Current map of the Early Universe: CMB Observations

Clem Pryke
University of Chicago

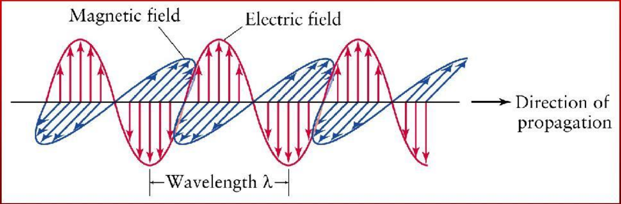
Cosmology Short Course

8 December 2007

Olbers Paradox

In an old, infinite Universe every line of sight hits a star - the night sky would be blazing bright

What is Light?



- Light is an electromagnetic wave. (For the current discussion anyway!)
- It moves forward always at the same speed - 186,000 miles per second.
- The distance from one peak to the next is called the *wavelength.*

Classic Doppler Effect

- Imagine three atoms emitting a ray of light from the same electron transition.
- One is stationary, one is moving towards us, one is moving away.
  - Moving towards -> "compressed" -> Appears bluer.
  - Moving away -> "stretched" -> Appears redder.

Edwin Hubble - Father of Modern Cosmology

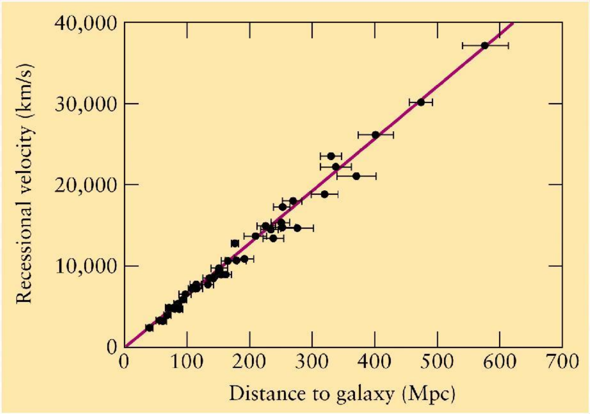
Galactic Redshifts

- Hubble measured the Doppler shifting of lines in the spectra of many galaxies.

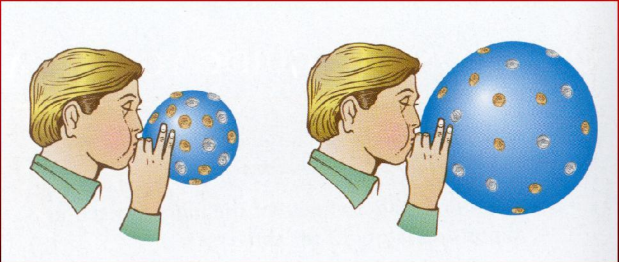
- Surprisingly he found that most appear to be moving away from us --- "redshifted".

- Furthermore, he found that the more distant ones were receding faster...

Hubble Diagram

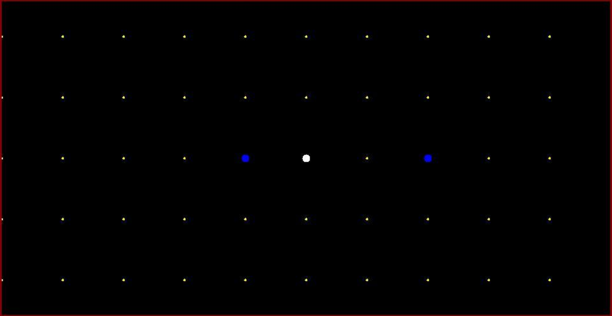


Expanding Universe?



- Simplest explanation - the Universe itself is expanding!
- This will make more distant objects appear to recede faster.

Cosmological Doppler Shift

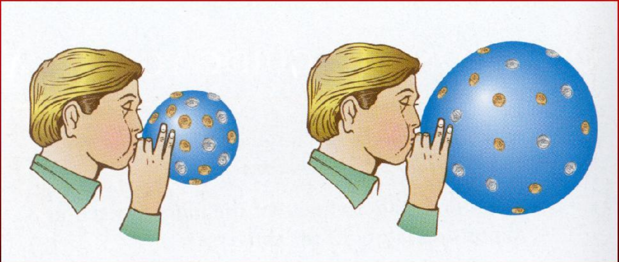


- Light rays "stretch" with the Universe.
- Stretch factor called the "redshift" of an object (Actually stretch factor minus one.)

Big Bang!

- If everything is moving away from us are we at the center?
  - No! - every place is the "center".
- If everything is moving away from everything else some time in the past everything was on top of one another?
  - Yes! - Winding the clock back we reach a time of infinite density - the Big Bang!
- Assuming constant expansion, the age of the Universe is 14 billion years.

Winding the Clock Back

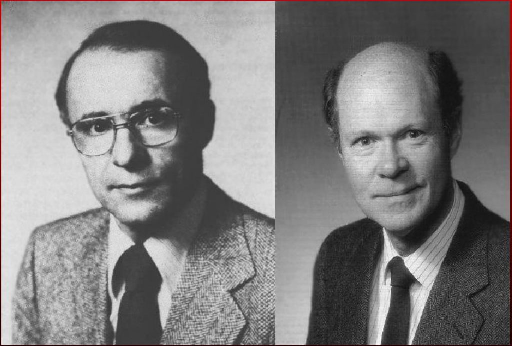


- Imagine deflating the balloon
    - Eventually galaxies touch
        - Further back denser/hotter
- Hot objects emit light...

Prediction and Observation of the Cosmic Microwave Background

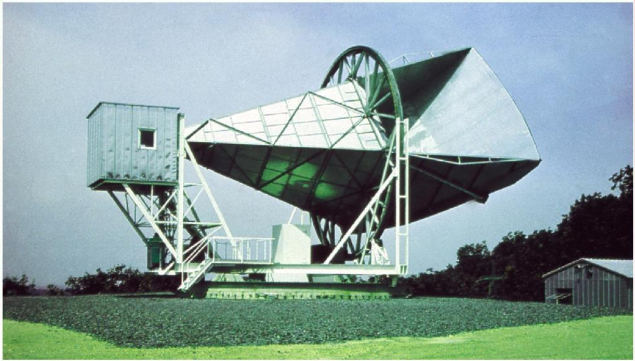
- 1940's: Gamow, Alpher and Hermann were developing theories of dense, hot early Universe.
- 1960's: Princeton University crew were building experiment to look for this "relic light" left over from early times.
- 1965: Down the road Penzias and Wilson at Bell Labs were puzzling over excess noise in their microwave receiver...

