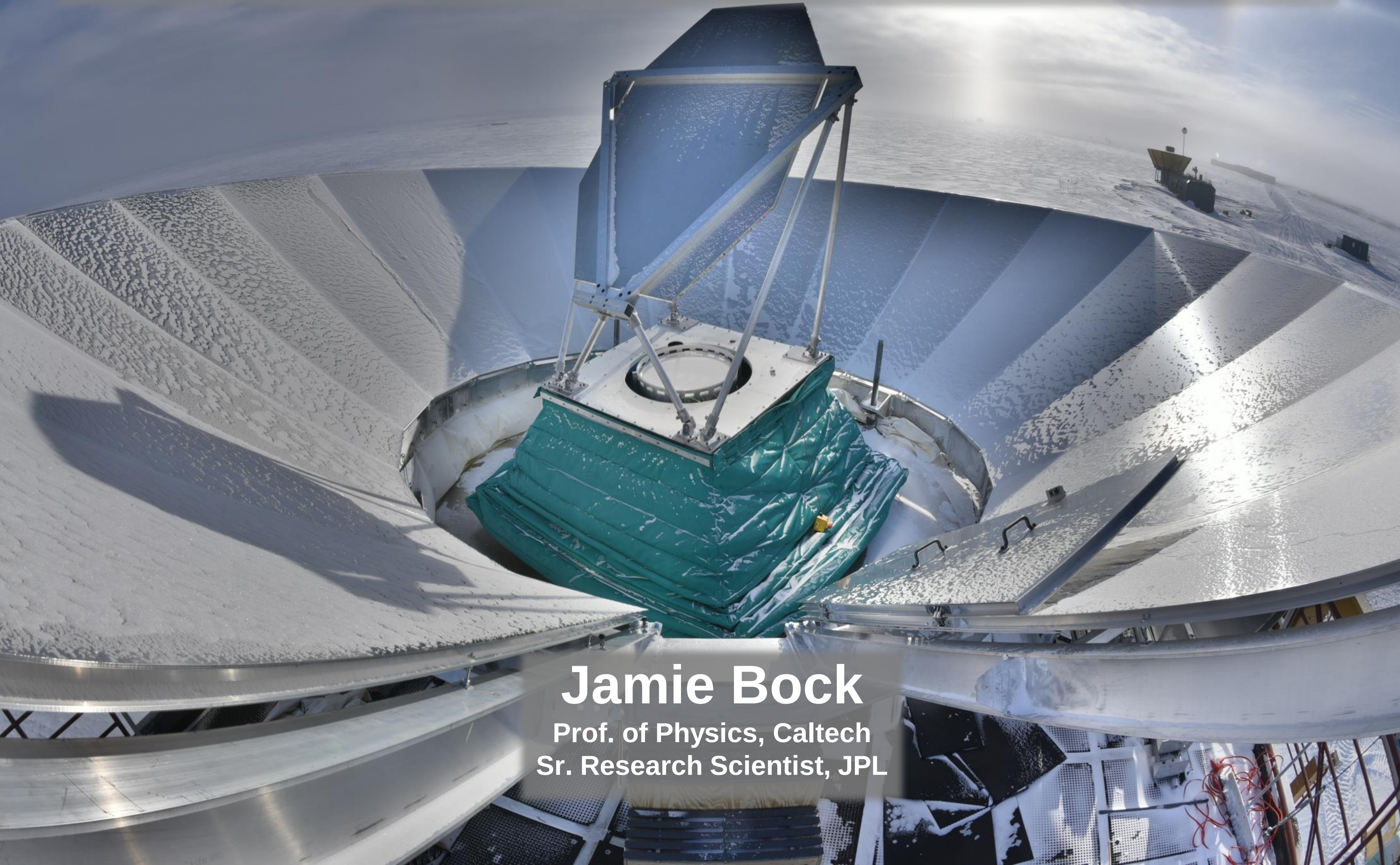
Searching for a Cosmological Background of Gravitational Waves



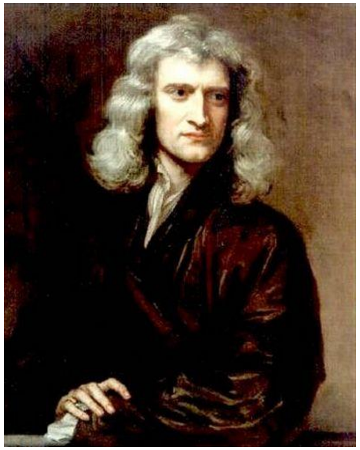
Jamie Bock

Prof. of Physics, Caltech

Sr. Research Scientist, JPL

Using Gravitation to Explain the Universe -- and Conversely

Evolution of a Homogenous & Isotropic Universe

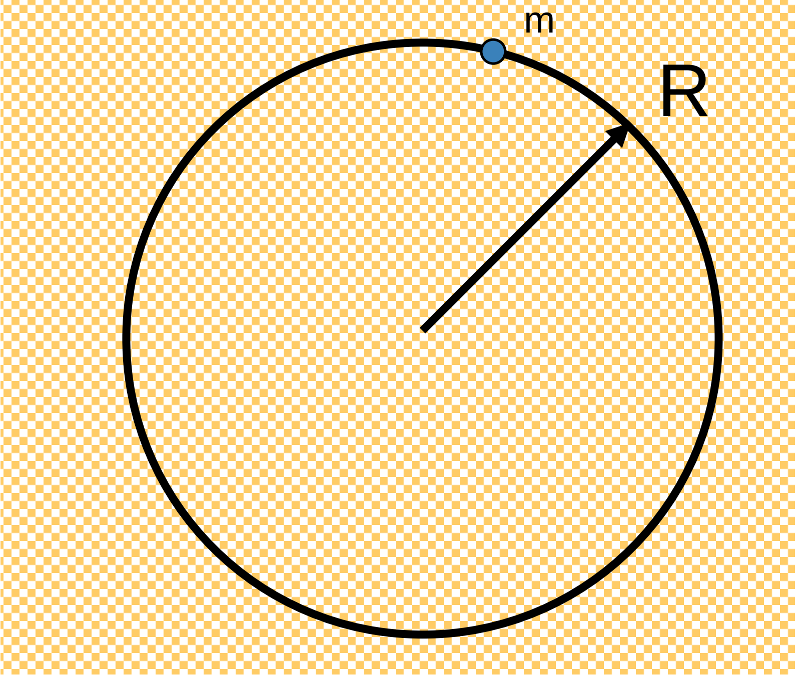


Isaac Newton

Mass*acceleration = Force

$m\, d^2R/dt^2 = -GmM(<R)/R^2$

$M(<R) = \rho\, 4/3\pi R^3 = \text{constant}$



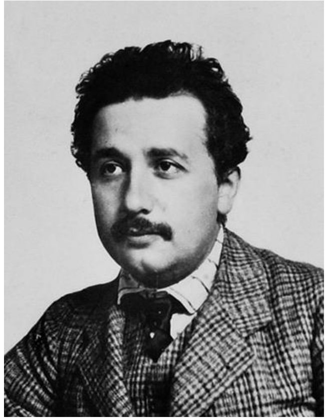
A Uniform Bit of the Universe

$d^2R/Rdt^2 = -4\pi G\rho$

$d\rho/dt = -3\, dR/Rdt\, \rho$

Equations of Motion for a Homogenous Universe

Evolution of a Homogenous & Isotropic Universe



Albert Einstein

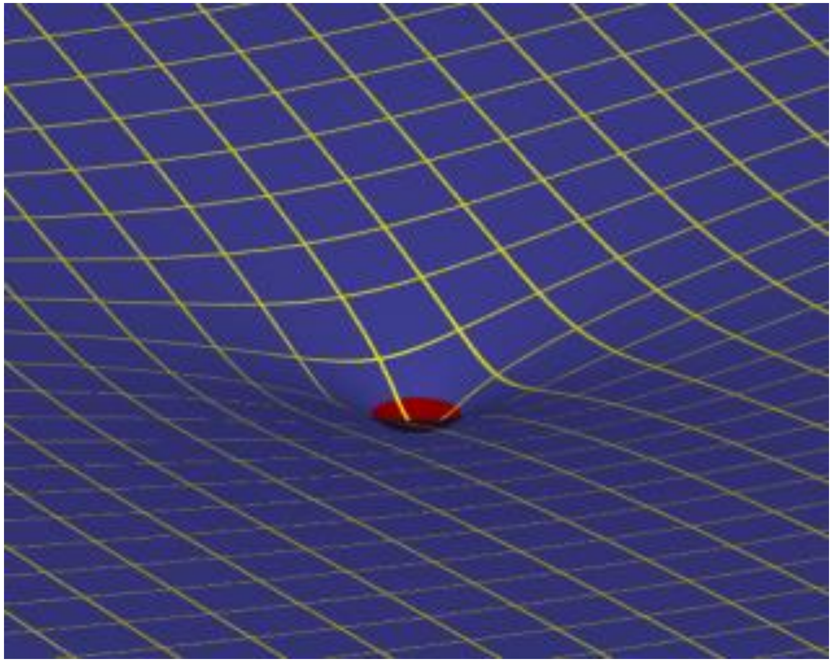
Bonus constant! Should it be 0?

