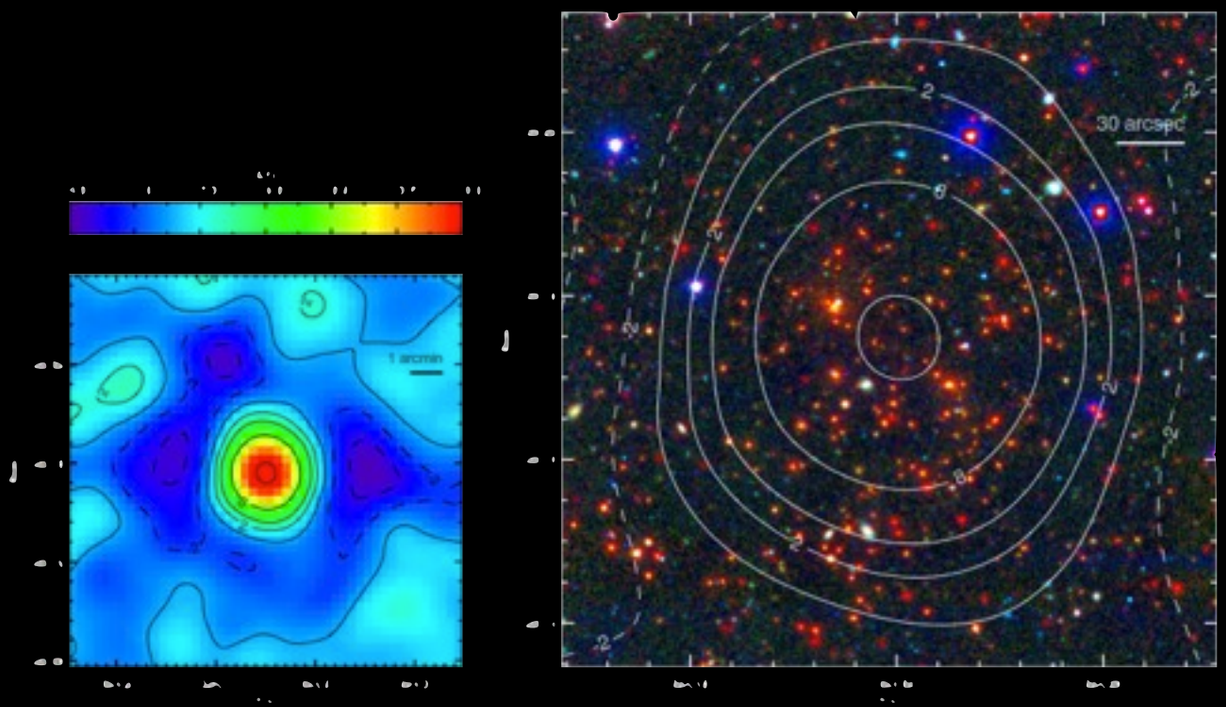

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