Penzias and Wilson

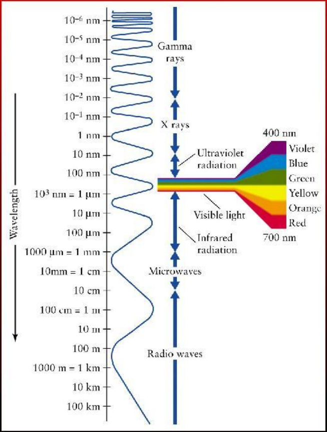


1978 Nobel Prize for discovery of the CMB

Bell Labs Horn Antenna



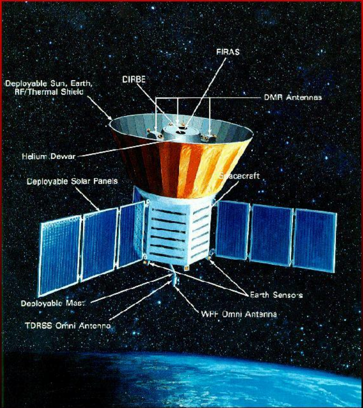
Recap: The Electromagnetic Spectrum



Why is the CMB Microwaves?

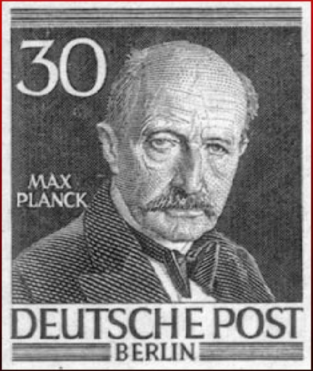
- Hot objects glow primarily in visible light.
  - The night sky is dark.
  - But it's glowing brightly in microwaves...
  - In a way Olbers was right...
- Why? Because the CMB photons have "stretched" with the expansion of the Universe.
  - They have been cosmologically Doppler shifted way down through the infra-red into the microwave...

COBE Satellite - 1989



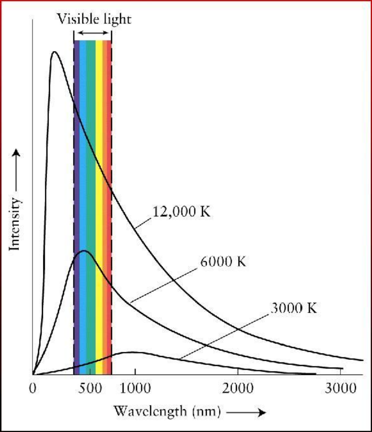
Taught us three crucial facts about the CMB

Max Planck

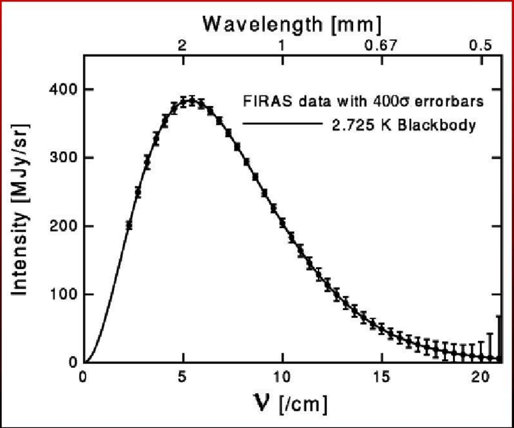


In 1900 explained the spectrum of light from a hot object. ⇒ The birth of Quantum Mechanics!

Spectrum of Light from a Hot Object



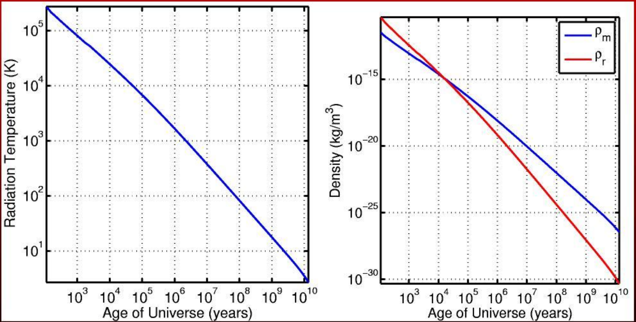
I: CMB is Perfect "Hot" Object Light



Nature of Planck Spectrum

- Theory predicts not just the shape of the curve, but also the exact intensity of light at each wavelength.
- COBE FIRAS measured exactly the expected amount, at every wavelength, as if we are inside a glowing object whose temperature is 2.7 degrees Kelvin (4.9 F above absolute zero).
- The Universe has clearly expanded a lot since it was hot and dense!

Evolution of Temperature and Density



Light dilutes faster than matter due to stretching

Where do the CMB Photons Come From?

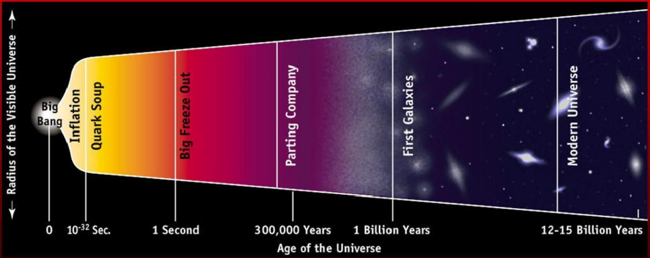
- Back in time denser / hotter.

- Eventually hot enough that atoms become ionized:
  - Plasma - The Fourth State of Matter

- Three familiar states of matter:
  - Solid - atoms are bonded together rigidly
  - Liquid - atoms are bonded less rigidly
  - Gas - atoms move fast and freely

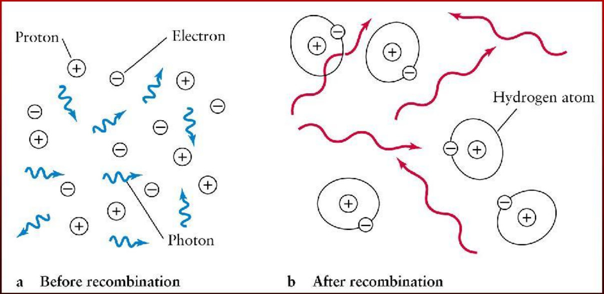
- Fourth state:
  - Plasma - atoms slam together so hard electrons are knocked free.
  - Becomes a "soup" of nuclei, electrons and photons.

Cosmic Timeline



Going back in time - hotter and denser
Solid, liquid, gas, plasma - 4th state of matter
Early Universe was "fire ball" of hot plasma

Plasma Universe was Opaque



In a plasma light rays constantly bump into electrons which changes their directions.

