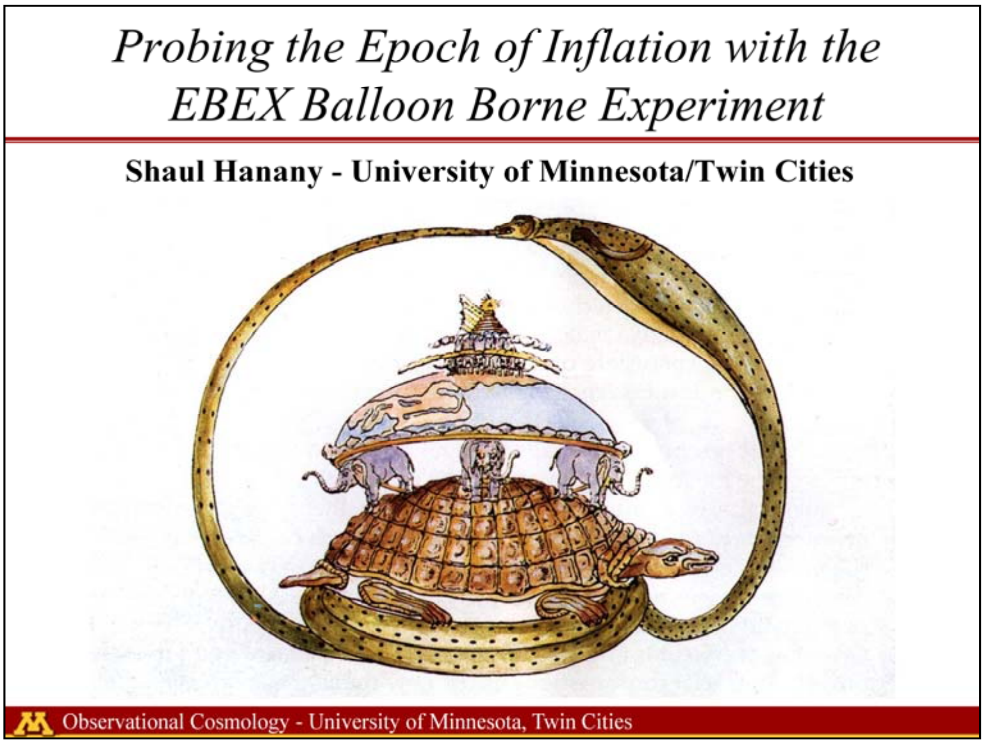
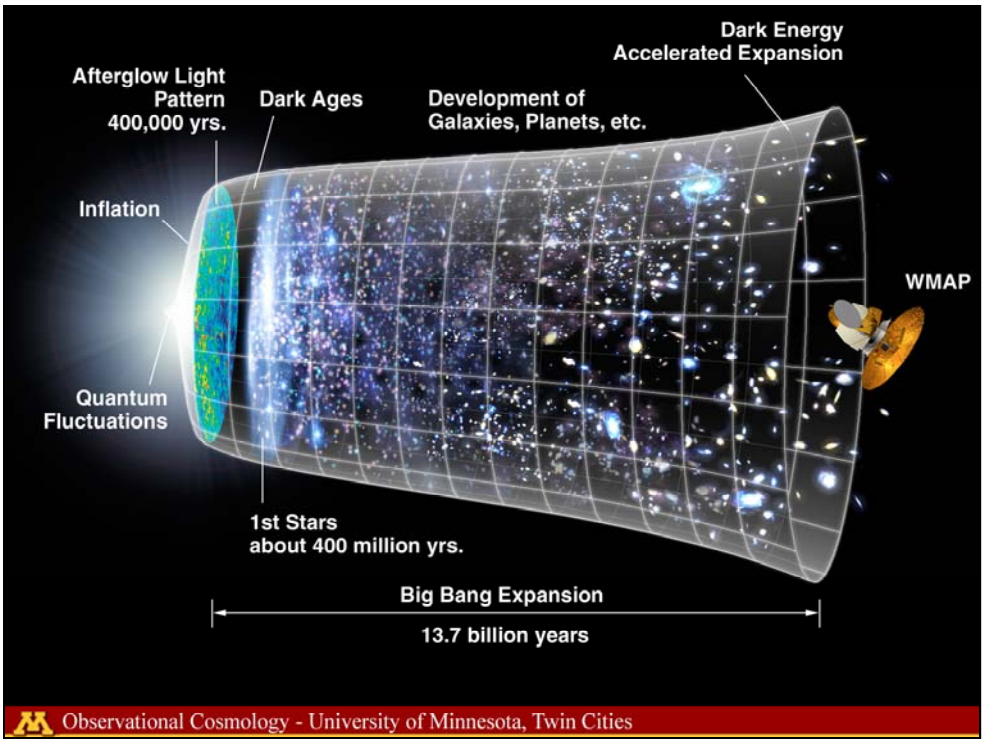


One of humanity's ever lasting and never ending quests is to understand the origin and evolution of the Universe. Here we see the vision of Hindu mythology where Earth is suspended on the back of three elephants, the three elephants stand on a giant turtle, which in turn rests upon an even larger serpent.

Today we know that overall this is only a crude approximation of reality. Perhaps the part about the existence of Nirvana somewhere in the Himalayas is still correct, but this requires some more research.

Through spectacular advances in astrophysics and cosmology, we now have a different **and reasonably well tested**, more modern view for the evolution of the universe.



Which looks like this

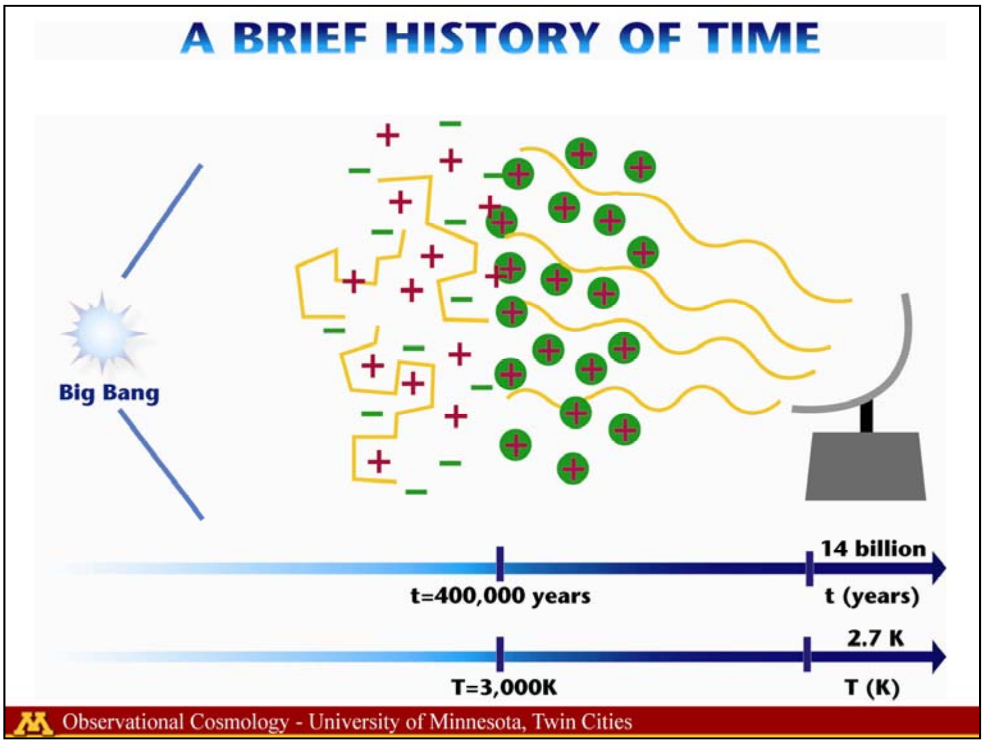
Spatial dimensions are along the vertical axis and time follows to the right.

The Universe expands from a hot and dense phase. This is what has become known as the Hot Big Bang model.

There is substantial uncertainty about the physics during the first 10^-12 seconds or so. However the evidence suggests that sometime during that period the universe had undergone immense inflation. Spatial dimensions have increased by at least by a factor of 10^26. When Inflation ends, the universe continues to expand, albeit at a much slower pace. The fundamental particles are born, nuclei of the light elements are synthesized, and the universe continues to cool as it expands.

When the Universe is about 400,000 years old radiation decouples from matter and the cosmic microwave background is born. Under the force of gravity matter slowly coalesces to form the first stars, then galaxies and then clusters of galaxies.

Debris from supernovae (which are explosions of massive stars) release heavy elements into space. This enables the formation of sophisticated molecules and animals, and some of these animals then ponder how this all began.



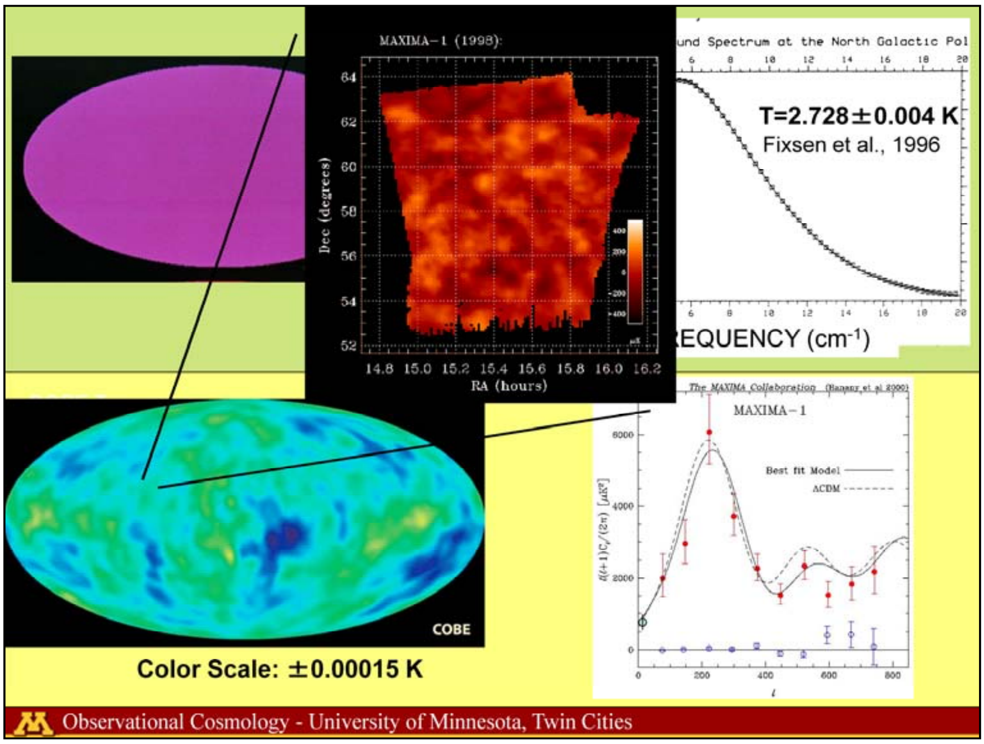
Here is another view …

We will focus our attention …

At that time the universe contains a plasma of mostly electrons, protons, and electromagnetic radiation (abundance of light nuclei <=10%). The temperature is a little hotter than 3000 degrees K. The electromagnetic radiation scatters continually from the free electrons, so that the radiation and plasma are in **thermal equilibrium**. As the universe continues to cool, and the temperature drops below 3000 K, hydrogen begins to form very rapidly. Within a very short period of time, only about 30,000 years, most of the universe is transformed from a plasma of electrons and protons, to being completely hydrogen dominated.

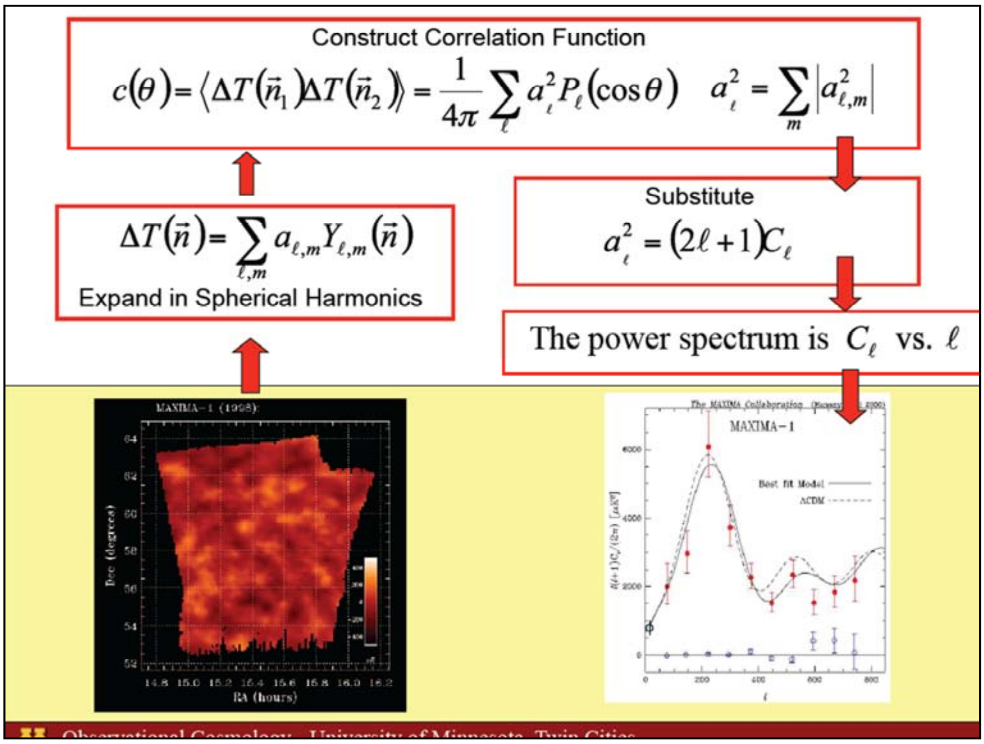
Whereas photons scatter strongly from free electrons, the scattering cross section with neutral hydrogen is orders of magnitudes smaller. Effectively the universe has become transparent. The radiation is now free to stream through the universe. **This event is called the epoch of decoupling.** Electro magnetic radiation has decoupled from electrons and protons. It is also sometimes called the '**surface of last scattering**' to signify that this was the last time the CMB photons have scattered.

These photons still stream freely through the universe today. This is the cosmic

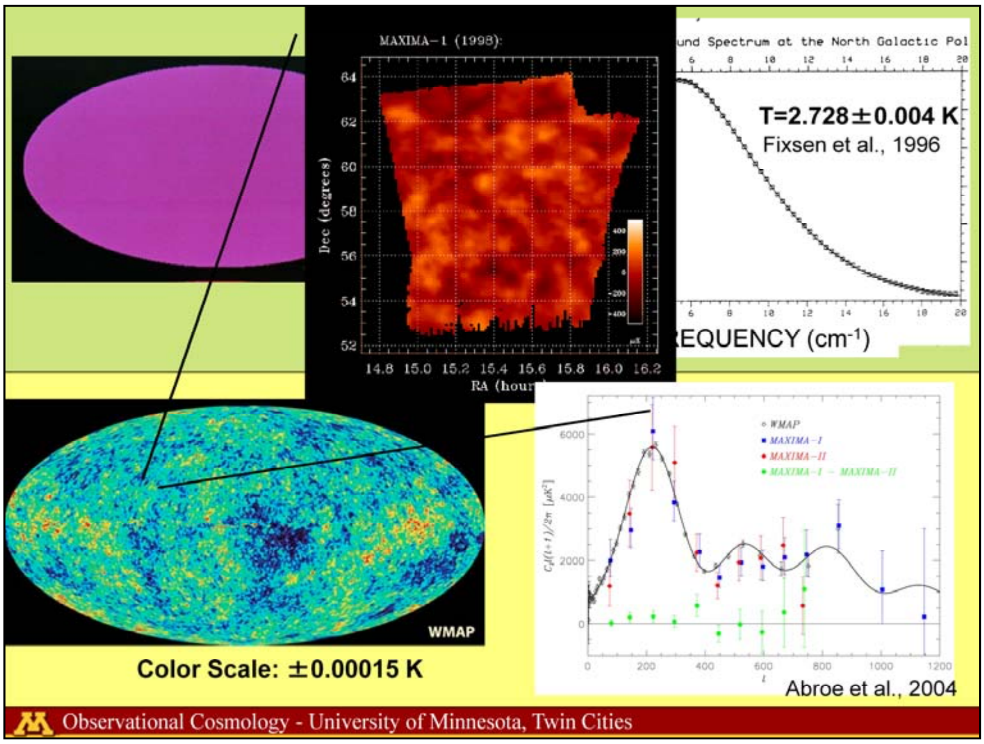


Here is how the CMB sky looks like. It is spectacularly spatially uniform with an effective temperature of 2.7 degrees. A measurement of the spectrum, carried out by John Mather and his collaborators with an instrument on COBE, gives an exquisite agreement with a black body, exactly the prediction of the hot big bang model. (This is the measurement for which Mather received the Nobel prize.)

