Gravitational Waves, Inflation, and the Big Bang:
BICEP-2 Result and LIGO

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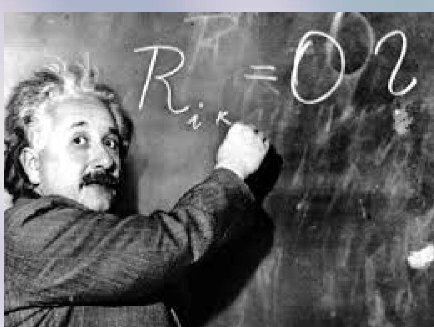
Outline

- Gravity Theory and Gravitational Waves
- Early Universe Cosmology
  - Big Bang Theory
  - Cosmic Microwave Background
  - Inflation
- Measurements of the Early Universe
- BICEP-2 Result, Implications, and Follow-up
- High Frequency Interferometric Gravitational Wave Detection

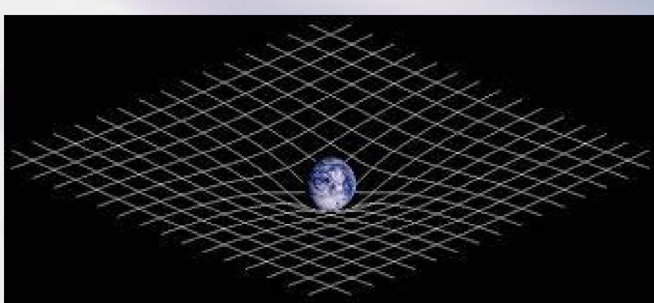
Gravity

- First mathematical theory of gravity, Isaac Newton in 1687
  - Static, gravity everywhere

$$F = \frac{GM_1M_2}{r^2}$$



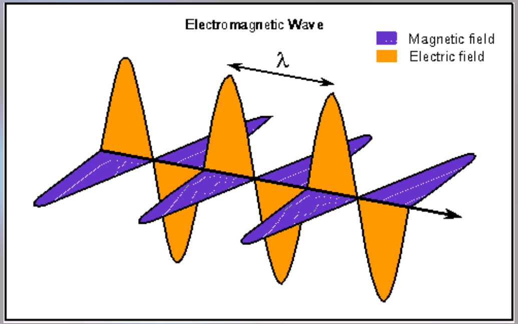
- Einstein developed modern theory of gravity in 1915
  - General Theory of Relativity
  - Model of gravity as curvature of space-time



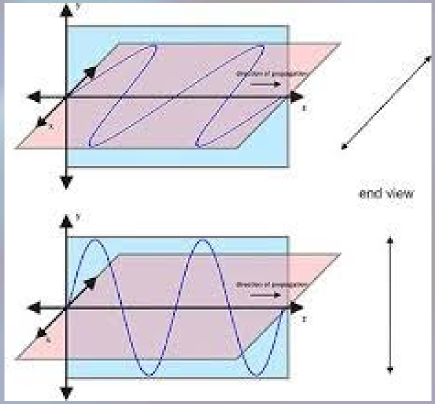
$$G_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

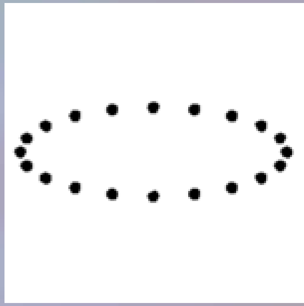
Gravitational Waves

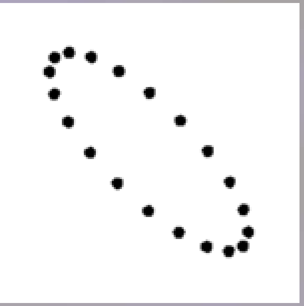
- Propagation of gravity at speed of light called gravitational wave



- Similar to light wave with important differences
  - Gravitational wave effect much smaller
  - Each have two polarizations, but different shapes
  - Distinctive pattern from gravitational waves



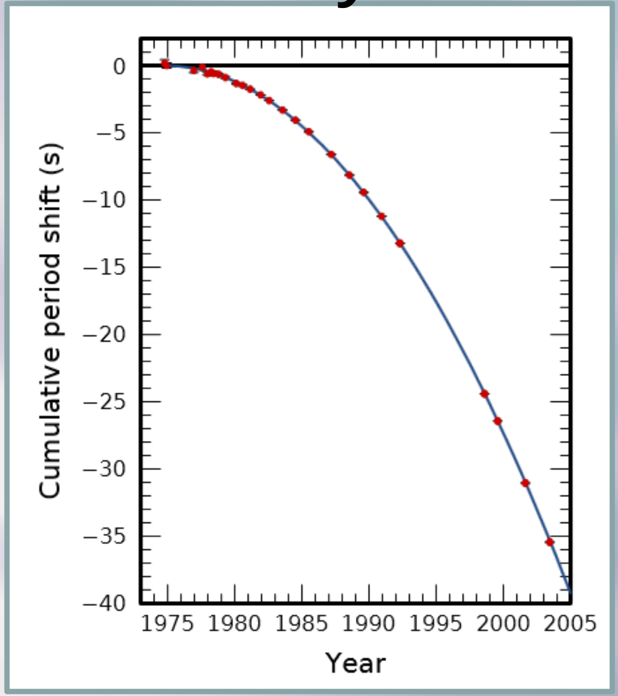




Evidence of Gravitational Waves

- Confident gravitational waves exist, have seen their effects

- Taylor/Hulse observed Binary Pulsar System PSR B 1913+16 from 1970s

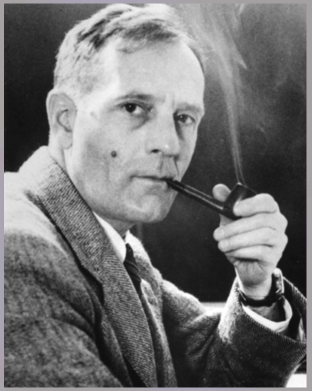


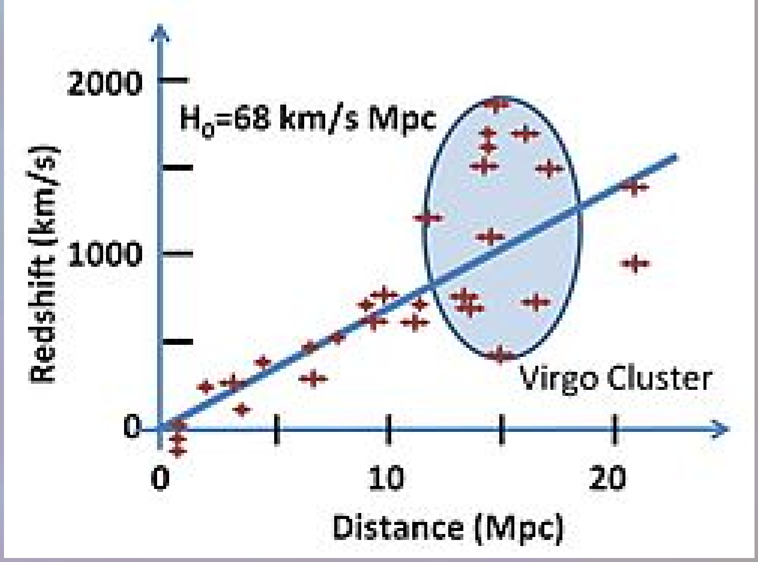
  - See change in orbit from gravitational waves
  - Nobel Prize 1993

- Similarly in neutron star/white dwarf pair PSR J0348+0432 in 2013

The Big Bang

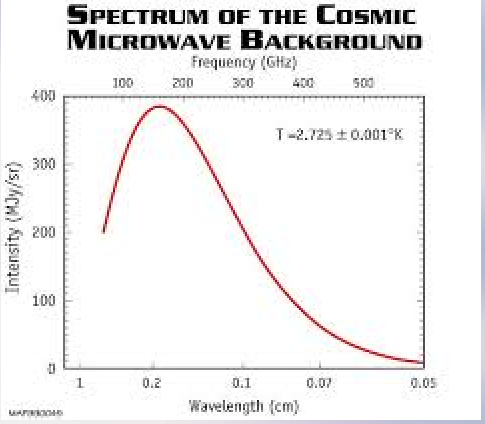
- 14 billion years ago the universe began from a compact, hot, dense state
  - All of space-time compressed
- Proposed by LeMaitre in 1927
- Evidence from Hubble in 1929
  - Hubbell's Law $v = H_0 D$
- Alternative to Steady State Cosmology
- Competitor until 1964





Cosmic Microwave Background (CMB)