Looking back

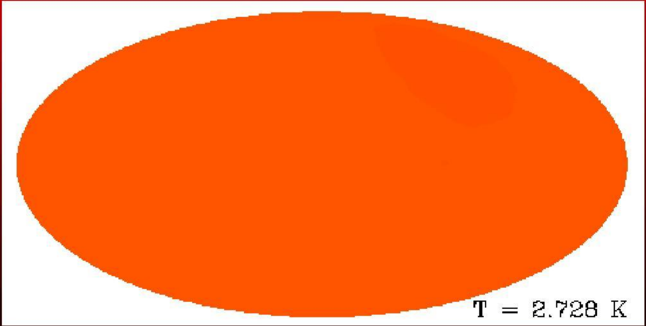
As we look out into space we look back into time...

Carl Sagan

- The CMB photons which we are receiving now set off in straight lines 14 billion years ago when the plasma combined to form neutral atoms.

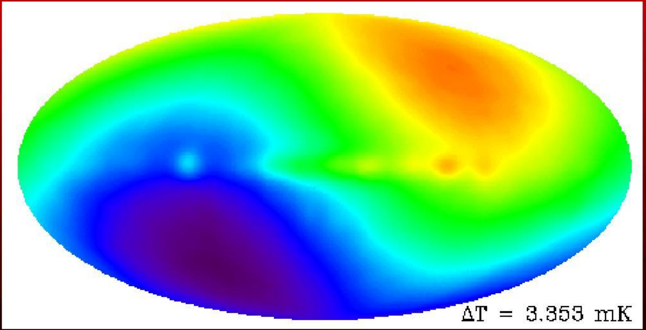
- So they started from a spherical "shell" all around where the Earth would later form
  - the so called "Surface of Last Scattering".
- Variations in their brightness tell us about variations in the density of the plasma at that time...

II: CMB Has Equal Brightness in All Directions



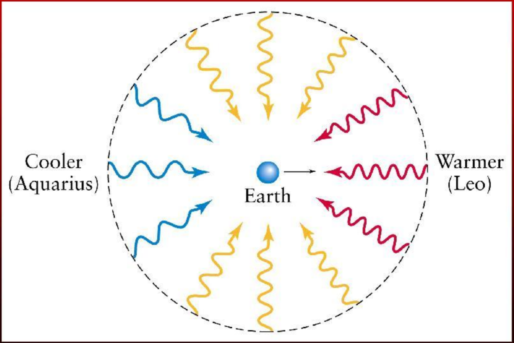
Well *nearly* equal brightness - The plasma was very smooth!

Our Motion Through the CMB



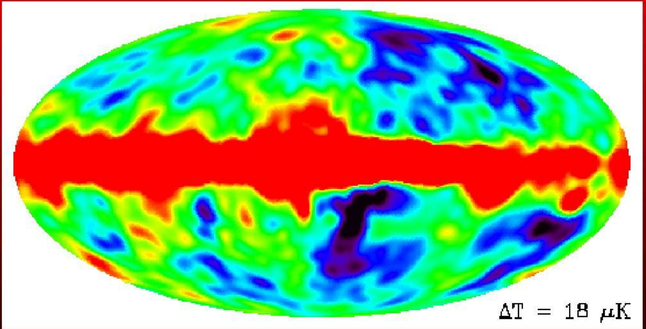
1 part in a thousand (standard) Doppler shift

Our Motion Through the CMB



We are moving at 370 km per second through the CMB

III: Unevenness of the CMB



Removing the effect of our motion reveals tiny residual unevenness in the brightness of the CMB.

Unevenness of the CMB

- This unevenness gives us a snapshot of the clumpiness of the plasma at that time.

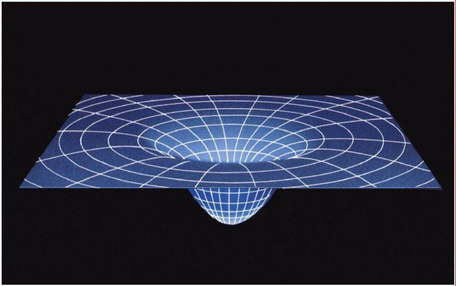
- This clumpiness is crucially important - it was the seeds that went on to form the beautiful and complex structure that we see around us in the Universe today.

- The amount of clumps of different sizes can tell us an amazing amount about the parameters of our Universe:
  - The set of numbers which Cosmologists use to distinguish our Universe amongst the set of all possible universes...

Ingredients of the Standard Cosmological Model

- General Relativity
  - The best theory of gravity that we have.
- The Robertson-Walker Metric
  - Describes how space-time evolves over time.
- The Friedmann Equation
  - Connects density and global geometry.
- Assumes on large enough scales the Universe is smooth
  - Cosmological principle
    - Homogeneous and Isotropic

General Relativity



Mass curves space

In fact any energy density curves space

Einstein's Biggest Blunder

- 1915: General theory of gravity - natural framework for cosmological theory.
- Einstein "fudged it" by adding dark energy to produce a static Universe -
  - Big mistake! He could have *predicted* the expansion of the Universe.

Friedmann Equation

$$\dot{R}^2 - \frac{8\pi G}{3}\rho R^2 = -kc^2$$

- Connects Expansion Rate and Curvature of Space.
- Implies a "Critical Density" which gives zero spatial curvature:

$$\rho_c = \frac{3H^2}{8\pi G}$$

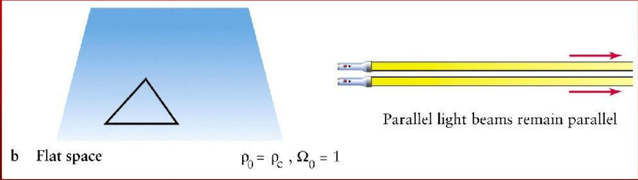
Omega

- We often measure density in units of the Critical Density and denote it by the letter Greek letter Omega:

$$\Omega = \frac{\rho}{\rho_c}$$

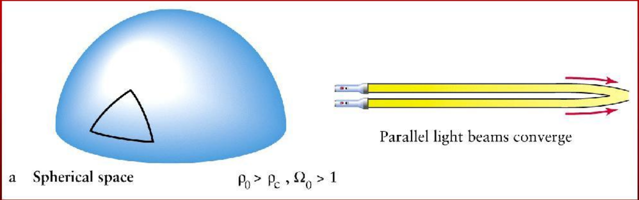
- If we say $\Omega = 0.5$ we mean there is half as much stuff in the Universe as would be required to “bend space flat”.