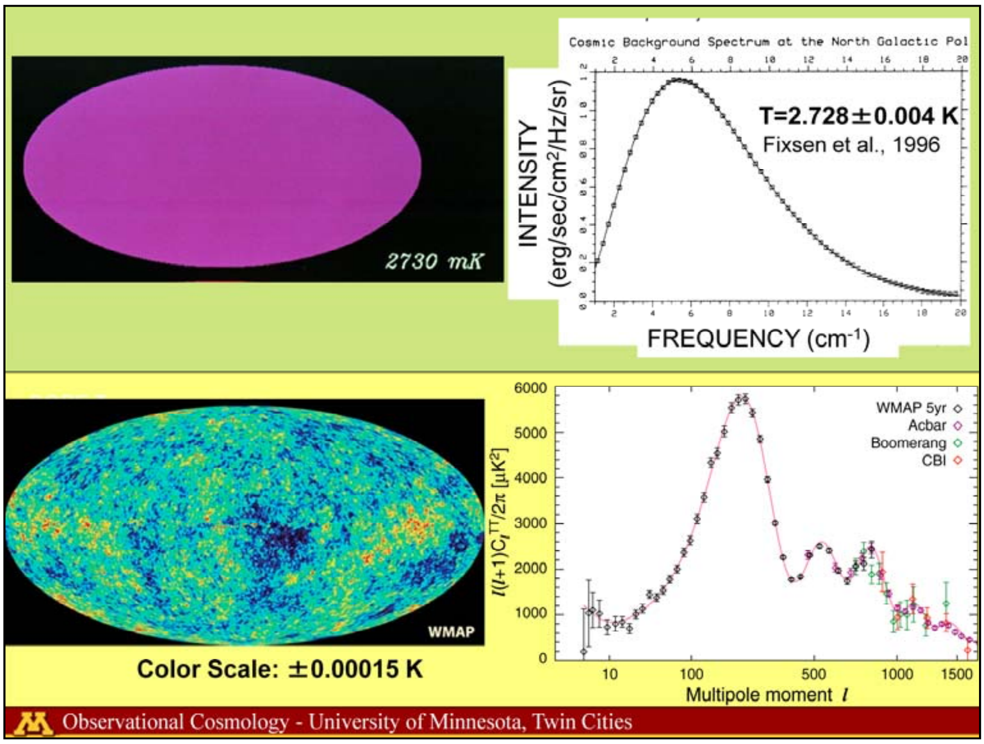
Increasing the intensity resolution of the map to few parts in 10^5, COBE was the first to detect the anisotropy in the spatial distribution of the CMB. Other experiments soon followed, here I am showing measurements from our own MAXIMA instrument. When this data was released in 2000 it was the highest resolution map of the CMB, and produced power spectrum measurements over the broadest range of angular scale and with the smallest systematic uncertainty. Science magazine called this and a similar measurement from the boomerang experiment “One of the ten …”.



Key point: all the discussion is done in terms of the power spectrum.

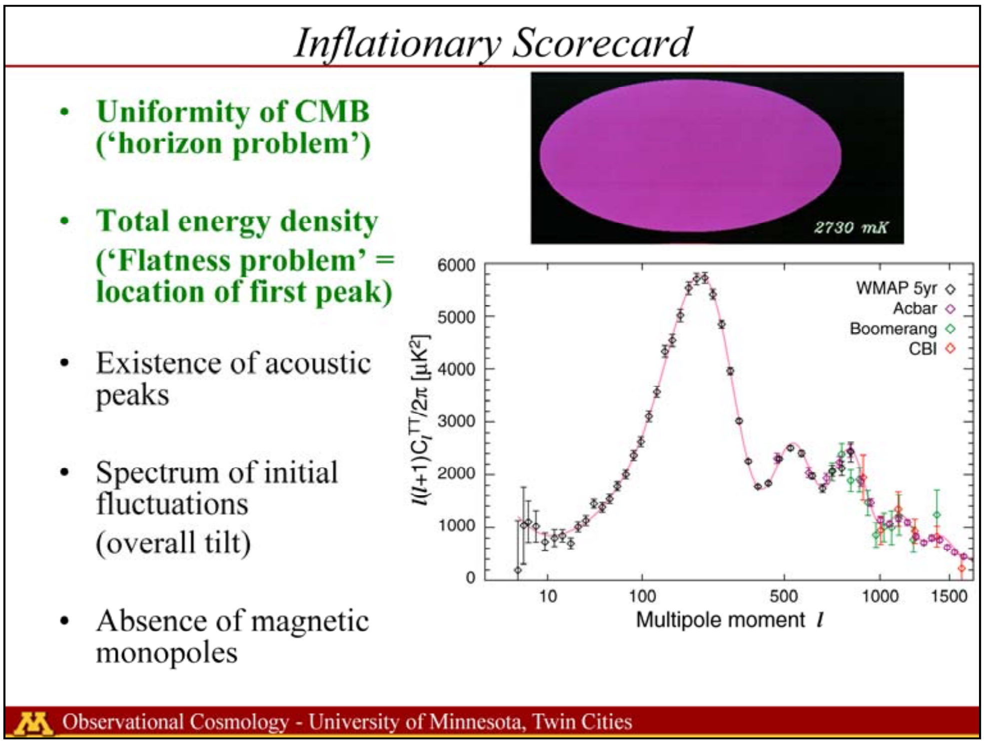


More recently the wmap satellite released data about the anisotropy



The data collected so far strongly suggests that inflation is a paradigm that is on the right track to explain the evolution of the Universe.

Here is a brief scorecard

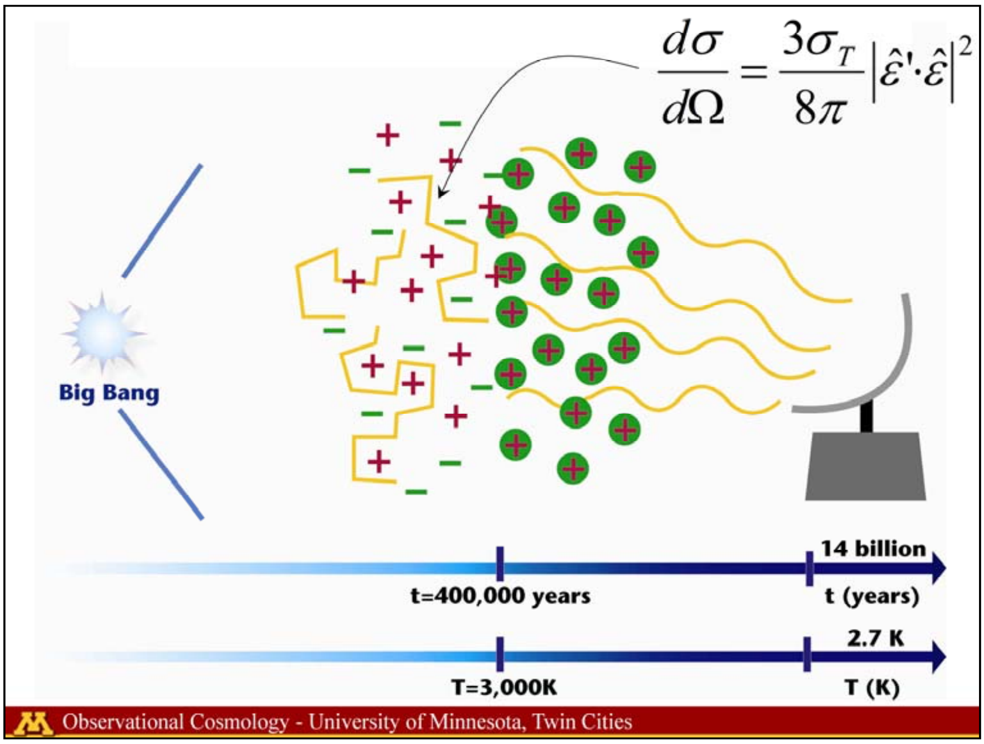


Here is a brief scorecard, without expanding on any of these details. There are some slides in the back discussing the Uniformity

Although these are reasonably strong arguments in its favor, Inflation also predicts an um-ambiguous signature in the **polarization** of the cosmic microwave background radiation.

Let us understand this signature and discuss how to measure it.

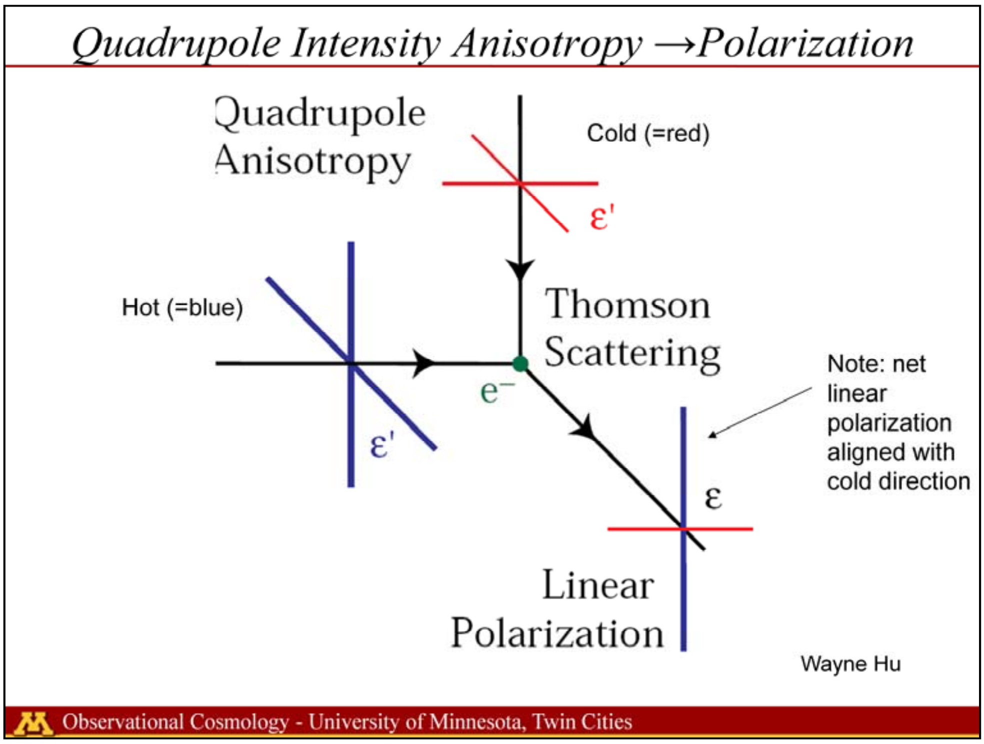
Let look again at the CMB photons at the epoch of decoupling.



During the epoch of decoupling the photons scatter from electrons in the plasma. Each of these scattering events is governed by the Thompson scattering cross section, which does depend on polarization. Here the polarization of the outgoing photon, here denoted as epsilon, has the same polarization as the incident one, here shown as epsilon'.

Since the photons have many scatterings before they decouple, and the plasma is a black body, we generally do not expect the radiation to be polarized. However, each one of the photons has one last scattering event before it streams freely into the Universe. This last scattering event gives the CMB a net measurable polarization.

Let's focus our attention on this last scattering event.

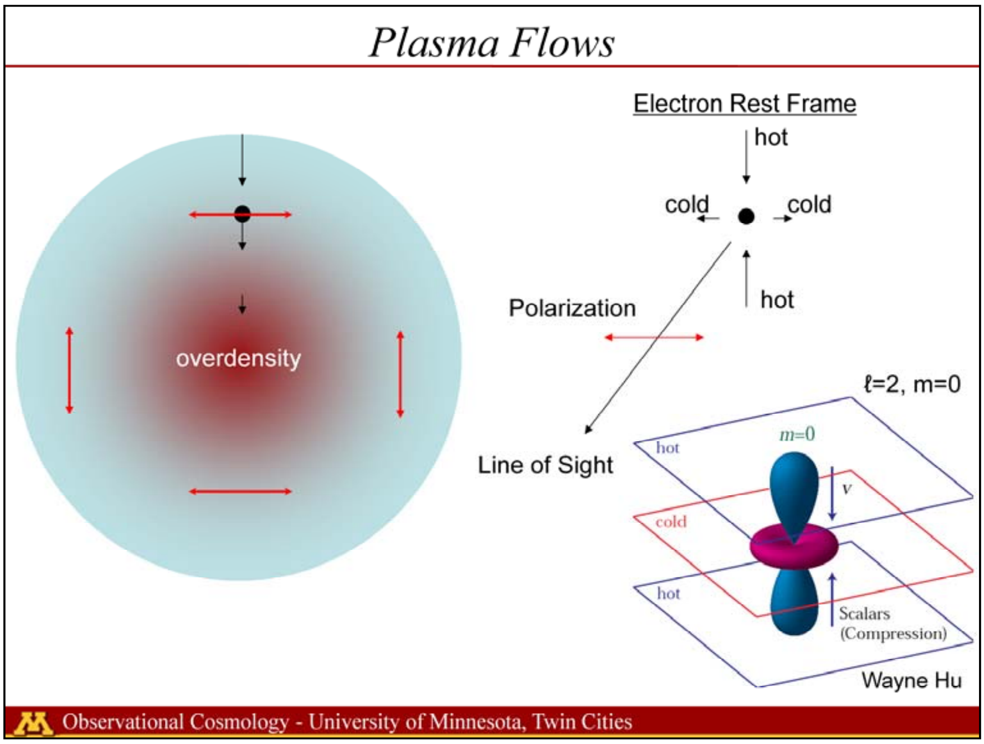


Consider an electron at the last scattering surface. Imagine a radiation field incident on the electron from all sides. Symmetry dictates that if the radiation field is isotropic the outgoing radiation in this direction should not be polarized.

However if the radiation field has a quadrupole intensity distribution a net polarization arises. Radiation from the top can be polarized either like this or like that. Because of the Thomson cross section, only this component propagates in our direction. Radiation from the left can be polarized like this or like that. Again, only this component propagates in our direction. If the radiation is more intense left right, and less intense top/bottom, this is the signature of a quadrupole distribution, net polarization will result.

It is relatively easy to see that because of symmetry **no other multipole** would contribute to net polarization. A dipole anisotropy: hot top and cold bottom would cancel each other, and so would the octupole and higher moments of the distribution.