Pressure is a kind of energy

$$d^2R/Rdt^2 = -4\pi G\,(\rho + 3p) + \Lambda/3$$

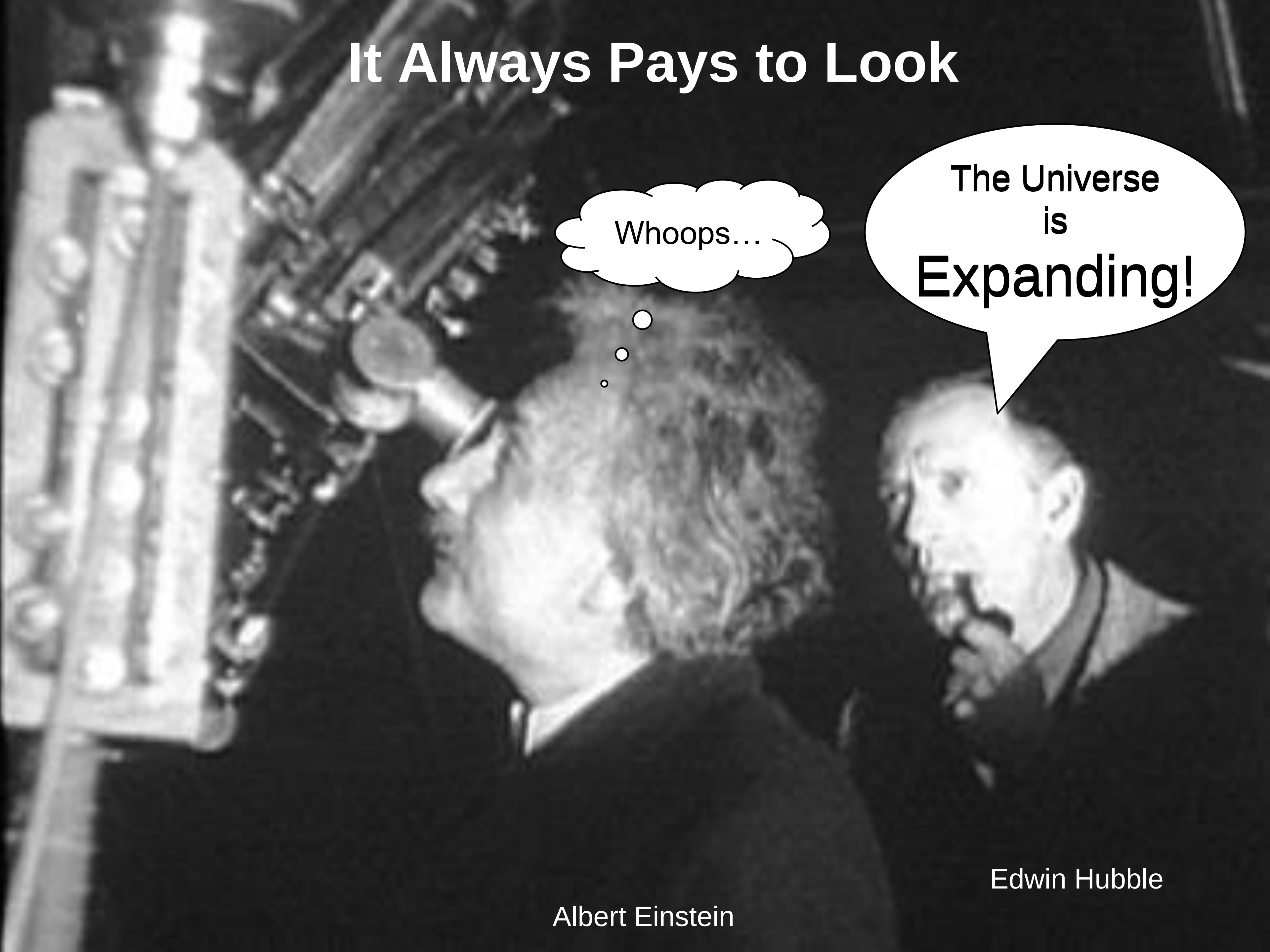
$$d\rho/dt = -3\, dR/Rdt\,(\rho + p)$$

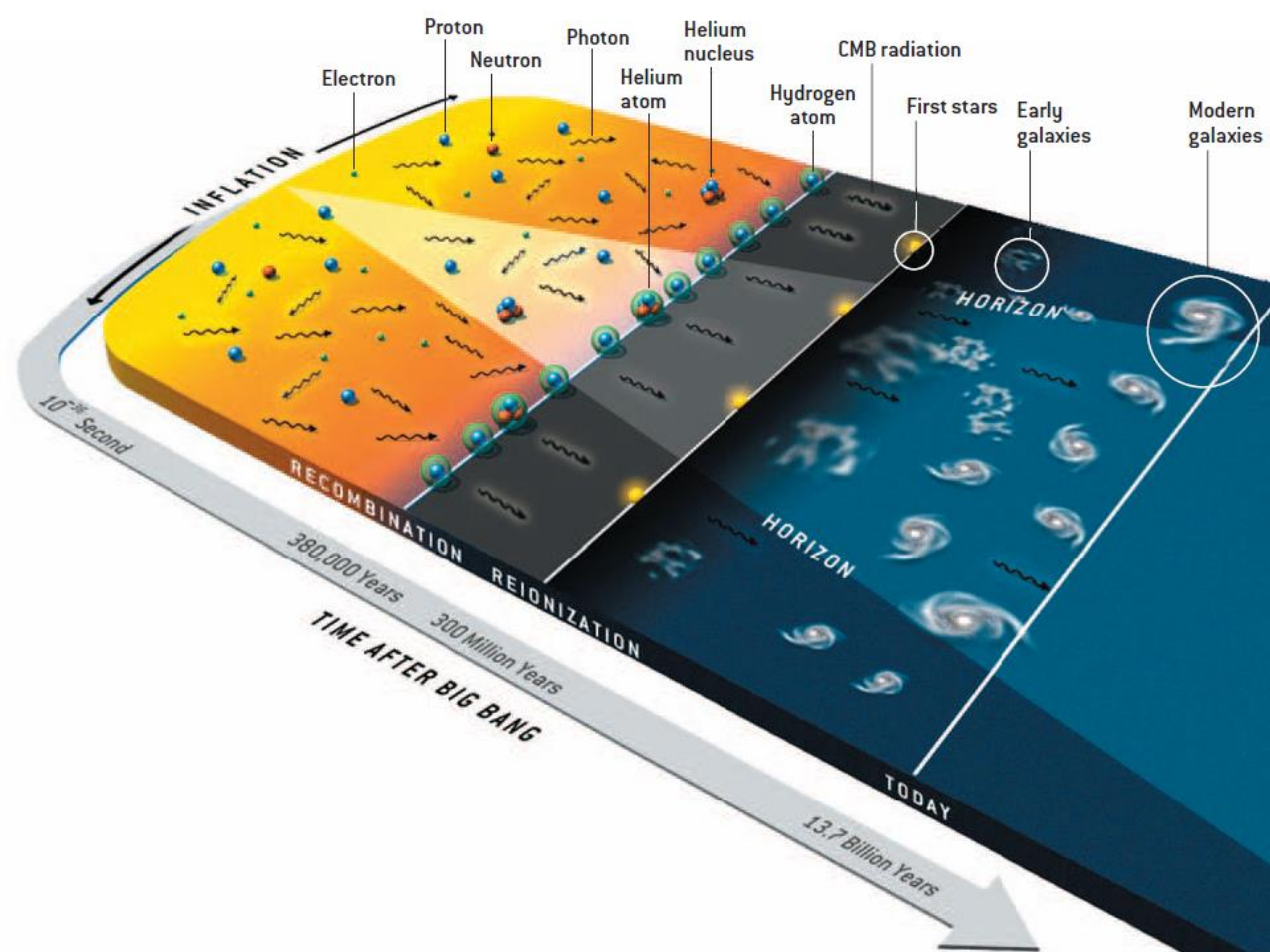
Equations of Motion for a Homogenous Universe



Matter-Energy Bends Space-Time

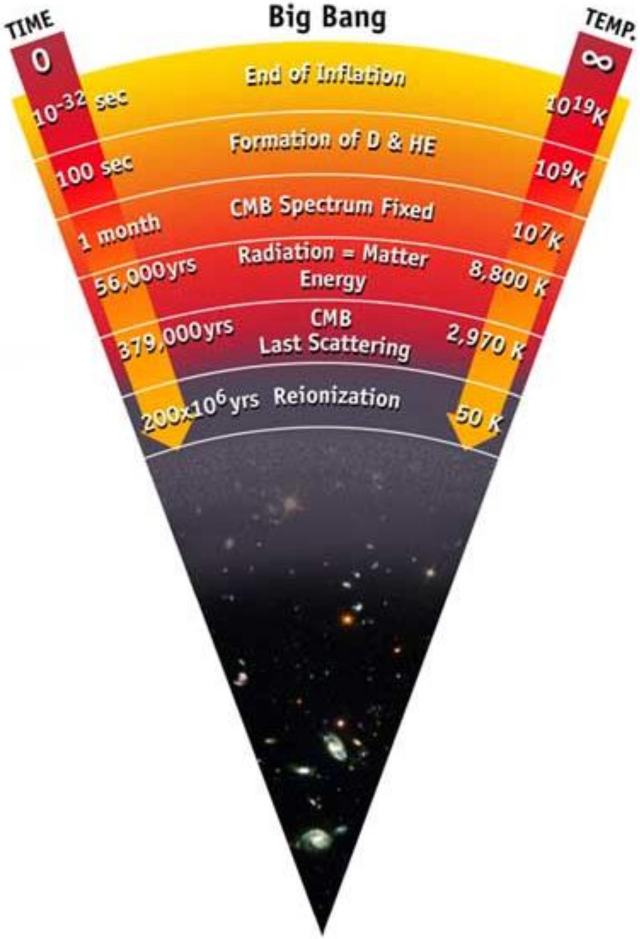
It Always Pays to Look





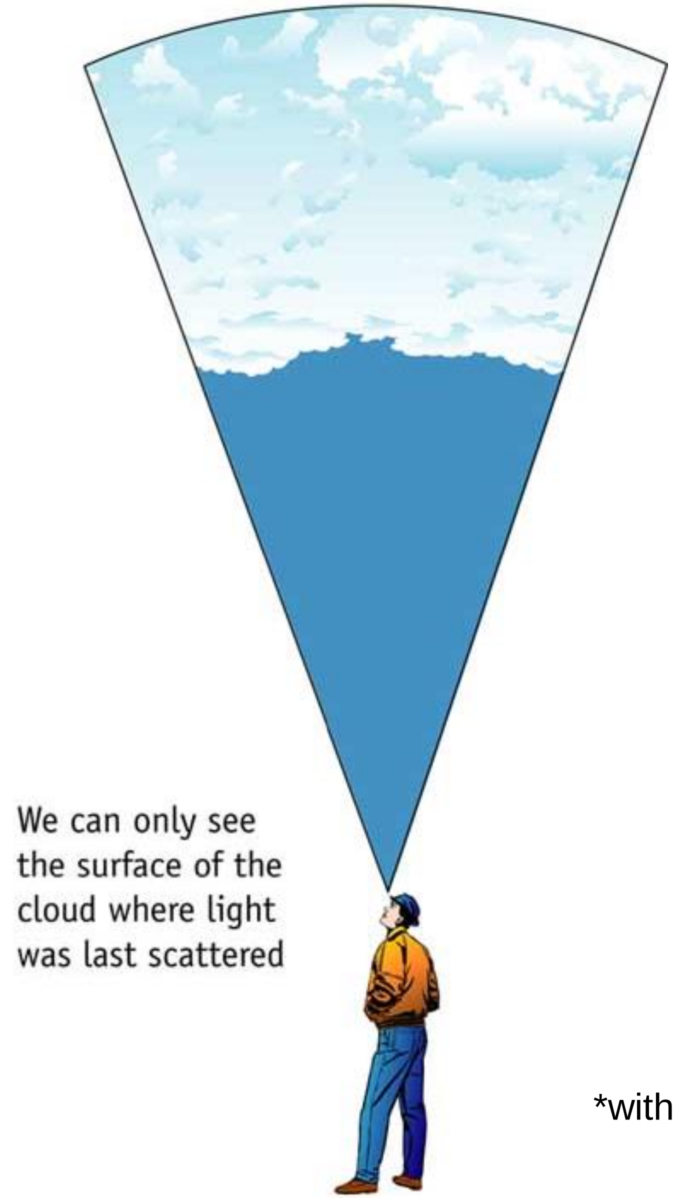
Proton
Neutron
Photon
Helium
nucleus
CMB radiation
Electron
Helium
atom
Hydrogen
atom
First stars
Early
galaxies
Modern
galaxies
INFLATION
HORIZON
HORIZON
RECOMBINATION
REIONIZATION
TODAY
10^{-36} Second
380,000 Years
300 Million Years
13.7 Billion Years
TIME AFTER BIG BANG

The CMB is the Furthest Back We Can See*



PRESENT
13.7 Billion Years after the Big Bang

The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



*with photons

Modern cosmology c. 1980

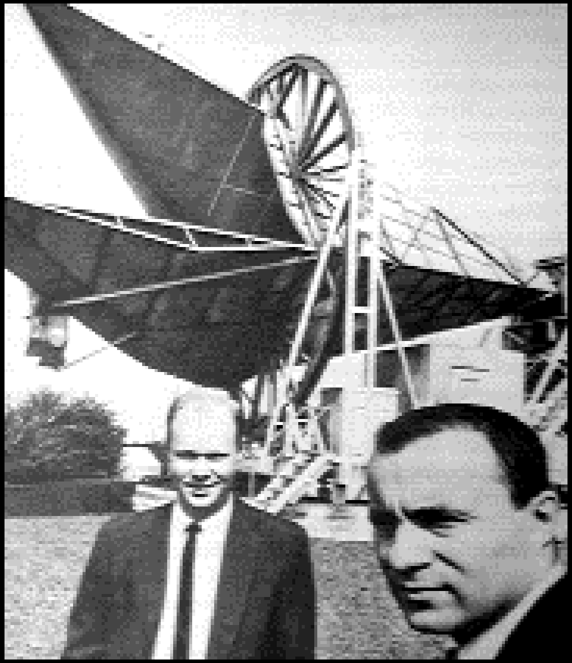
Edwin Hubble

1) The universe is expanding.

