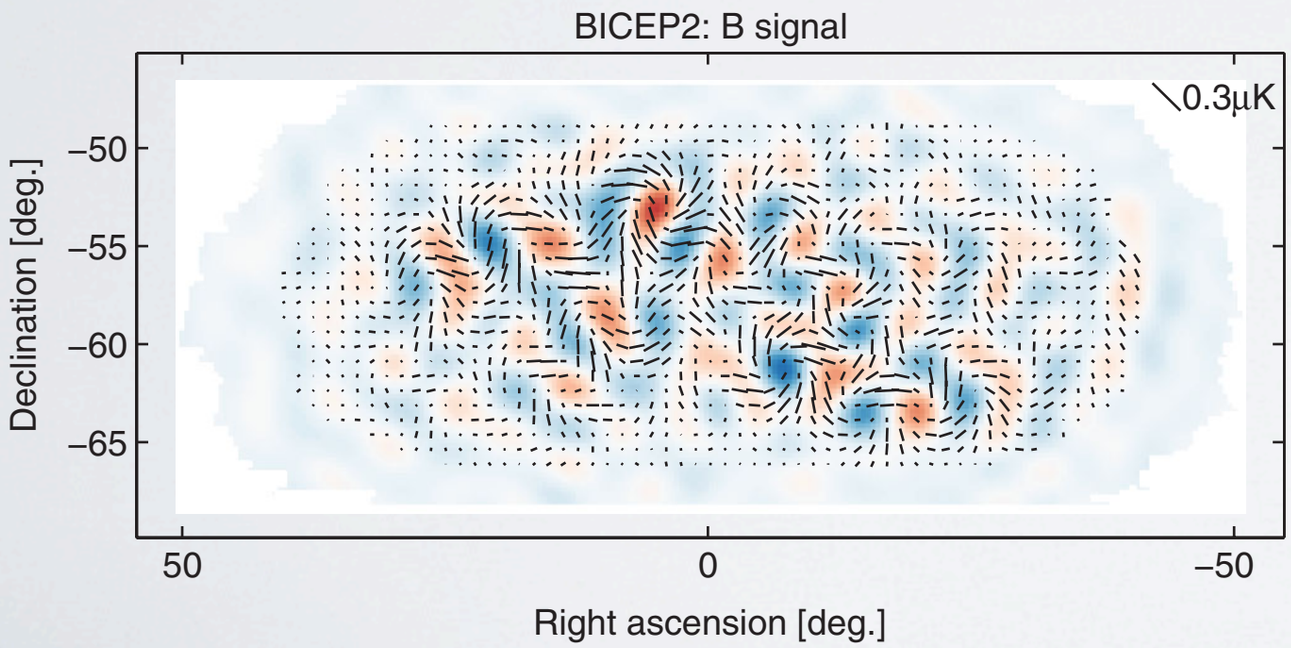
BICEP2 AND DISCOVERY OF INFLATIONARY GRAVITY WAVES?



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Primordial gravitational wave discovery heralds 'whole new era' in physics

Gravitational waves could help unite general relativity and quantum mechanics to reveal a 'theory of everything'

Stuart Clark
The Guardian, Monday 17 March 2014 14.08 EDT

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Scientists detected telltale signs of gravitational waves using the Bicep2 telescope (far left) at the south pole. Photograph: Keith Vanderlinde/NSF

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Phys.Org

BICEP2 Big Bang 'Discovery' Team Urges Caution

Discovery News - by Ian O'Neill - Jun 21, 2014

View Related Gallery ». The sun sets behind **BICEP2** (in the foreground) and the South Pole Telescope (in the background). Steffen Richter (Harvard University).

Science AAAS

BICEP2 scientists publish cosmic inflation paper hedging...

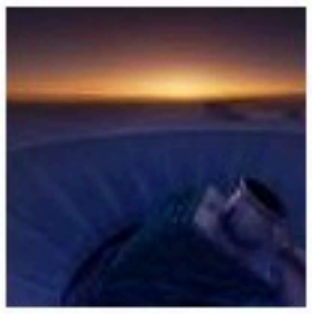
Washington Post - by Joel Achenbach - Jun 19, 2014

The scientists behind the **BICEP2** experiment had noted, all along, that galactic dust could contaminate their observations to some degree. But they originally ...

BICEP2 Images the Past, Cosmology Looks to the Future

Physics - Jun 19, 2014

Explore in depth (14 more articles)



Will the **BICEP2** Results Hold Up?

PBS (blog) - May 29, 2014

Using a telescope at the South Pole called **BICEP2**, they picked up swirls in the polarization, or alignment, of the cosmic microwave background (CMB) radiation, ...

OUTLINE

- Introduction to Big Bang Theory, Cosmic Microwave Background (CMB), and Inflation
- Signals of Gravitational Waves Produced During Inflation
- Polarized CMB light as observed by BICEP2
- Discovery of Gravity Waves or Dust?
- The Future