On general terms we expect the radiation field at the surface of last scatter to **have all multipole components**, so we should not be surprised to find that the CMB is polarized. **But it is instructive to examine what are the specific mechanisms that give rise to the quadrupole.**



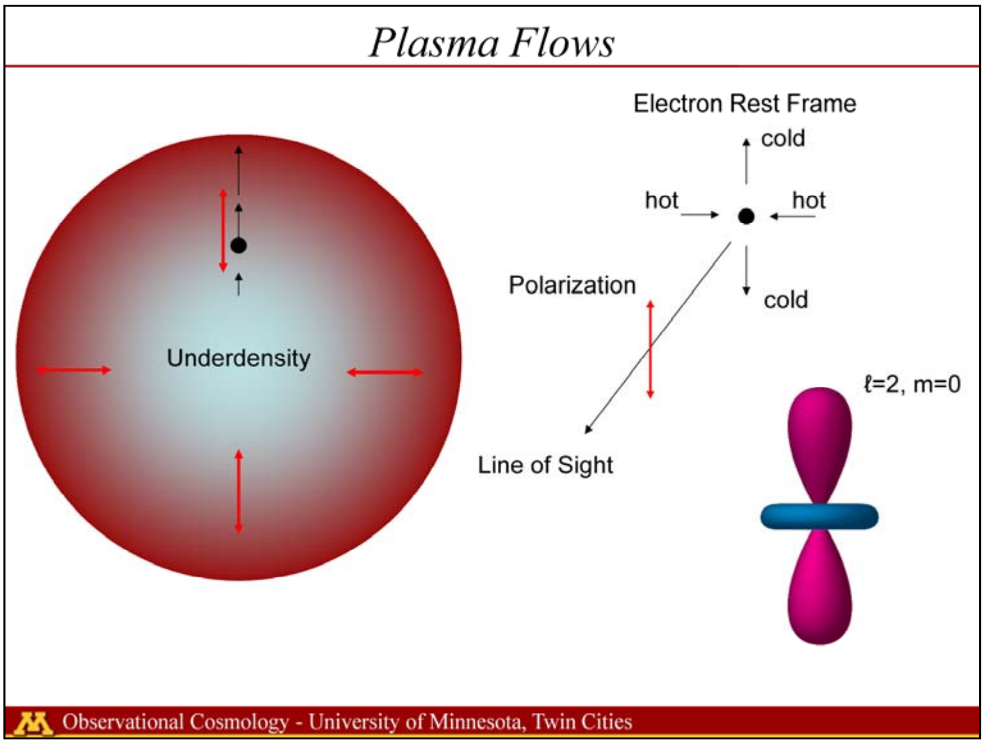
The first is due to flows in the electron, proton, photon plasma.

Consider a matter overdensity at the surface of last scatter. Matter flows into this overdensity, with velocity increasing with radius away from the center. Now look at the bulk flow as seen by a frame moving with this electron.

We see that bulk flows at the surface of last scatter lead to polarization patterns that are either tangential or radial with respect to temperature hot and cold spots.

We call this pattern an ‘E polarization pattern’, because it is symmetric under a parity operation. Mirroring around the center …

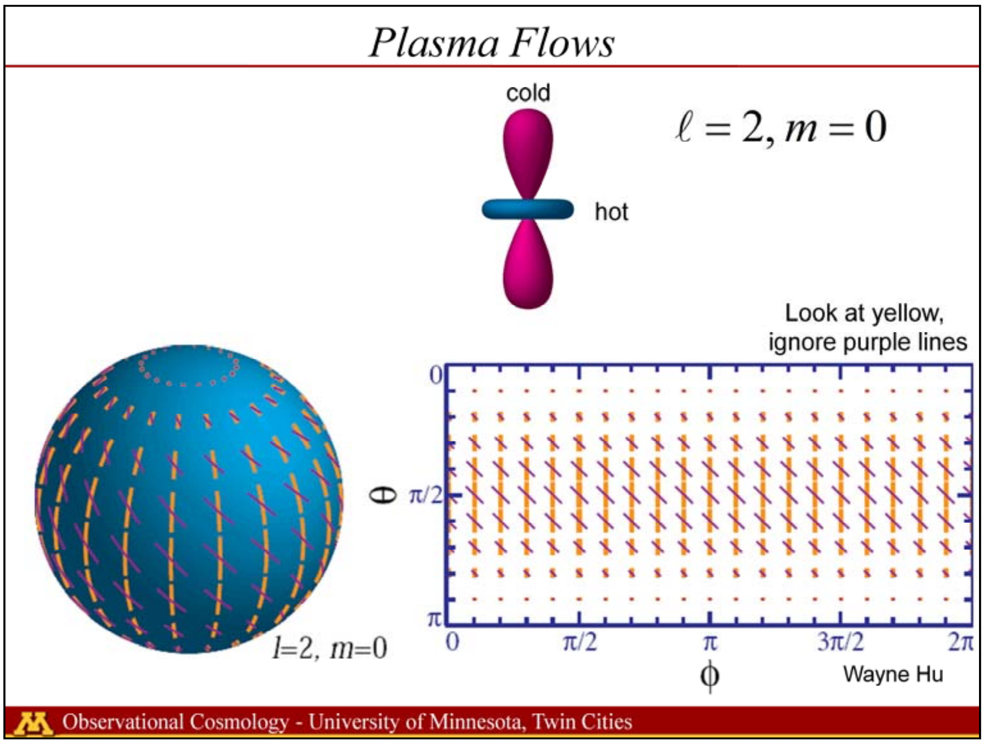
If I reverse the overdensity to underdensity



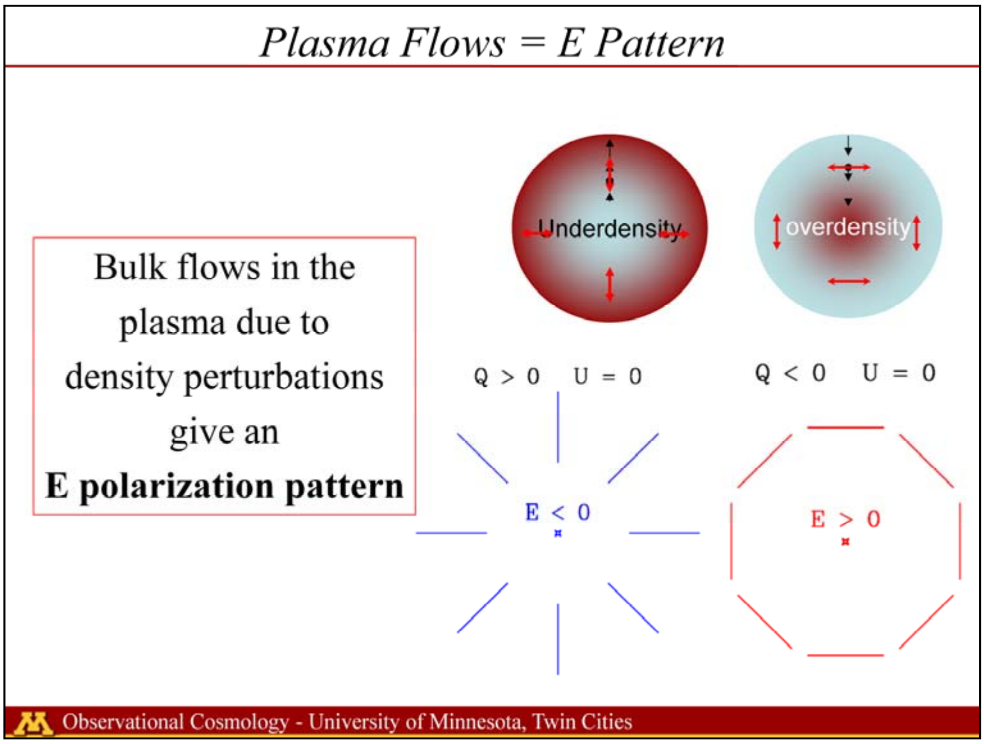
Explain again flows… moving to rest frame…

This too falls under the category of E

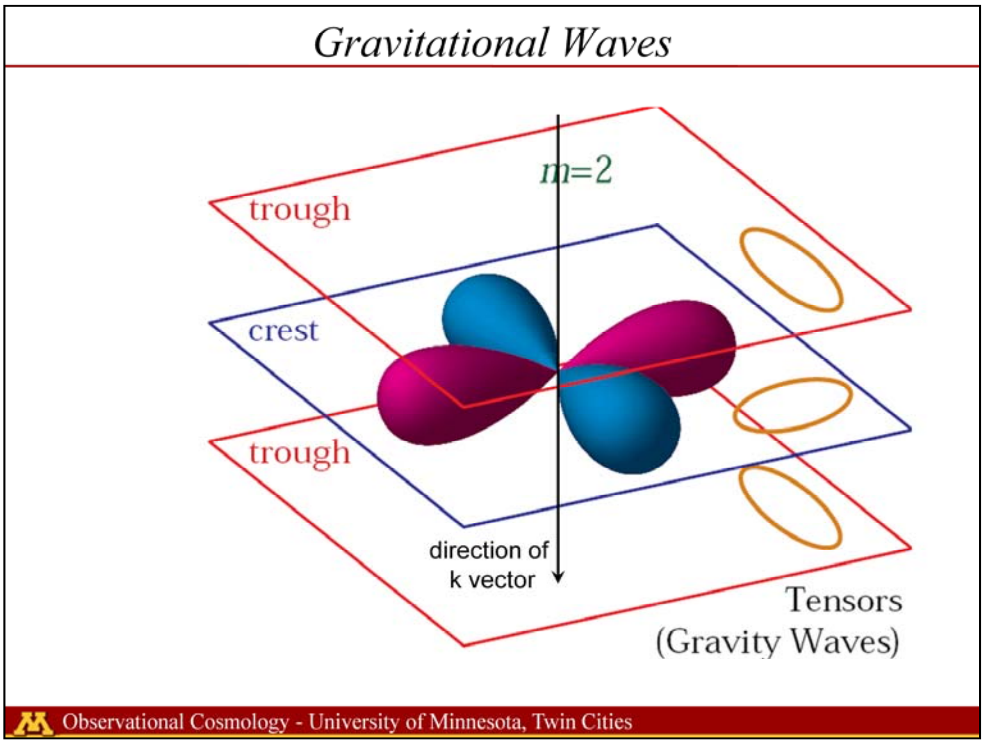
The line of sight we chose so far was at along the equatorial plane of the l=2,m=0 quadrupole function. For reasons that will become apparent in a minute let me show how the polarization vectors would look if I viewd this function from any direction.



Note that the polarization in any direction maintains its orientation – only its magnitude changes.



So we find that

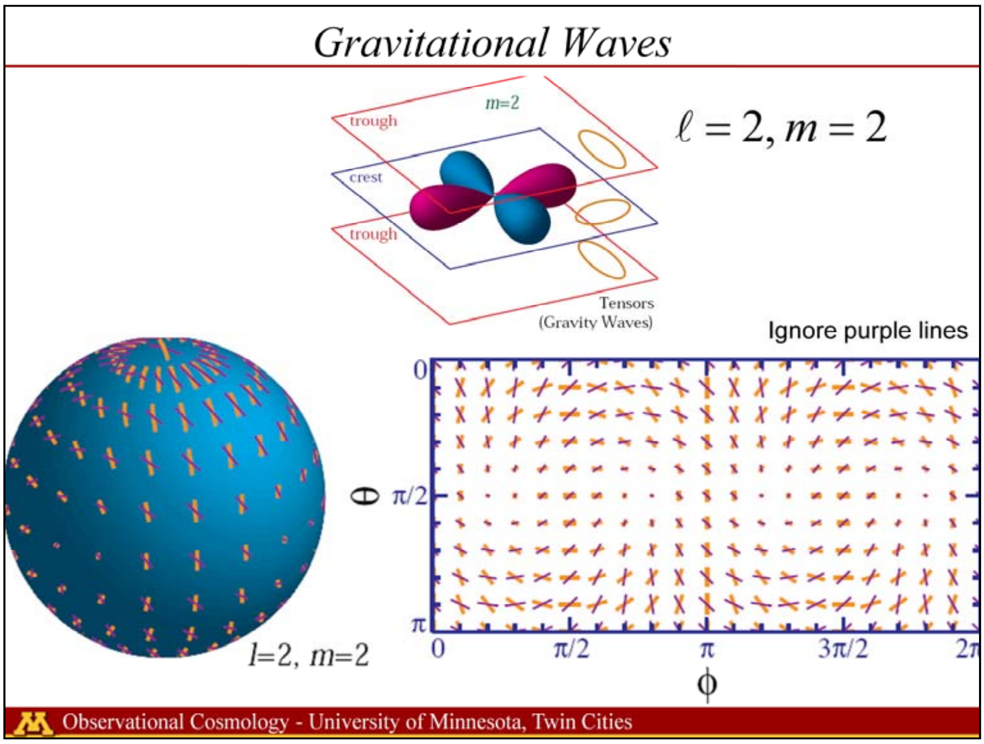


A second physical effect giving rise to quadrupole anisotropy at the surface of last scatter is the stretching of space by the passage of gravitational waves.

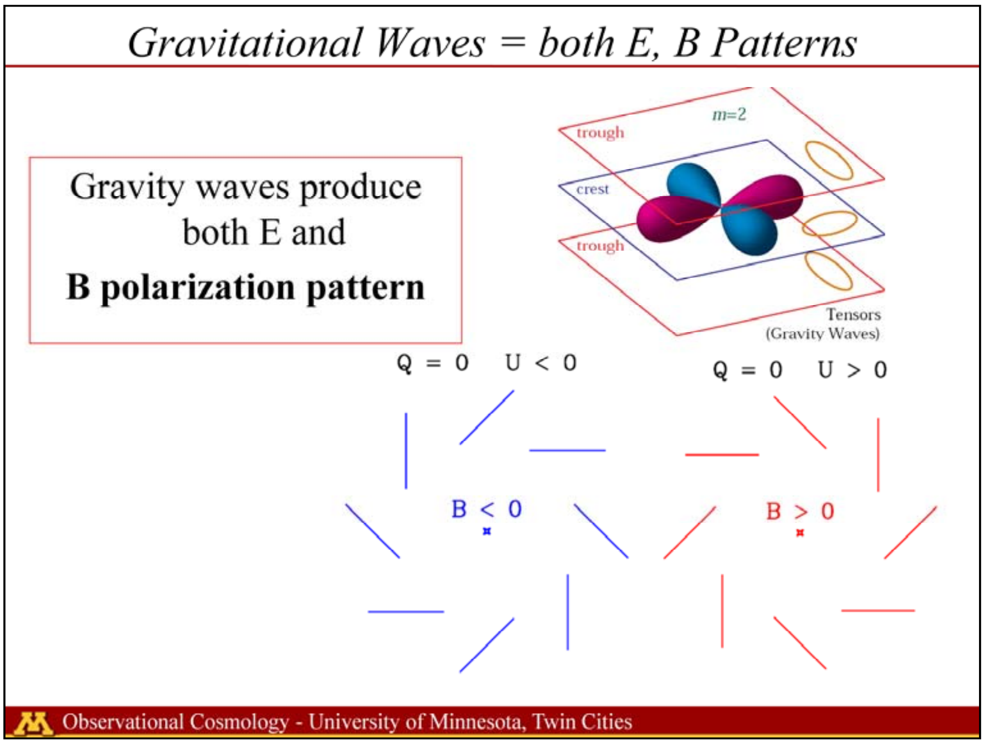
Here a plane gravity wave traverses space from top to bottom along the z axis. The gravity wave stretches space in one direction and contracts it in another doing the same for the radiation field. The result is the following local quadrupole pattern for the radiation field. The specific polarization orientation and magnitude that would arise from this quadrupole depends on the viewing angle relative to this pattern.