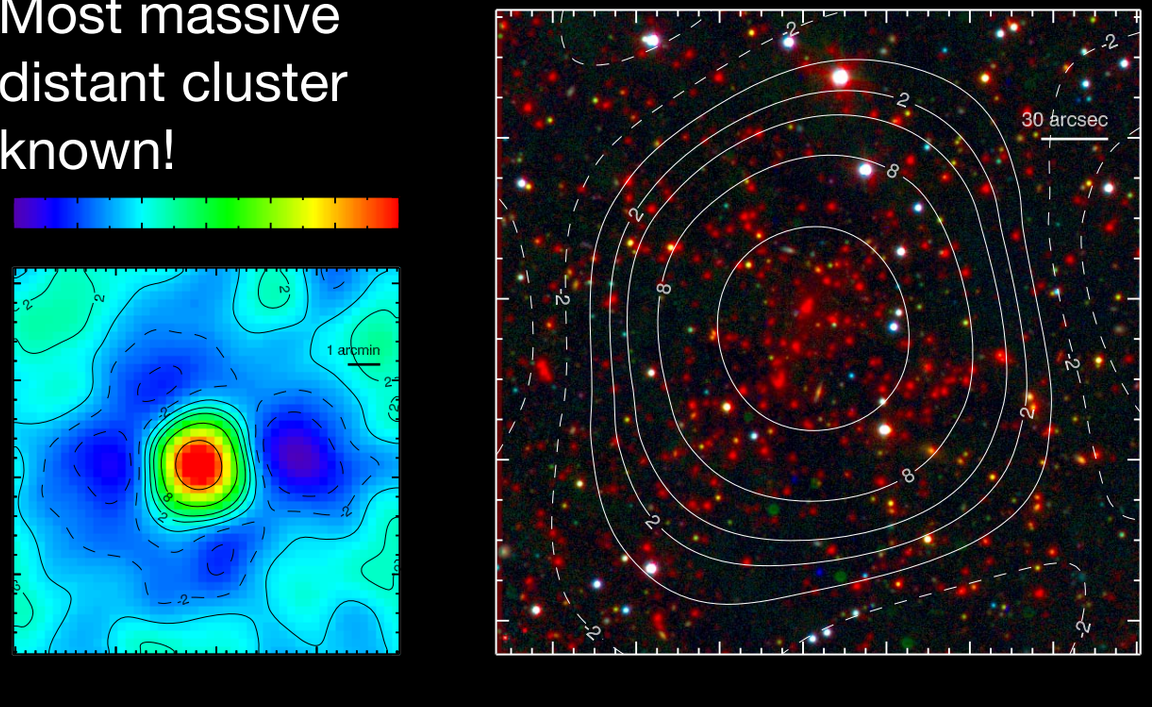
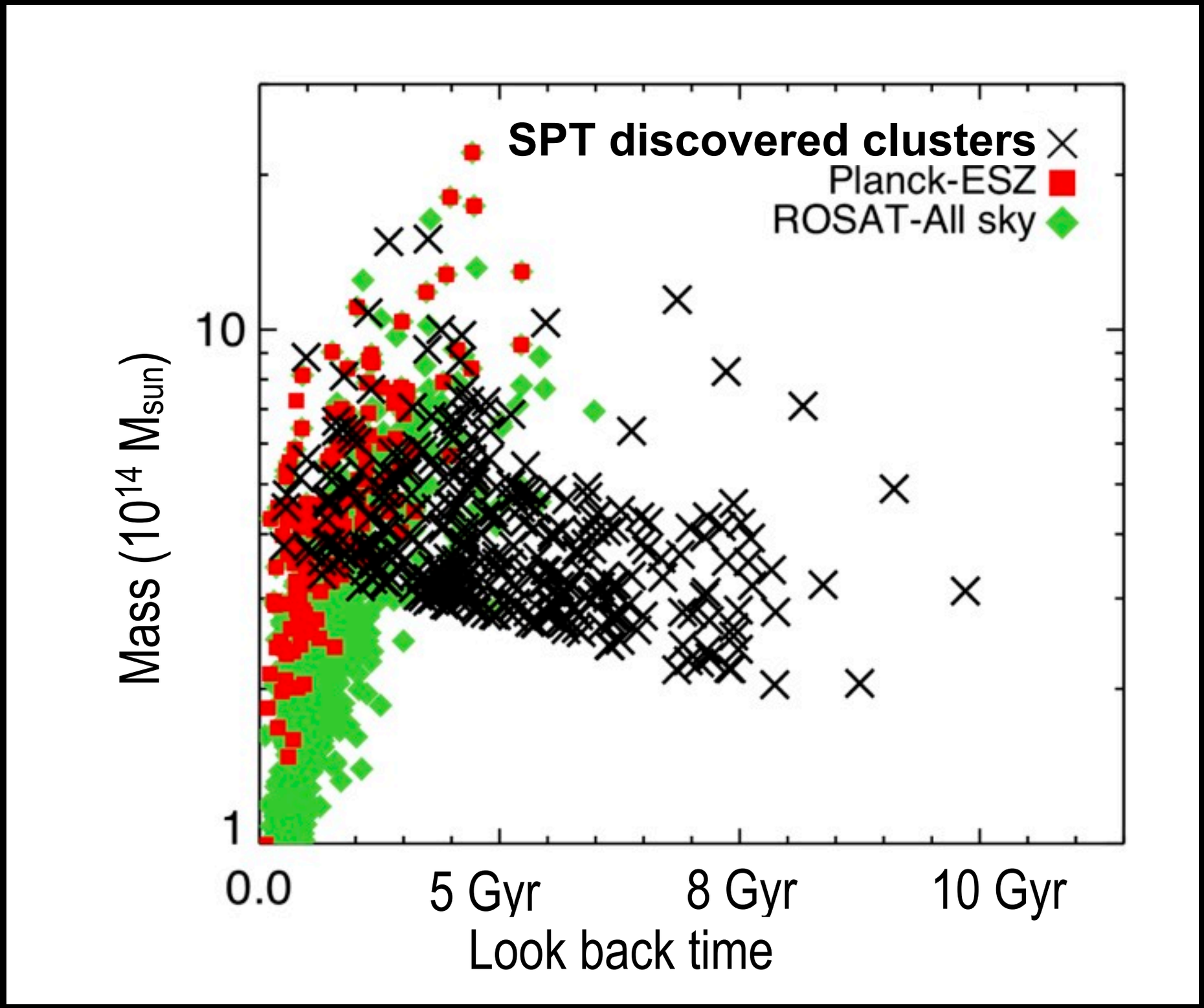