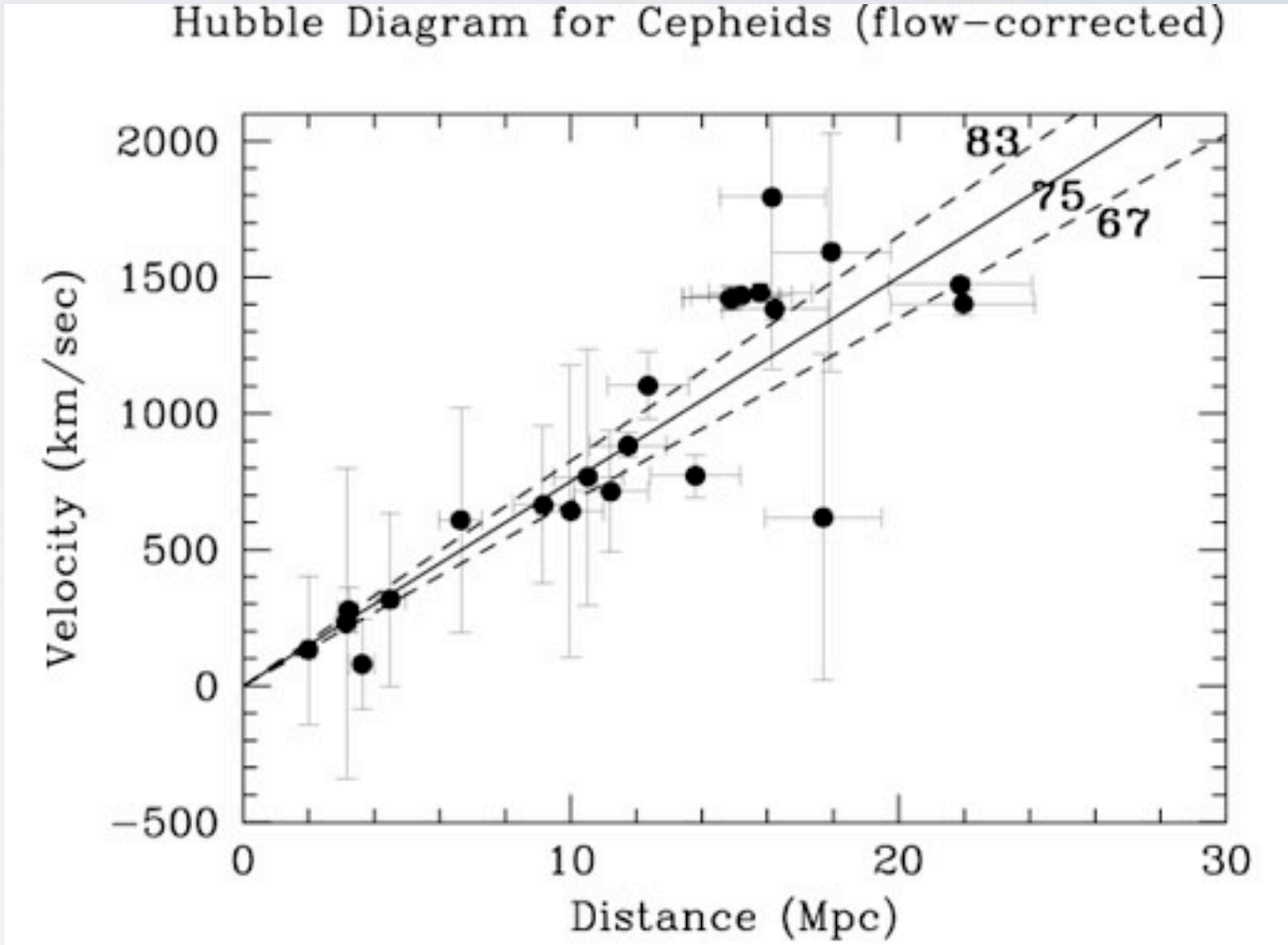
EXPANDING UNIVERSE

Hubble ('29) discovered that the Universe was expanding

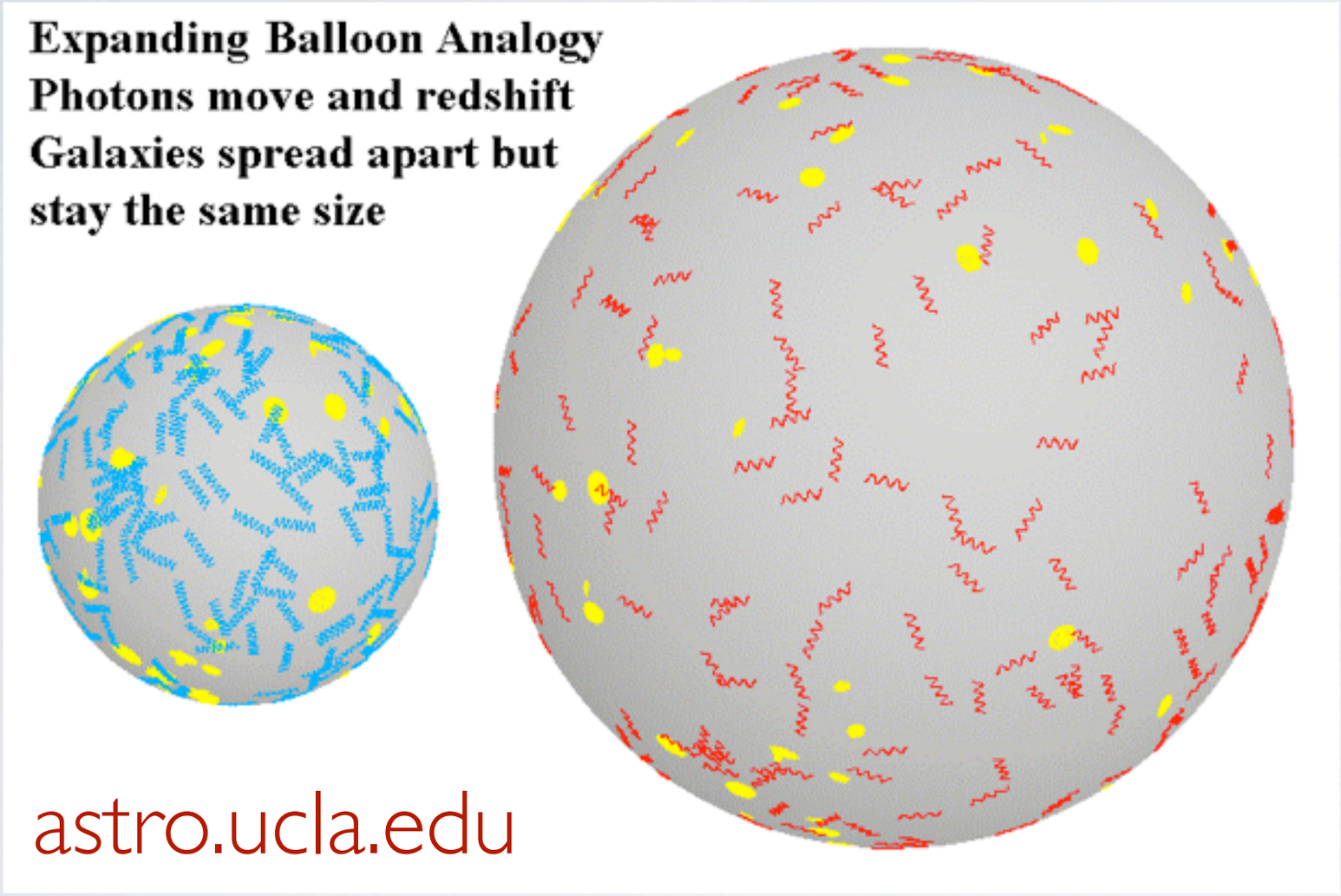
On average, objects are moving away with velocity that grows linearly with distance

$$v = Hd$$

H = Hubble Constant



HUBBLE EXPANSION



Universe expansion is like a balloon expanding

$$d = a\,x$$

a = scale factor
x = coordinate on balloon

$$H(t) = \frac{1}{a}\frac{da}{dt}$$

Hubble constant isn't a constant!

BIG BANG

Evolution of scale factor is determined by energy content of the universe (radiation, matter, cosmological constant)

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

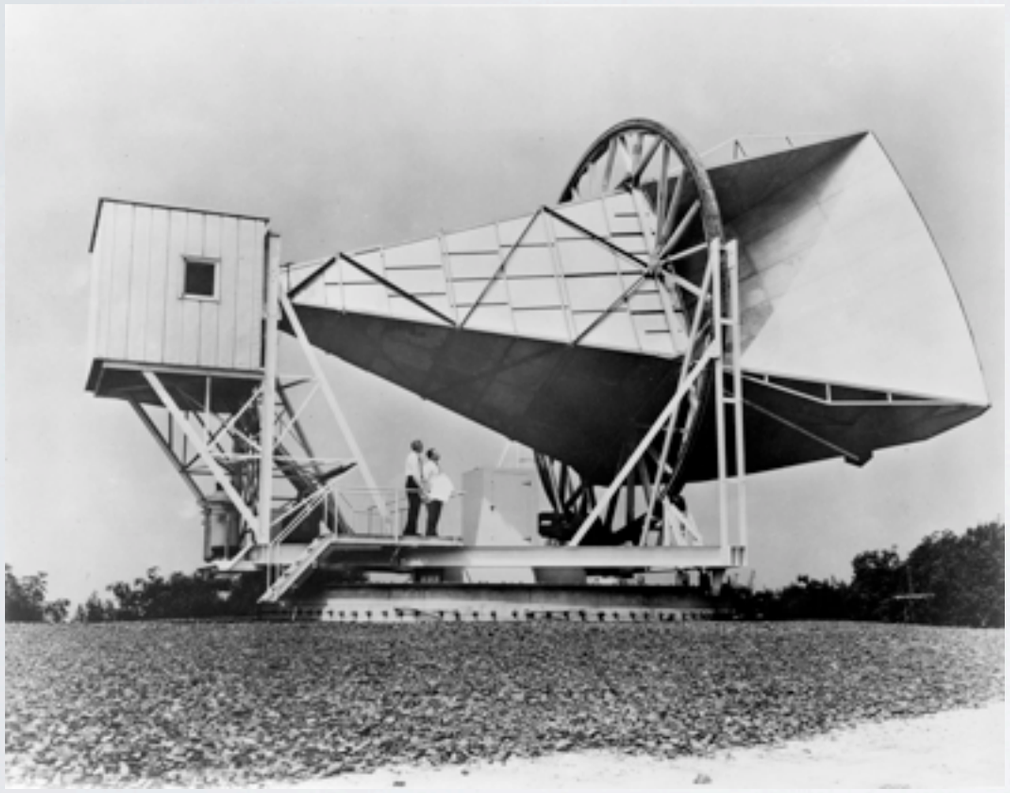
Friedmann eqn.

ρ = energy density

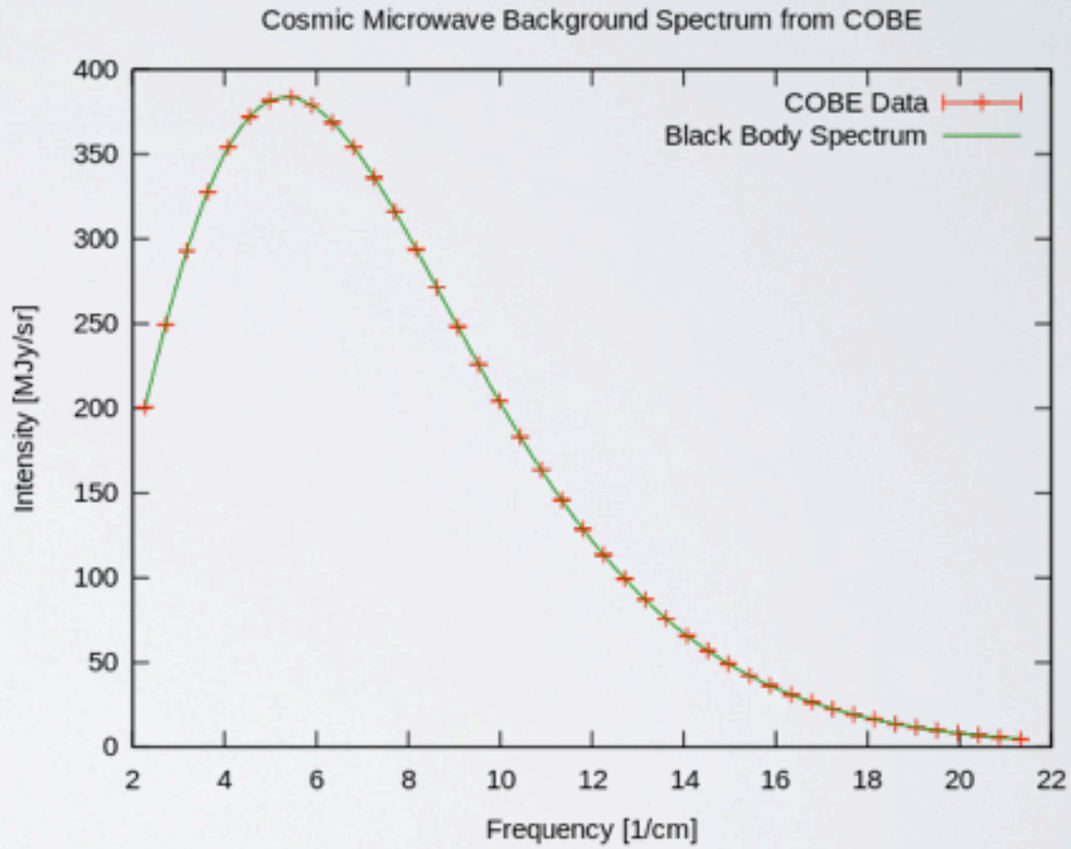
As one goes back in time, eventually a goes to zero
This infinite density and temperature
state is the Big Bang

COSMIC MICROWAVE BKGD

As Universe expands, it starts to cool, so
we expect some thermal radiation left over
which is emitted 300,000 years after Big Bang