Flat Space



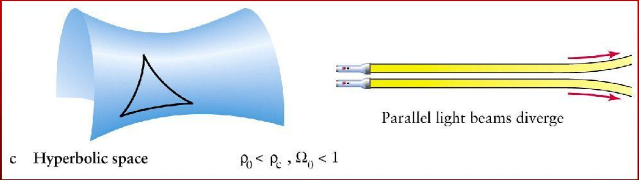
- $\Omega = 1$
- The Universe is infinite.
- Angles of a triangle add to 180 degrees.
- Parallel lines remain an equal distance apart.
- Familiar case!

Positively Curved Space



- $\Omega > 1$
- The Universe is finite.
- Angles of a triangle add to more than 180 degrees.
- Parallel lines converge.

Negatively Curved Space



- $\Omega < 1$
- The Universe is infinite.
- Angles of a triangle add to less than 180 degrees.
- Parallel lines diverge.

Cosmology is Deterministic

- If we know the present day values of the cosmological parameters we also know them at all times in the past and future.
  - "Clockwork Universe"?!
- Therefore only the present day values are usually quoted.
  - Past and future values are implied.

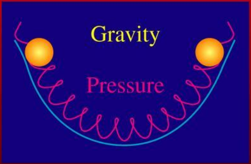
The Primordial Plasma

- Existence of CMB shows that the Universe was once a hot dense smooth plasma.

- But not perfectly smooth.
  - We assume that it initially had a simple pattern of lumpiness (come back to this).

- Simple physics predicts how the lumpiness will evolve over time.
  - Plasma is well understood.

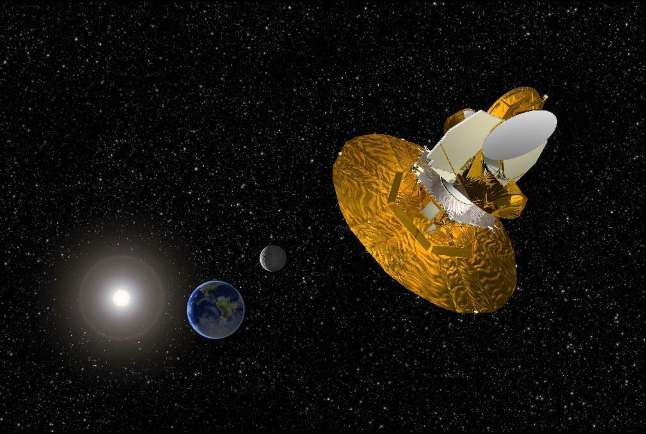
Oscillation of the Primordial Plasma



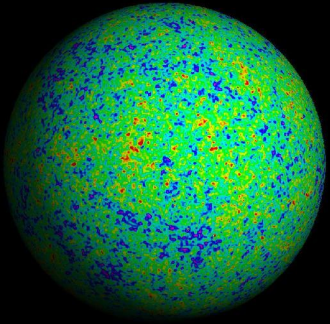
- Gravity squeezes an over dense region together.
- Photon pressure resists pushing it apart again.
- The plasma quivers like jello! (until combination...)

Animation from Wayne Hu

WMAP Spacecraft

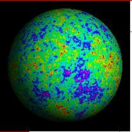


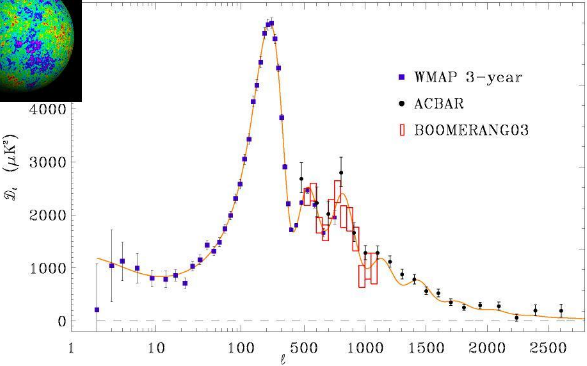
CMB Sky as Measured by WMAP



CMB is a sample of the density structure on a shell cut through the 400,000 year old Universe.

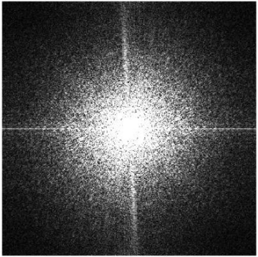
Current CMB Power Spectrum Results





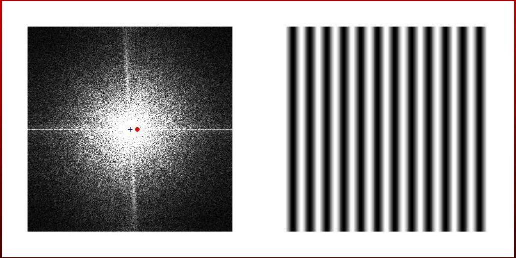
From Kuo et al, astro-ph/0611198

Image and its Fourier Transform

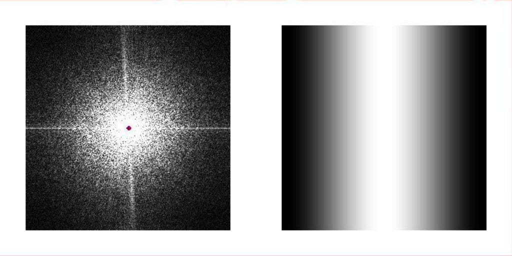


FT has same number of pixels as Image.

Fourier Components I

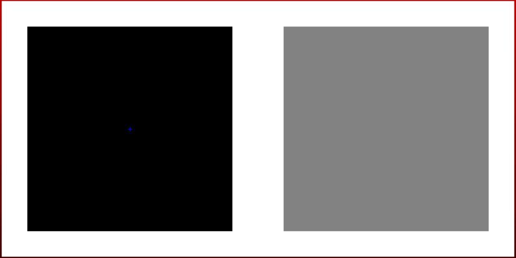


Hold radius fixed - vary the angle to center



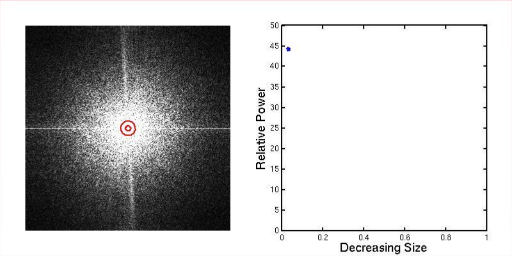
Hold angle fixed - vary the radius.