If the observer is at the top, she would view the full quadrupole pattern and would see a polarization along the red lobe. If the viewing angle happens to be along the plane and at an azimuthal angle between the red and blue lobes, the net polarization would be zero.

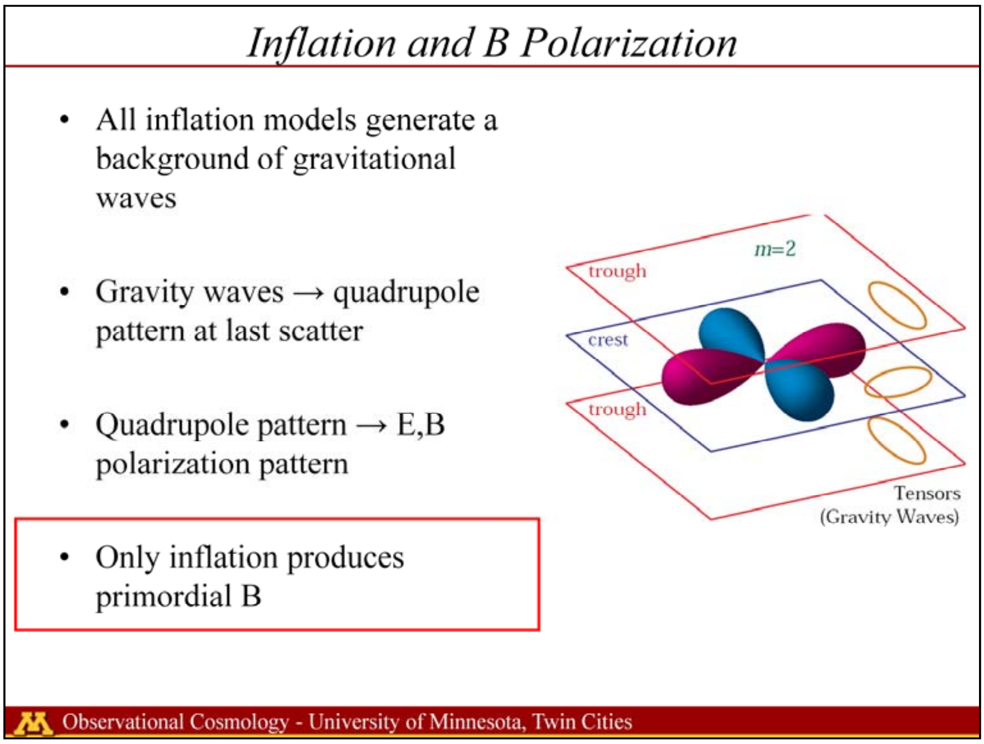
Here is the same picture I showed before, but now for the l=2, m=2



Note that now the yellow vectors have E patterns but they also curl. They have a B pattern



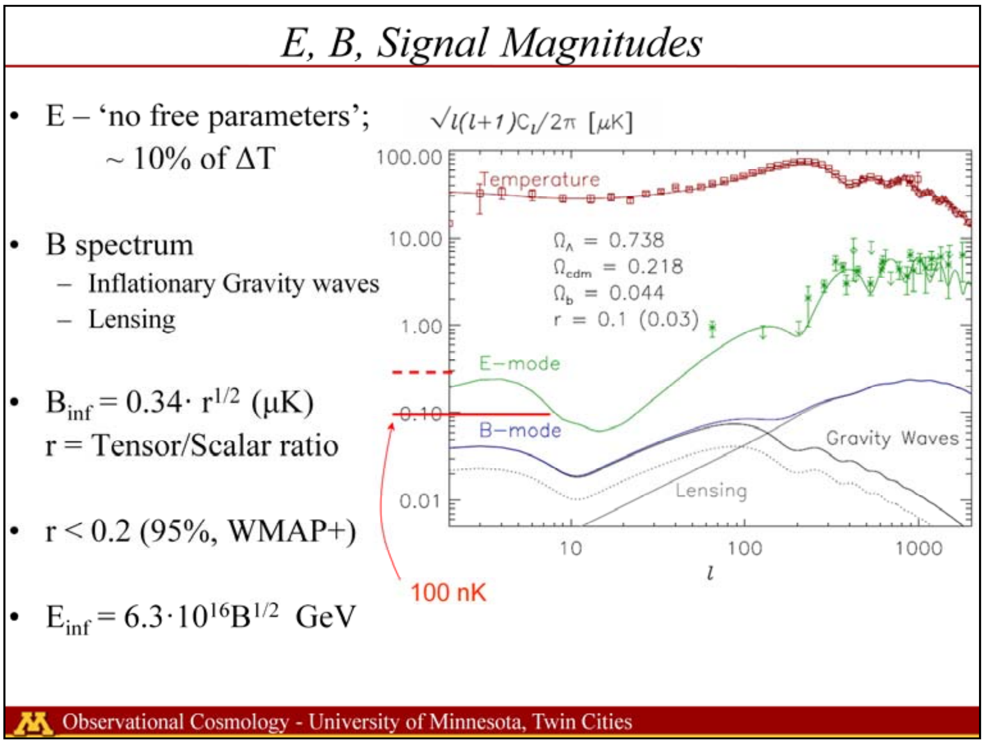
It is called a B pattern because it is odd under a parity transformation.



It is interesting to understand the effect of gravity waves because ALL inflation models generate a background of gravitational waves that traverse the Universe, just like the CMB does.

As we have seen, gravity waves produce a quadrupole intensity anisotropy at the surface of last scatter, and that anisotropy gives an imprint on the polarization of the CMB. **So a detection of this B pattern is equivalent to detecting Inflation directly.**

The quantitative question is whether this imprint is observable?



The quantitative question is whether this imprint is observable?

Just like for the analysis of the temperature anisotropy, the comparison between models and data for polarization is carried out in the multipole domain.

Here are the predicted polarization power spectra.

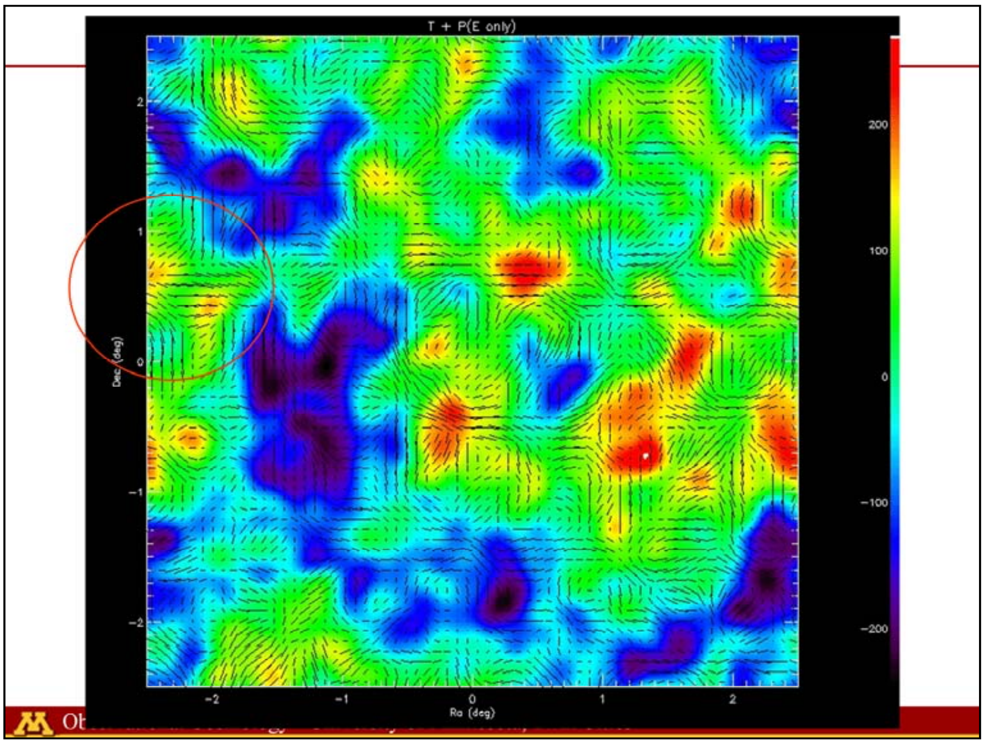
Talk about

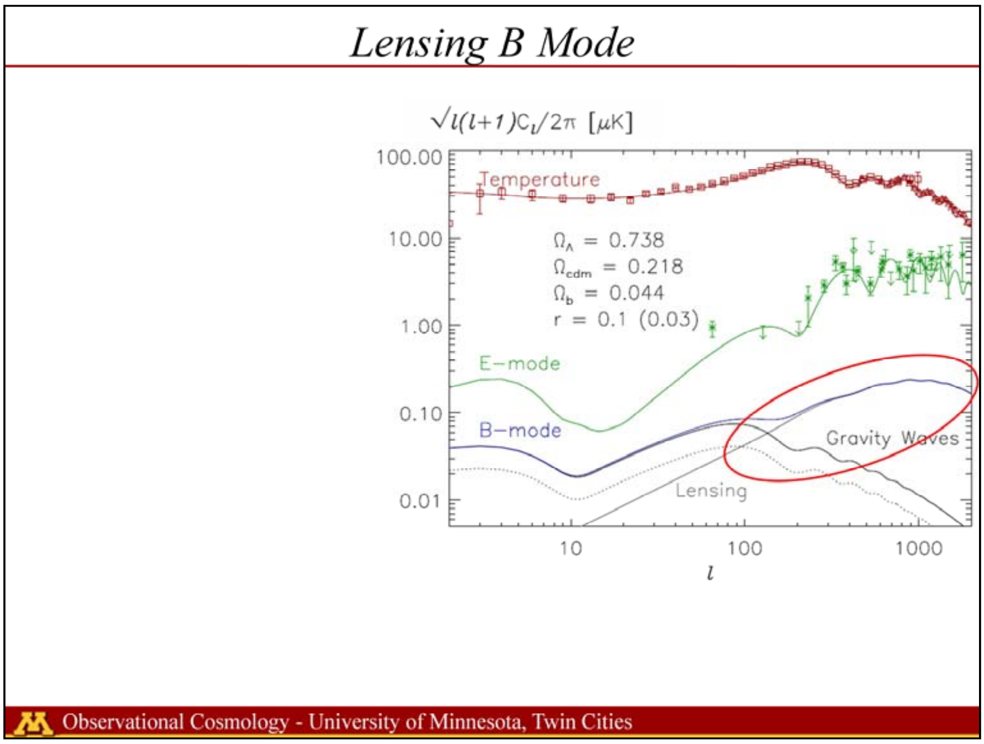
E mode, B mode, Density perturbations do not produce B! show level of 100 nK.

Tensor/Scalar ratio,

Lensing, Reionization bump, Add WMAP polarization constraint, Detection of E, significance of detection of E.

Order of magnitude of signal, we have only upper limit, scaling of signal with energy scale of inflation.


T + P(E only)
Dec (deg)
Ra (deg)



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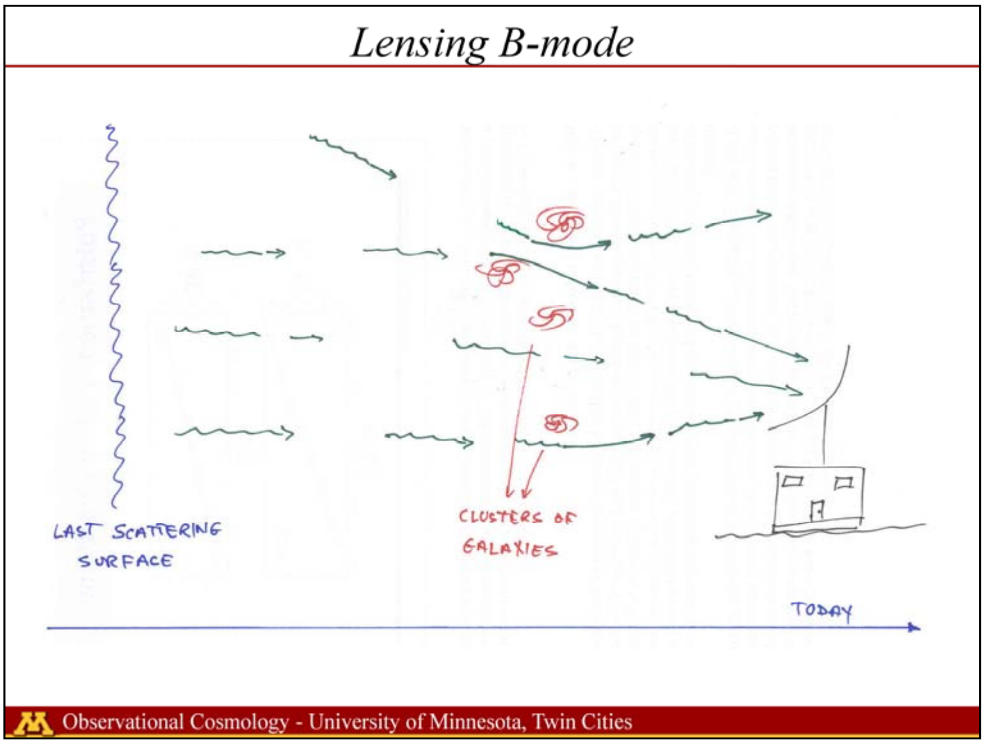

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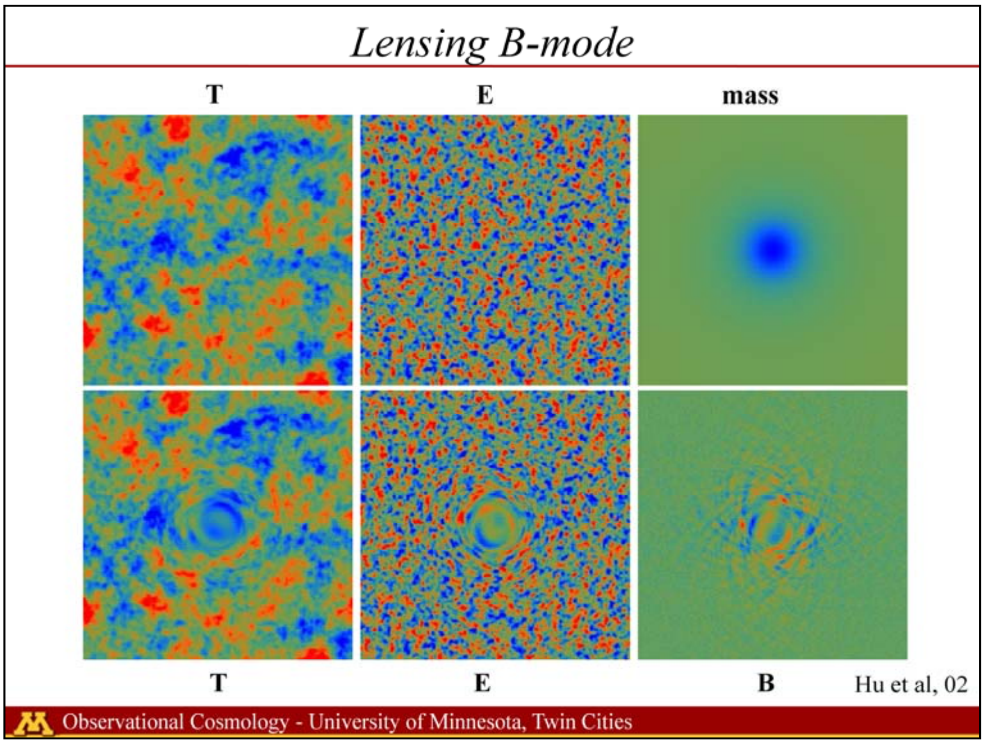