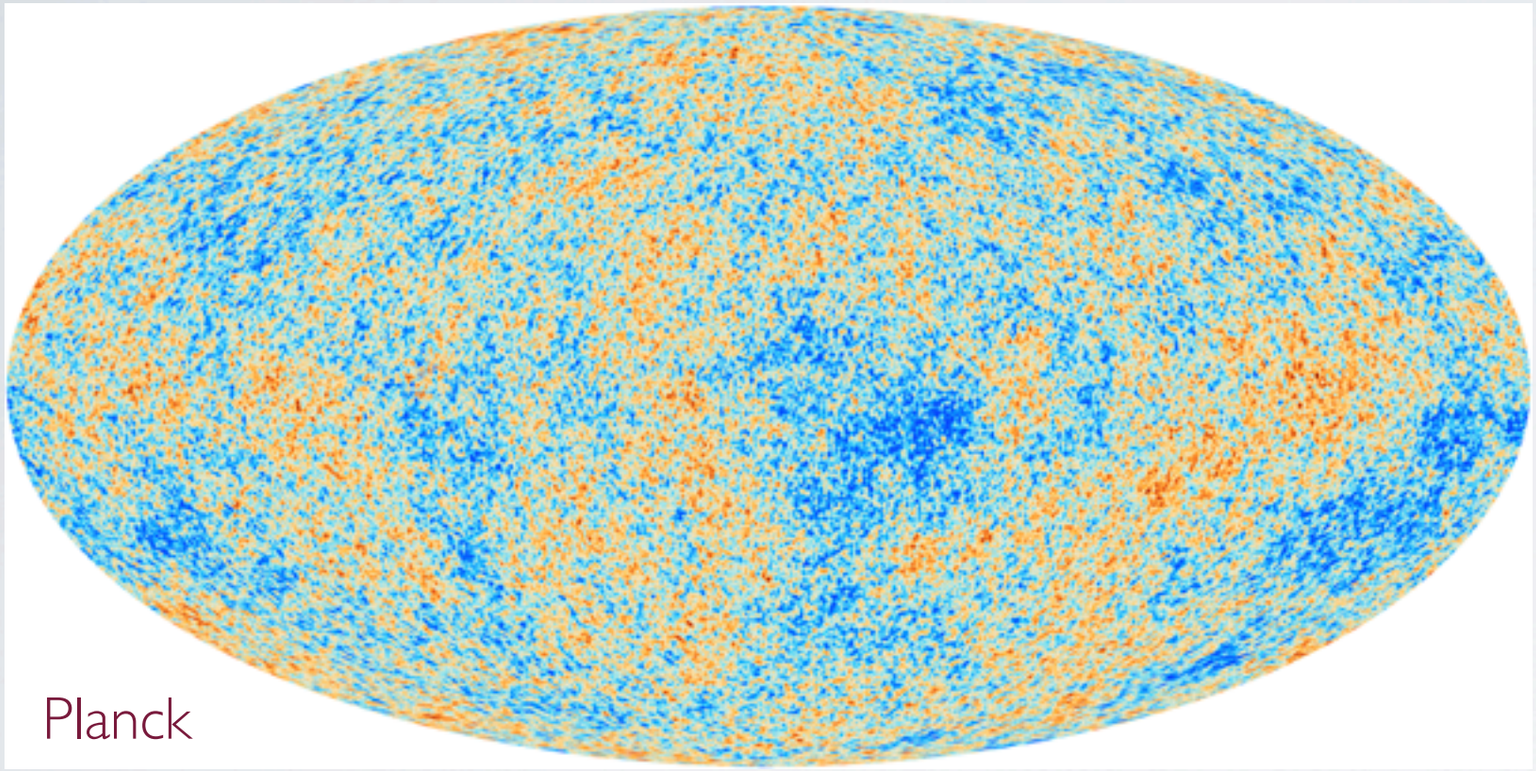


Discovered by
Penzias, Wilson, '64

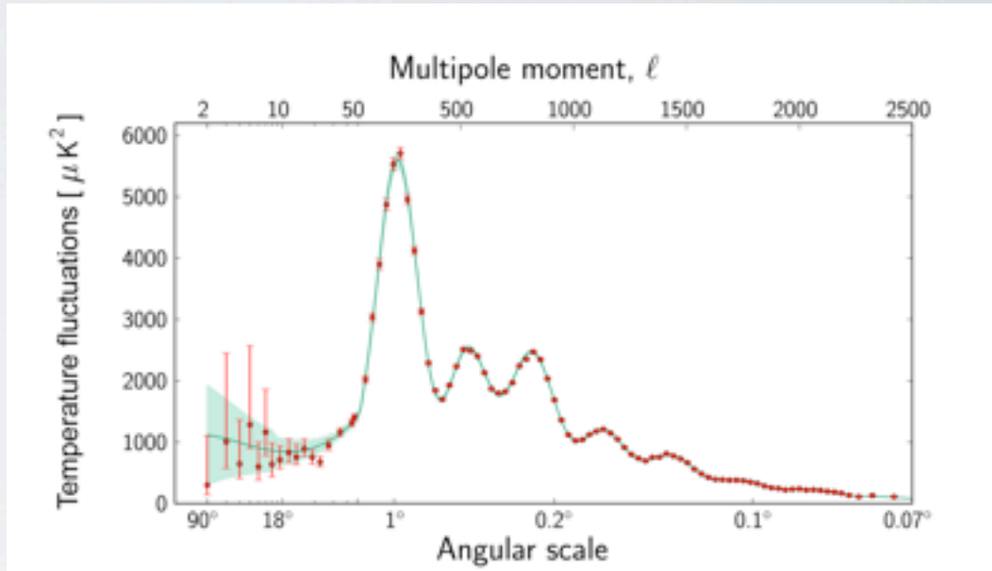


Blackbody Spectrum
COBE '90
Temperature = 2.7 K

COSMIC MICROWAVE BKGD



Planck

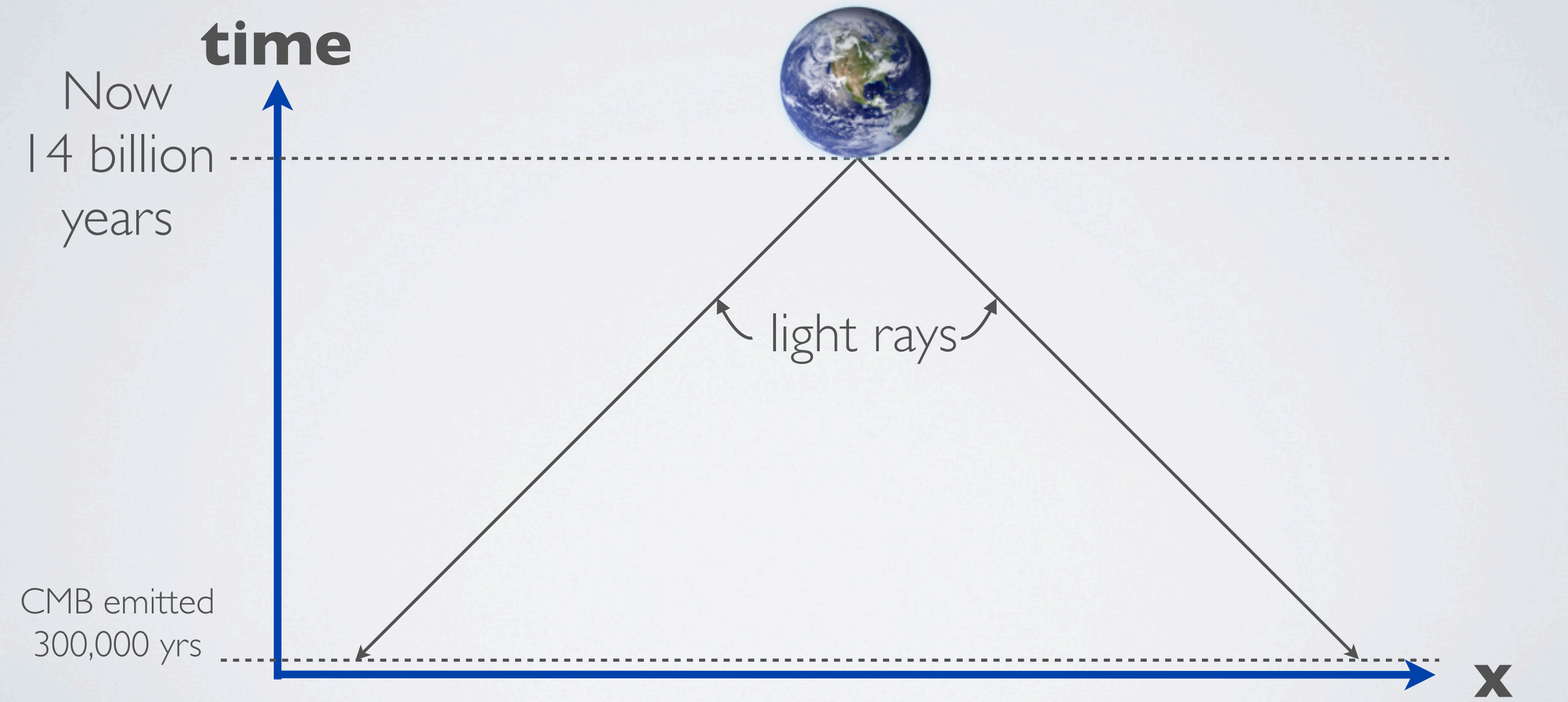


Extremely uniform

Temperature fluctuations are 10 μK

HORIZON PROBLEM

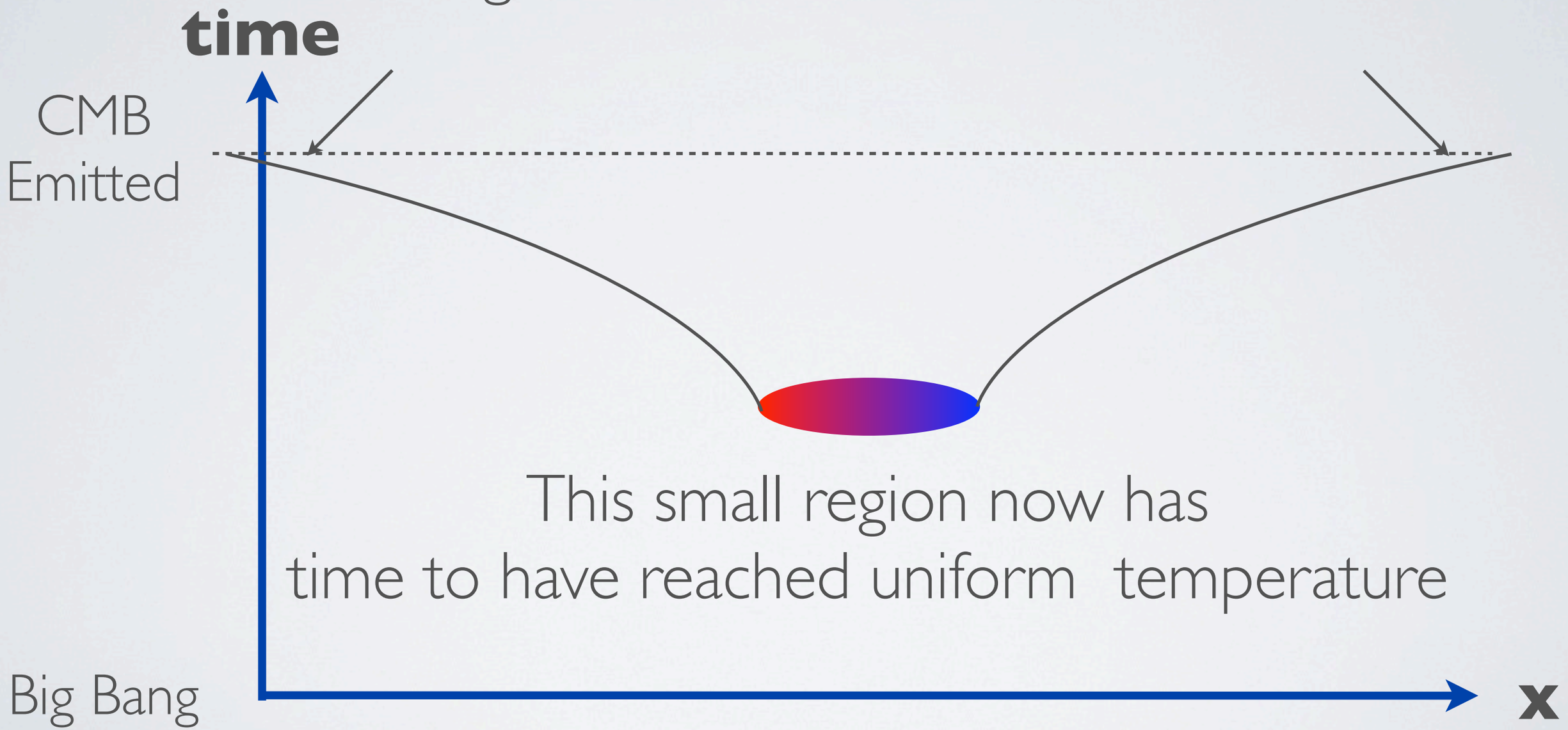
This is a problem! How did these regions in opposite directions know to be ~ same temperature?