Where are the discovered galaxy clusters?



initial results are looking great...

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Press Release 12-066

South Pole Telescope Provides New Insights Into Dark Energy and Neutrinos

Neutrinos were thought to be without mass until recently

South Pole Telescope findings are the most recent results produced by NSF-funded researchers.
Credit and Larger Version

April 2, 2012

Analysis of data from the National Science Foundation- (NSF) funded 10-meter South Pole Telescope (SPT) in Antarctica provides new support for the most widely accepted explanation of dark energy, the source of the mysterious force that is responsible for the accelerating expansion of the universe.

The results begin to hone in on the tiny mass of the neutrinos, the most abundant particles in the universe, which until recently were thought to be without mass.

The SPT data strongly support Albert Einstein's cosmological constant--the leading model for dark energy--even though researchers base the analysis on only a fraction of the SPT data collected and only 100 of the over 500 galaxy clusters detected so far.

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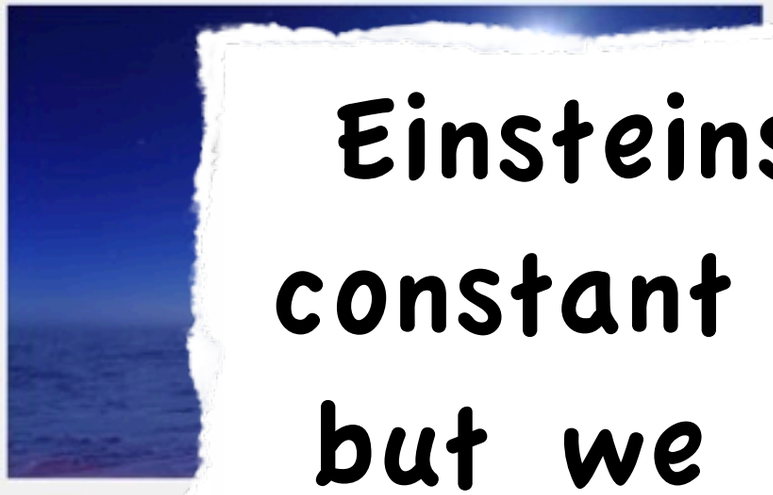