(Hubble, 1920s)

2) It was once hot and dense, like the inside of the Sun.

(Alpher, Gamow, Herman, 1940s)

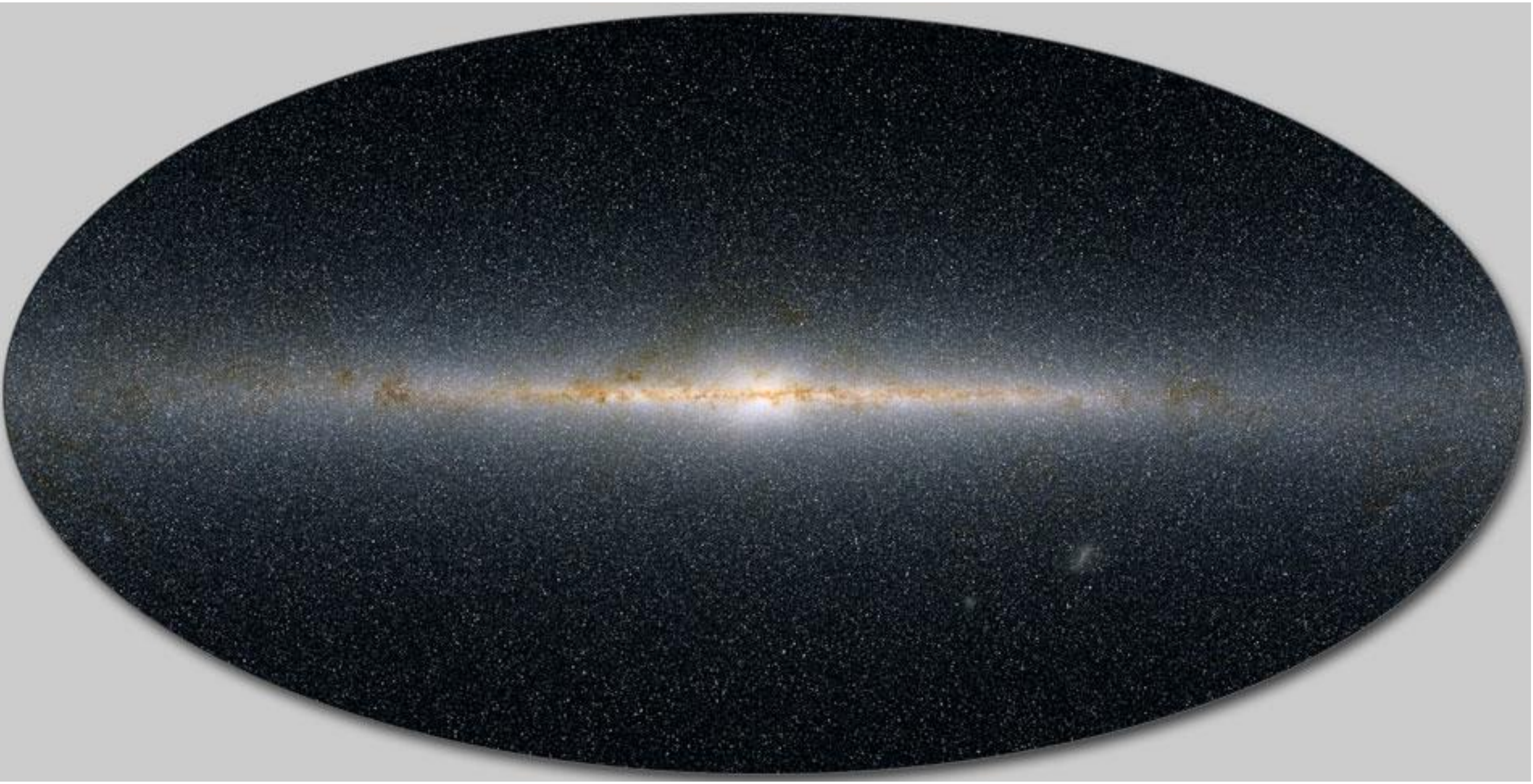


Bob Wilson & Arno Penzias
1978 Nobel Prize

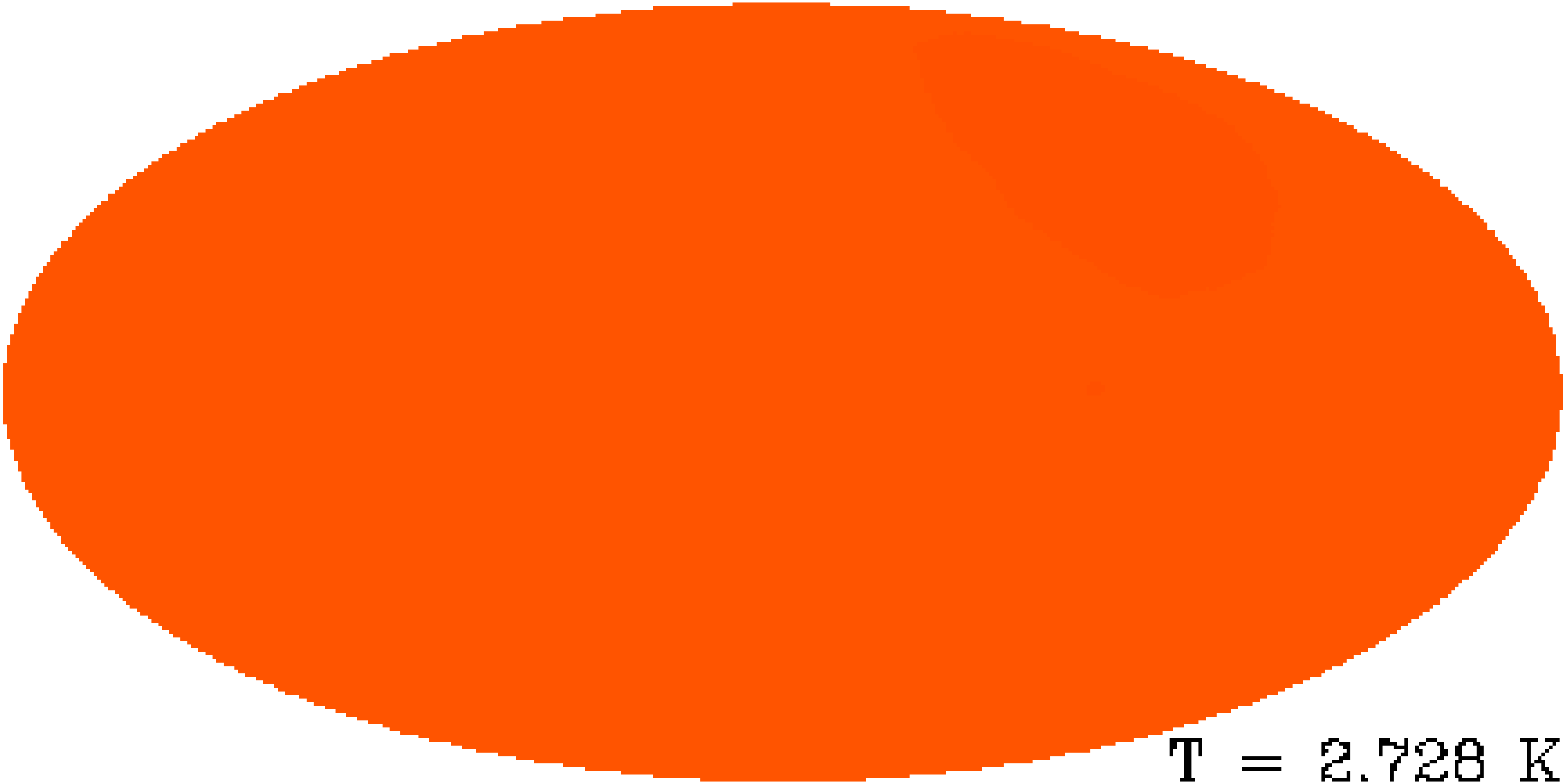
3) You can still see the glow!
The *Cosmic Microwave Background*
(Penzias & Wilson, 1964)

⇒ acceptance of the "HOT BIG BANG"

The Sky at ~Optical Wavelengths

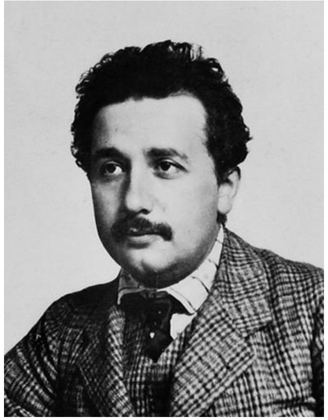


The Sky at Millimeter Wavelengths



Every Direction is the SAME Temperature to ~10 ppm!
How Can This BE? A Deeply Troubling Question for Cosmologists in 1980…

Evolution of a Homogenous & Isotropic Universe



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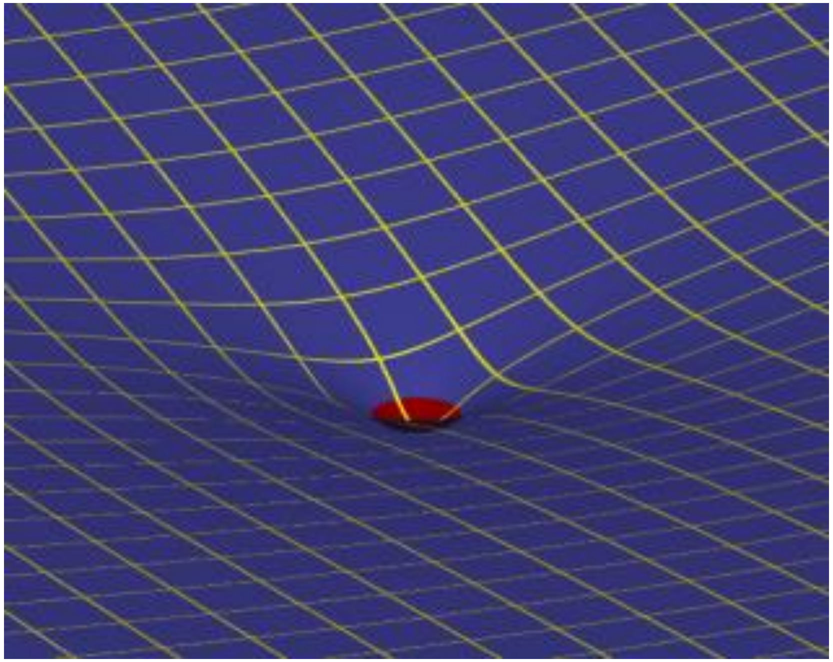
Equations of Motion for a Homogenous Universe



Matter-Energy Bends Space-Time

$\Lambda \neq 0$?