Not enough time from Big Bang for 2 regions to communicate!

INFLATION

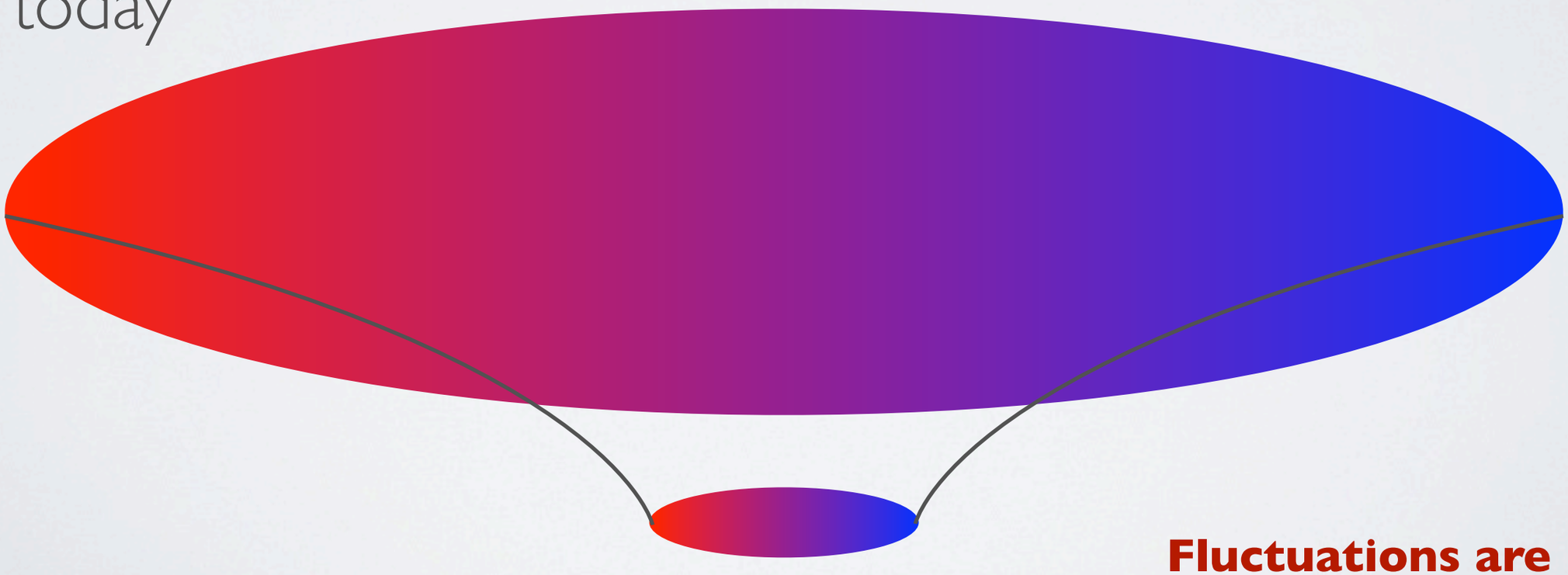
Period of accelerated expansion faster than light allows regions to have thermalized



INFLATIONARY SUCCESSES

- Solves horizon and flatness (why our Universe is spatially flat) problem

- It also generates the (quantum) fluctuations in cosmic microwave background, matter that grows into the galaxies we see today



Fluctuations are quantum mechanical!

STATUS OF INFLATION

- Many in the cosmology and particle physics community believe that inflation as a paradigm has passed many important tests

- Still know very little about the theory behind inflation

- For the skeptics, need a smoking gun signal to be convinced

GRAVITY WAVE FLUCTUATIONS

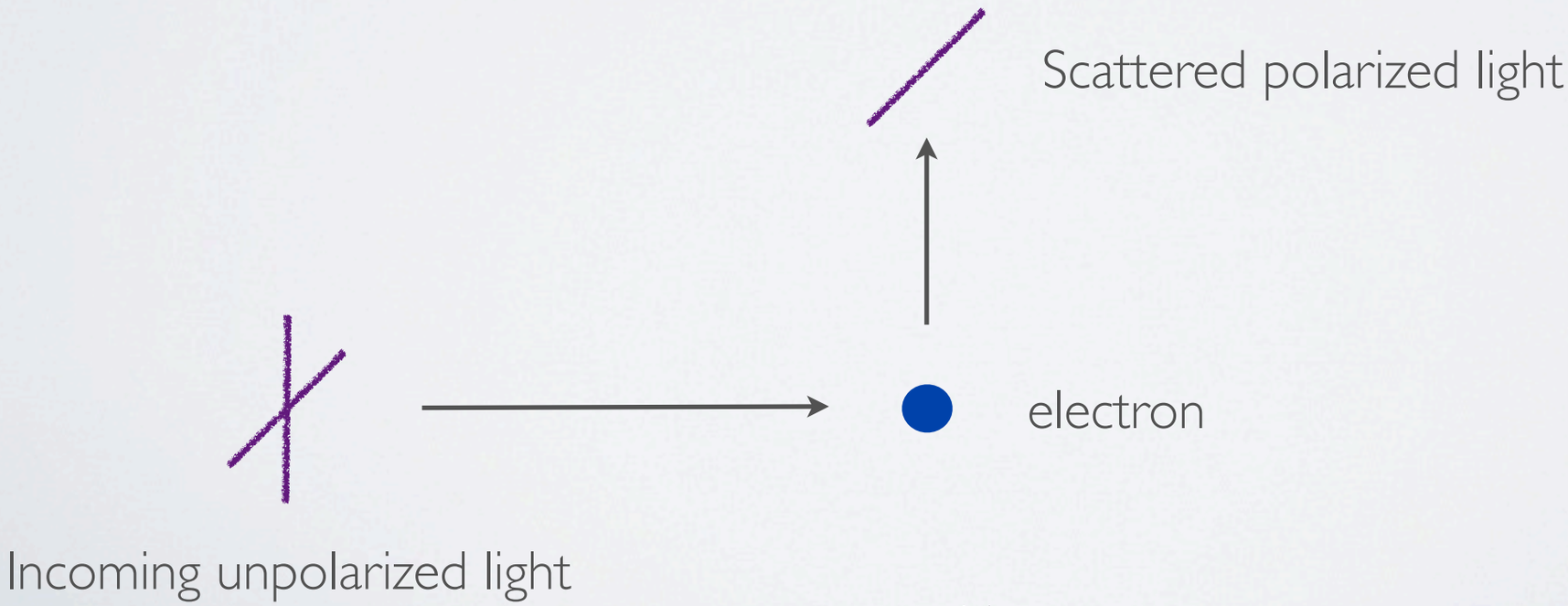
- Inflation also predicts that there are gravity wave fluctuations produced during inflation

- Their amplitude is set by the energy density that drives inflation, so detection would give a strong hint that inflation exists and give insight into the theory behind inflation

POLARIZATION

We have to look at polarization of the CMB in order to detect inflationary gravity waves

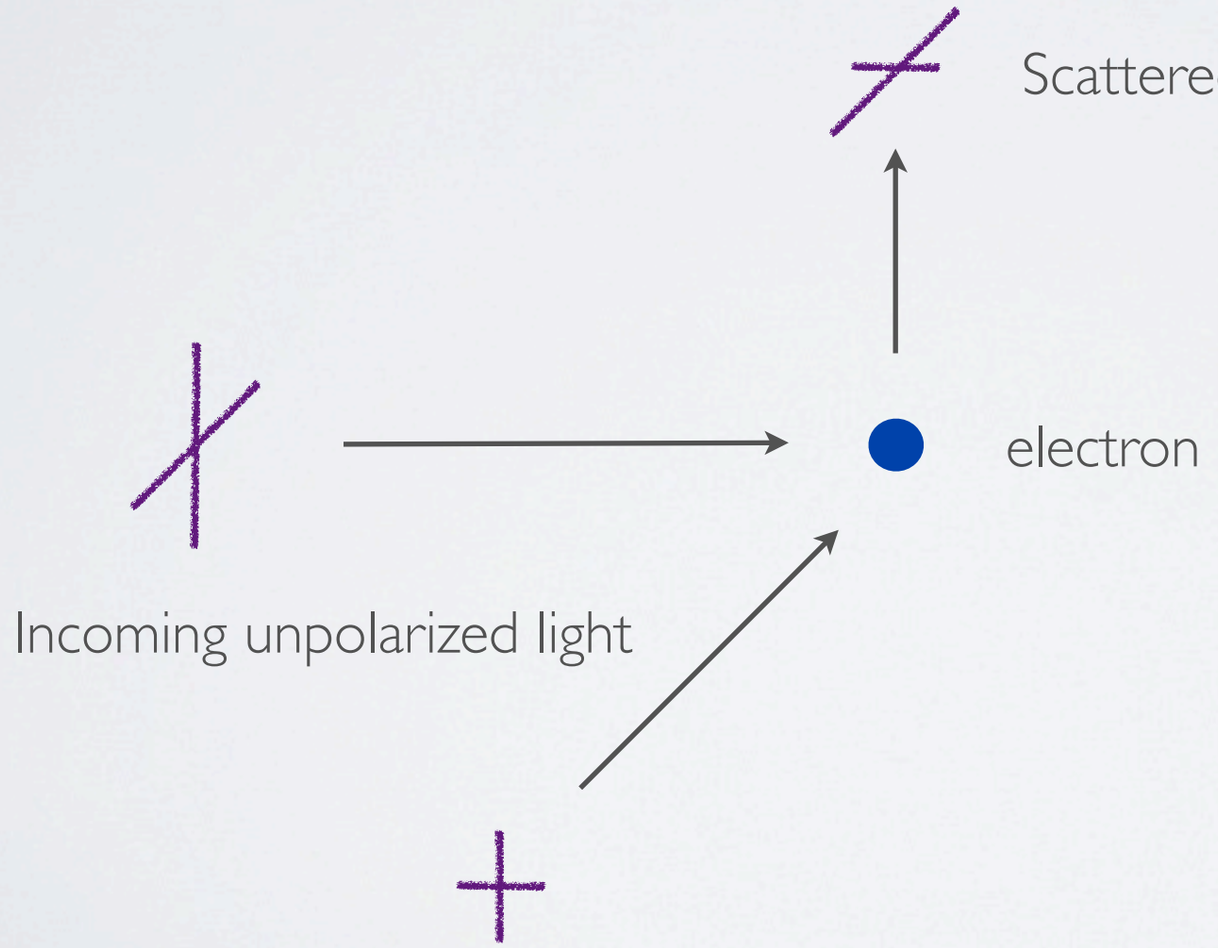
In early Universe, photons and electrons are strongly interacting, leading to photons being unpolarized. Once Universe starts to become transparent, can generate a polarization.