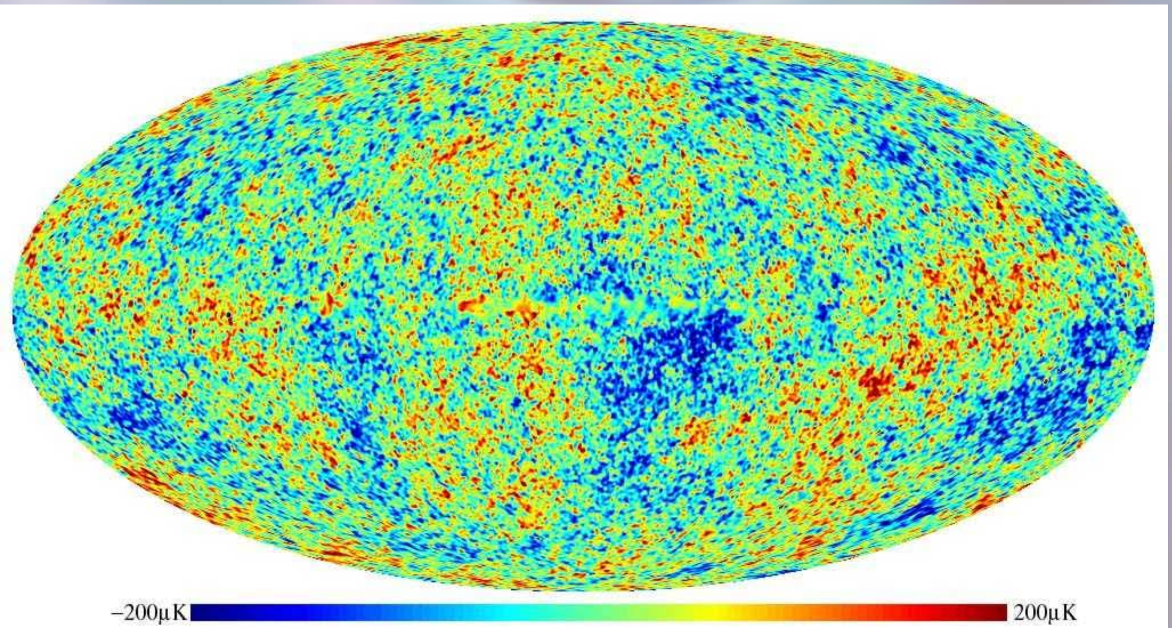
- Light that has not interacted with matter since near the Big Bang called the Cosmic Microwave Background
  - Theoretically predicted
  - Discovered (by accident) in 1964
  - Nobel prize 1978, Penzias and Wilson



- 380,000 years after Big Bang atoms form, no more free charge
  - Recombination, last scattering
- Frequency distribution same as from a 2.7 K hot object

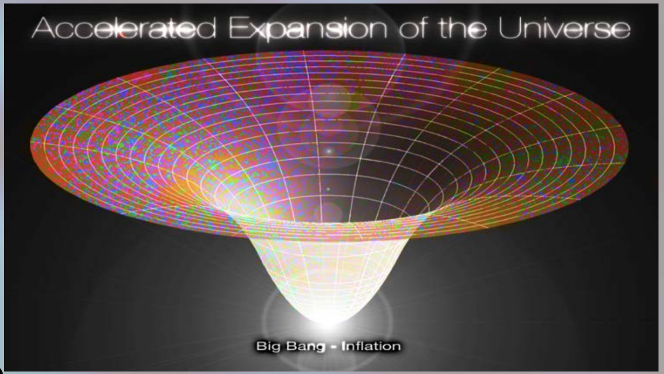
Uniformity of CMB

- CMB temperature $\pm 18\ \mu$K across whole sky
- Points 180° across the sky outside of each other's "light cone"
  - Not enough time for light to go from one to other

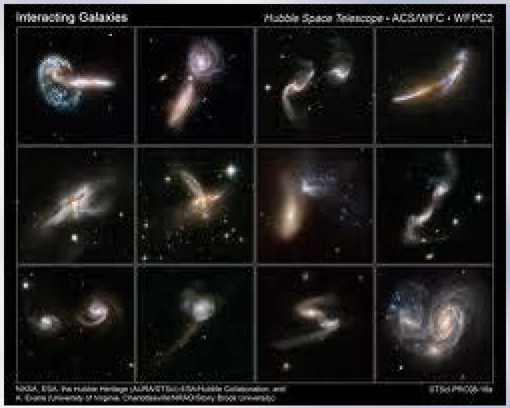


Inflation

- Inflation, faster than c expansion of the very early universe
  - Proposed by Guth in 1980
  - 10^{90} increase in volume
  - 10^{-36} seconds to 10^{-32} seconds

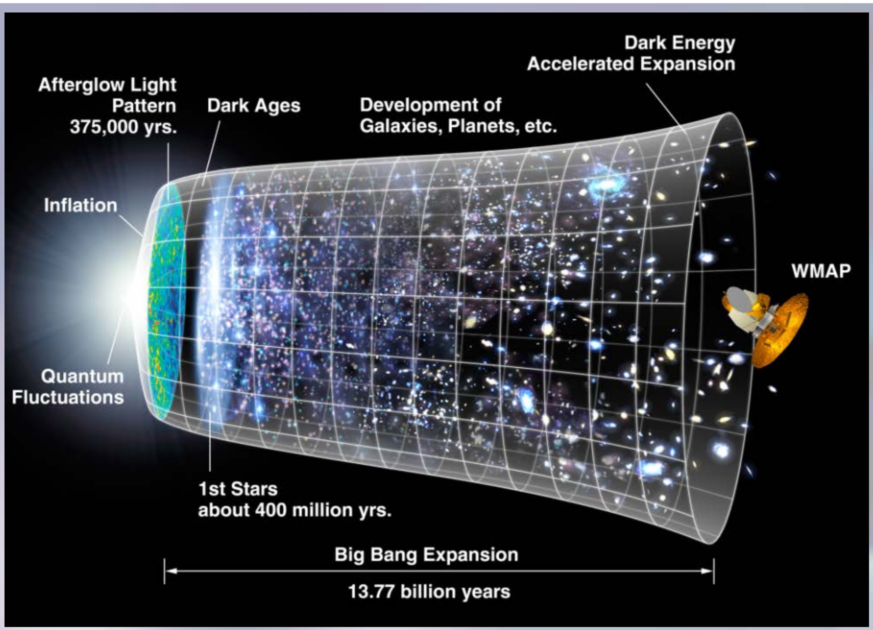


- Explains why universe same in all directions
  - Temperature uniformity
  - Curvature uniformity



- Quantum particle fluctuations inflated into the seeds of galaxies

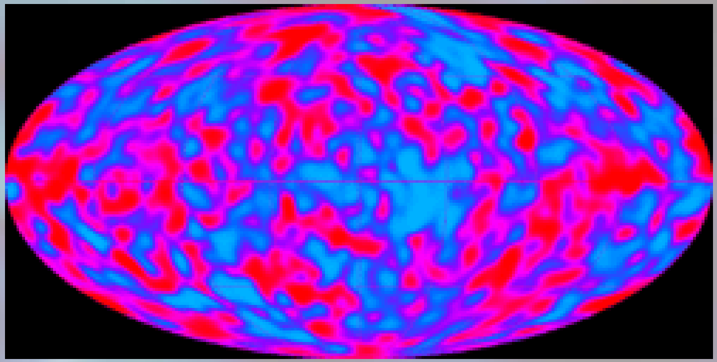
Gravitational Waves from the Big Bang

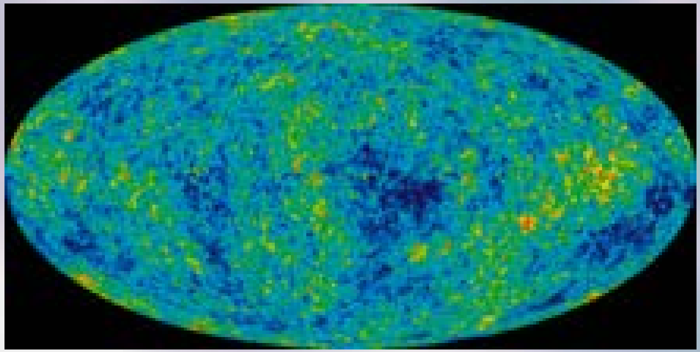


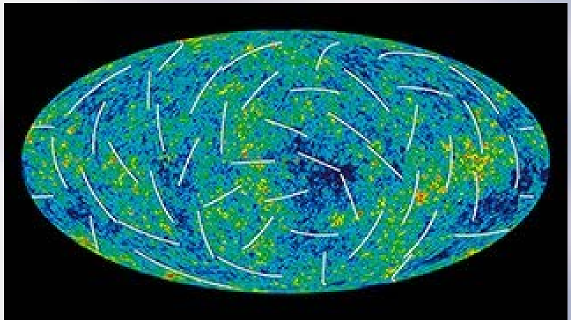
- Gravitational waves created nearly at the beginning of time
- Gravitational waves not influenced by recombination
- Energy scale of inflation important and unknown
- Quantum nature of gravity
  - Important at very beginning
  - Major missing piece of physics