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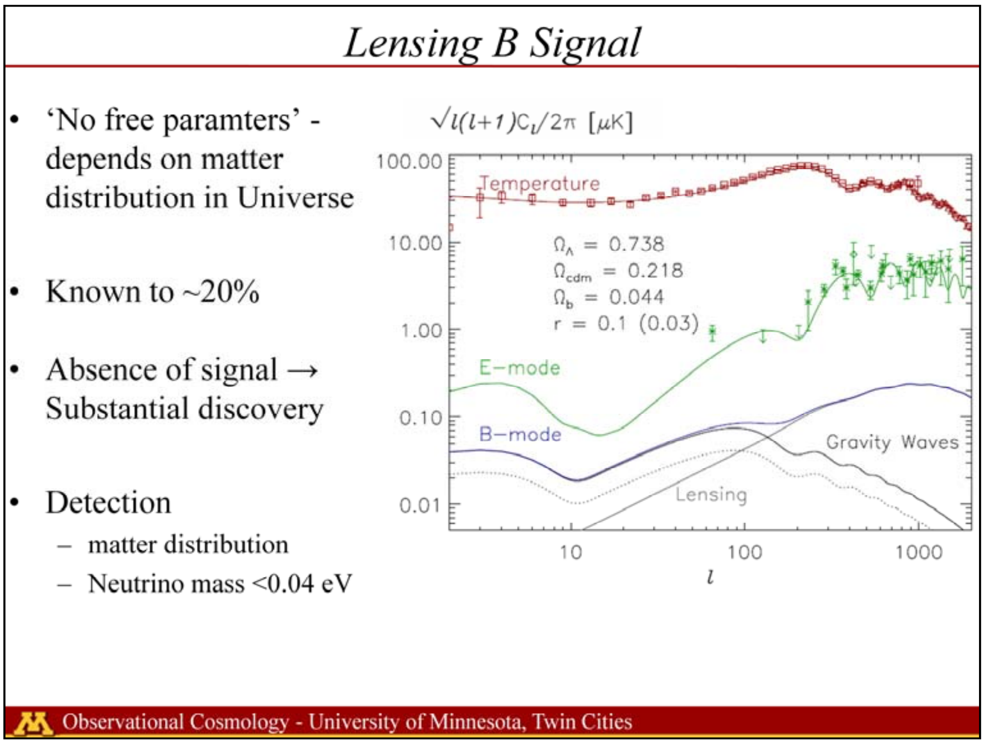

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Order of magnitude of signal, we have only upper limit, scaling of signal with energy scale of inflation.

Intermediate Summary

- Inflationary models generate a background of gravitational waves
- Gravity waves imprint a B-mode signal on the polarization of the CMB.
- Only known direct probe of Inflation
- Detection
  - Fixes energy scale of inflation
  - Gives clues about the inflaton field
  - Provides input to GUT-scale/String theory models
- Non detection
  - Broad (and important) class of inflation models ruled out
  - Constrains GUT scale theories
- Signal is <150 nK
- Some theoretical prejudice for signal at 10 – 100 nK
- B from lensing of E $\rightarrow$ an opportunity to find a new signal

Observational Cosmology - University of Minnesota, Twin Cities

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EBEX in a Nutshell

- Long duration balloon borne
- Use 1476 bolometers
- 3 Frequency bands: 150, 250, 410 GHz
- Resolution: 8' at all frequencies
- Polarimetry with half wave plate

Collaboration

APC – Paris
Radek Stompor

Berkeley Lab
Julian Borrill
Christopher Cantalupo
Ted Kisner

Brown University
Andrei Korotkov
Greg Tucker

Cardiff
Peter Ade
Will Grainger
Enzo Pascale

Columbia University
Daniel Chapman
Joy Didier
Seth Hillbrand
Michele Limon
Amber Miller
Britt Reichborn-Kjennerud

GSFC
Brad Johnson

IAS-Orsay
Julien Grain
Nicolas Ponthieu

IAS-Princeton
Matias Zaldarriaga
Amit Yadav

Imperial College
Andrew Jaffe

INRIA – Saclay
Federico Stivoli

KEK- Japan
Tomotake Matsumura

LAL-Orsay
Matthieu Tristram

McGill University
Francois Aubin
Matt Dobbs
Kevin MacDermid
Graeme Smecher

NIST
Gene Hilton
Hannes Hubmayr
Kent Irwin
Carl Reintsema

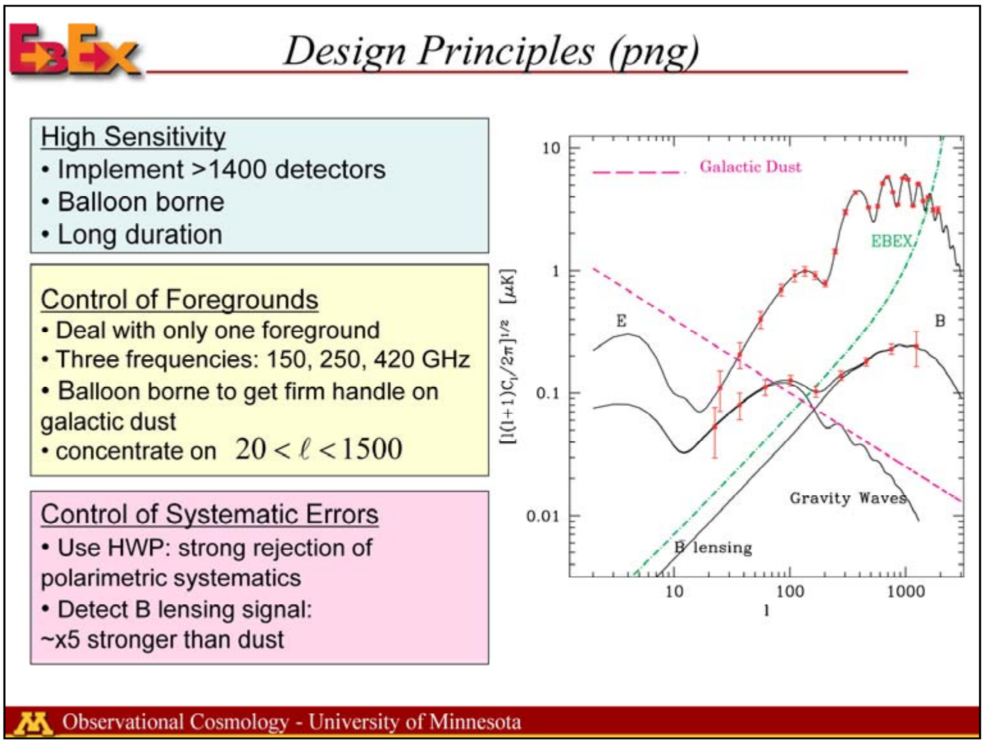
SISSA-Trieste
Carlo Baccigalupi
Sam Leach

University of California/Berkeley
Ben Westbrook
Adrian Lee
Xiaofan Meng

University of Minnesota/Twin Cities
Asad Aboobaker
Chaoyun Bao
Ben Gold
Shaul Hanany (PI)
Terry Jones
Jeff Klein
Michael Milligan
Kate Raach
Ilan Sagiv
Kyle Zilic

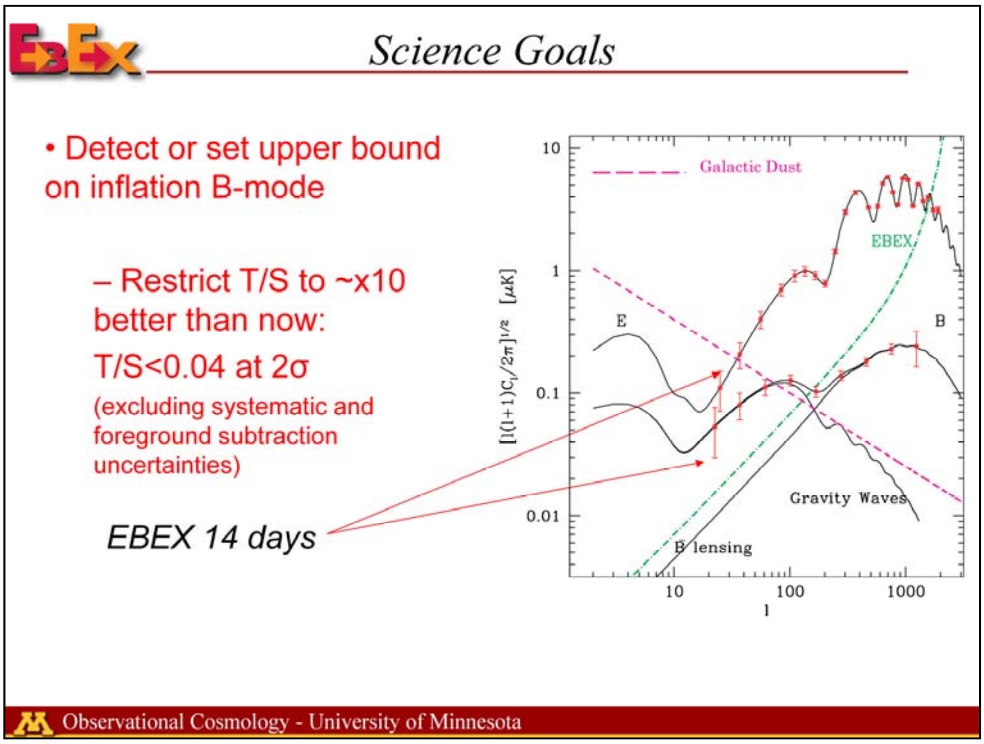
Weizmann Institute of Science
Lorne Levinson

Observational Cosmology - University of Minnesota



Do you have a figure showing the spectrum on the sky

For the first time in CMB studies we have reasonably high certainty that foregrounds will need to be removed!



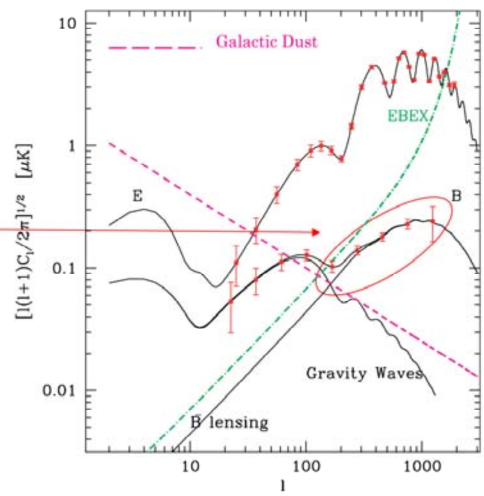
REPLACE WITH UPDATED FIGURE?

Science Goals

- Detect or set upper bound on B-mode

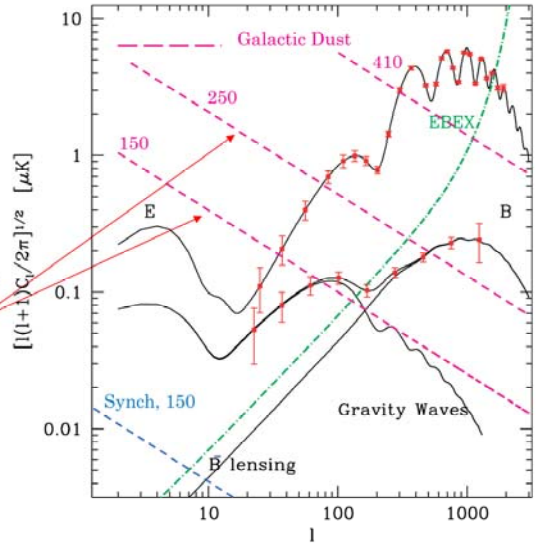
- Detect the lensing B-mode:

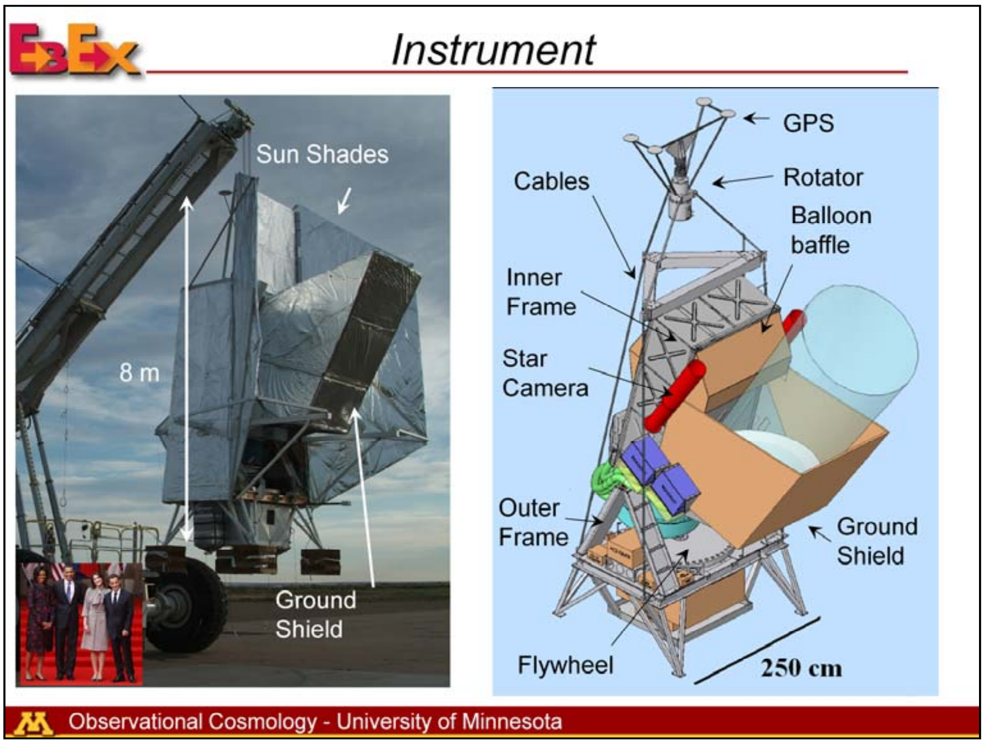
    - 5% error on amplitude of lensing power spectrum



Science Goals

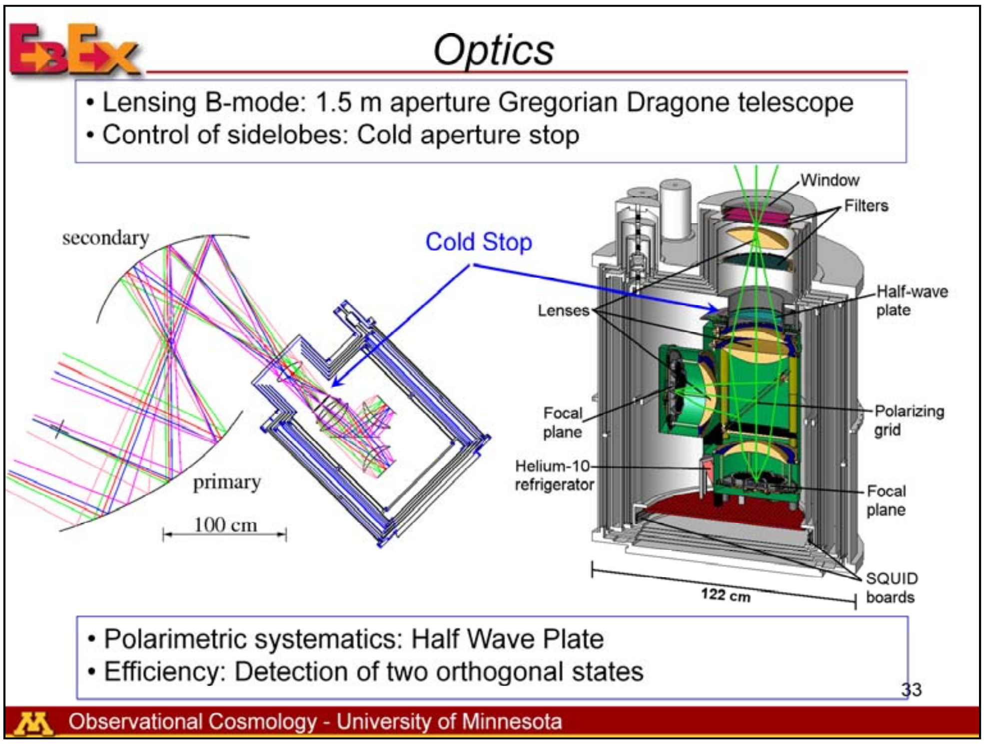
- Detect or set upper bound on B-mode
- Detect the lensing B-mode
- Determine properties of polarized dust





A cable suspended gondola similar to blast. This is the rotator, a spreader bar for the cables, star cameras, inner frame that can change elevation viewing angle through rotation about trunion bearings located here, and an A-frame that holds the inner frame relative to lower table.