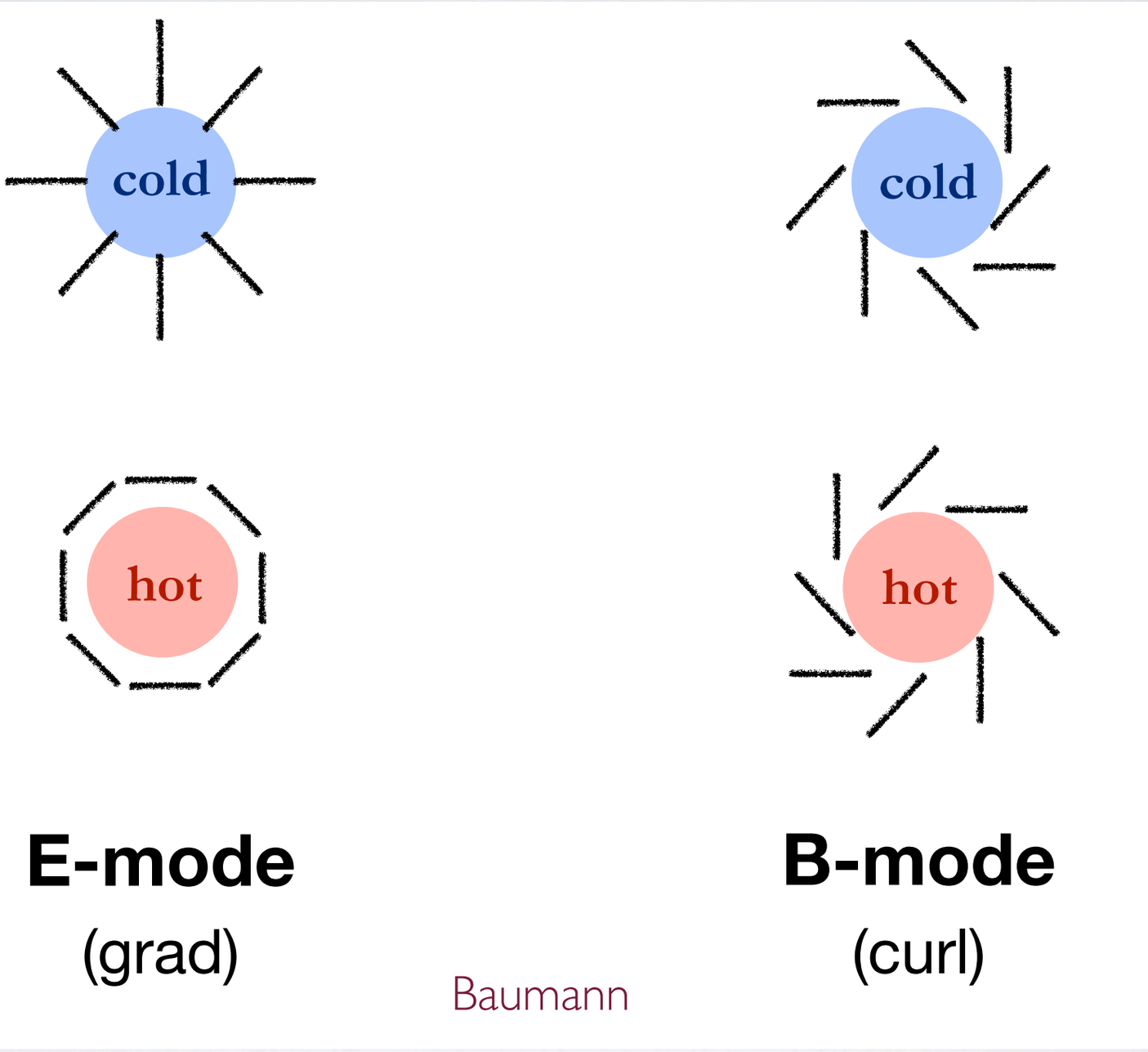
Thomson Scattering

POLARIZATION

Only a quadrupole anisotropy in unpolarized photons is scattered into polarized light



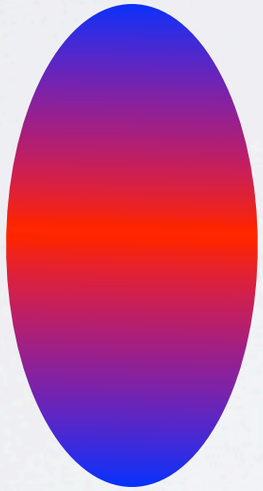
POLARIZATION MODES



B-mode polarization is only created by gravity waves (and vector perturbations)

GRAVITY WAVE QUADRUPOLES

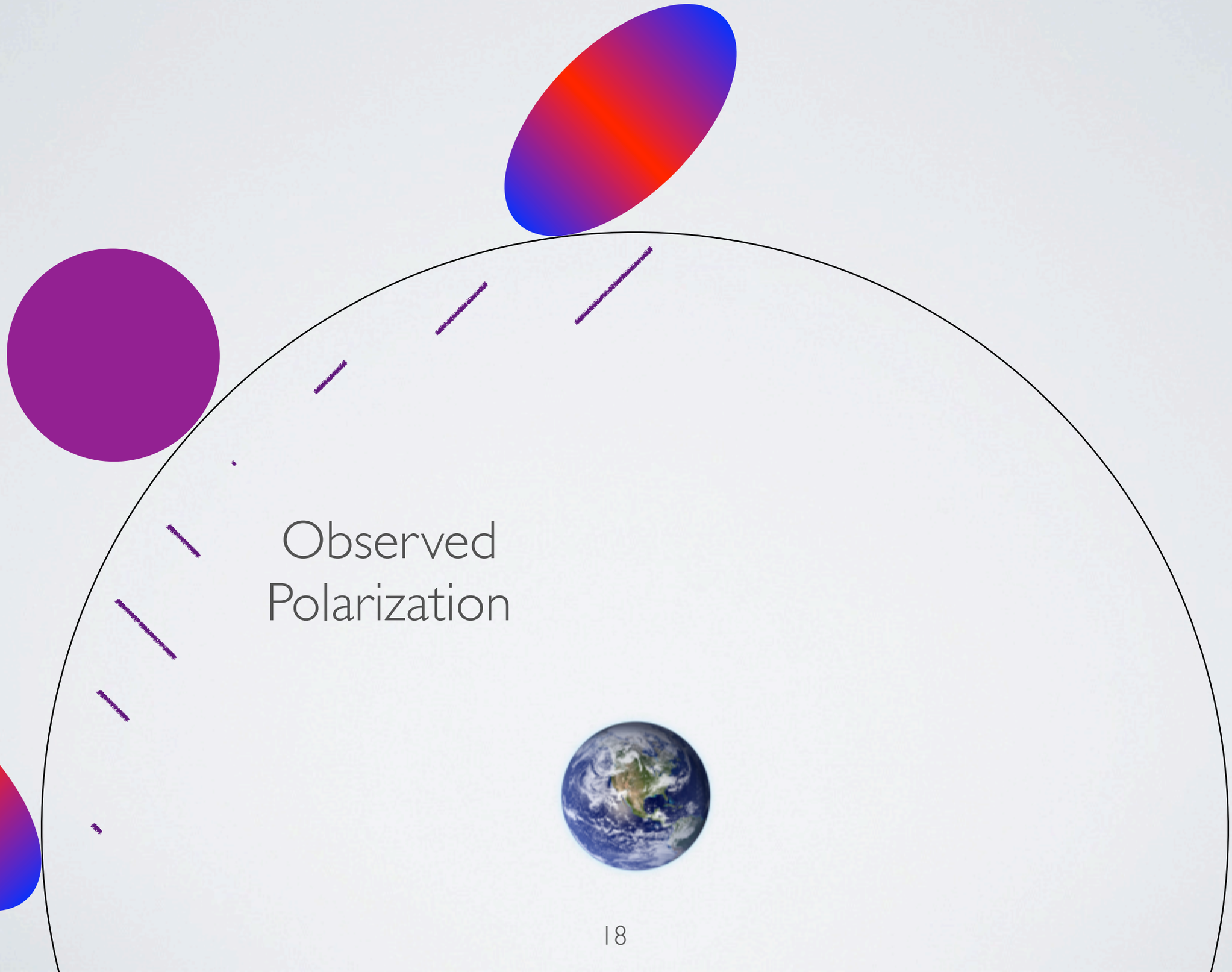
Gravity waves stretch and contract photon wavelengths cooling or heating them, giving a quadrupole anisotropy