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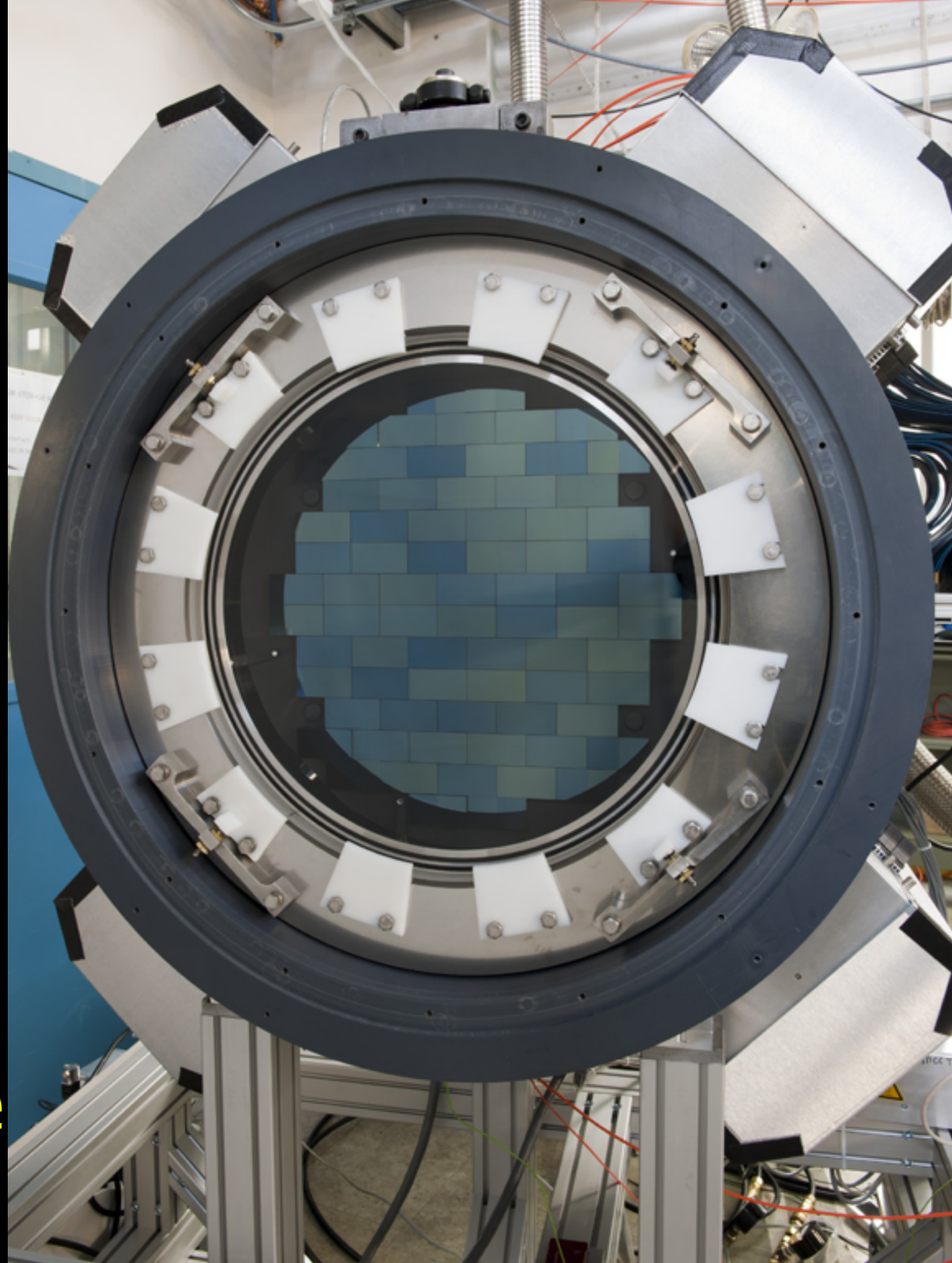
Einsteins's cosmological constant is holding up(!), but we will place much tighter constraints...

Combining SPT data with with optical Dark Energy Survey data

570-Million pixel camera for the Dark Energy Survey built right here at Fermilab!