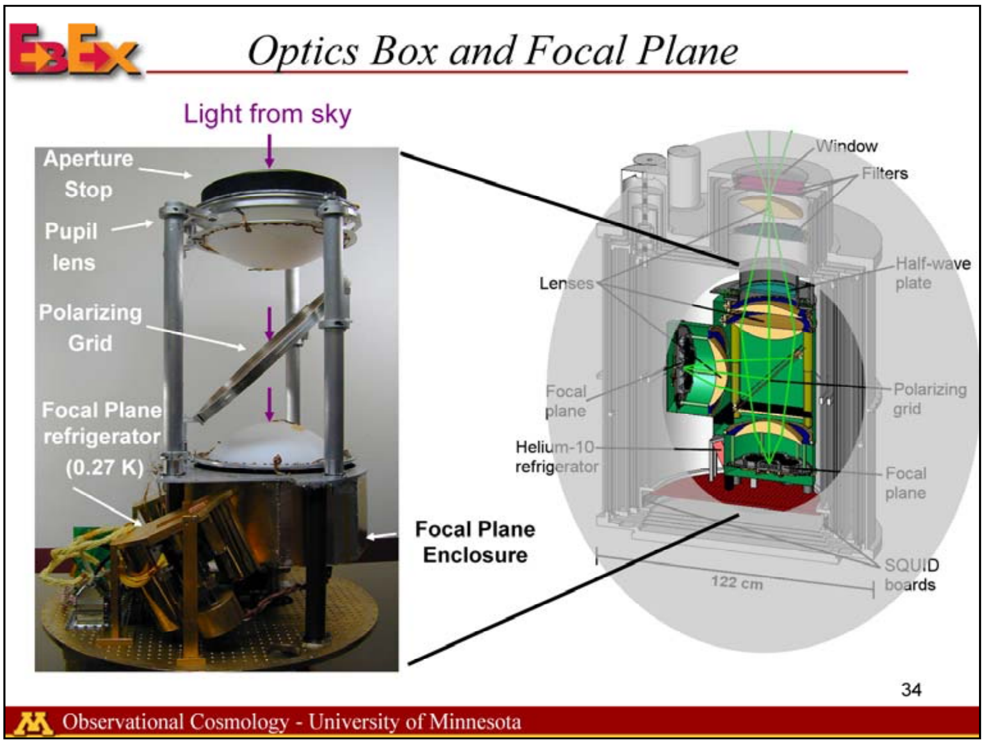
If you remove the inner frame baffle and some of the inner frame permanent baffles, you can see



Here is another view of the optical system, the warm part on the left and the cold part on the right.

This optical design is driven by the science goal of searching for the B-mode lensing signal. We are using the 1.5 meter aperture Archeops mirror to provide the resolution that extends our window function to an \ell larger than 1000. All the optical elements on the right are heat sunk to liquid He. We control sidelobes by using a liquid he cooled aperture stop that is formed by the field lens.

The polarimeter is based on a HWP located on the aperture stop and a rather large 40 cm wire grid analyzer. We are collecting incident photons in both polarization states by implementing two focal planes, one directly below the grid and one that collects photons with the orthogonal polarization state.



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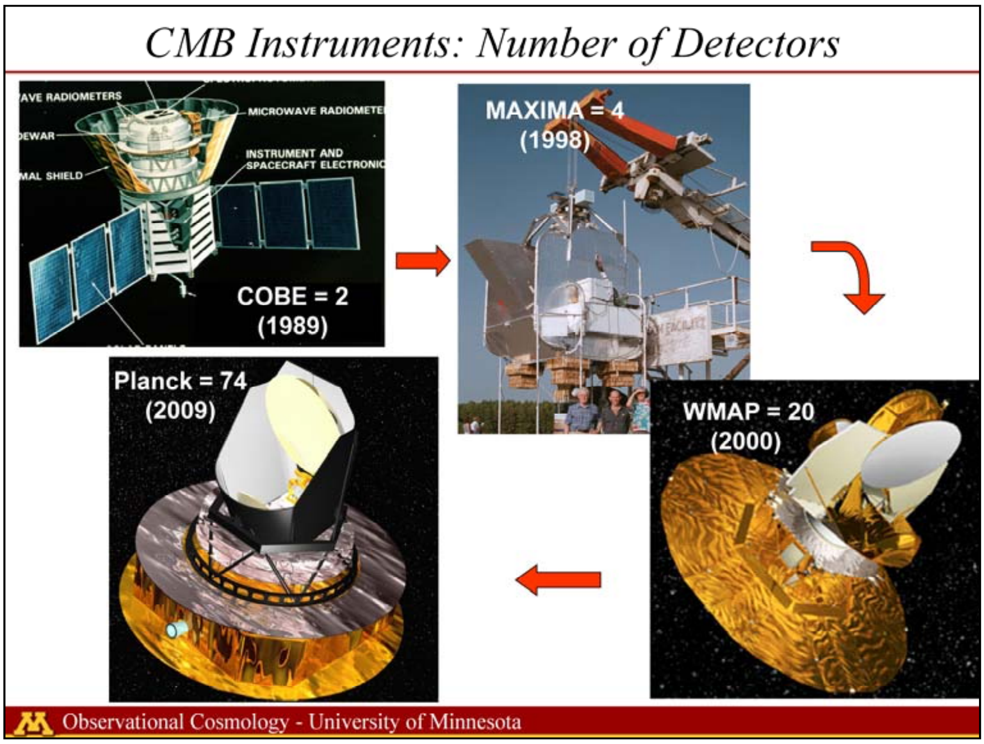
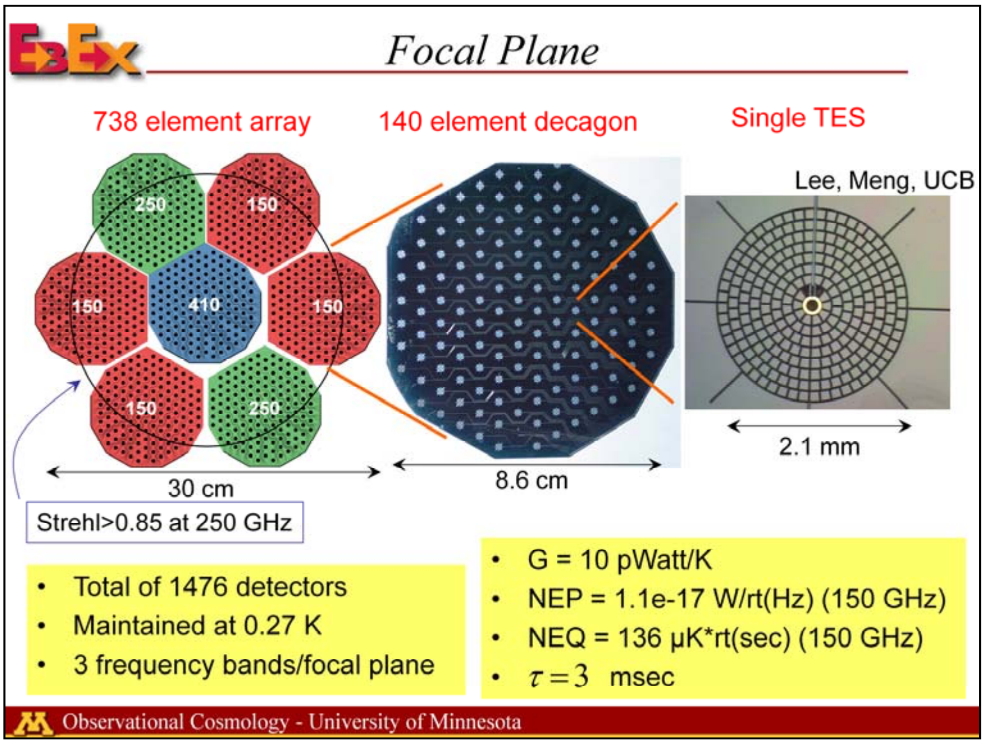
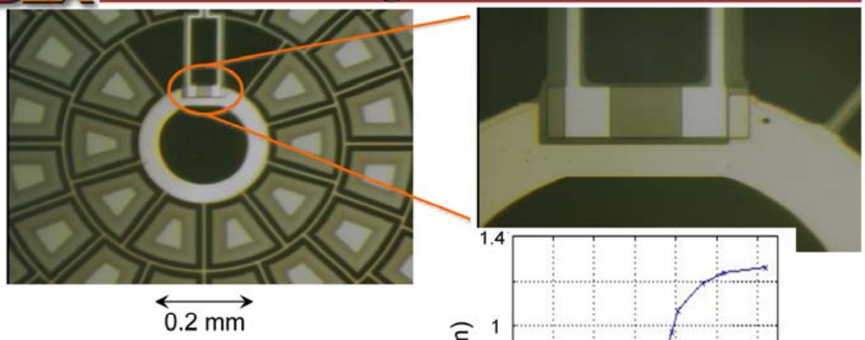


74 is the total number of detectors for the Planck mission. The number of polarized detectors is only 54 (for both LFI and HFI).

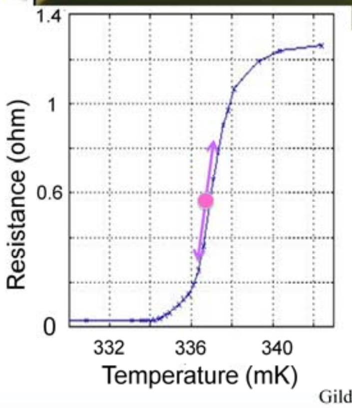

Focal Plane
738 element array
140 element decagon
Single TES
Lee, Meng, UCB
250
150
150
410
150
150
250
30 cm
8.6 cm
2.1 mm
Strehl>0.85 at 250 GHz
• Total of 1476 detectors
• Maintained at 0.27 K
• 3 frequency bands/focal plane
• G = 10 pWatt/K
• NEP = 1.1e-17 W/rt(Hz) (150 GHz)
• NEQ = 136 μK*rt(sec) (150 GHz)
• $\tau = 3$ msec
Observational Cosmology - University of Minnesota

Transition Edge Sensor Bolometer



Changes in absorbed power =
Changes in temperature =
Changes in resistance =
Changes in current

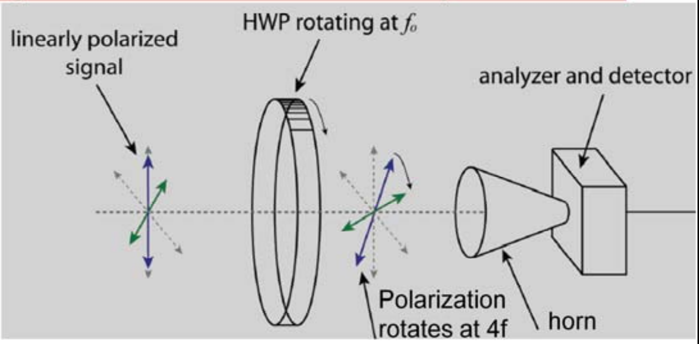
$\Delta I \cong 0.1\ 10^{-9}$ amps

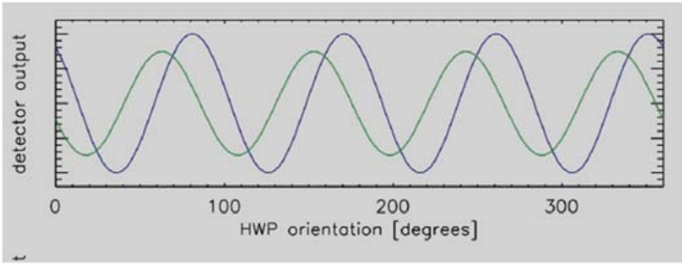


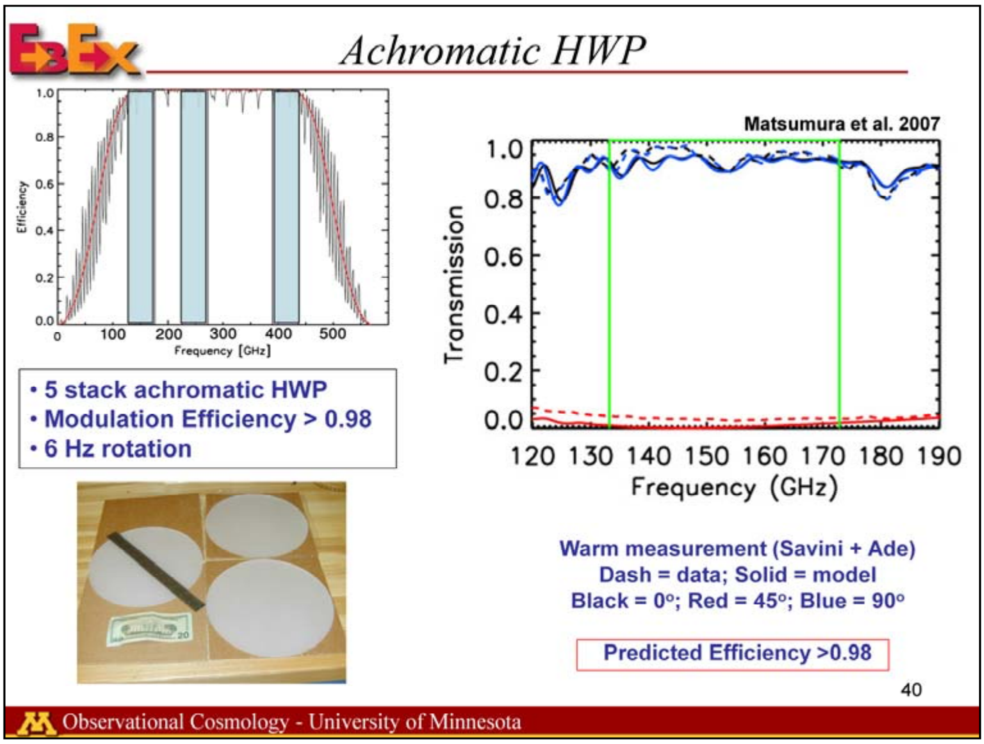
Gildermeister (2000)

Half-Wave Plate Polarimetry

- HWP modulates polarization state without changing beam pattern
- Fast modulation→ avoid 1/f noise
- Entire polarization measurement with a single detector
- Challenge: continuous cryogenic rotation



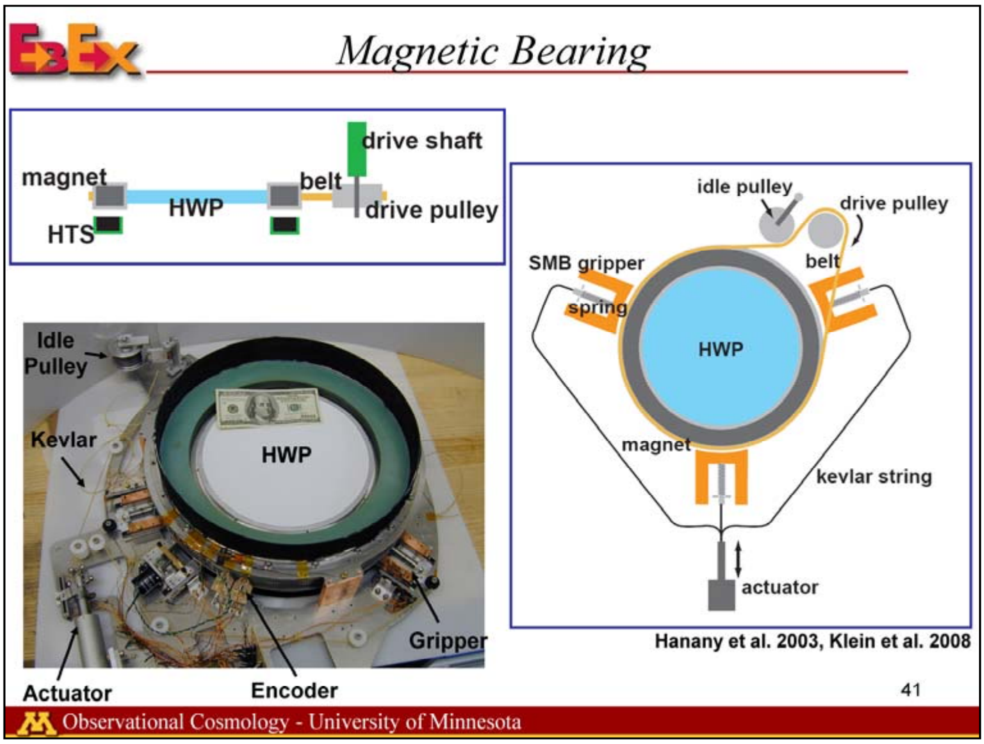




We will use a continuously rotating HWP to modulate the incident polarization. In that regard we are following on the footsteps of the maxipol experiment, which was the first to show a successful implementation of a rotating HWP with a CMB experiment.