+ mode

- mode

GRAVITATIONAL WAVE ACROSS SKY



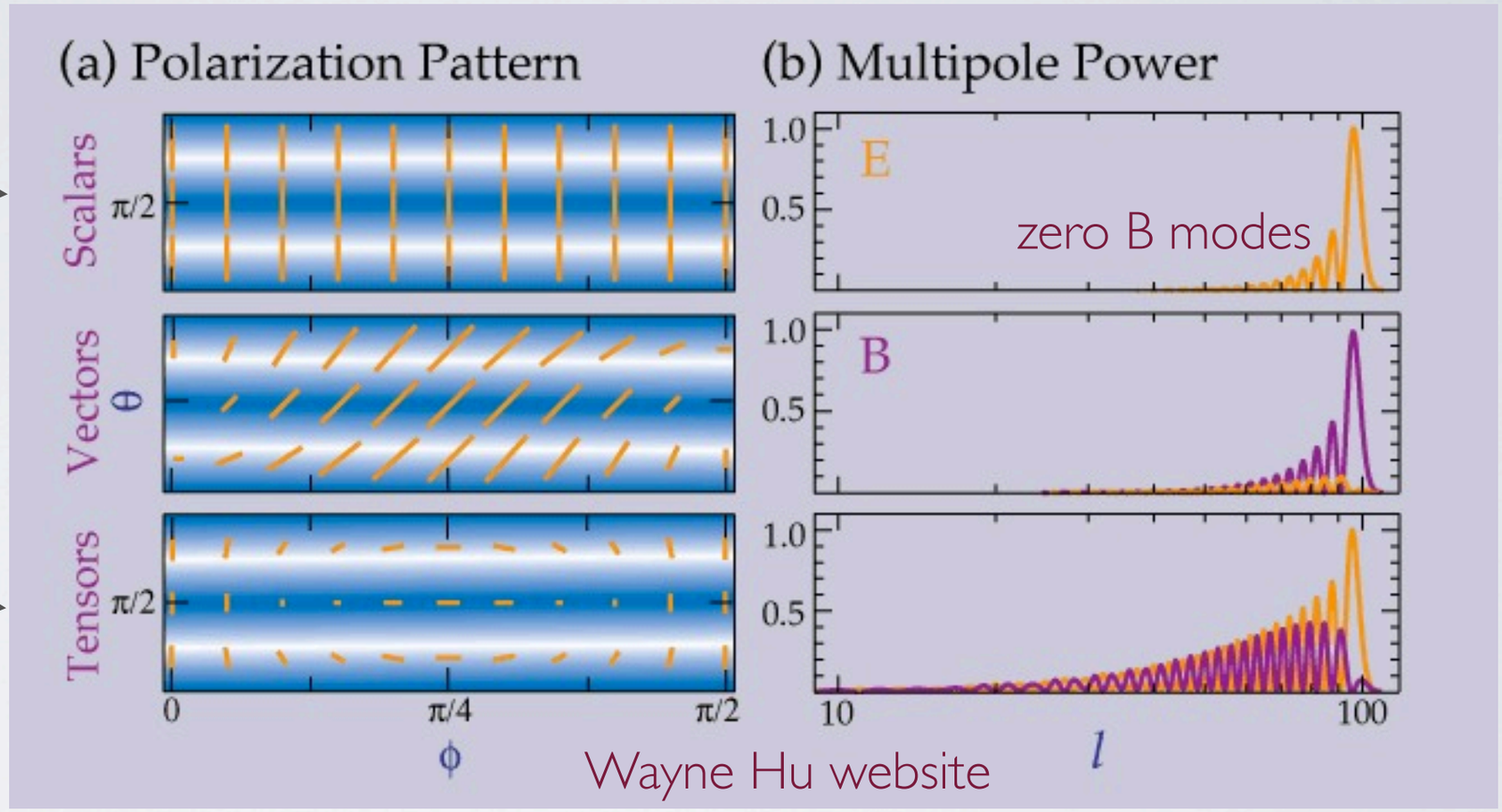
GRAVITATIONAL WAVE ACROSS SKY

Observed Polarization

B-mode

POLARIZATIONS

Inflation generates

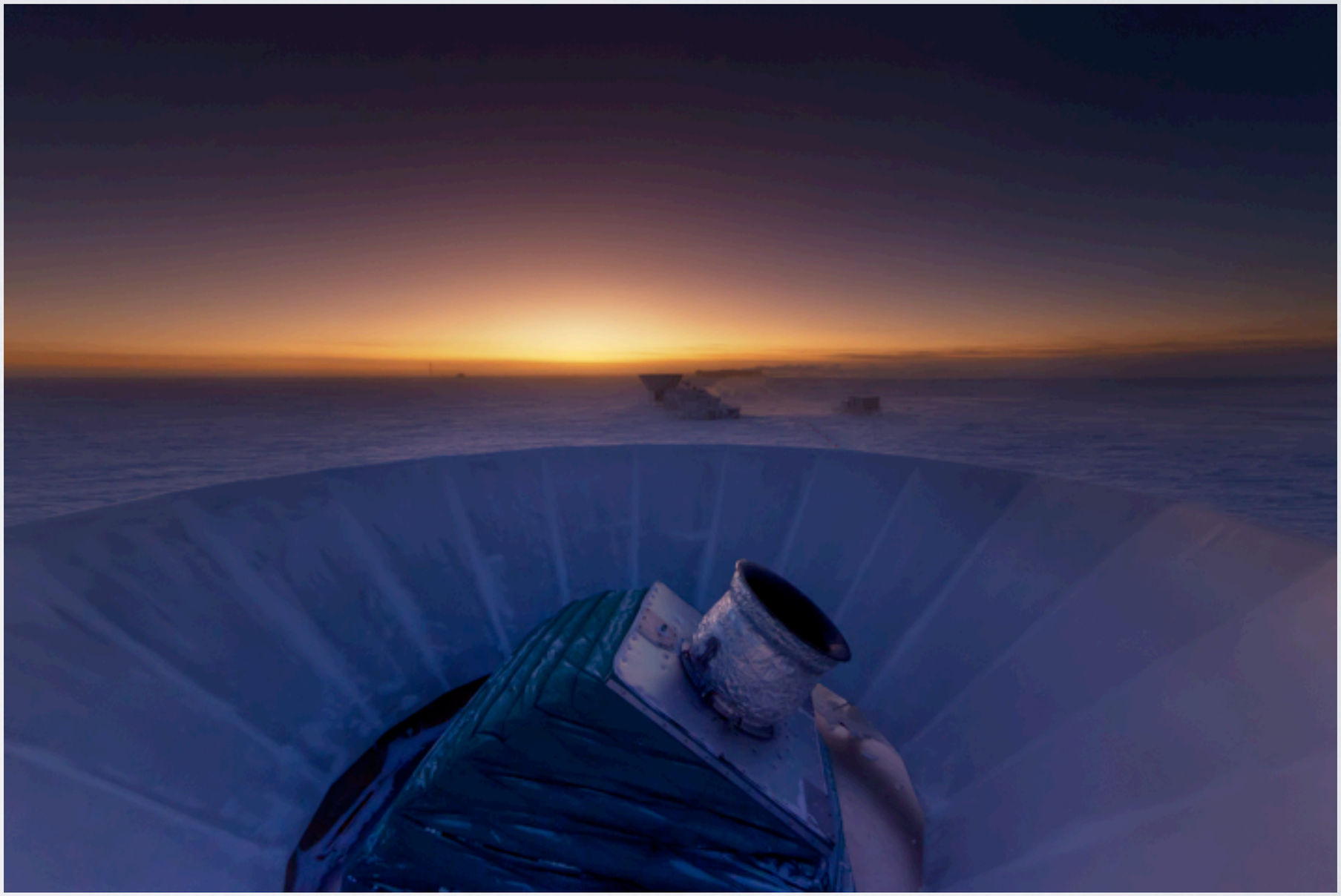


Gravity waves as tensor perturbations have additional directional dependence which allows them to generate B modes

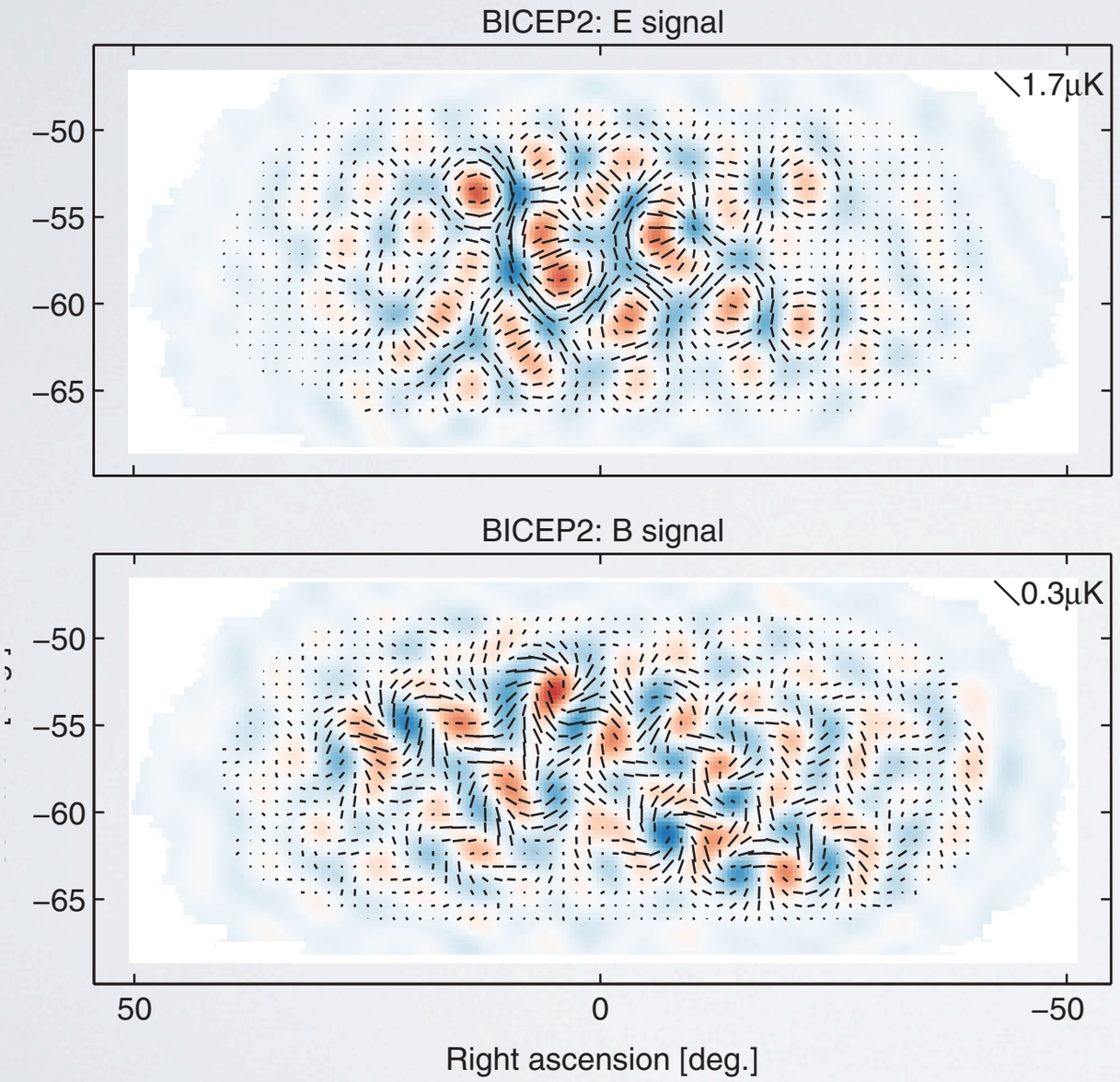
Thus, a clear signal would be a major discovery!