Building the Image from its FT



As we add more FT components the image becomes more and more like the original.

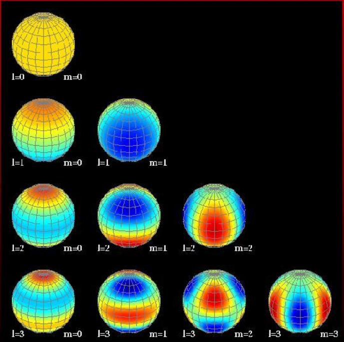
Power Spectrum from FT Components



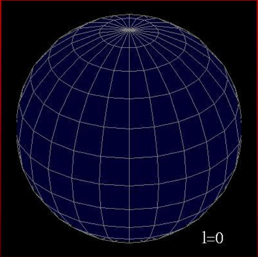
Power spectrum is the mean of the square of the FT components in each annulus.

Spherical Multipoles

$$T(\theta,\phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{+l} a_{l,m} Y_{l,m}(\theta,\phi)$$

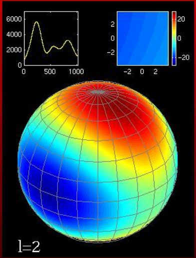


Topographic Map of the Earth



By adding up multipole patterns we can make any map

Building CMB Map from Multipoles



Equivalent to increasing the resolution of the telescope...

Image and Its Power Spectrum I

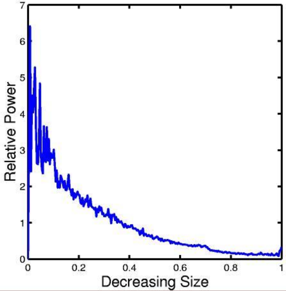
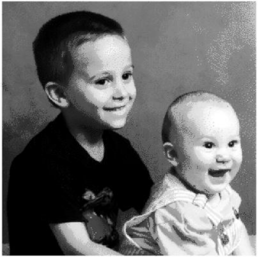
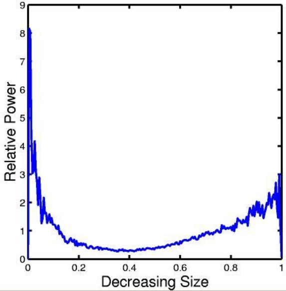
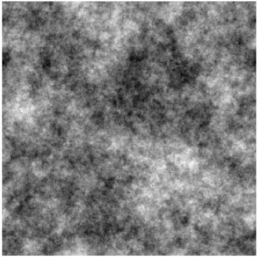


Image and Its Power Spectrum II



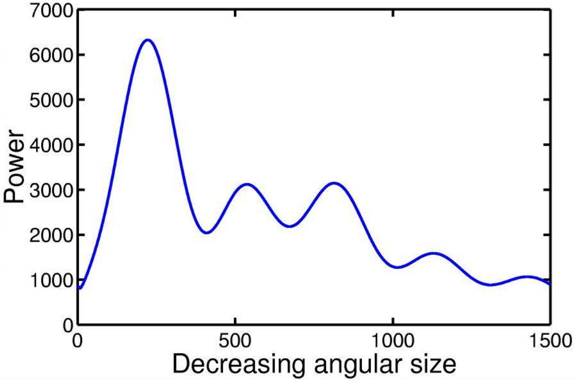


Two Images with Same Power Spectrum

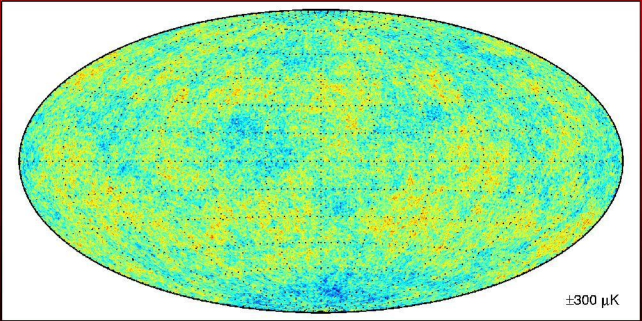


Most images contain a lot more information than is encoded in their power spectrum.

Power Spectrum of the CMB



...and a Possible Corresponding Sky



Theory predicts only the statistical properties of the pattern...

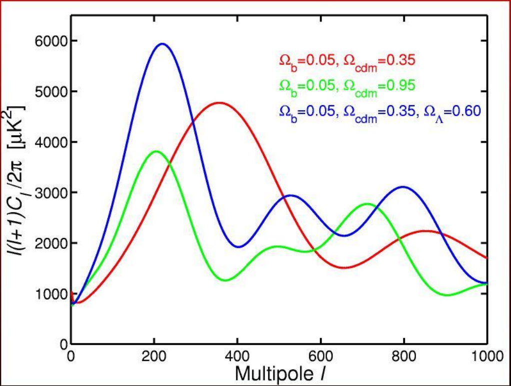
Modeling the Plasma Epoch

- Theory of gravitational oscillations in a plasma is easy!
- For given initial conditions the evolution of inhomogeneity ("lumpiness") in the primordial soup can be accurately calculated.
- Prediction: CMB should be a Gaussian random pattern whose total information content is encoded in it's angular power spectrum.
- Angular power spectrum is C_l, the variance of the $a_{l,m}$ at a given l.

Cosmological Parameters

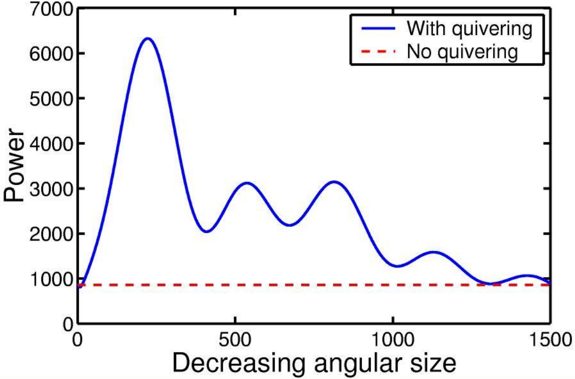
- Include how much of the various types of "stuff" the universe has in it, along with some other parameters:
  - Ω_b - Ordinary baryonic matter.
  - Ω_{cdm} - Cold Dark Matter.
  - Ω_λ - Cosmological constant.
  - H - The Hubble constant.
  - n_s - Slope of initial perturbation spectrum.
- Omega just means mass measured in units of the *critical density* required to produce a *flat universe*.