installed on the Blanco 4m telescope on Sept. 2012



Dark Energy Camera on the Blanco Telescope

DARK ENERGY SURVEY

DES image

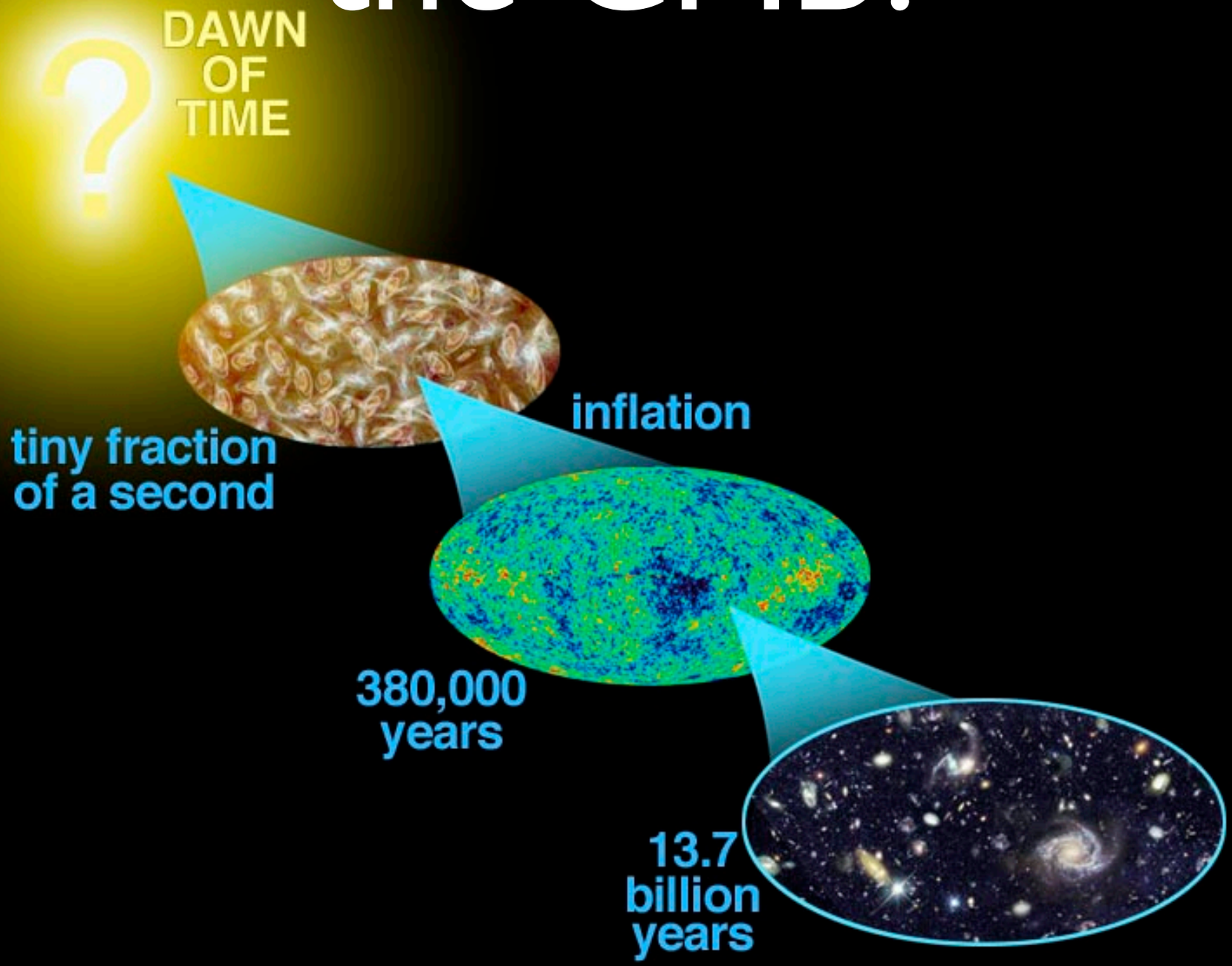
Standard model of Cosmology

Rests upon three mysterious pillars

All implicate new fundamental physics!