BICEP2

A telescope at South Pole looking for CMB polarization



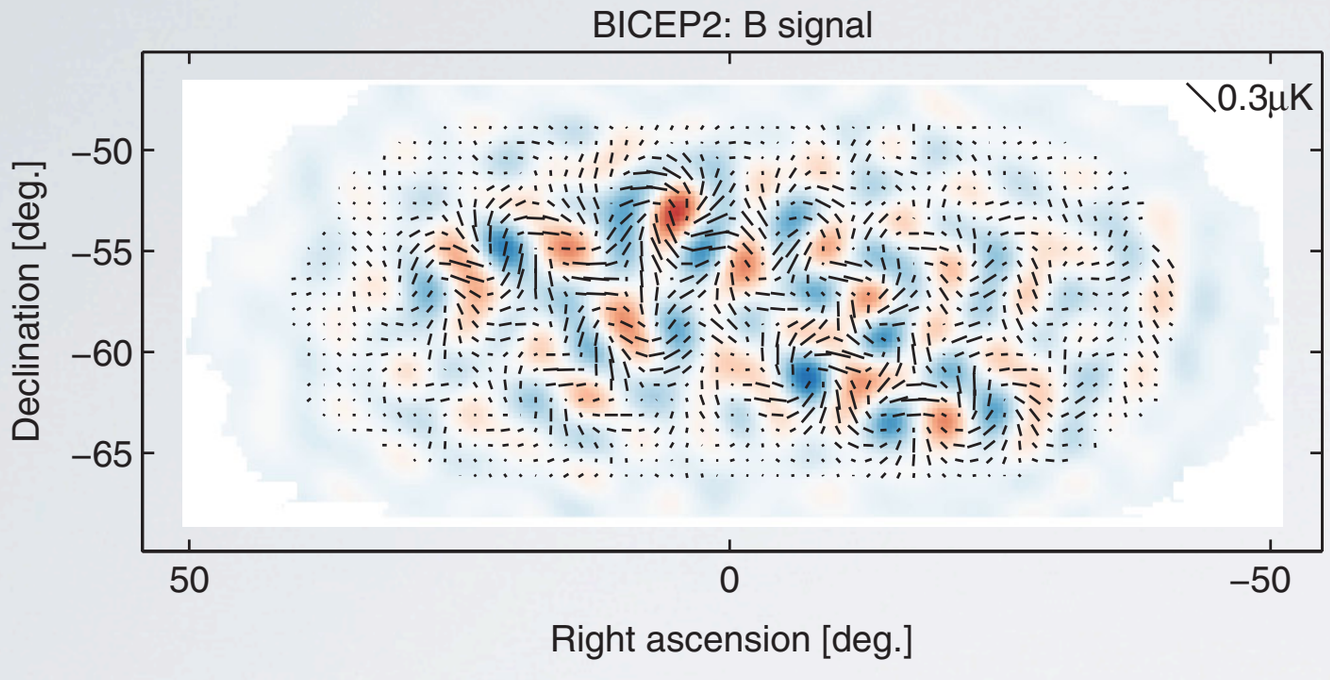
WHAT THEY FOUND



Divergence Modes

Curl Modes

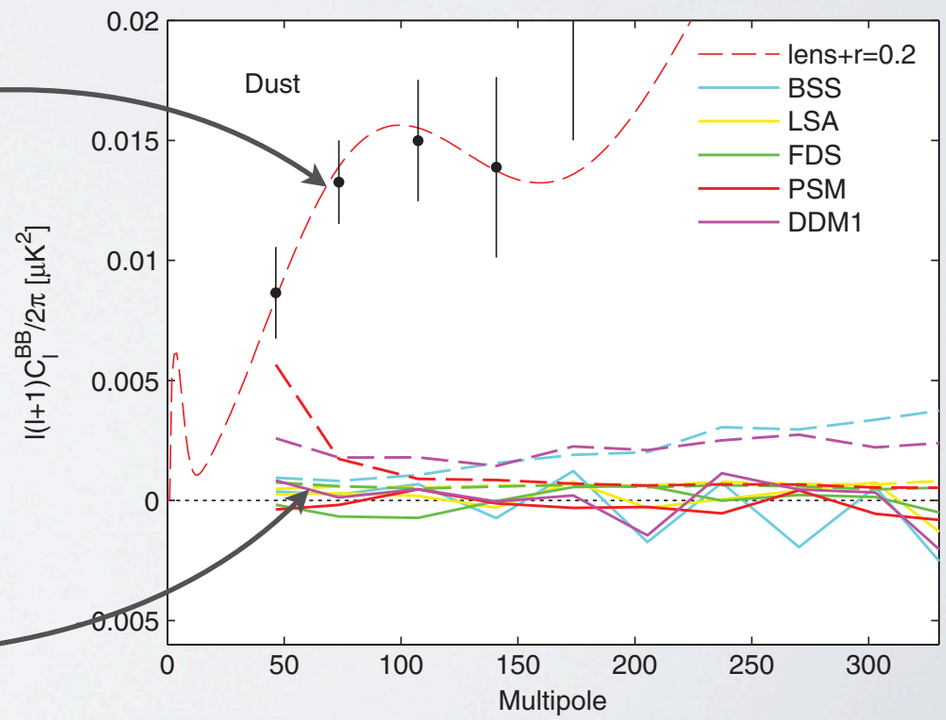
EXTRACTED SIGNAL



Detected a significant B-mode polarization

Signal predicted from an inflation model

Predictions for potential dust contributions



IMPLICATIONS

- Would be strong confirmation of inflationary prediction, with energy density near grand unification scale

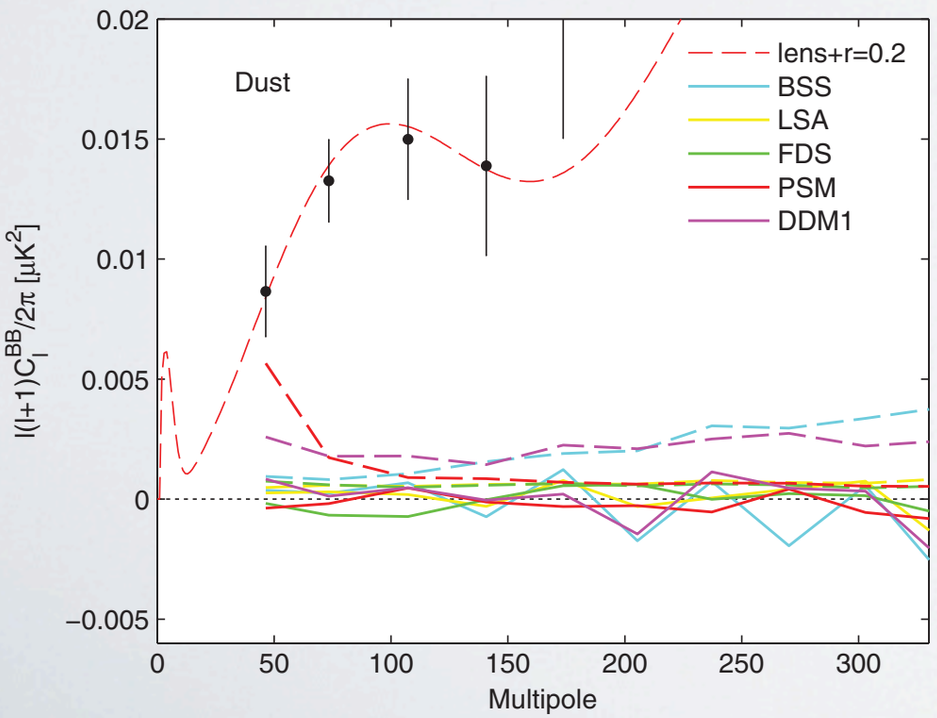
- Indirect evidence that gravity waves are quantized, similar to how light waves are quantized as photons

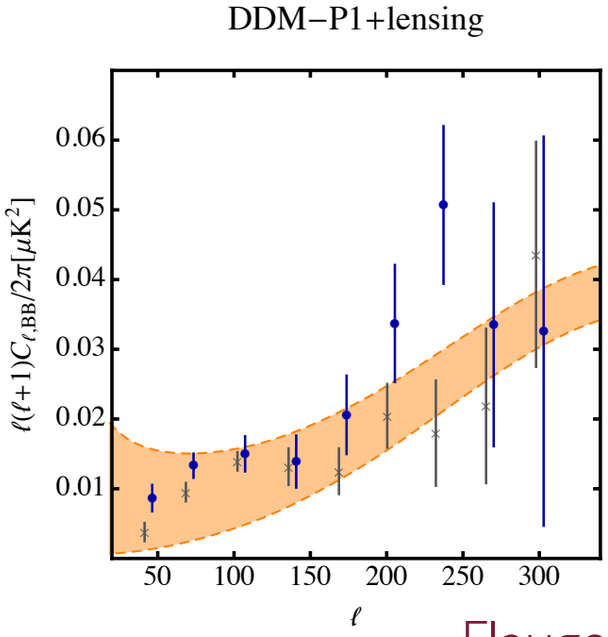
- Also has strong trickle down effects on many other aspects of particle physics and cosmology

FOREGROUNDS

Unfortunately, the signal may not be due to gravity waves
It could also come from microwave emission from
dust in our galaxy

This measurement is the first of its kind at this
sensitivity and the BICEP2 telescope does
not have the capability to distinguish these possibilities





Flauger, et.al.