Model Power Spectra



Models: cmbfast.
Explanation: http://background.uchicago.edu/~whu/intermediate/ringing.html

Quivering Shapes Power Spectrum



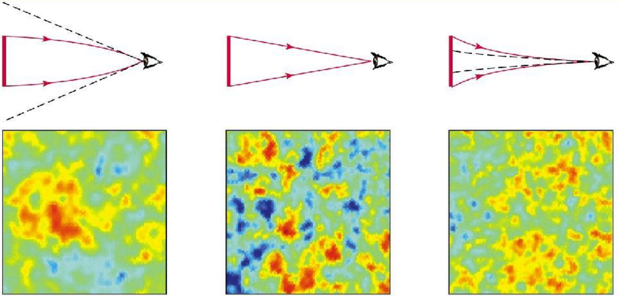
Origin of Peaks

- First peak corresponds to regions of size such that they have had time to compress or rarefy once before combination occurs.
  - Second peak to those that have oscillated a full cycle.
    - And so on...

- Sound speed and time elapsed to combination approx same in wide range of models
  - Gives us a standard ruler to measure spatial curvature!

- Peak height ratios depend on relative amounts of ordinary and dark matter...

Seeing the Sound Horizon



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

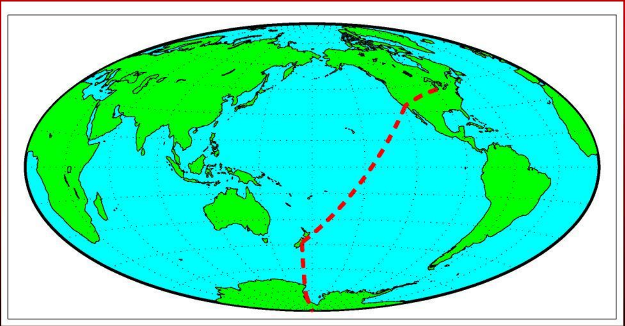
The Nature of the Experimentalists Game

- Measure the power spectrum of the CMB
- Calculate the expected spectra in a wide range of possible universes.
- Compare -
  - Find out what kind of Universe we live in!

UNITED STATES ANTARCTIC PROGRAM

NATIONAL SCIENCE FOUNDATION

Journey To The Pole



Chicago - California - New Zealand - McMurdo - South Pole

Christchurch NZ - Clothing Warehouse

Big Program!

Checking In

Leaving Civilization!

Military Comfort

McMurdo

On the coast - Main US Antarctic base.

Scott Memorial

Antarctic Continent

Larger than the US - Ice sheet two miles thick!

On to the Pole - Transantarctic Mountains

Arrival at Pole

Old Base (The Dome)

New Base (Ugly Box - but Comfy!)

Old Sleeping Quarters

Cold Walk to the Bathroom

New Sleeping Quarters

Old Galley

New Galley

Greenhouse

Medical

Band Practice Room

Clem at the Actual South Pole

Ceremonial South Pole

Pretending to be an explorer…

Sun Dog

Nothing Out There...

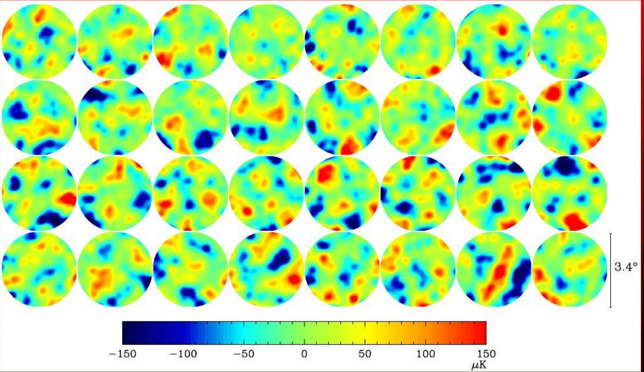
Walk to Work

Why at the South Pole?

- Very cold, and high altitude - Very dry atmosphere.
  - -40F (-40C) summer, -110F (-80C) winter.
- Atmosphere extremely stable.
- No Sun for 6 months of the year:
  - Work on instrument in summer.
  - Observe in the winter.
- Fields remain at constant elevation angle.
- Existing infrastructure and logistics.

DASI at Sunset

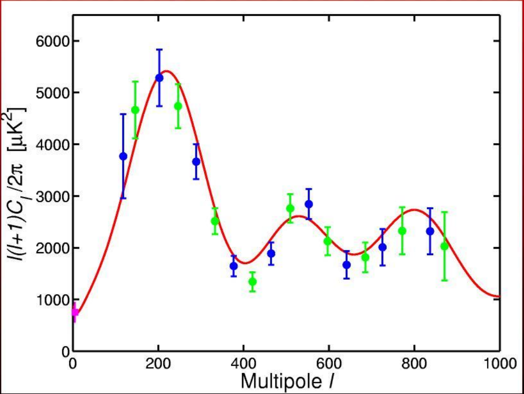
DASI Maps After One Winter



Leitch et al - astro-ph/0104488

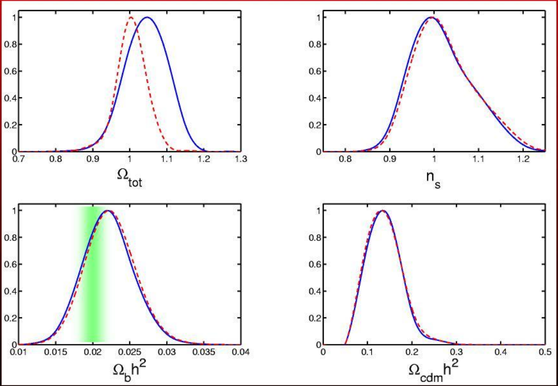
http://xxx.lanl.gov/abs/astro-ph

Lump Sorter Output



Halverson et al - astro-ph/0104489

DASI Parameter Constraints



Pryke et al - astro-ph/0104490

"All the News That's Fit to Print"

The New York Times

VOL. CL .... No. 51,739

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 roiling 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 A6

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, these 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."