$R = R_0 \exp[(\Lambda/3)^{1/2}\,t]$

Exponential Expansion!!

Negative pressure? $p=-\rho$

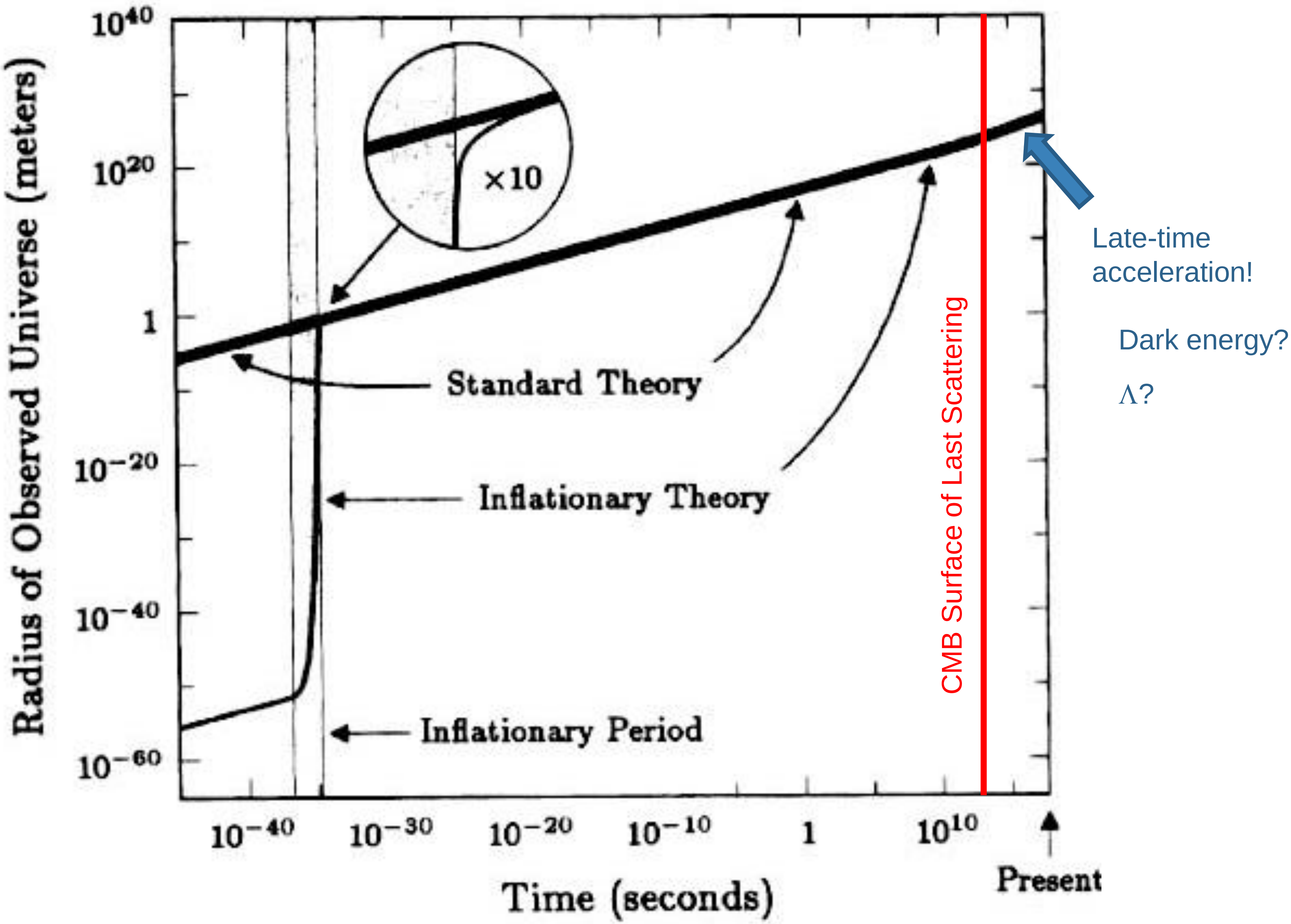
$d\rho/dt = 0$, ρ = constant

$R = R_0 \exp[(8\pi G\rho)^{1/2}\,t]$

Exponential Expansion!!