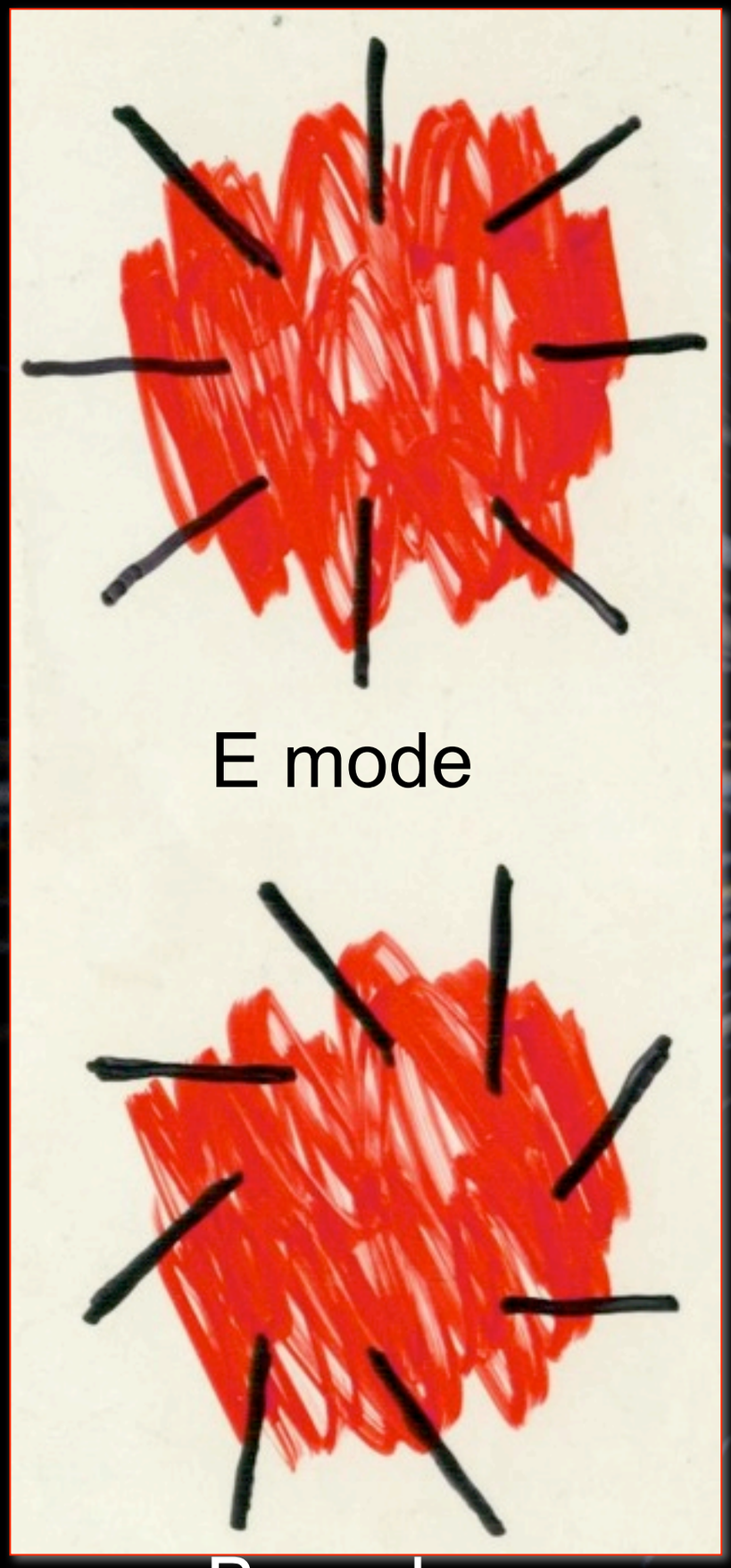
Slide from M. Turner

How do we look past the CMB?



NASA

Unknown, from Camille Flammarion's 1888 book L'atmosphère: météorologie populaire



E mode

B mode

Smoking gun of inflation:
Inflation produced gravity waves

Leave imprint on the CMB:
'B-mode' polarization
→Swirls in the sky!

Holy Grail of Cosmology
(or wild goose?)

Slide from M. Turner

SPT polarization sensitive camera

(1176x) 150 GHz detectors (NIST)

(376x) 90 GHz detectors,
(Argonne National Labs)