Here I show a power spectrum of one section of Q data from maxipol.

EBEX will use an achromatic hwp. This is a stack of 5 HWP oriented in particualr orientation relative to each other to provide high modulation efficiency over a broad band of frequencies.



We will use a continuously rotating HWP to modulate the incident polarization. In that regard we are following on the footsteps of the maxipol experiment, which was the first to show a successful implementation of a rotating HWP with a CMB experiment.

Here I show a power spectrum of one section of Q data from maxipol.

EBEX will use an achromatic hwp. This is a stack of 5 HWP oriented in particualr orientation relative to each other to provide high modulation efficiency over a broad band of frequencies.

EBEX Status – 2009 Test Flight

- First balloon-borne operation of TES bolometers
- First implementation of novel readout system
- First implementation of magnetic bearing for polarimetry

North American Test Flight, June 11, 2009

EBEX Test Flight, 11th June 2009

~10 hours at float
~35 km

EBEX In Flight

www.realufos.net

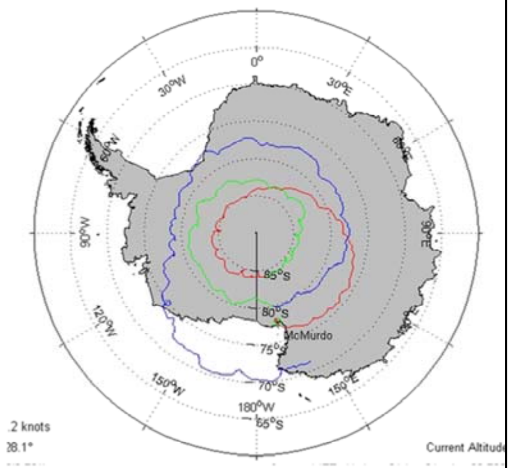
Thursday, June 11, 2009

Bright UFO over Phoenix Arizona 11th June 2009

Everyone is emailing me about this!
Did you see the huge bright Ufo over Phoenix Arizona 11th June 2009?
Real Ufos wants to know, please respond to this post your information asap!

Current Status + Timeline

Antarctic long duration: Dec. 2011

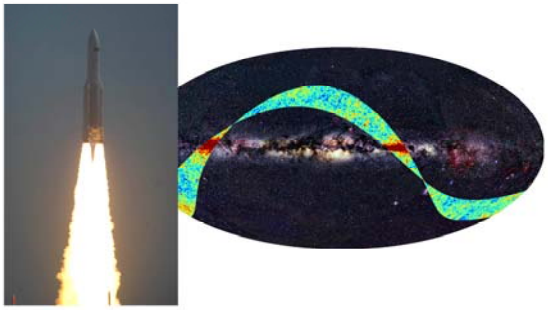


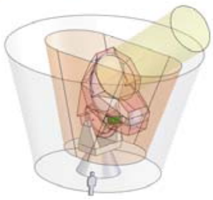
Flights are 14 days average
>40 days achieved

Observational Cosmology - University of Minnesota

The Competition

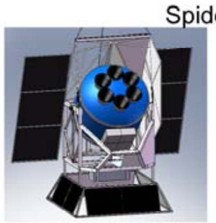
- Planck:
  - launch in May 14, 2009
  - 1 year data ~end 2010
  - 54 polarization sensitive detectors
- Ground
  - Polarbear (Berkeley)
  - BICEP/Keck (Harvard)
  - SPT-Pol (Chicago)
  - ACT-Pol (Princeton)
- Balloon
  - Spider (Princeton)
  - Piper (Goddard)





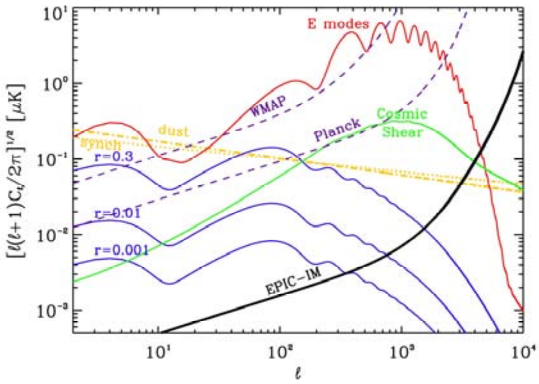
Polarbear

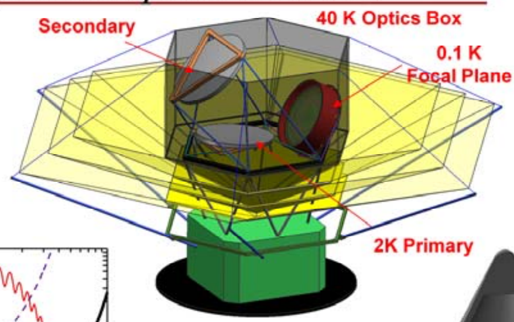
Spider



EPIC – A Definitive Space Mission

- 1.4 meter Dragone telescope
- **11094 detectors**
- 30 – 850 GHz
- 4 year duration
- **5.4 nK/2° beam**





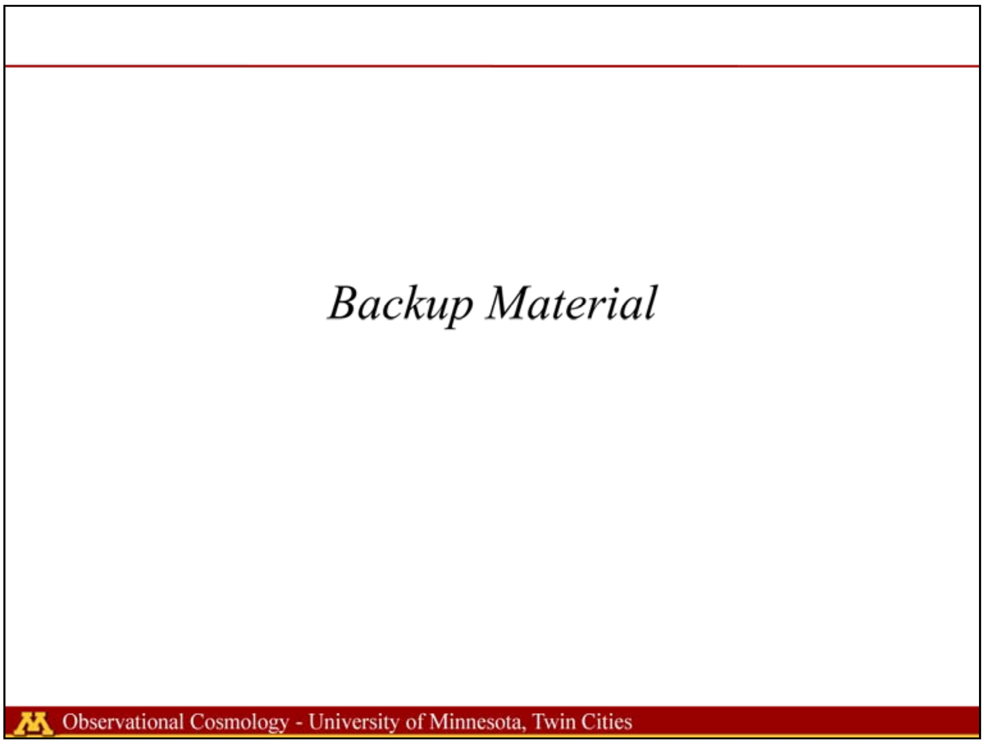
Atlas 4-m shroud

Summary

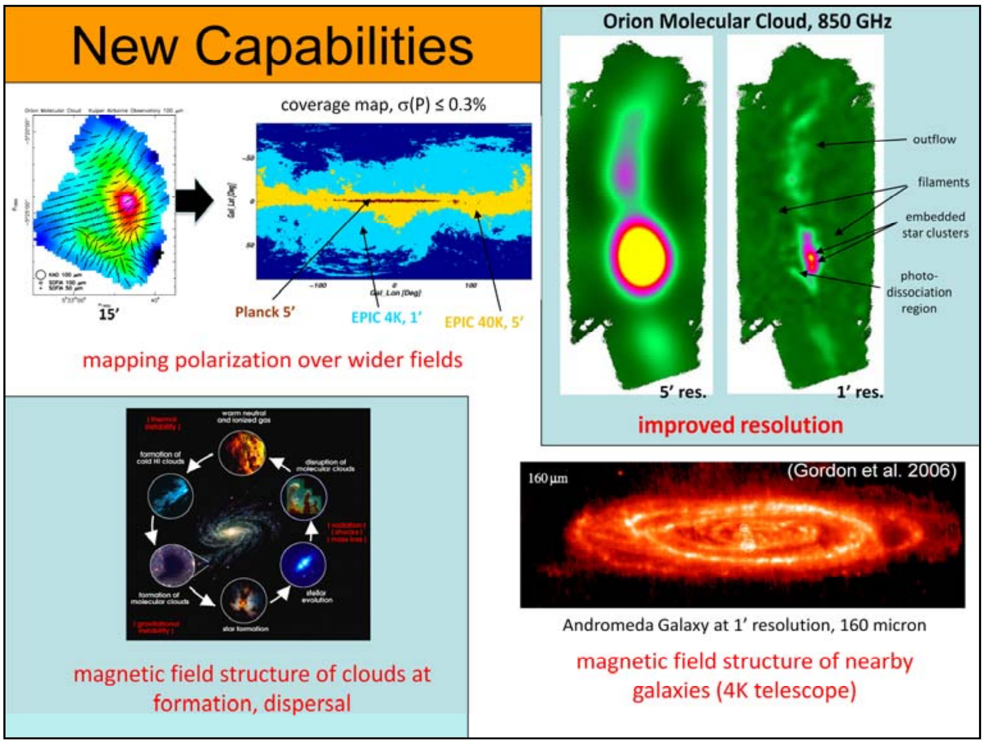
- CMB Polarization provides a unique opportunity to probe the epoch of inflation (and fundamental physics)
- Sub-orbital measurements will begin to probe the interesting parameter range over the next few years
- Instruments with thousands of detectors are required to ensure high signal to noise ratio
- A space mission can provide a definitive measurement

Observational Cosmology - University of Minnesota, Twin Cities

Spectacularly unique and fundamental science that goes to the heart of our existence and that you can’t do any other way



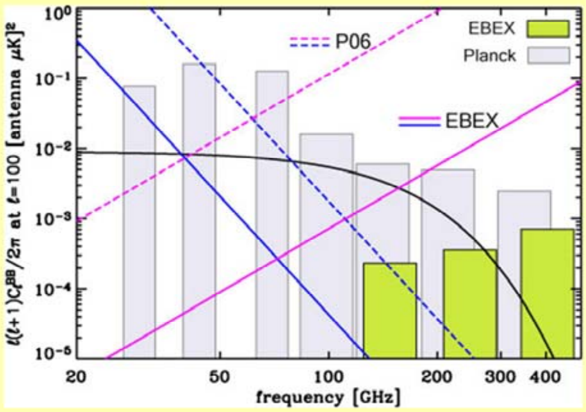
Spectacularly unique and fundamental science that goes to the heart of our existence and that you can't do any other way



First two are comparisons with Planck (and suborbital).
The 40 K telescope doesn't have enough sensitivity to do Andromeda well.

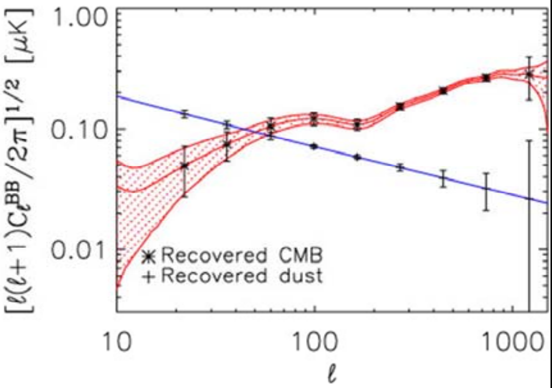
Dust Determination and Subtraction

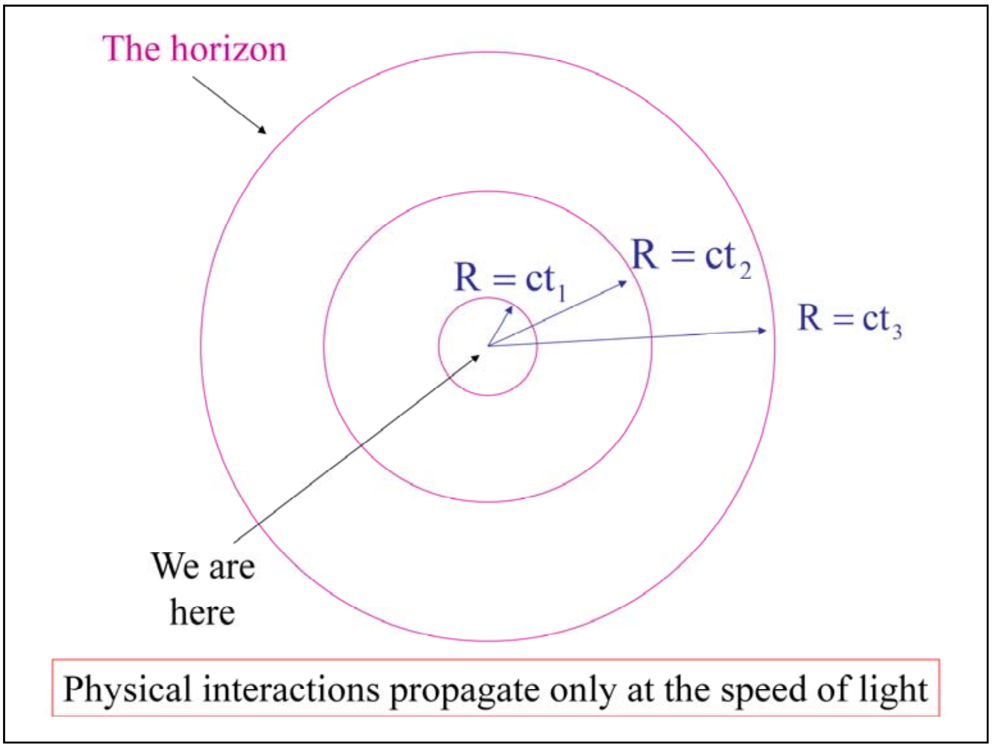
CMB-B, Dust, Synch outside P06 and in EBEX region, and Planck + EBEX sensitivity