COBE and WMAP

- Cosmic Background Explorer (COBE)
- Satellite launched in 1989
- Anisotropy in CMB
- Nobel Prize 2006



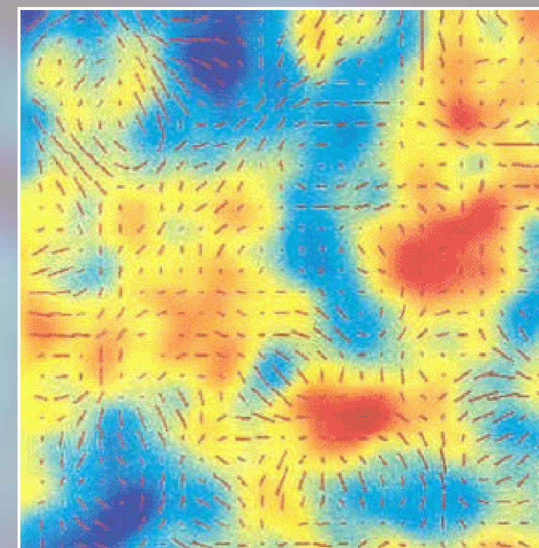


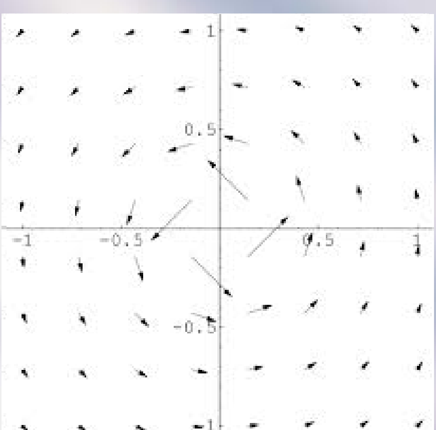


- Wilkinson Microwave Anisotropy Probe (WMAP)
- Satellite launched in 2001
- Better measurement of CMB anisotropy $\delta T = 5 \times 10^{-4}$ K
- Measure polarization of CMB

Polarization and Gravitational Waves

- Sources of polarization
  - Density fluctuations
  - Gravitational waves
- Polarization vector pattern
  - E mode spreads from a point
  - B mode circles around a point

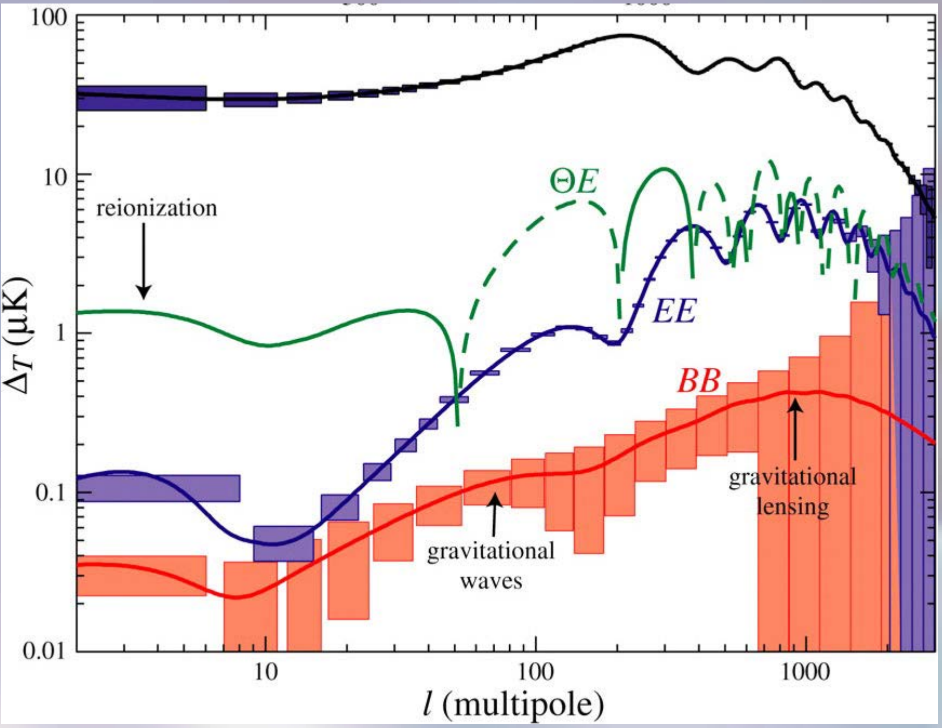




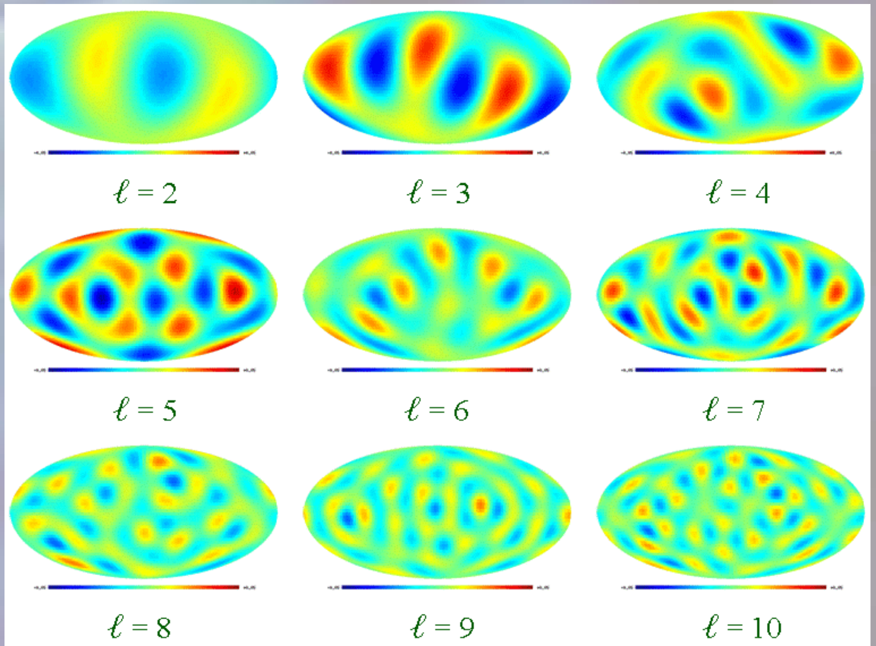
B Mode

- Pattern depends on source
  - Density causes E
  - Gravitational waves cause E and B
  - Ratio r of gravitational waves/density

Expected CMB Spectra



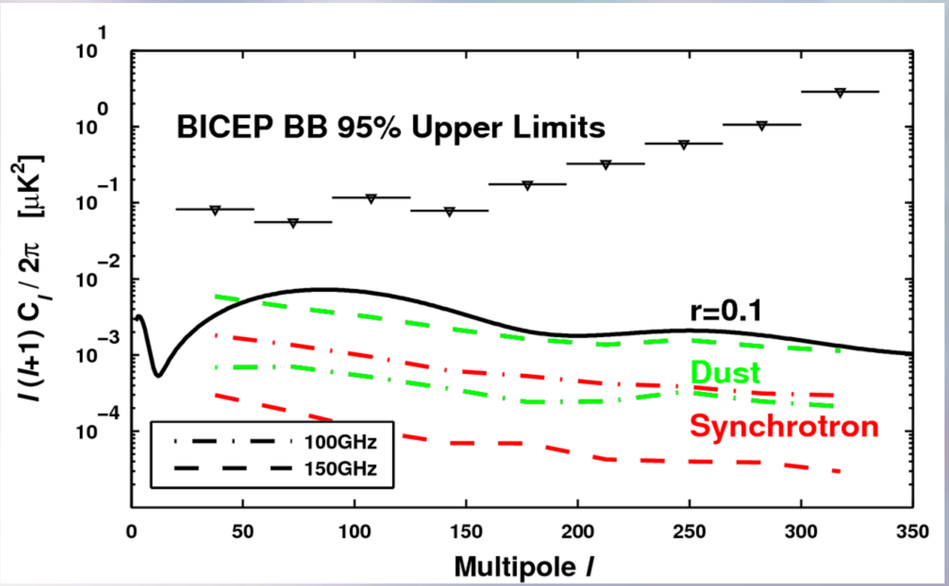
- Compare E mode and B mode across sky
- Quantify using ℓ
  - Roughly $\Delta\theta \approx {}^{180^\circ}/_{\ell}$