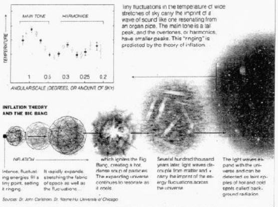
Sir Martin Rees, an astrophysicist at Cambridge University, said scientists were left with the question of whether fundamental physical laws would someday explain that strange mixture of ingredients, or whether the precise amounts were a sort of accident of how the universe came into being — something 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 pattern 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

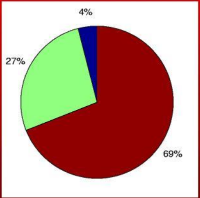
THE MEASUREMENT



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

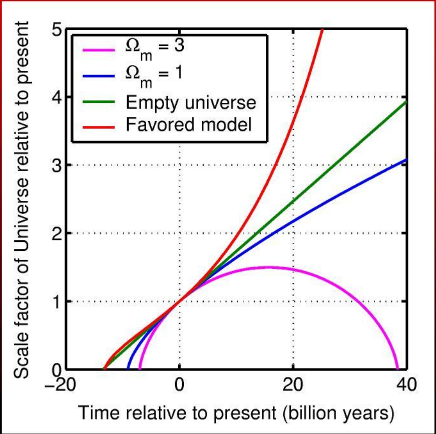
The New York Times; Radiation chart courtesy of University of Chicago

Results - The Cosmic Pie

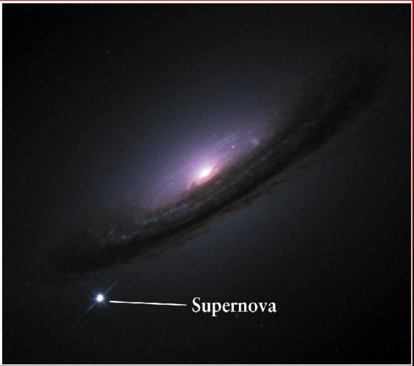


- At this epoch normal matter is only 4% of the total!
- Dark matter makes up 27% more...
- But we also measure that space is not curved
  - So total must be 100%
    - Must put back in Einstein's Blunder! The vacuum really does have energy after all
- All the evidence is strongly in favor but this is a deeply uncomfortable result...

Expansion History of the Universe

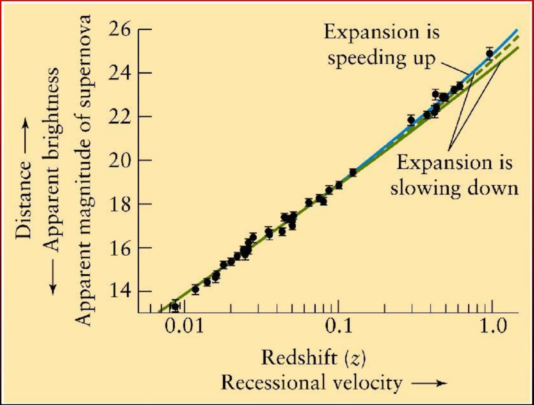


Supernova in Other Galaxies



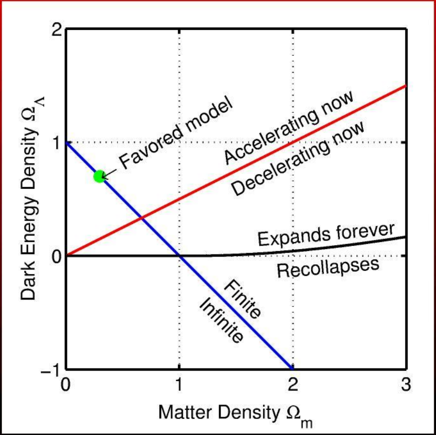
The ultimate Standard Candle -
For a short time out-shines an entire galaxy!

Distant Supernova Hubble Diagram



SN data also indicates expansion speeding up!

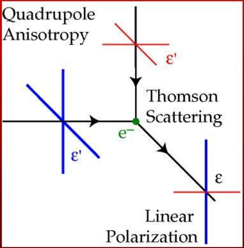
Properties of Matter/Lambda Universe



Glorious/Absurd Modern Cosmology

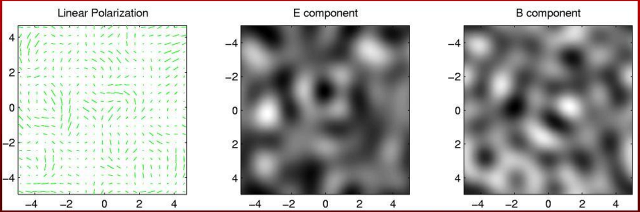
- Prediction/observation of CMB temperature acoustic peaks an incredible scientific result!
- Supernova data also indicates accelerating expansion
- In fact many kinds of data all fit with the "Standard Cosmological Model"
- But a hopelessly incomplete model with uncomfortable consequences
  - Need to Check the paradigm every way we can!

Polarization by Scattering



- If electrons are exposed to incoming radiation which differs at 90 degrees the re-radiated light will be (partially) polarized.
- At CMB last scattering quadrupole generated by Doppler shift due to moving material.

E,B Decomposition of a Vector Field



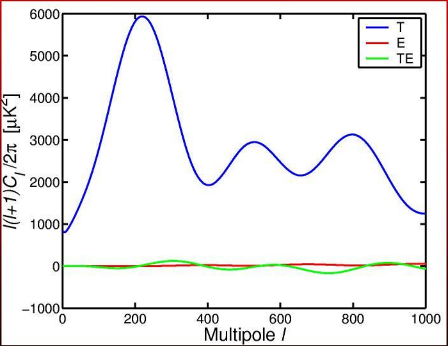
- Decompose polarization pattern to make 2 scalar fields
- E=Grad, B=Curl
- Can make power spectra from the E and B patterns on the sphere just as for the total intensity - and also the TE cross power spectrum.

"First Order" Polarization of the CMB

- Density perturbations at last scattering produce T anisotropy.
  - Associated motions of material produce E polarization - but zero B.
    - Since density perturbations produce the motions there is TE cross correlation.

- Given T spectrum and standard cos model can predict expected E and TE spectra.
  - ...if measurements don't match the whole framework falls apart! - Critical test!

T, E and TE Spectra

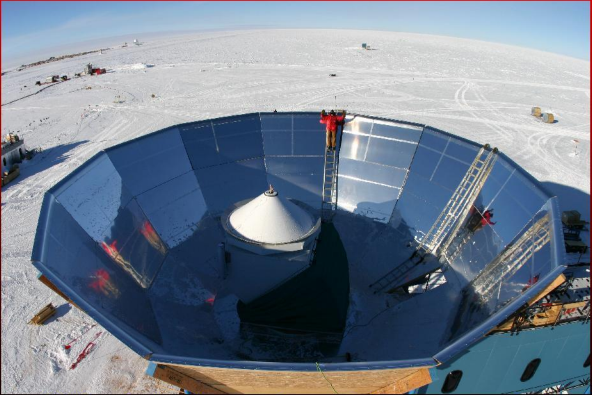


- Polarization less than 1% (in power units)
- A long struggle to get to the required sensitivity...