OK, so you need a strange form of matter-energy to get negative pressure…

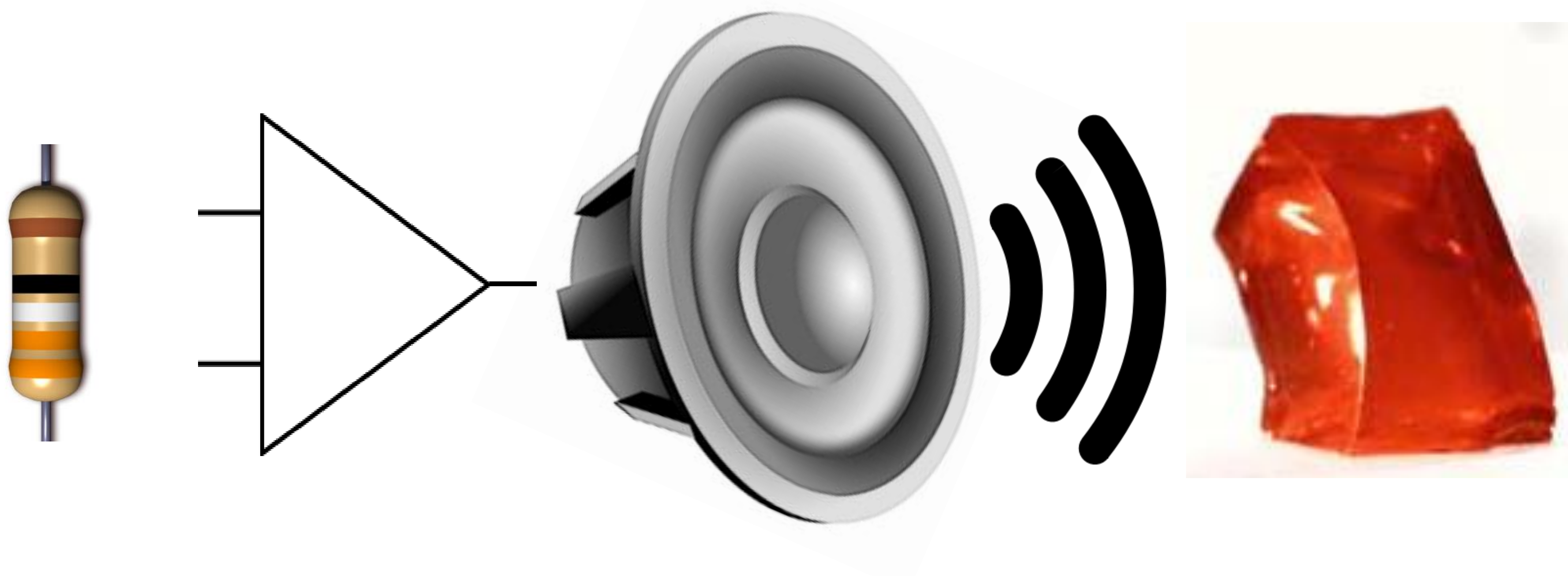
The Remarkable Theory of Inflation



A. Guth

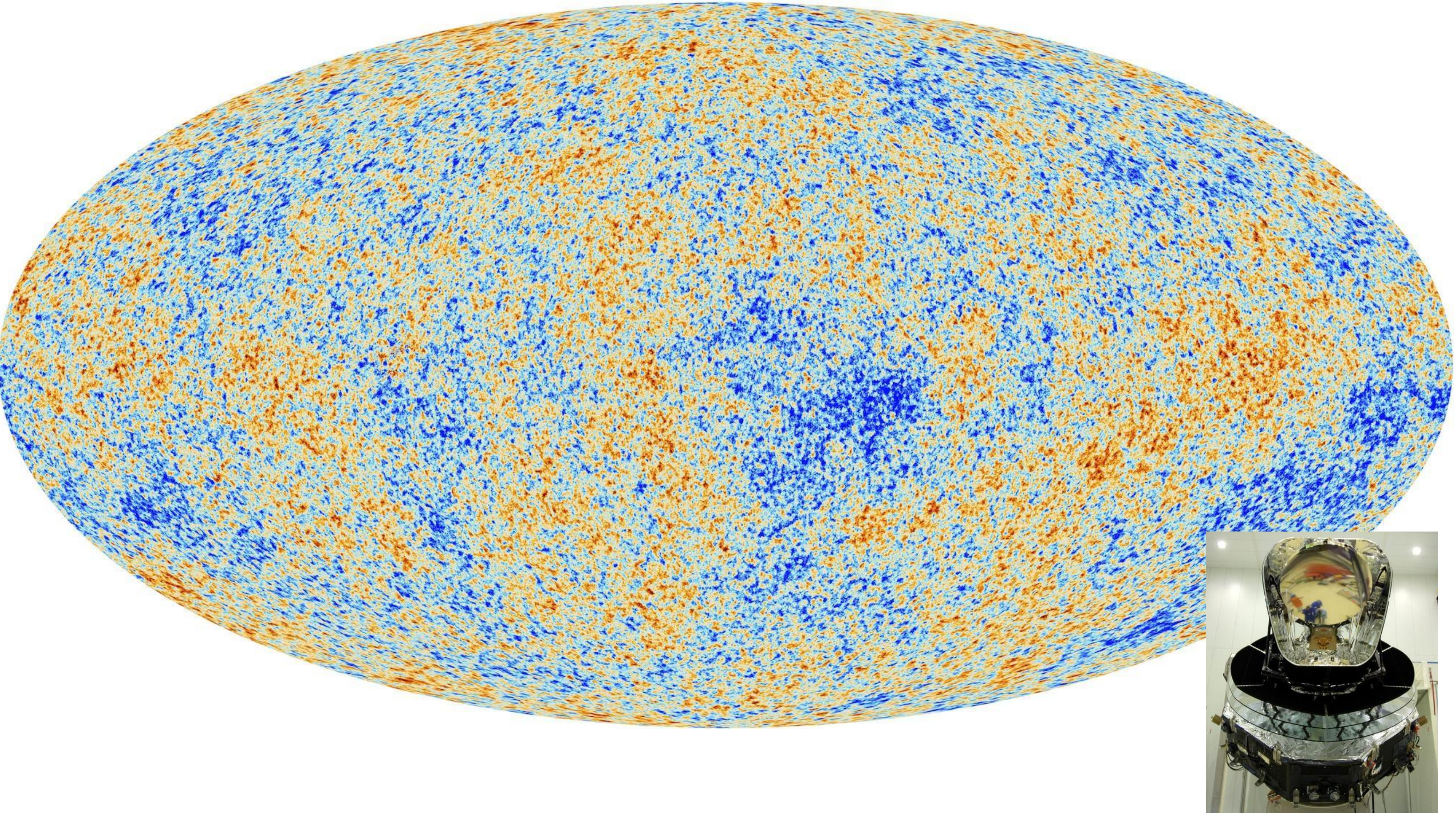
Kitchen Cosmology

resistor | amplifier | speaker | jello



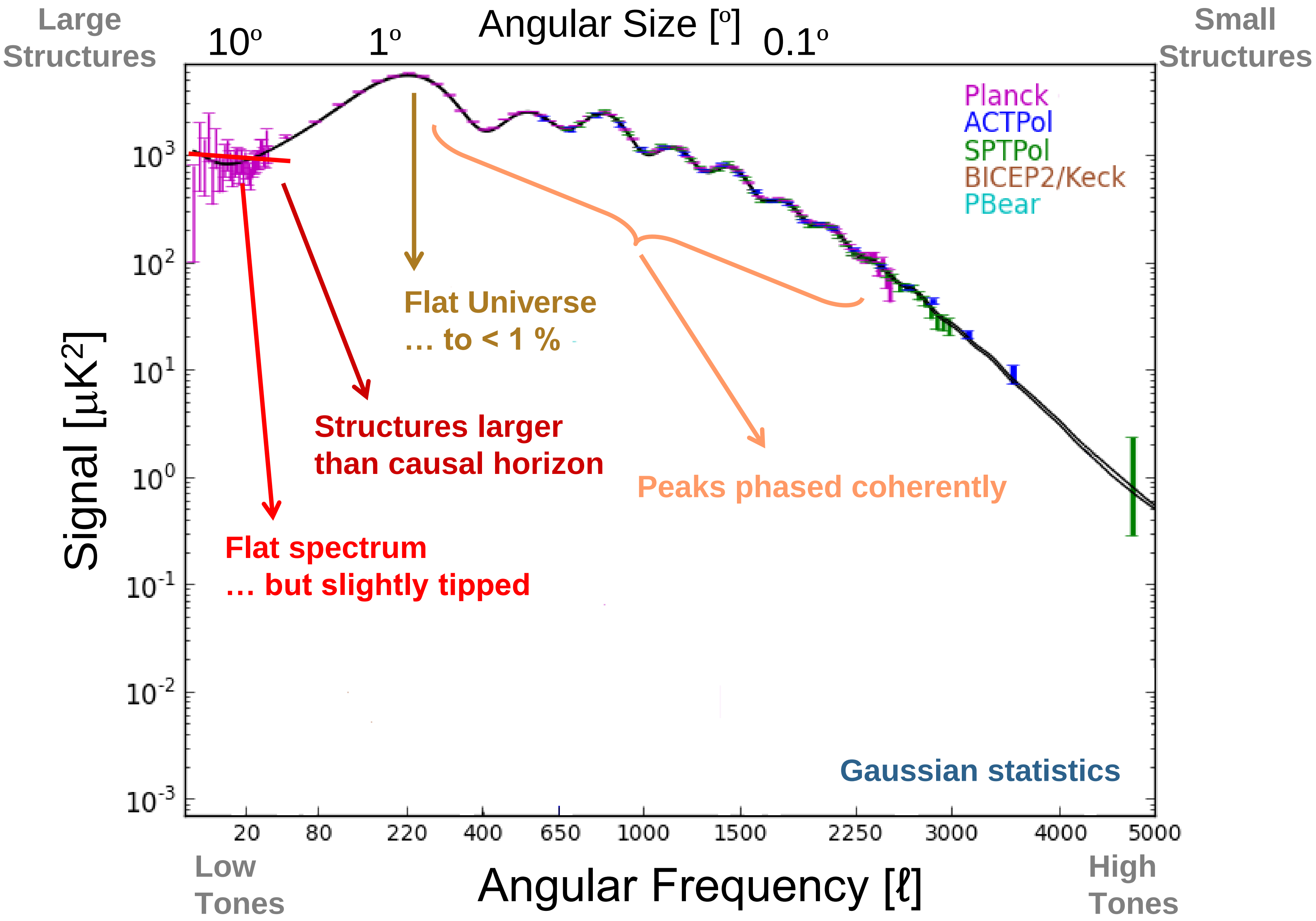
quantum fluctuations | inflation | density waves | primordial plasma

Cosmic Microwave Background



The Planck Satellite

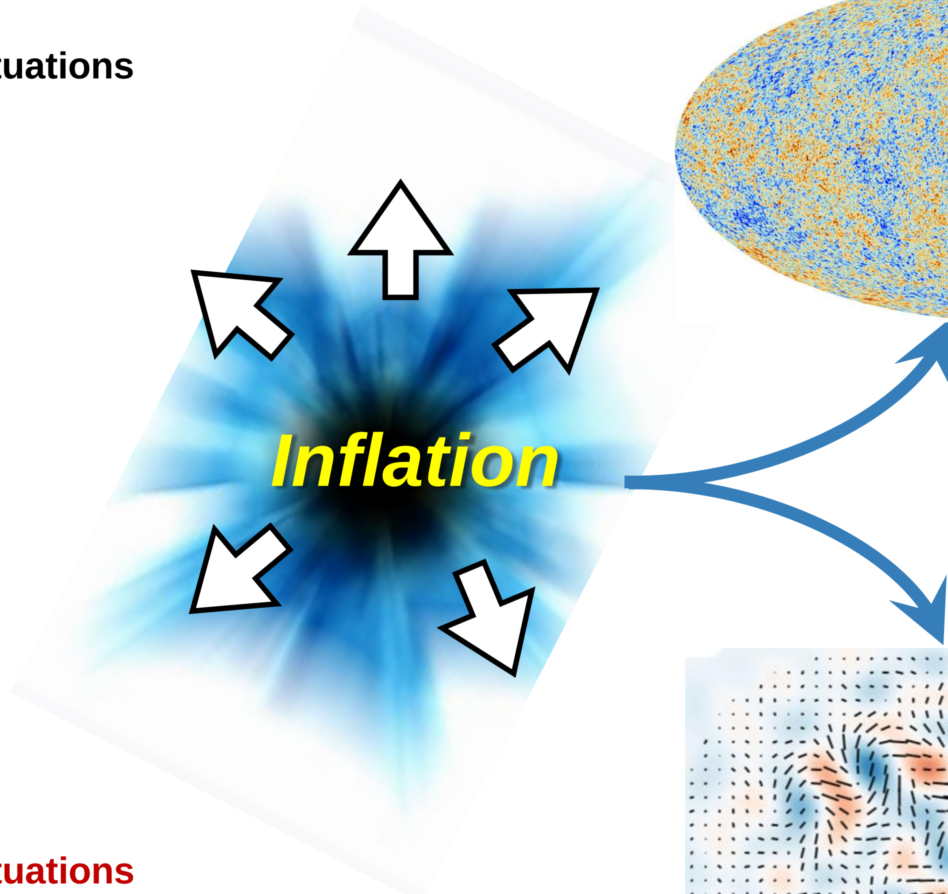
CMB Temperature Power Spectrum

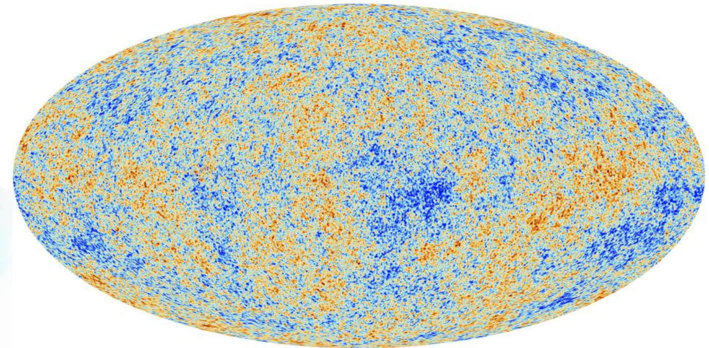


How Can We Test Inflation Further?

Sub-atomic vacuum fluctuations of “inflaton”

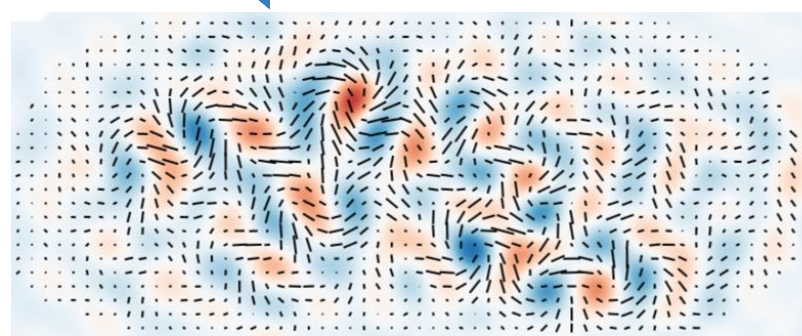
Sub-atomic vacuum fluctuations of *graviton* (quanta of gravity)