Dust Determination and Subtraction

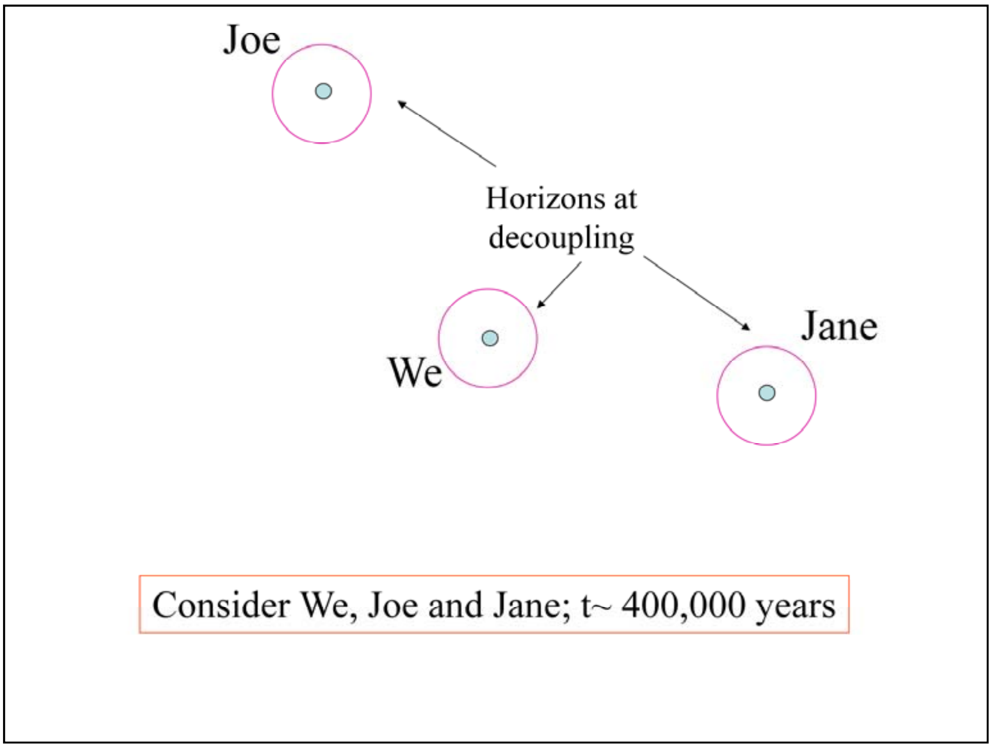
- Simulate CMB, dust, noise
- Reconstruct dust + CMB maps (using parametric estimation)
- Red = instrument noise + sample variance
- Black dust = errors of reconstruction
- Black CMB = variance of 10 simulations
- No systematic uncertainties



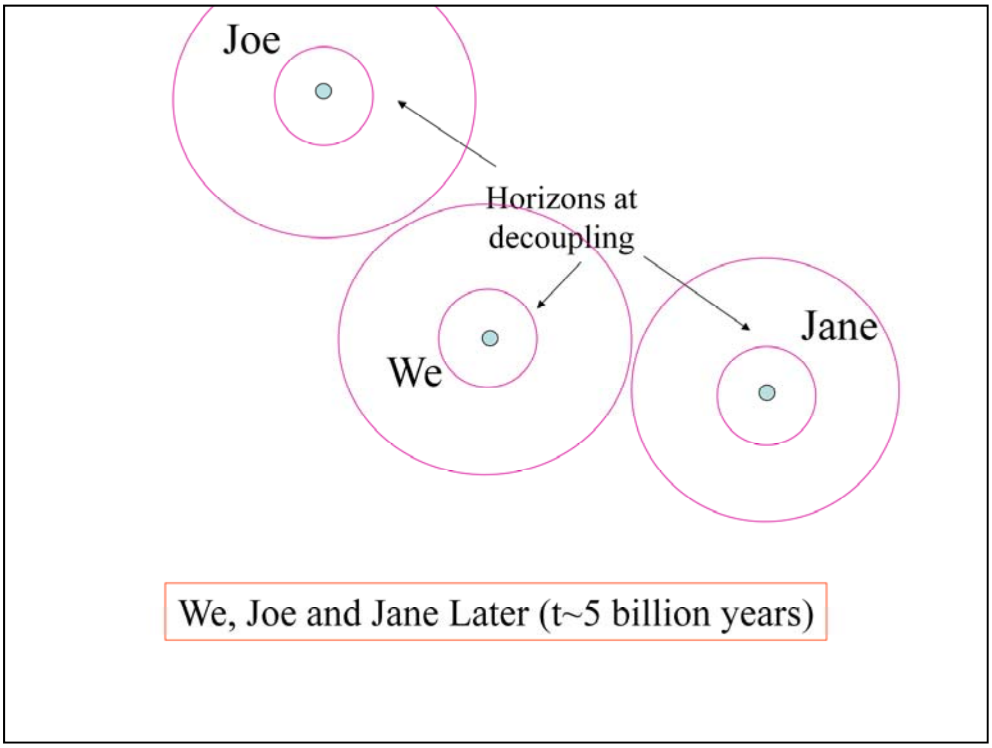


We all know that light, information and physical interactions are all transmitted at the speed of light; not any faster.

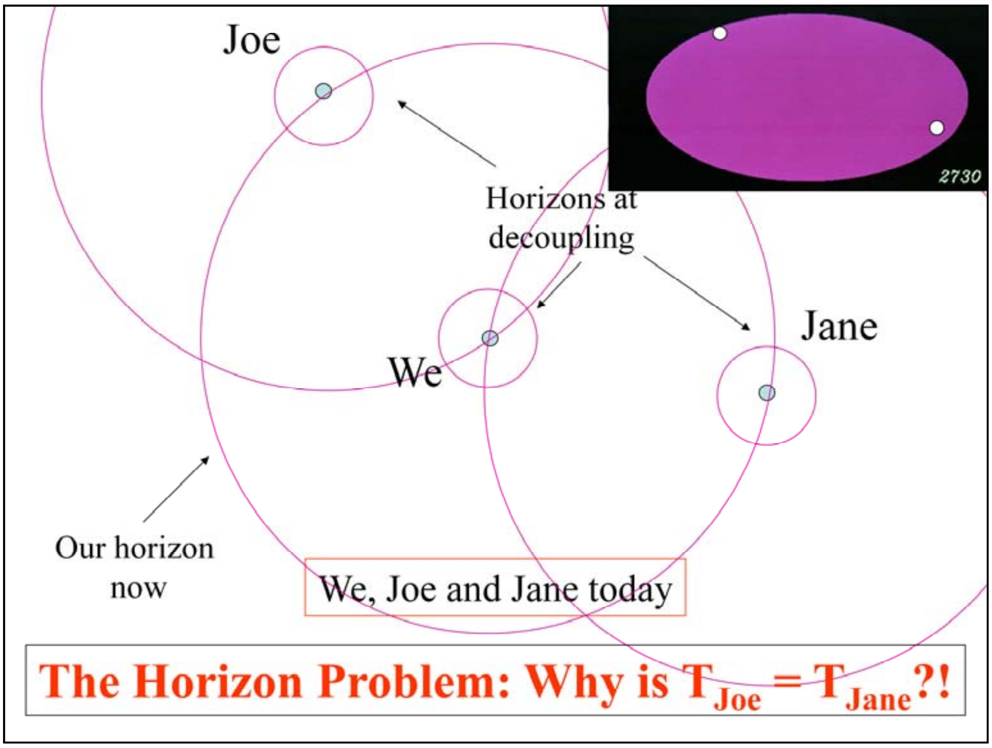
Let's imagine that I am sitting somewhere in the universe, and I am pressing my stop-watch right after the big bang. Being a student of physics I know that at every point of time after the bang, I can only communicate with regions of space which are within a sphere which has a radius of C* time from the bang. That radius increases with time, and slowly physical interactions propagate through larger and larger portions of the universe around me. A larger and larger piece of the Universe is in **CAUSAL CONTACT WITH ME** in the sense that it is connected through physical interactions. The radius of this sphere at any point of time is called the **horizon**.



Imagine that just like us, Joe and Jane are sitting someplace in the Universe, far away from us at the time of the bang. At the time of decoupling this our horizon, this is Joe's and this is Jane's. I have arranged it such that by the time of decoupling we have had no physical contact with either Joe or Jane.

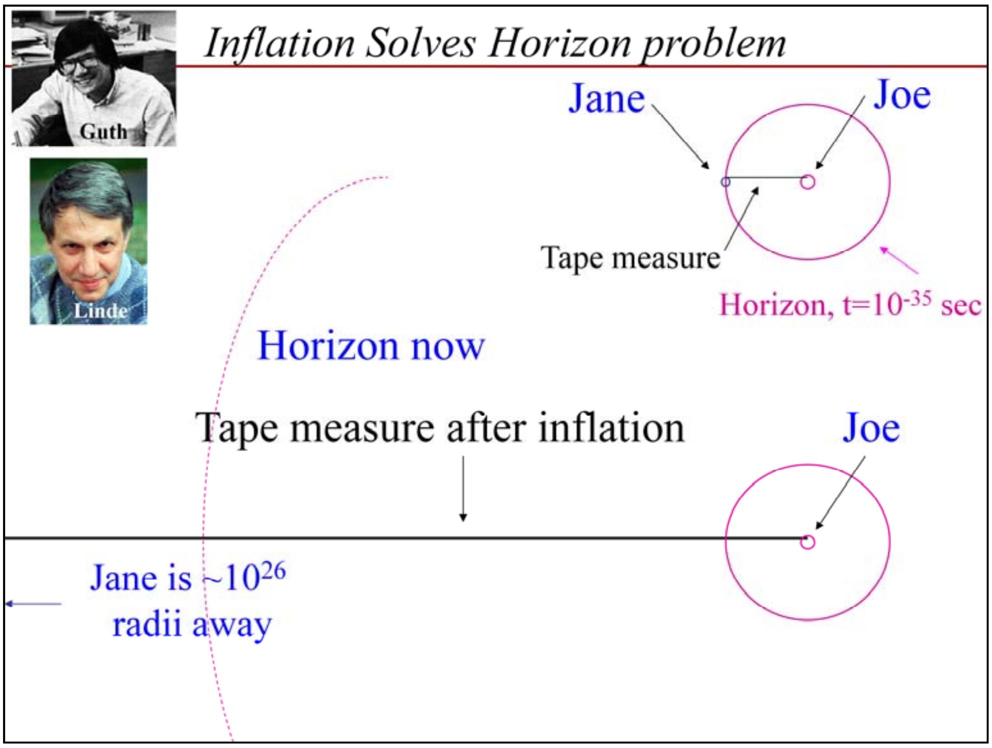


After 5 billion year our horizons have expanded, although we still can not communicate with each other.



And this is our horizon today. I have arranged it such that today CMB radiation is arriving from both Joe and Jane are now in causal contact with us. However Joe and Jane still can not communicate with each other; they are not in causal contact with each other.

But here is the puzzle: if Joe and Jane have never been in any contact, how is it that EM radiation we receive from one is almost identical in its properties to the one we receive from other? What was the physical mechanism that had made the properties of the radiation the same between these two locations in the Universe that have never been in causal contact before?

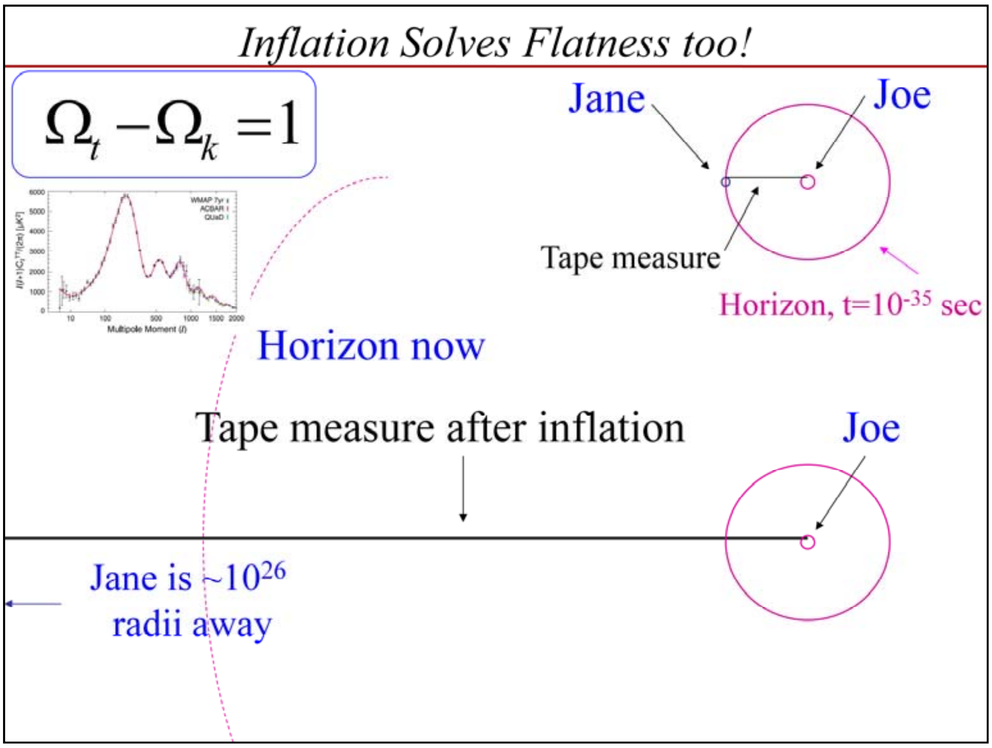


Inflation, invented by Guth and Linde in the 1980's, posits that close to the big bang, about 10^-35 second after it, the universe underwent exponential inflation. Here is a heuristic illustration of what we think happened.

Imagine that you are sitting within your causal sphere shortly after the bang and having dinner with a friend; its kind of cozy because the size of your causal sphere is rather tiny. No matter, you are having good time, and you are showing your friend a new tape measure you have just purchased. Its one of those tape measure that rolls out of a box and has cm and meter marks on it.

*Exactly as you hand your friend the edge of the tape the universe enters inflation. When inflation ends, very short time after it began, you look at your tape measure and notice that whereas previously your friend's distance was much less than an angstrom far from you, she has now been swept to millions of light years away.

*Although this is sort of ruins your evening, it has the effect that for many billions of years after inflation, your horizon, as it grows encompasses regions that have, at some point in the past been in causal contact with you. They have left causal contact during inflation, but they had an opportunity in the past to communicate. **That is why the CMB sky appears uniform in all directions.**



Inflation also explains why the normalized energy density of the universe is close to 1.

According to General relativity the normalized total energy density and the curvature of space are related through this equation. Inflation stretches space such that it is essentially flat, so that Omega_k = 0, which is the value if the universe is spatially flat, therefore the total energy density has the value of 1. This is all consistent with the measurement of the location of the first peak in the CMB power spectrum.