DASI Polarization 2002

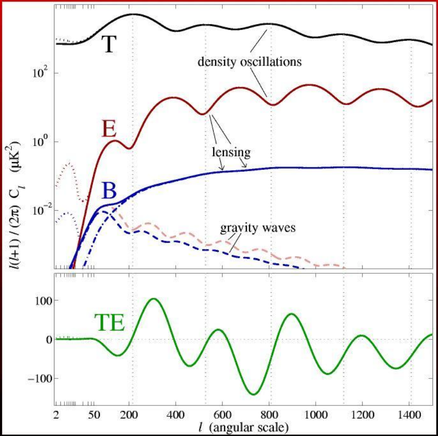
CMB polarization finally detected - E consistent with expected amplitude, B consistent with zero.

Our Latest CMB Polarimeter - QUaD

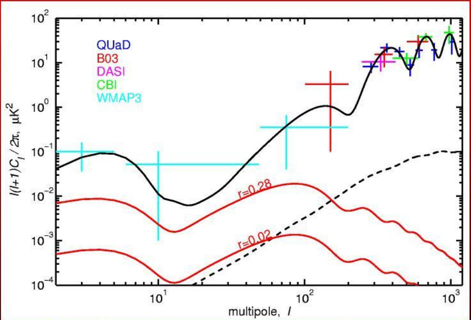


CMB polarization continues to look as expected

Why Go Further?

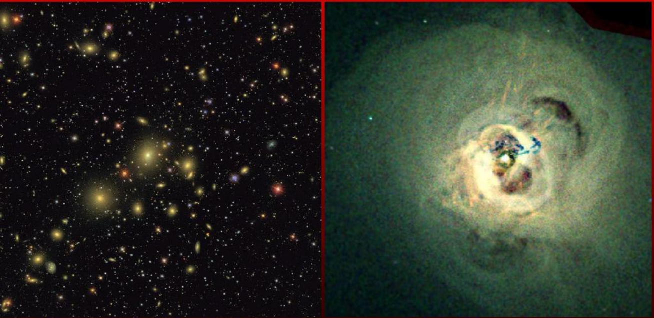


The quest for gravity wave B polarization



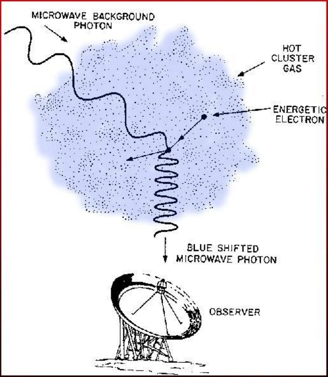
- The imprint of gravity waves in the plasma coming from the moment of creation
- Health warning: theorists refuse to say how small this signal may be!

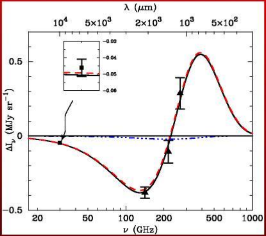
(Galaxy) Clusters



- Huge invisible dark matter potential well containing
  - Galaxies
  - Hot gas (shock heated by infall)

SZ Effect Distorts the CMB

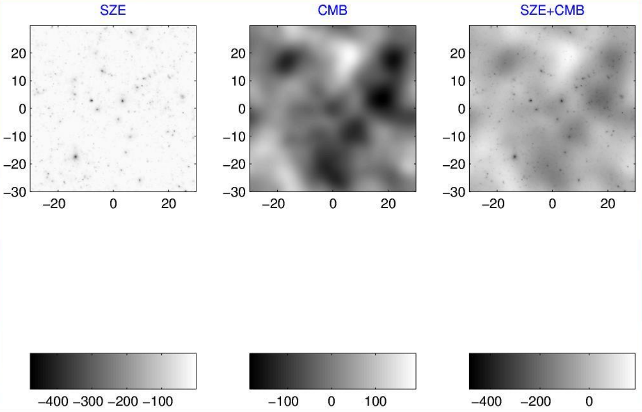




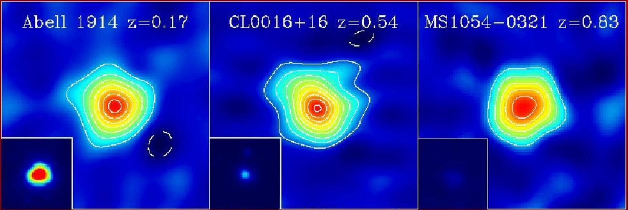
- Hot gas up-scatters CMB photons to higher energy
  - Punches holes in the CMB sky at lower freqs

[redacted]

SZE puts negative zits on the CMB



Redshift Independence of SZ Effect



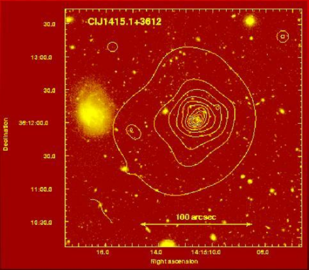
Main images SZ, insets X-ray

- Because CMB is backlight find the galaxy clusters regardless of distance!
- Number as a function of time depends on details of dark energy

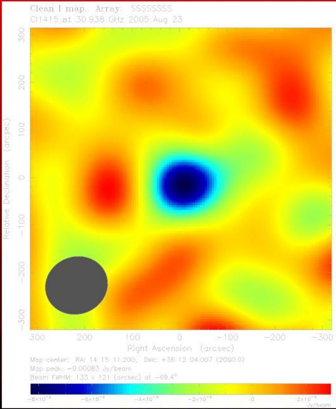
The SZA

- Array of telescopes in Owen's Valley California
  - detailed studies of SZ effect...

Cl1415 new in SZ at z=1



- Cl1415+36, $\sim 4 \times 10^{14} M_{\odot}$
  X-ray WARPS sample,
  B. Maughan et al, astro-ph/0503455



SZA unpublished (Stephen Muchovej)

The South Pole Telescope

- SPT will find many thousand galaxy clusters!
  - Detailed probe of the mysterious dark energy...

Summary

- CMB is the most ancient light we will ever be able to observe
  - Before that Universe was opaque
- Maps of the CMB show structure of the Universe 300,000 years after the big bang
  - pattern matches detailed theoretical predictions
  - is used to measure cosmological parameters
  - one of the cornerstones of the standard cos. model
  - but this model is absurd!
- CMB polarization is an important test of the paradigm
  - may also allow us to see gravity waves from the beginning of time
- CMB distorted on it's way to us by galaxy clusters
  - new telescopes are using this to map out the large scale structure and probe the dark energy