- B mode spectrum
  - Gravitational Waves $50 \lesssim \ell \lesssim 100$
  - Height determines r

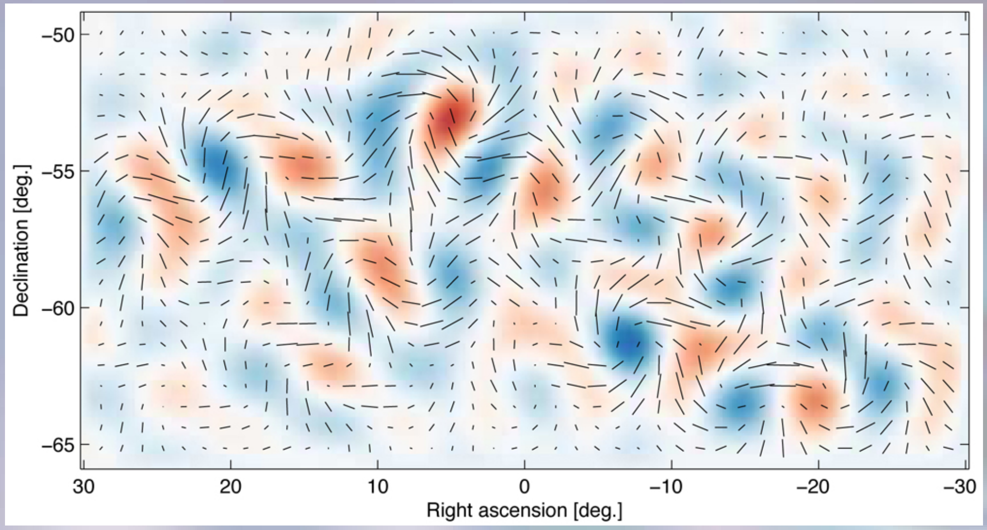
BICEP-2 Telescope

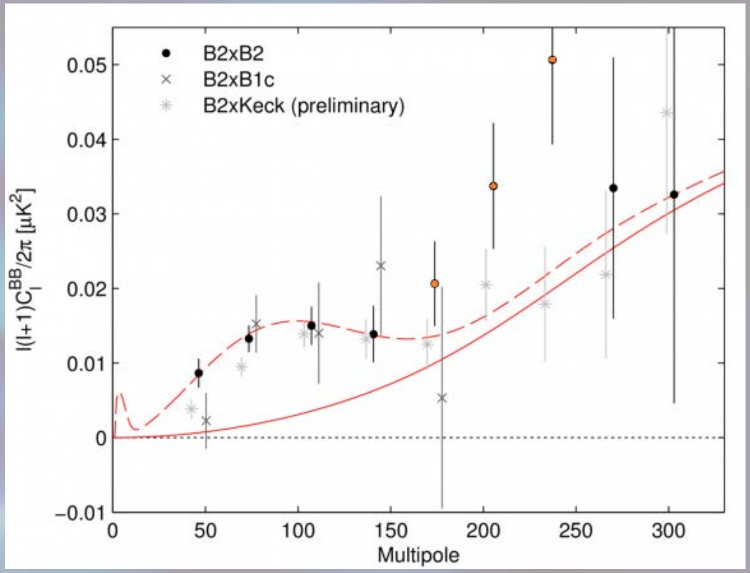
- Located at South Pole
  - Avoid water in atmosphere
- 3 year observation of a few degree patch
- Measures CMB polarization



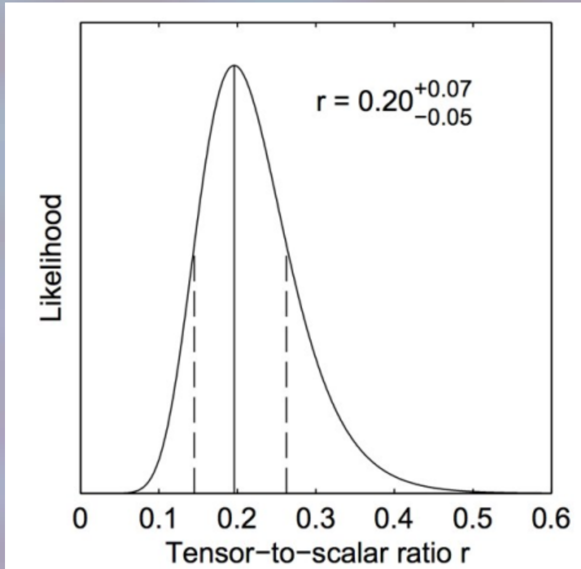
- Follows BICEP-1
  - South Pole
  - 2006-2008
  - B mode polarization
  - $r < 0.7$

BICEP-2 Result

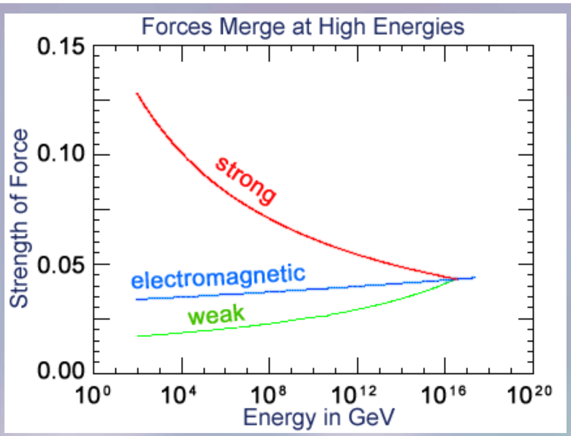




- B Mode polarization map
- B Mode spectrum against angular scale ℓ
- Gravitational wave to density ratio $r = 0.20^{+0.07}_{-0.05}$

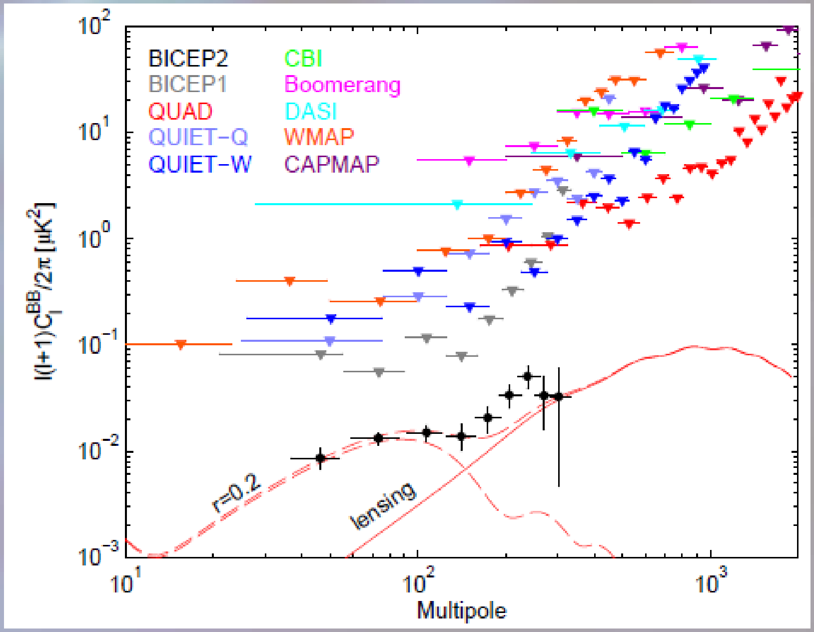


Implication and Confusion



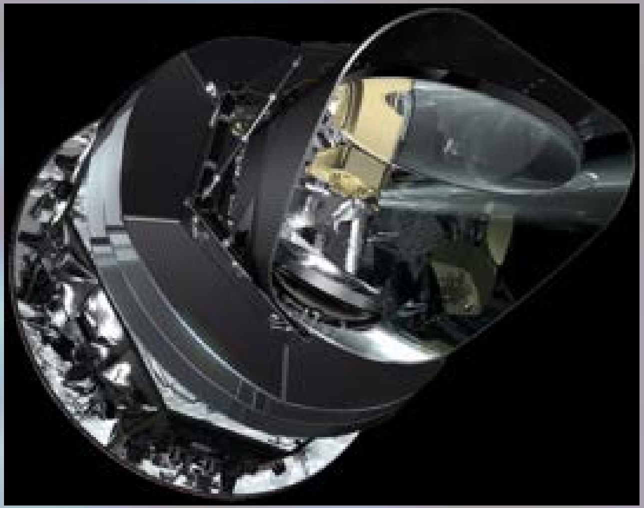
- r fixes energy scale of inflation
- $r = 0.2 \rightarrow$ Grand Unified energy
  - 10^{13} higher than accelerators
  - Quantum nature of gravity