SPT polarization sensitive camera

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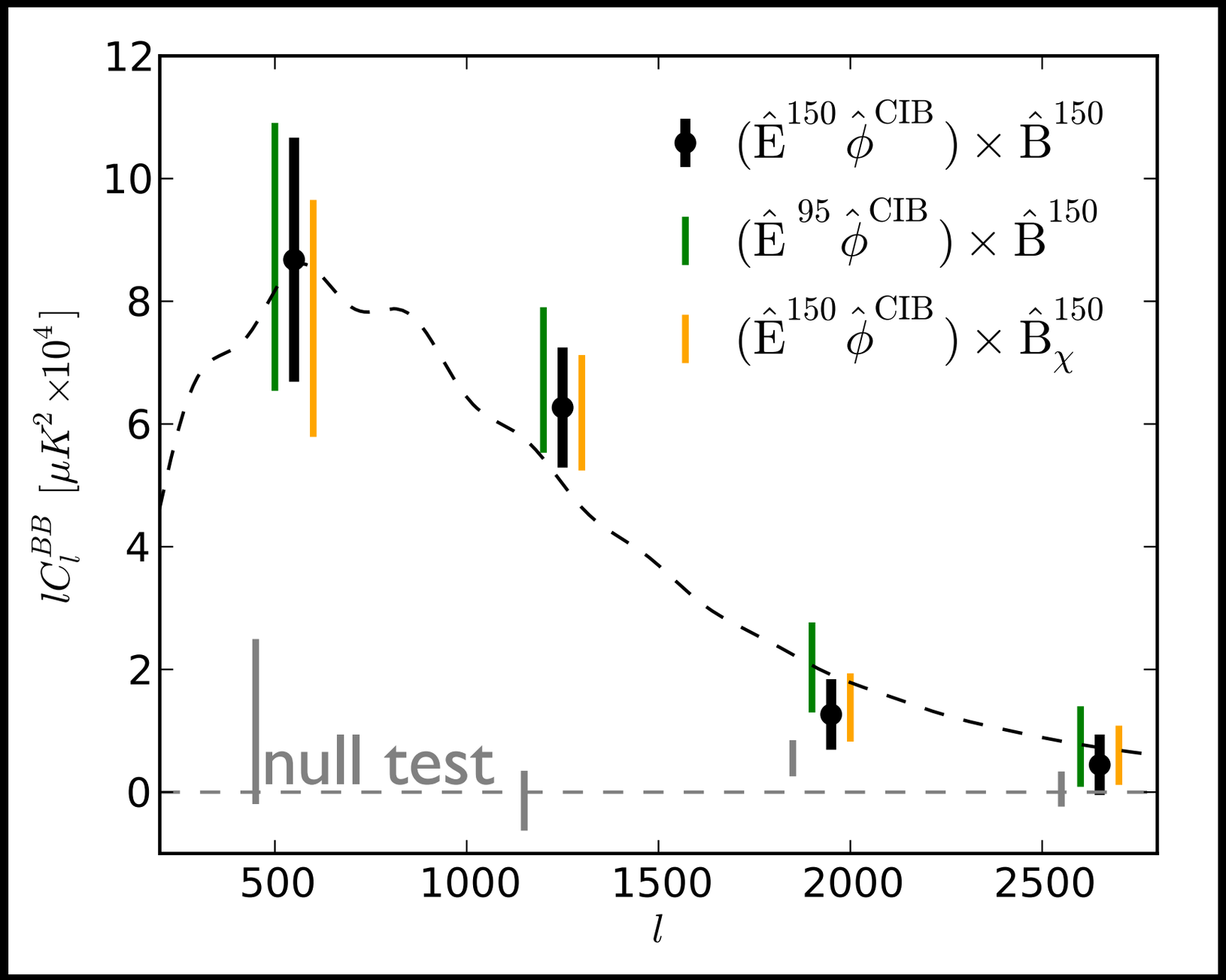
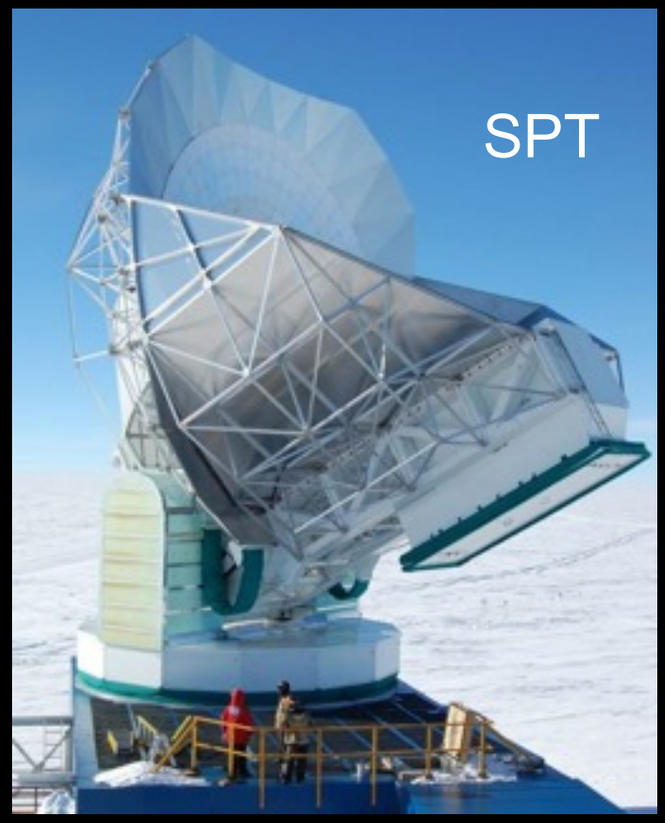
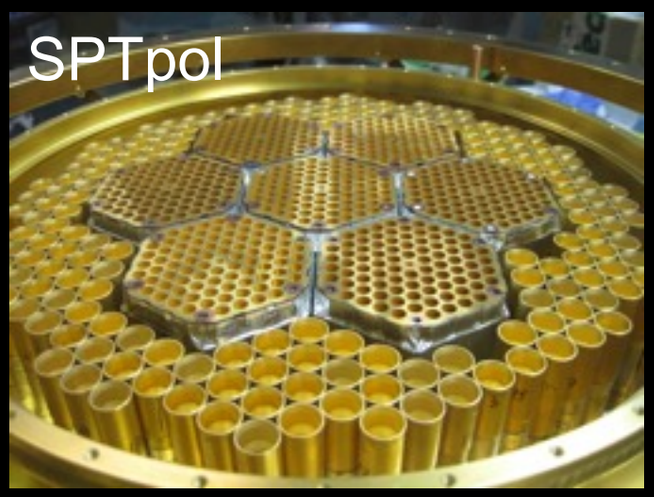
SPTpol 1st light January 2012