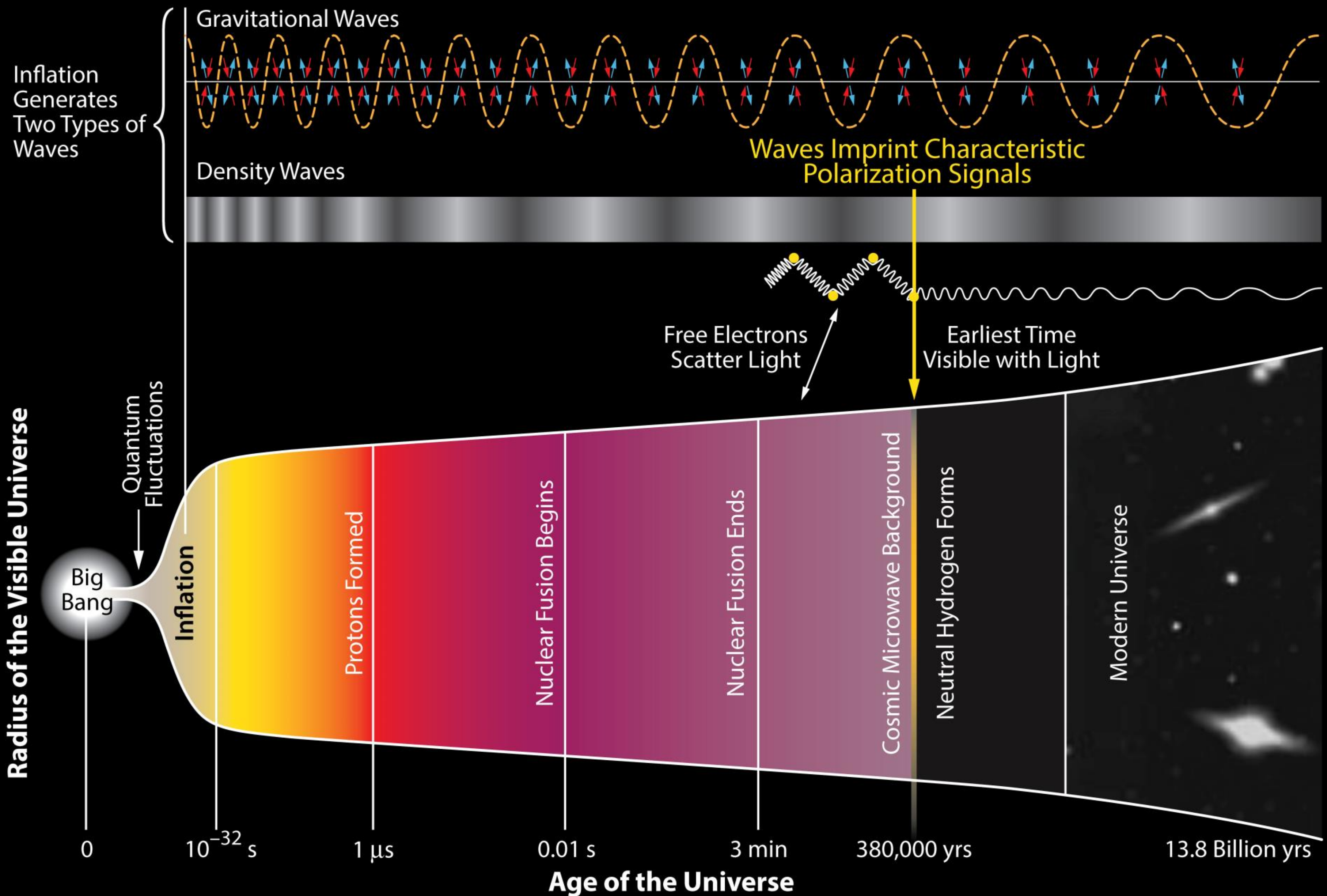
Density perturbations *studied* by Planck, WMAP, SPT, etc.

Gravitational waves?
→ telltale polarization pattern



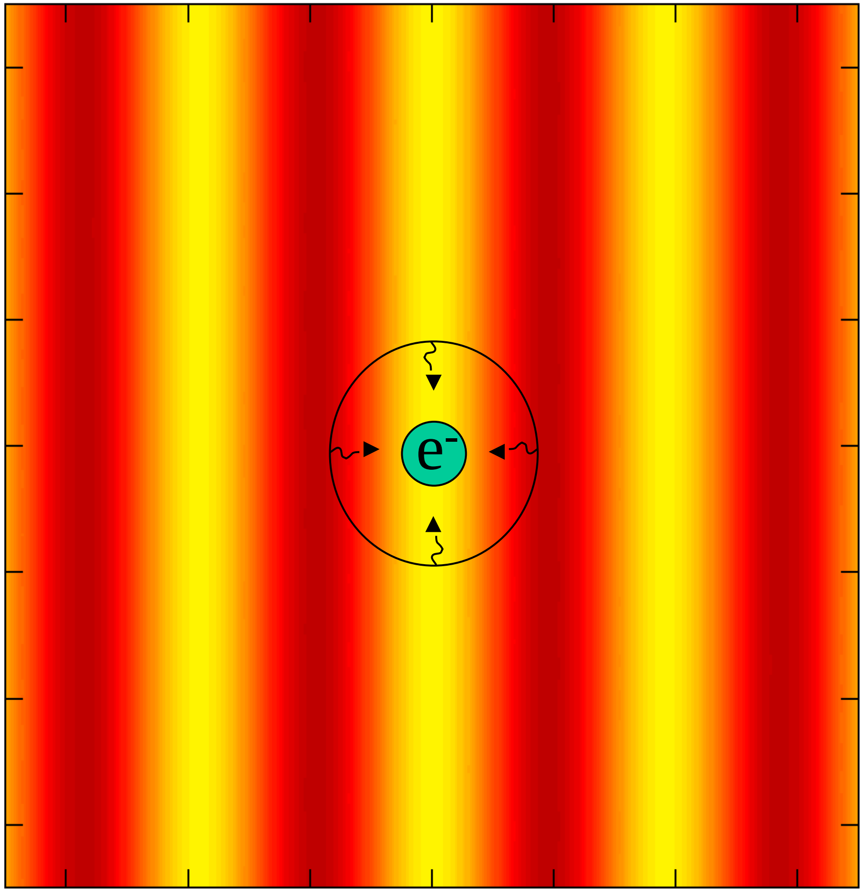
- **Inflationary gravitational waves:** CMB “B-mode” polarization
- **Spectral index of fluctuations:** CMB and large-scale structure of galaxies
- **Non-Gaussianity:** Sensitive to Inflaton field, large-scale structure (SPHEREx)

History of the Universe

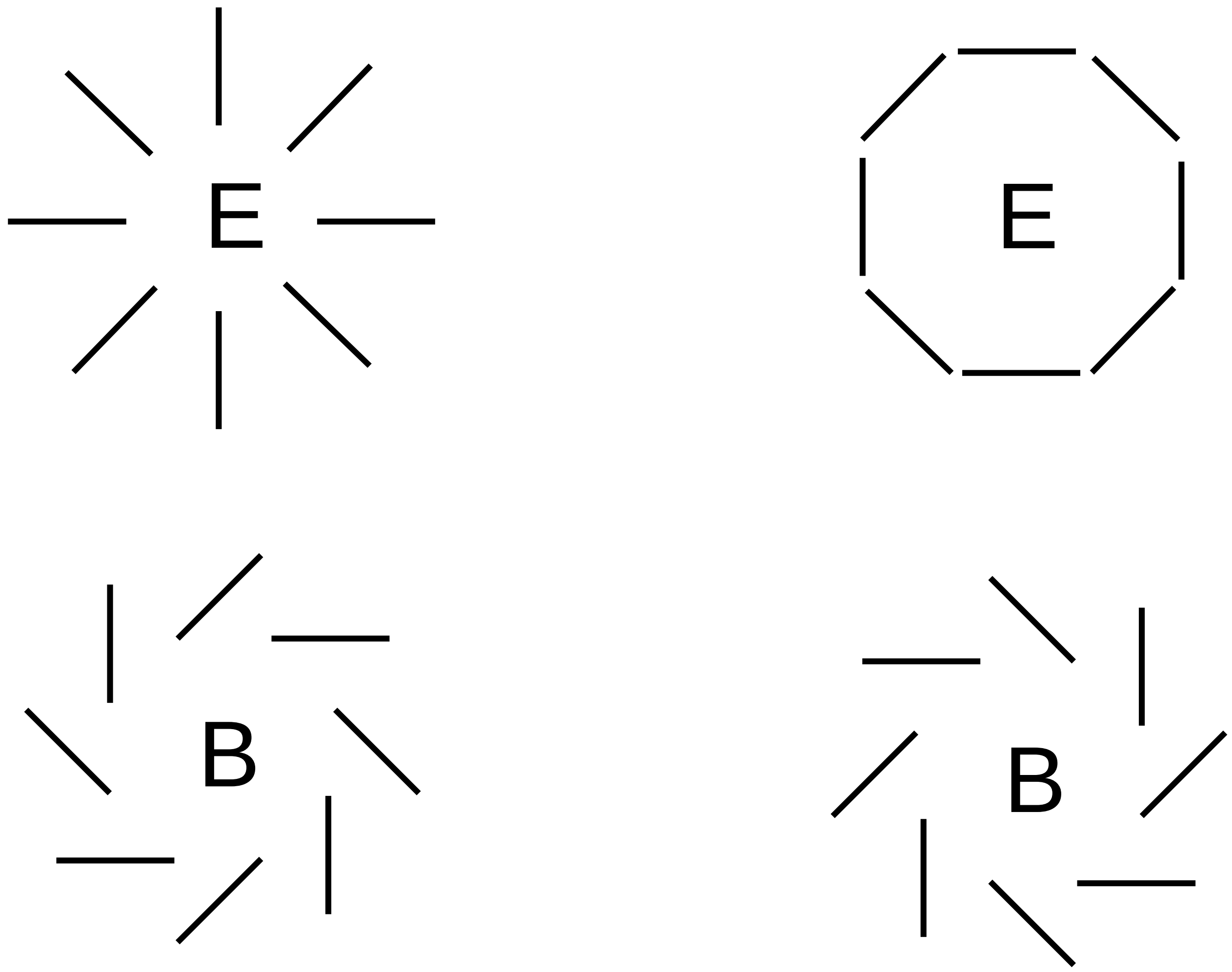


CMB polarization:
scattering from sound waves

what about graviational waves?