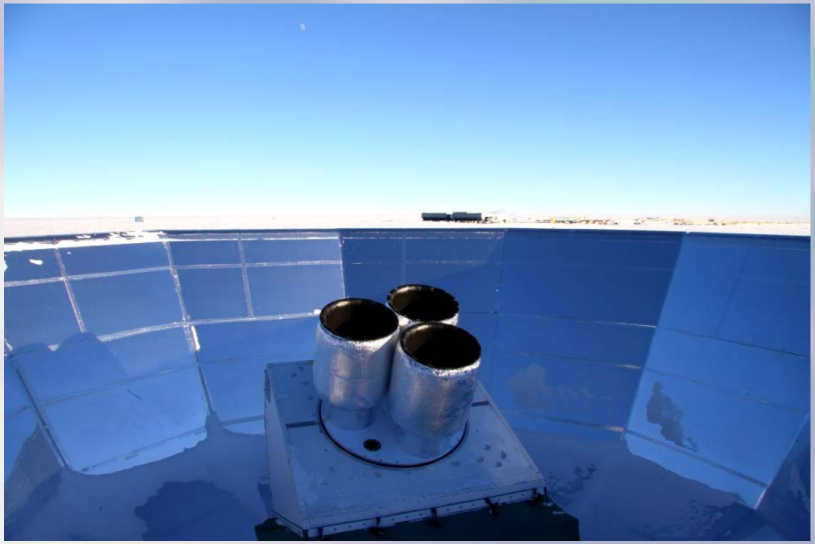
- BICEP-2 result $r = 0.20$
- Previous result $r < 0.11$
  - Planck Satellite/South Pole Telescope(SPT)/WMAP
  - Other dust models might make BICEP-2 $r = 0.16$



Near Future Results

- Planck Satellite
  – Data release late 2014
  – Should see clear evidence
- SPT, POLARBEAR etc. should also see evidence

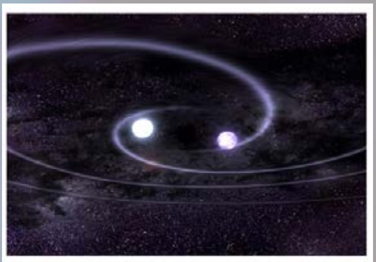




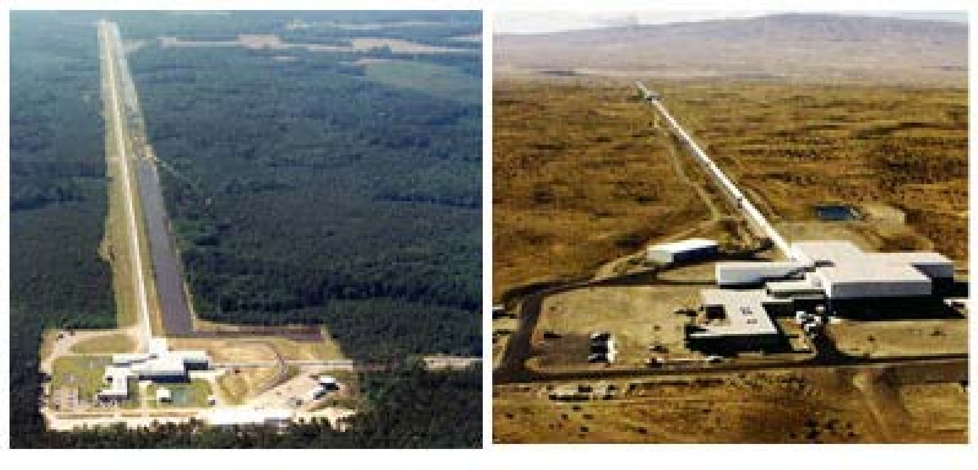
- Keck array is follow up to BICEP-2
- Multiple receivers
- Preliminary results used in BICEP-2 results

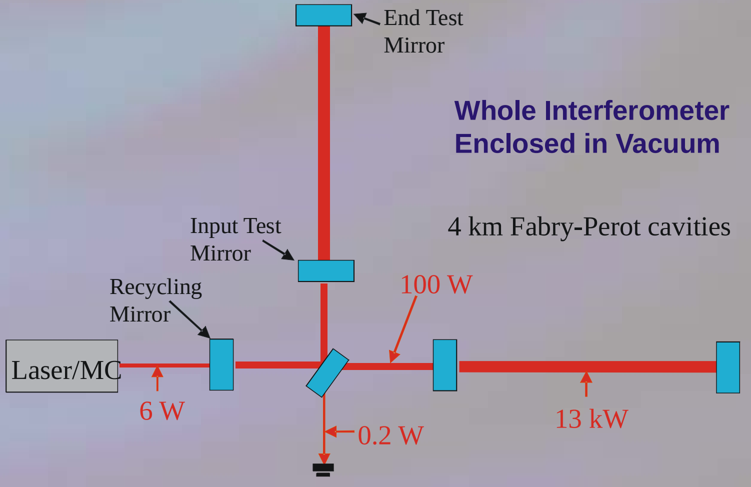
Higher Frequency Gravitational Wave Detection

- Gravitational wave interferometers on Earth
- Different gravitational waves than BICEP-2
  - Much shorter wavelength and higher frequency
  - Astronomical rather than cosmological
  - Black holes, neutron stars, pulsars, etc.



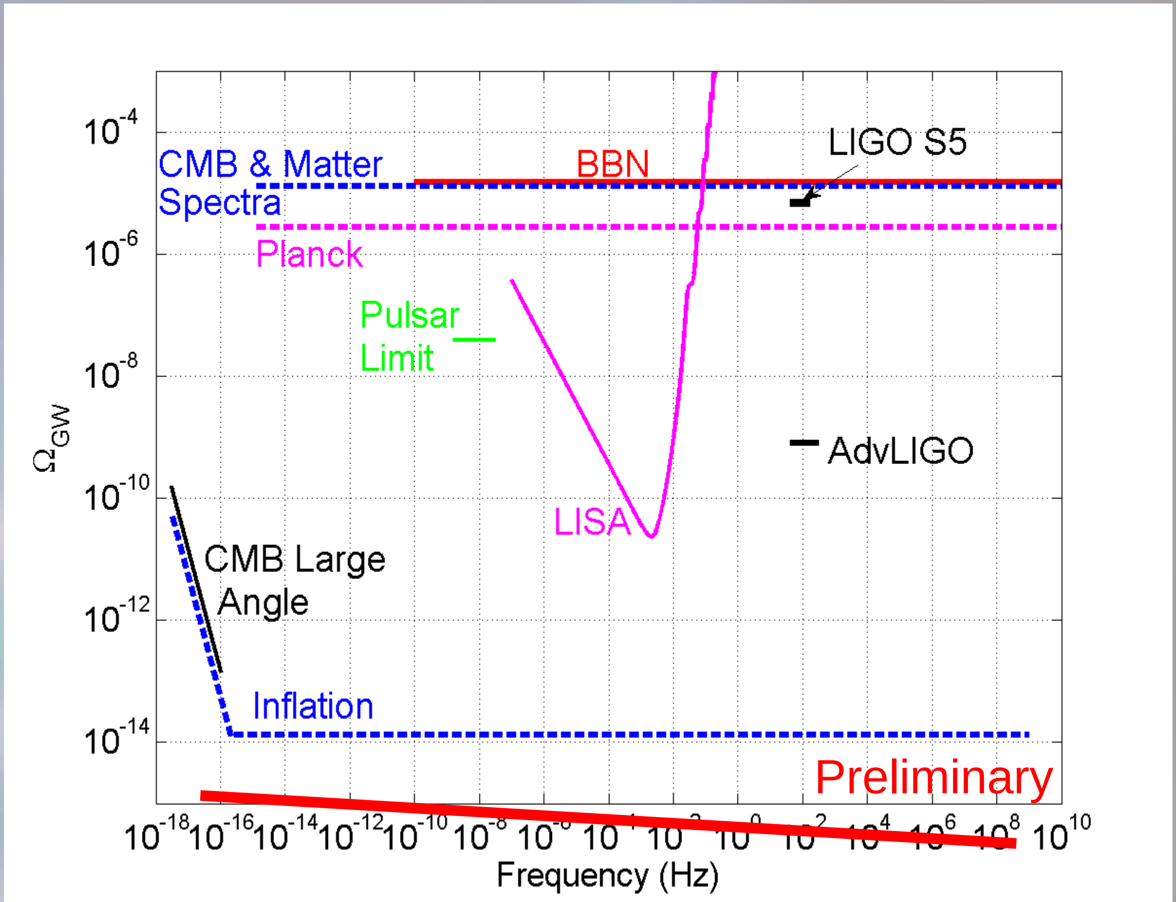
- LIGO detectors in the United States





Stochastic Background

- Before BICEP-2 did not expect LIGO to see Big Bang waves
- With BICEP-2 looks less likely
- Set limits on frequency dependence