Major step to inflation: SPT detects B-mode CMB polarization







B-model polarization from gravitational lensing

to inflation:
de CMB polarization

physicsworld
TOP 10
BREAKTHROUGH
2013

Physics World
Breakthrough of the Year 2013

A *Physics World* Top 10 Breakthrough of the Year is awarded for physics research published in 2013 and the decision is based on the following criteria:

- Fundamental importance of research
- Significant advance in knowledge
- Strong connection between theory and experiment
- General interest to all physicists

This is to certify that a *Physics World* Top 10 Breakthrough of the Year has been given to

The astronomers working on the South Pole Telescope

for being the first to measure B-mode polarization in the cosmic microwave background radiation.

Matin Durrani
Editor
Physics World

Hamish Johnston
Editor
physicsworld.com

December 2013

$$\hat{\phi}^{150} \times \hat{\mathrm{B}}^{\mathrm{CIB}}$$
$$\hat{\phi}^{95} \times \hat{\mathrm{B}}^{\mathrm{CIB}}$$
$$\hat{\phi}^{150} \times \hat{\mathrm{B}}^{\mathrm{CIB}}_{\chi}$$

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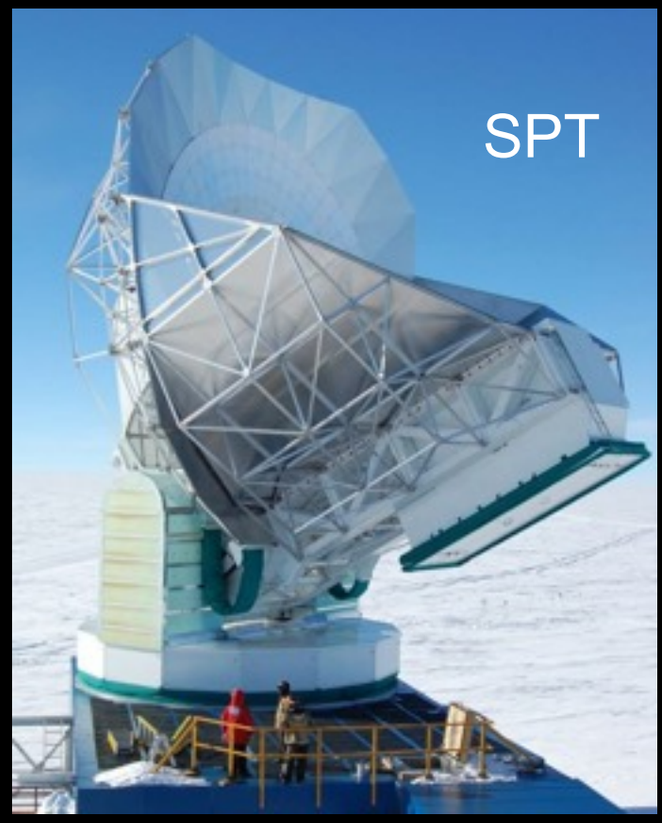

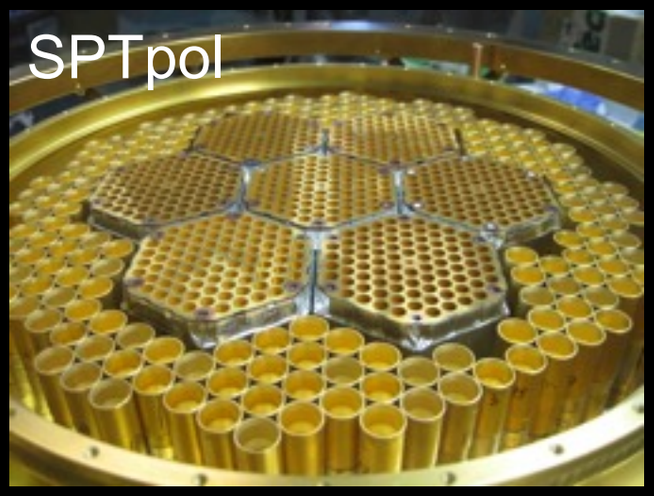

B-model polarization from gravitational lensing

Dark energy is in our sights

as well as hints of other interesting new physics including the nature of the elusive neutrinos.

In the works: polarization measurements to test inflation of the universe at 10^{-35} seconds.

Thank you!

For publications and more information see http://pole.uchicago.edu

Photo credit: Keith Vanderlinde