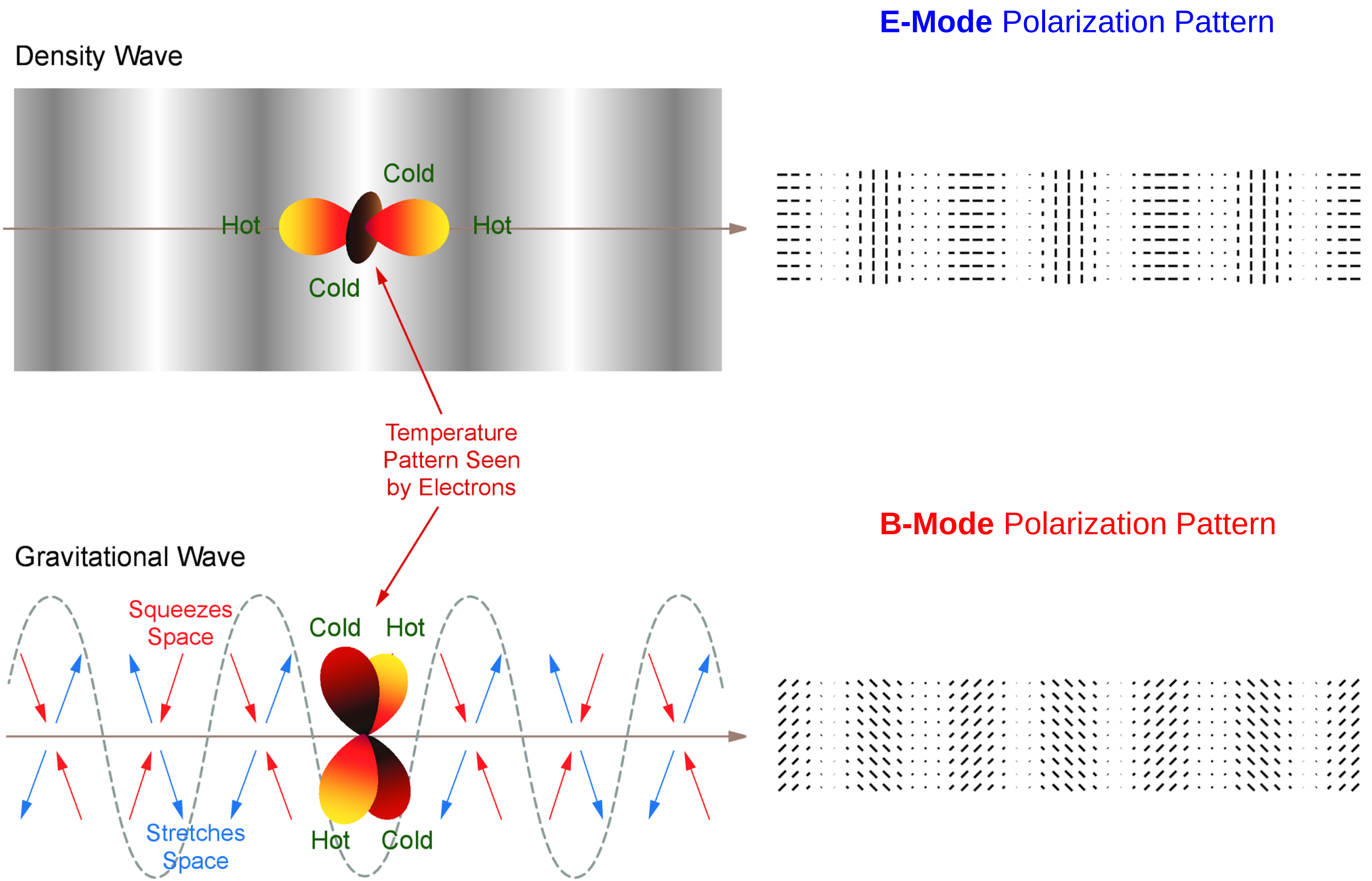


The Signature of Gravitational Waves

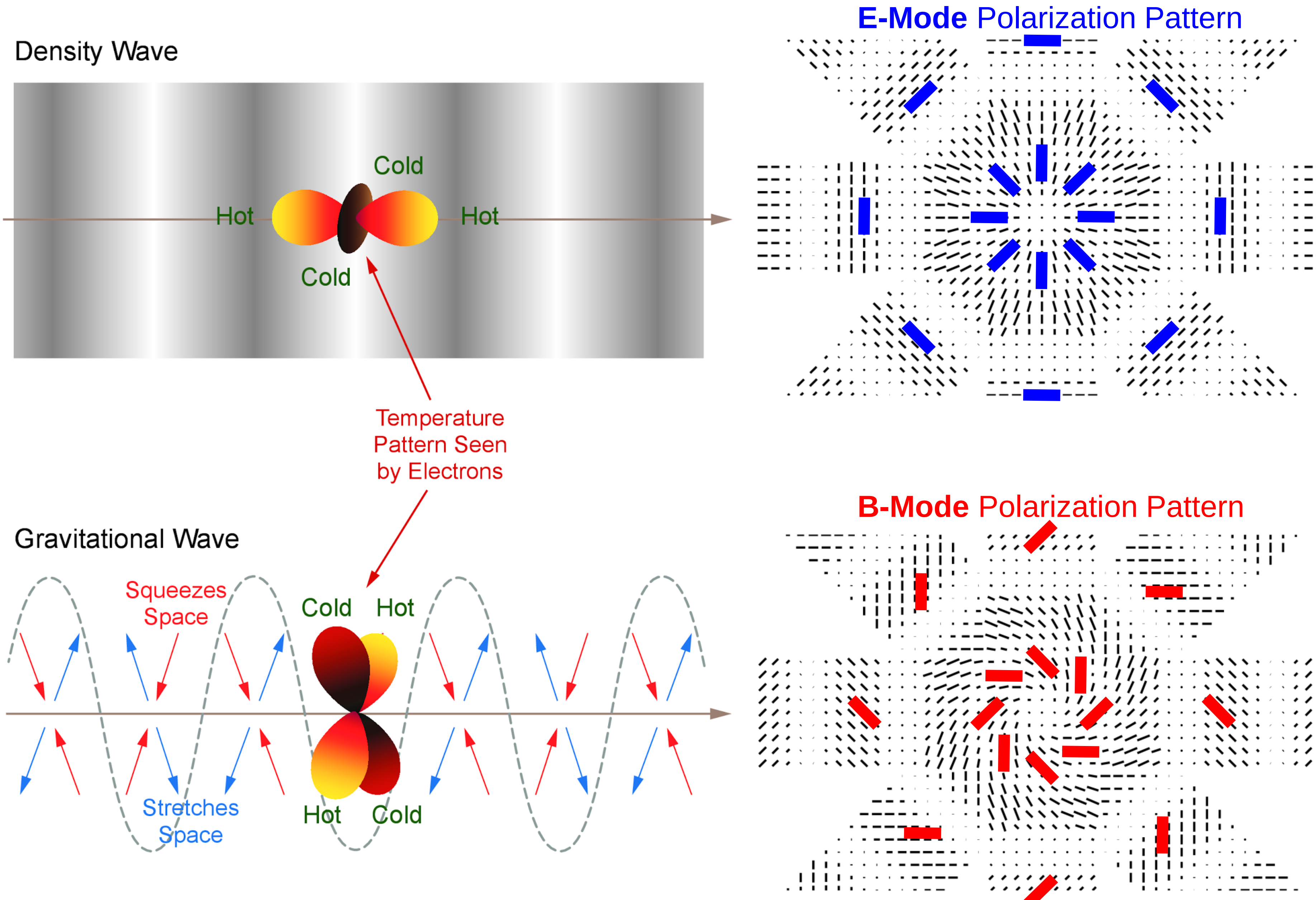


Density fluctuations *cannot* make B-mode patterns

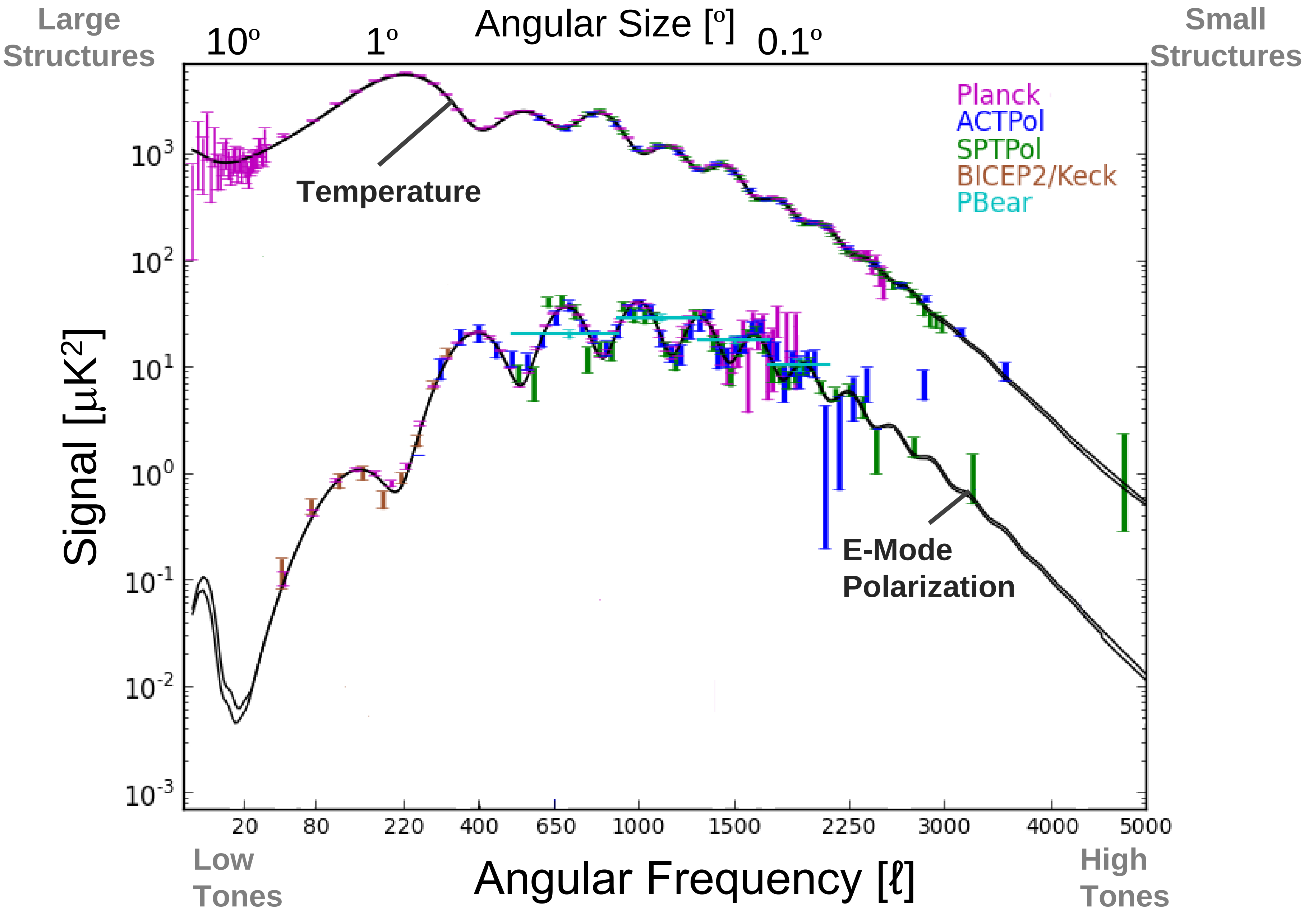
CMB Polarization



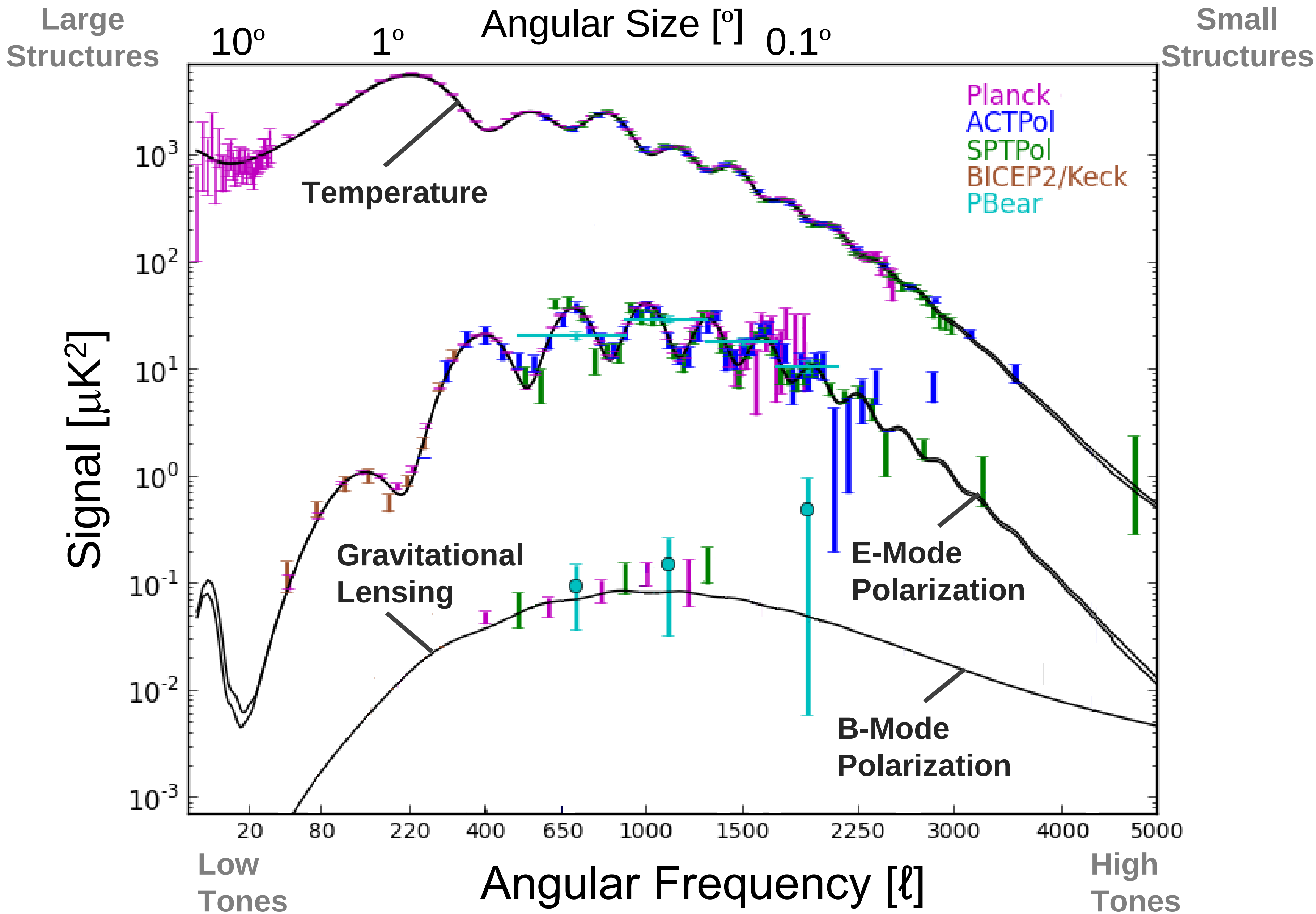
CMB Polarization



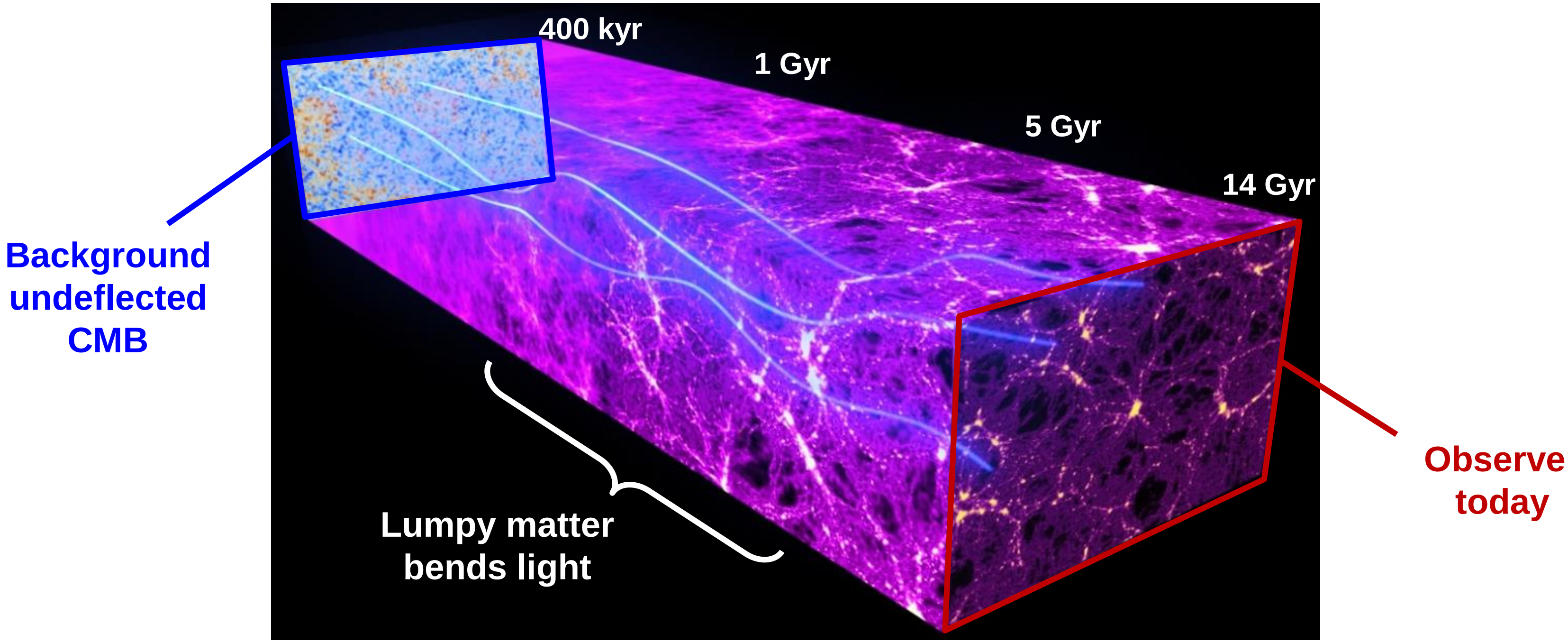
CMB Power Spectra