- Other models of inflation may allow for detectable waves at LIGO frequencies

Gravitational Wave Detection at AU

- AU is a member of the LIGO collaboration
- Will contribute to running of upgraded LIGO detectors
  - Starting in 2016

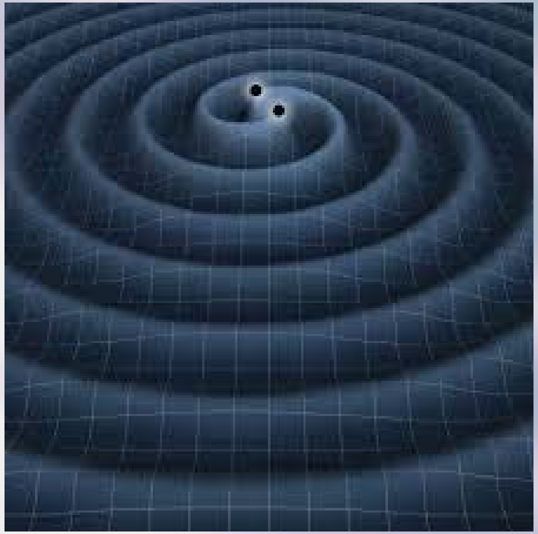
LIGO Scientific Collaboration

105 SCAN Summer 2013

- Campus lab working on LIGO sensitivity
  - Improve mirror properties
- Help guide upgrades and next generation detectors
- Train students to enter field

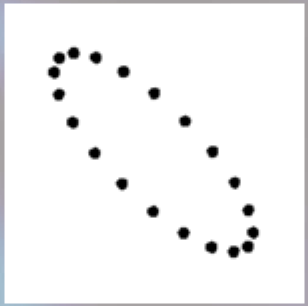
Dynamic Gravity

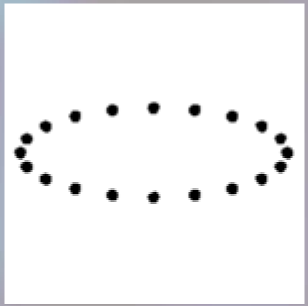
- Crucial difference between Newton and Einstein's theory is the speed of gravity
  - General relativity limits speed of gravity to speed of light c
  - Consistent with special theory of relativity



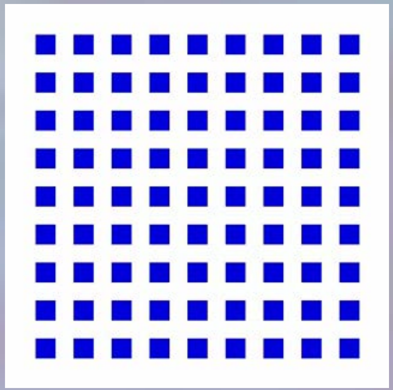
- Similar to Maxwell's equations compared to Coulomb's law
  - Maxwell requires wave of electromagnetism $\rightarrow$ light
- Comparable wave for gravity

Gravitational Waves

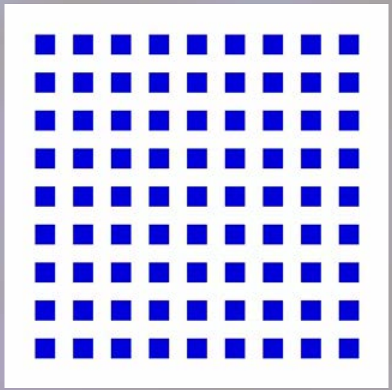




- Propagation of gravity at speed of light called gravitational wave
- Similar to light wave with two important differences
  - Effect much smaller $h = \frac{\Delta L}{L} \approx 10^{-21}$
  - Still two polarizations, but different shape
  - Distinctive pattern from gravitational waves



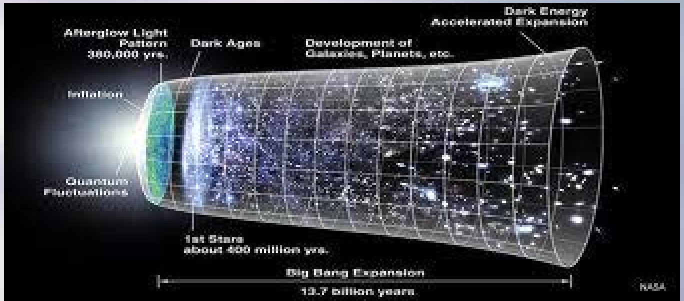
Electromagnetic Wave

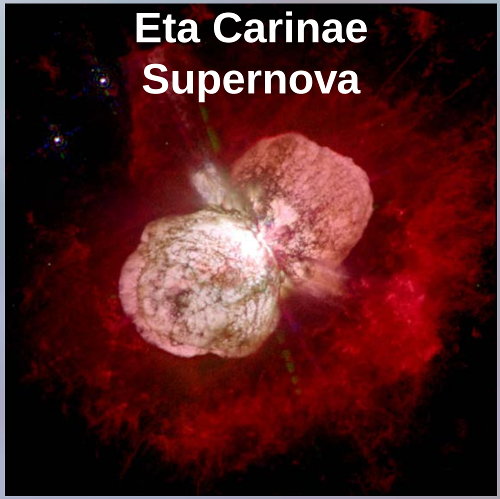


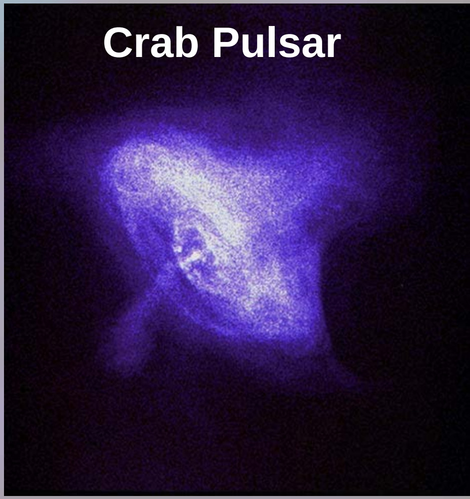
Gravitational Wave

Sources of Gravitational Waves

- Gravitational waves need astronomical masses moving near c as sources
- Pairs of black holes and neutron stars spirally together, supernova explosions, rapidly rotating pulsars
- Left over waves from the Big Bang

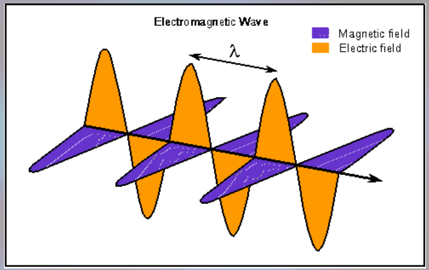






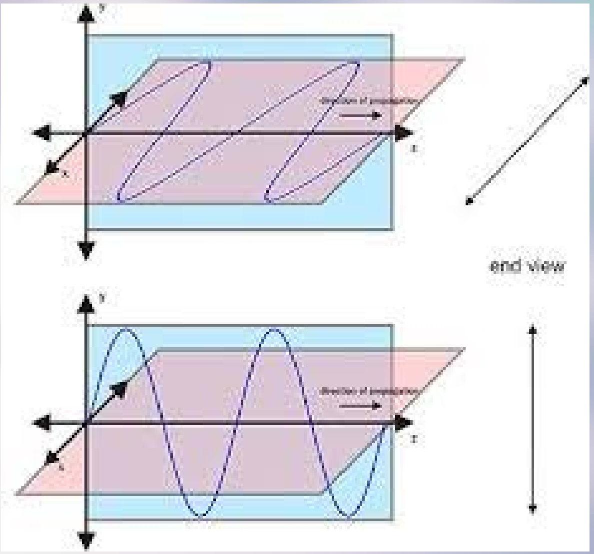
Polarized Light

- Light is interacting electric and magnetic fields



- These fields are vectors, have direction
- Maxwell’s equation ensure that electric field points 90º from travel direction

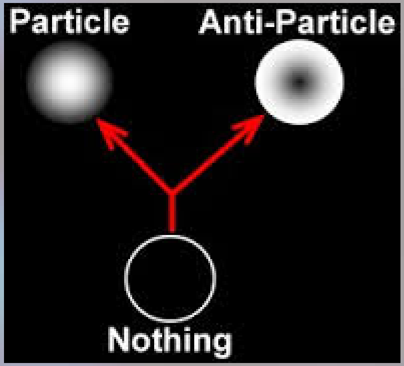
  - Two ways to do this
  - Two polarizations