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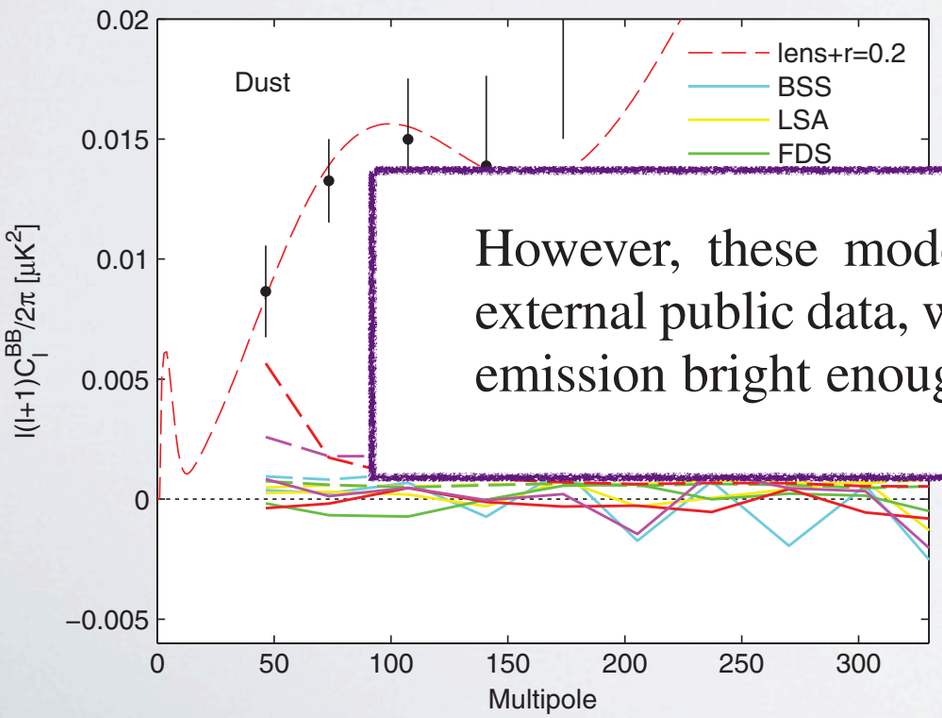
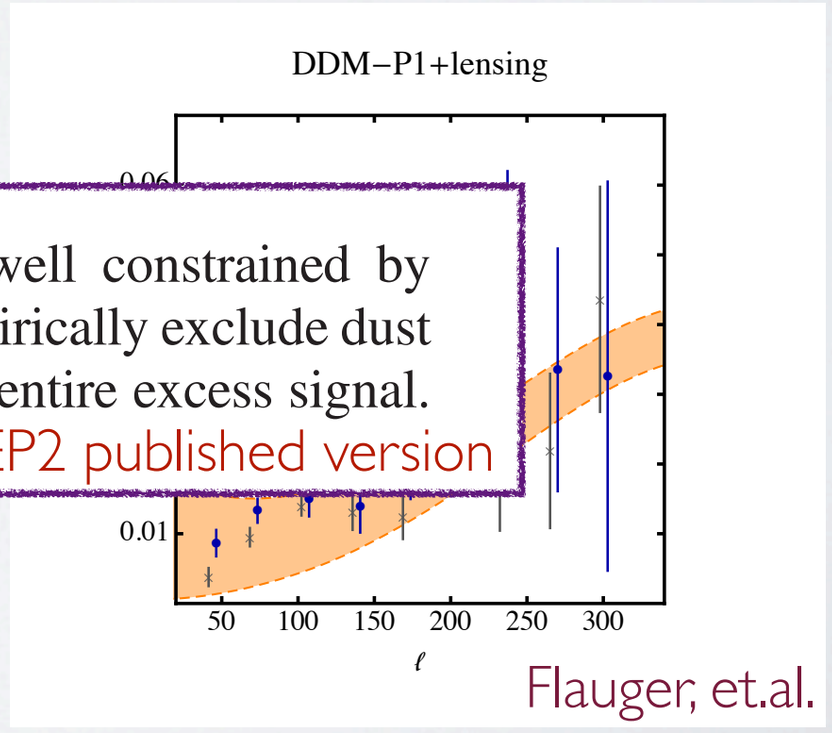


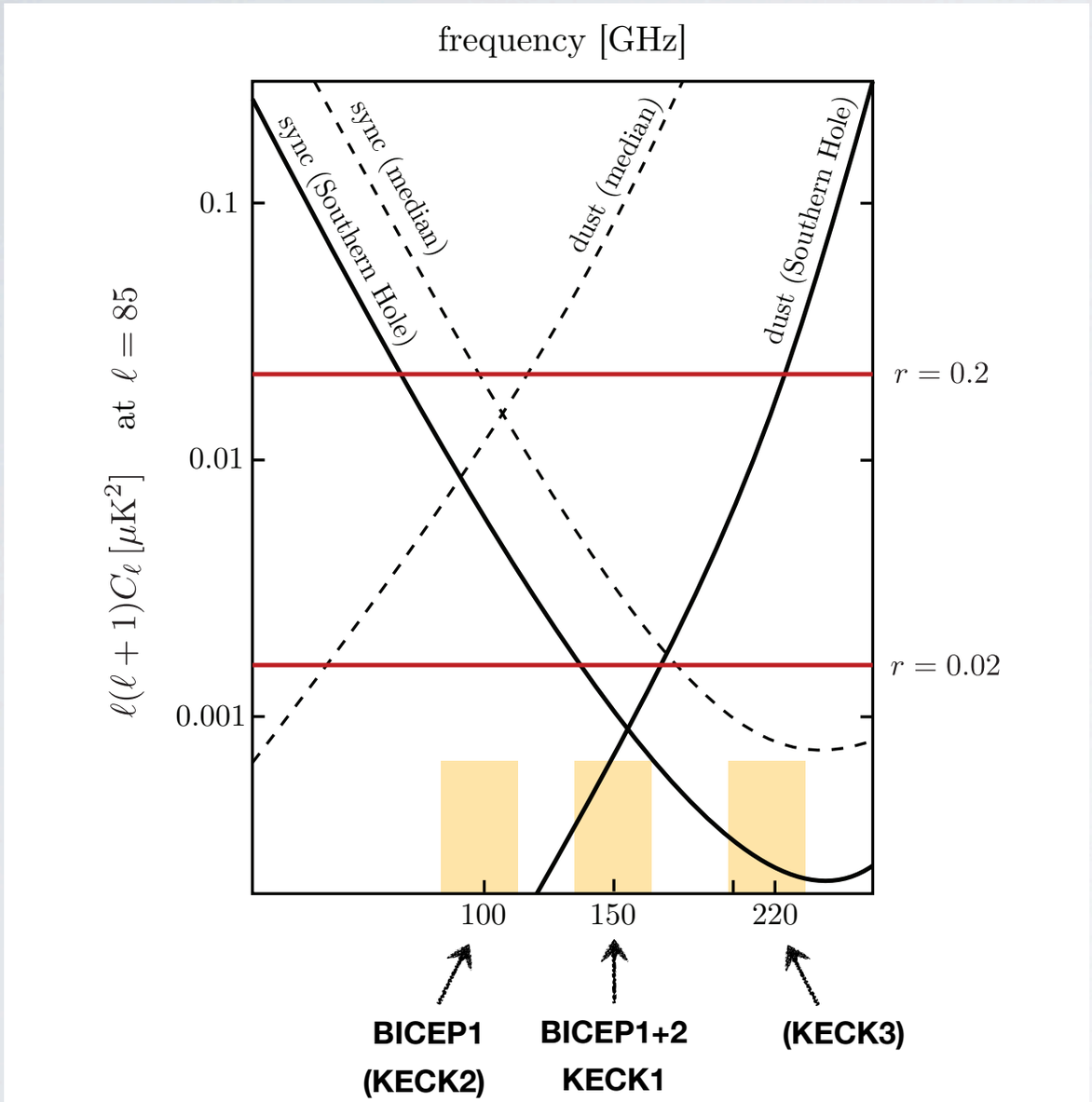


Flauger, et.al.

However, these models are not yet well constrained by external public data, which cannot empirically exclude dust emission bright enough to explain the entire excess signal.

BICEP2 published version

FUTURE RESOLUTION



Slide from D. Baumann

Dust component has a predicted scaling with frequency

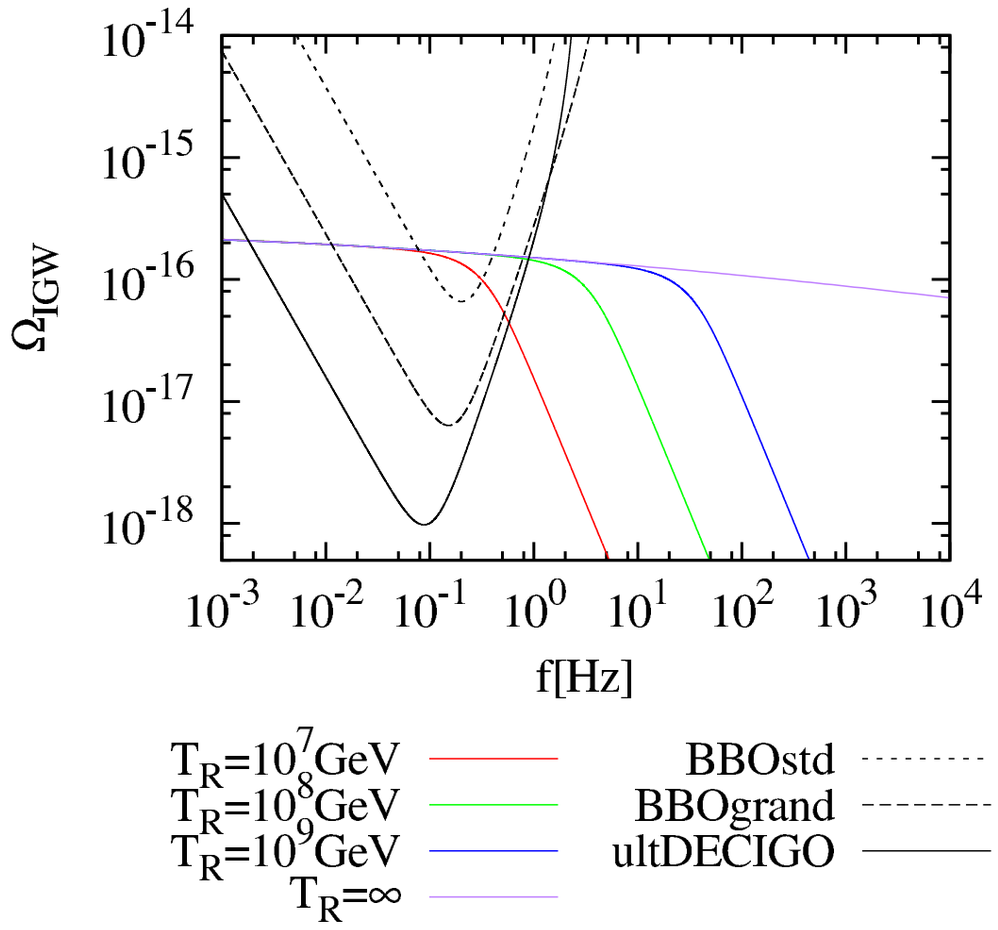
BICEP2 only had single frequency (150 Ghz)

Need other frequencies
Planck (4 bands)
Keck Array (100 Ghz)
to measure dust contribution

CONCLUSIONS

- Inflation is an intriguing idea motivated by our Universe
- Observation of gravitational waves effect on CMB polarization is inflation's smoking gun
- Is BICEP2's observations due to gravity waves or foregrounds? The correct interpretation is still unknown...
- If it is inflationary in origin, gravitational wave background could be detected at future space based GW detectors (BBO, DECIGO)

FUTURE



Jinno et.al.