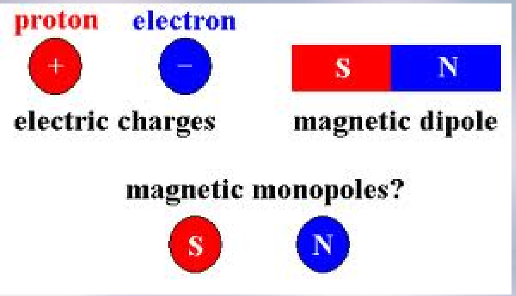
- Some light mix of polarizations
- Some light single polarization
  - Polarized light

Predictions of Inflation

- Isotropy of CMB
  - Anisotropy from quantum fluctuations
- Isotropy of universe curvature

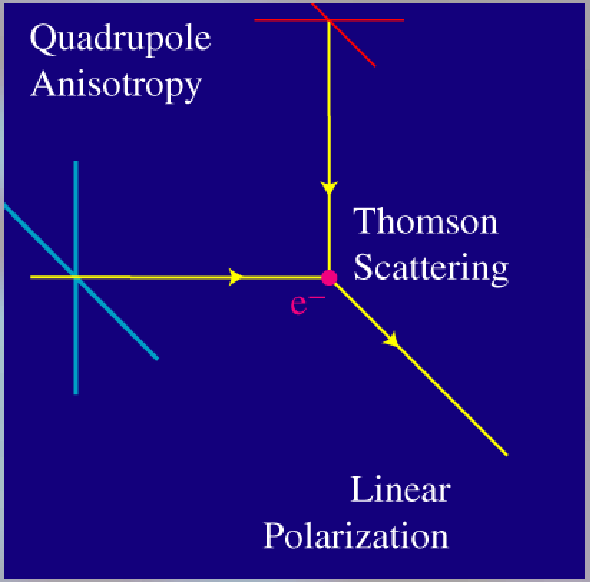


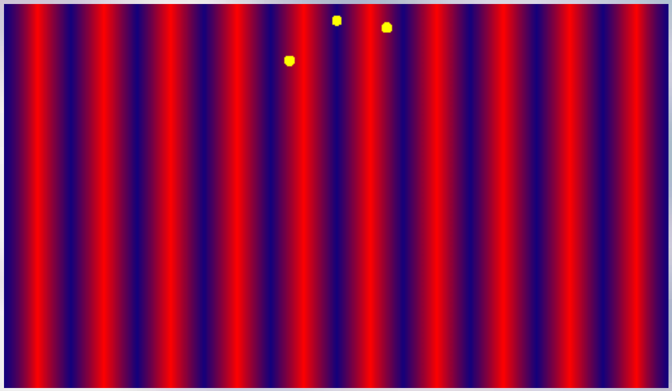
- Expansion must be 10^{26} in length to explain observations
- Lack of exotic high mass particles
  - No magnetic monopoles original reason for inflation proposal
  - Other particles predicted by some models not found



CMB Polarization

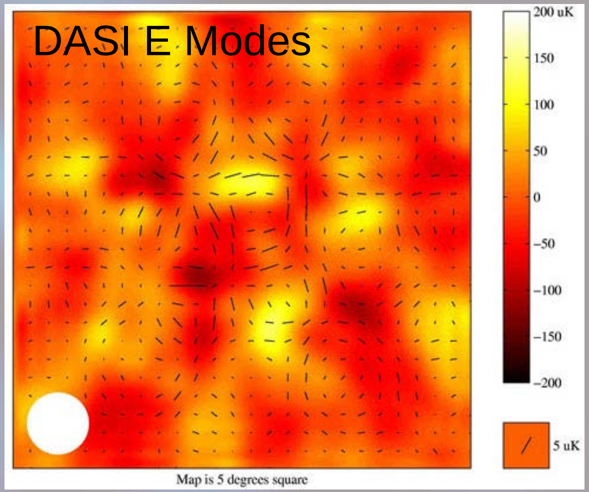
- Anisotropic scattering of photons off of electrons causes polarization
  - Called quadropole because direction must be $90° = \frac{360°}{4}$



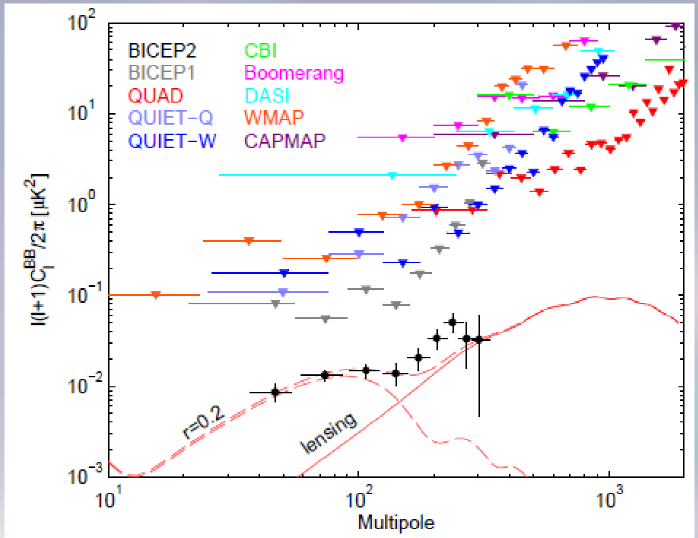


- Must scatter off free electrons
- Must not scatter afterwards
- Only happens during recombination/last scattering
  - Most photons not polarized

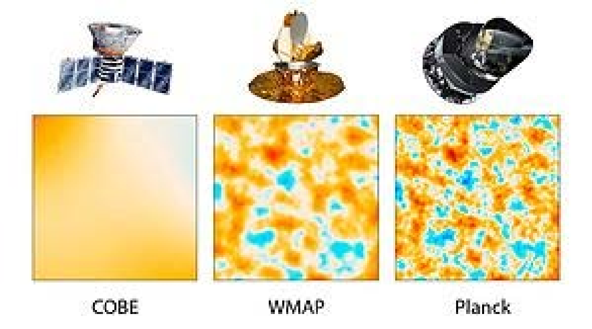
Previous Results



- E mode detected 2002 Degree Angular Scale Interferometer (DASI)



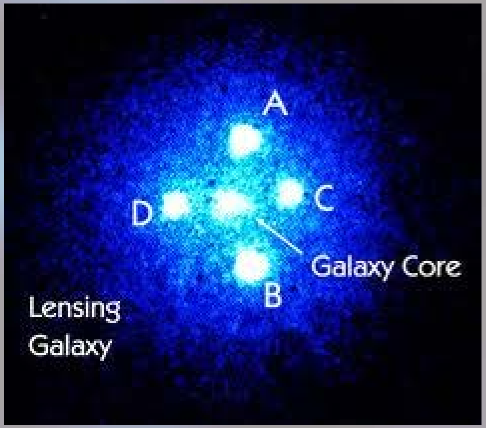
- Temperature correlations 2003 WMAP
- South Pole Telescope (SPT) sees hints of B mode 2013

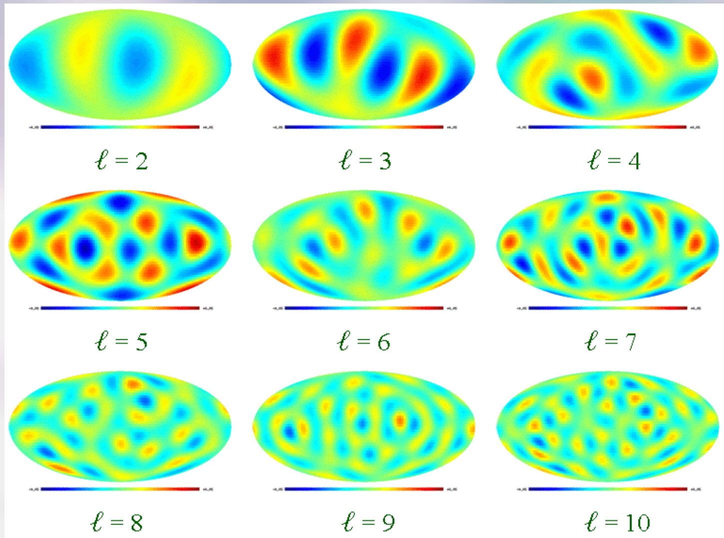


- POLARBEAR sees B mode from lensing 2014
- SPT/WMAP/Planck satellite limits on ratio $r < 0.11$

Gravitational Lensing

- Gravitational lensing occurs when light goes near a massive object
  - Observed from Sun and quasars
  - CMB from galaxies

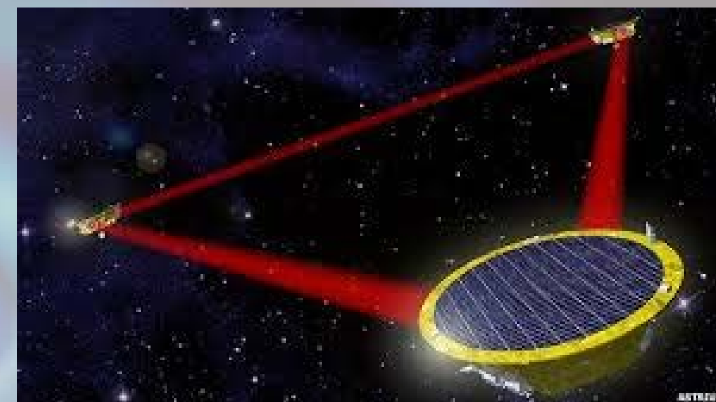


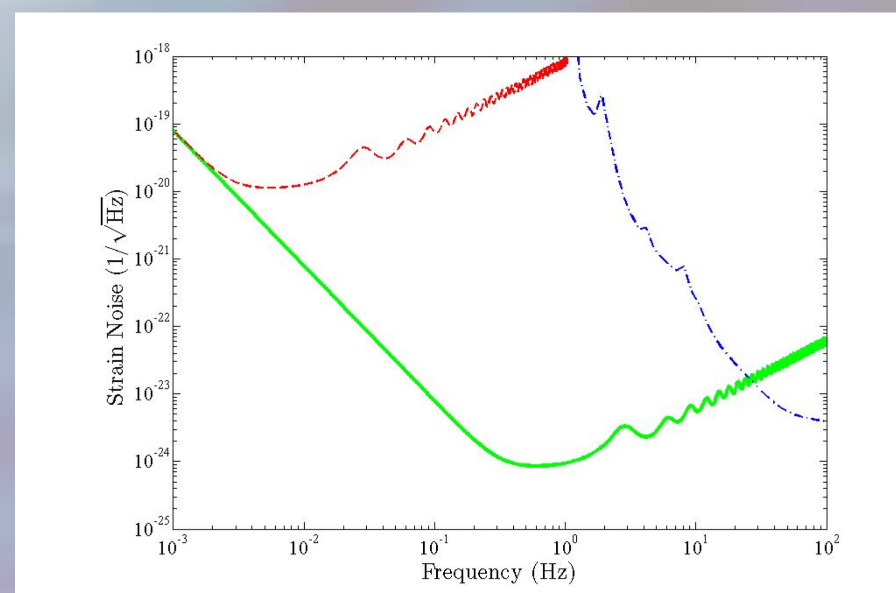


- Gravitational lensing can convert E mode to B mode
- Observe when comparing light nearby on the sky
  - High values of "ℓ"
  - Roughly $\Delta\theta \approx {}^{180°}/_{\ell}$

Space-based Detectors

- Spaced based interferometers
- LISA launch date 2034
- Big Bang Observer (BBO) possible follow-up mission
  - Designed to see gravitational waves from Big Bang





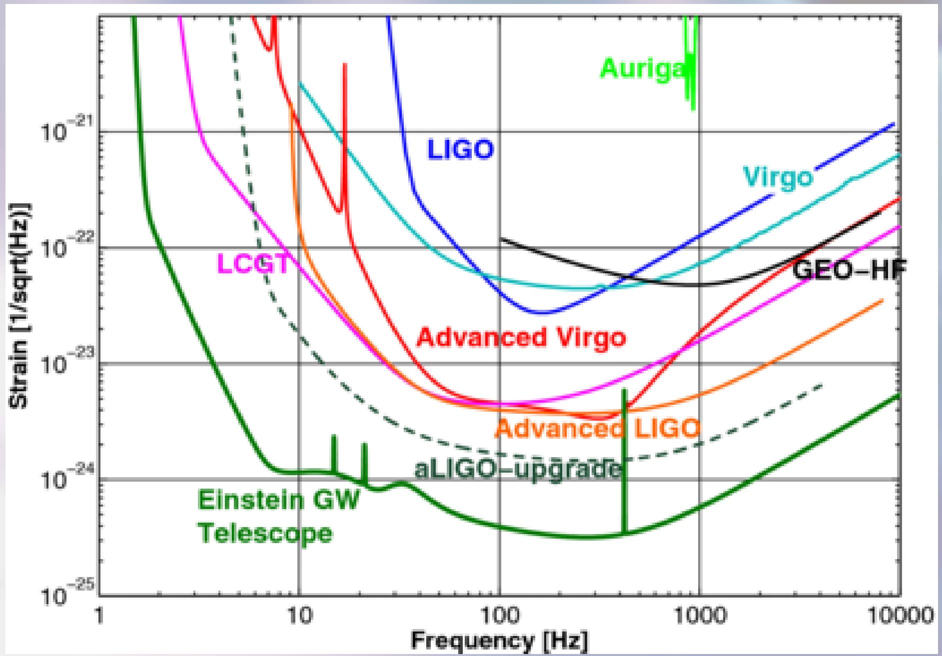
- Long arm lengths
  - 5×10^6 km for LISA
- Different frequency ranges

Ground-based Detectors

- LIGO detectors in US
  - 4 kilometer arm length
  - LIGO India likely as well
  - Advanced LIGO ready ~2016


Livingston, LA

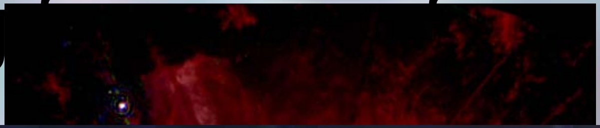

Hanford, WA

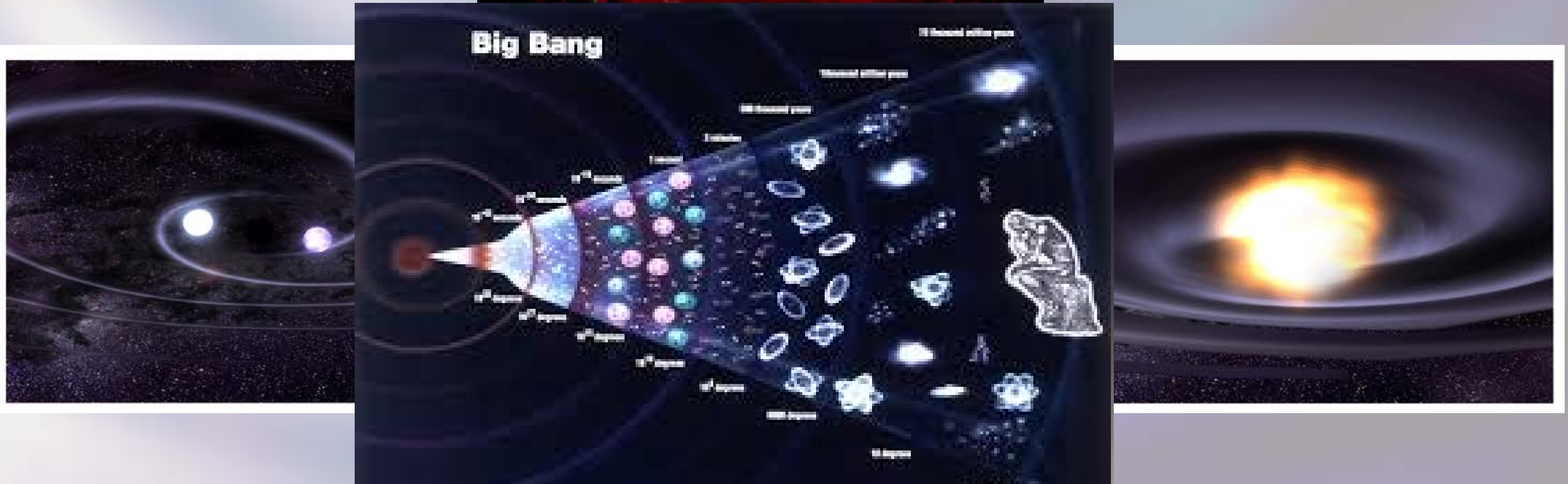


- Virgo in Italy
  - Lower frequency
- GEO in Germany
  - Squeezed light
- KAGRA in Japan
  - Underground/Cooled

LIGO Sources

- Sources for ground based detectors astronomical, rather than cosmological
- Binary neutron stars and/or black holes
- Supernova explosions of stars
- Also looking [illegible] Big Bang





Other Models

- Many different models of how to extrapolate CMB results to LIGO band
- Preheating resonance
  - Peak from energy scale
- Axion models
- LIGO results crucial