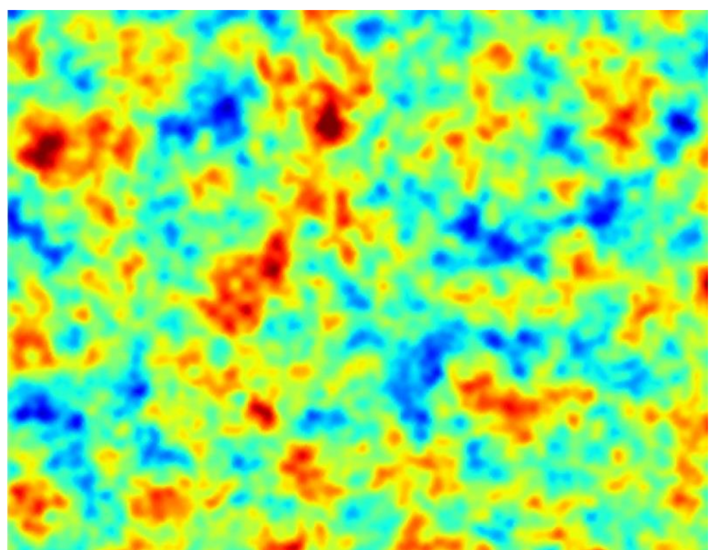
CMB Power Spectra



Gravitational Lensing of the CMB

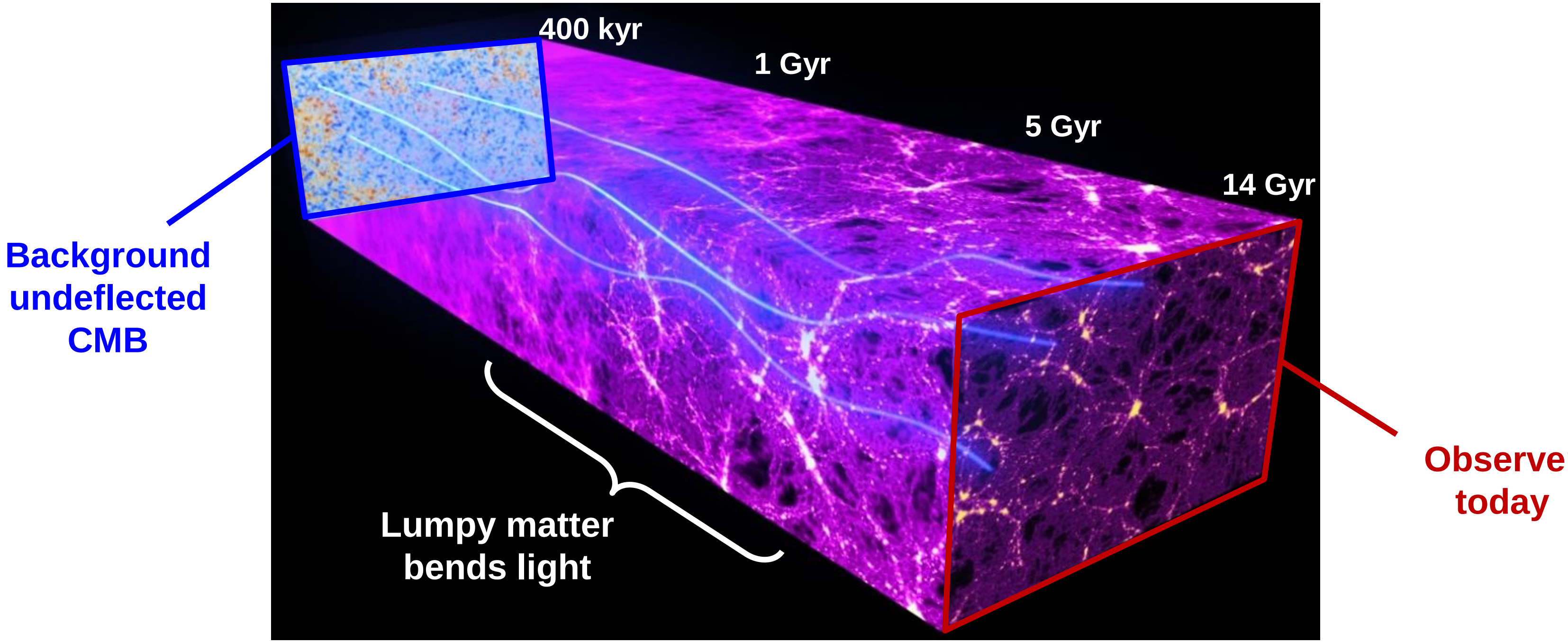


CMB without lensing

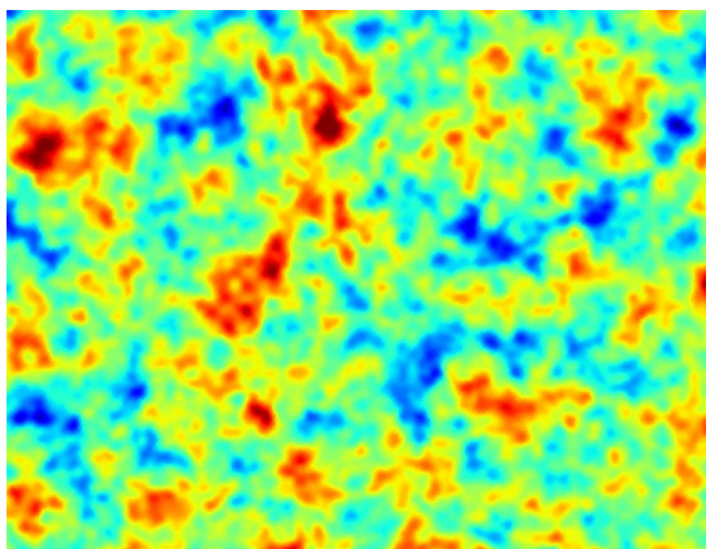


Observed CMB: slightly deflected by gravitational lensing

Gravitational Lensing of the CMB



CMB with lensing



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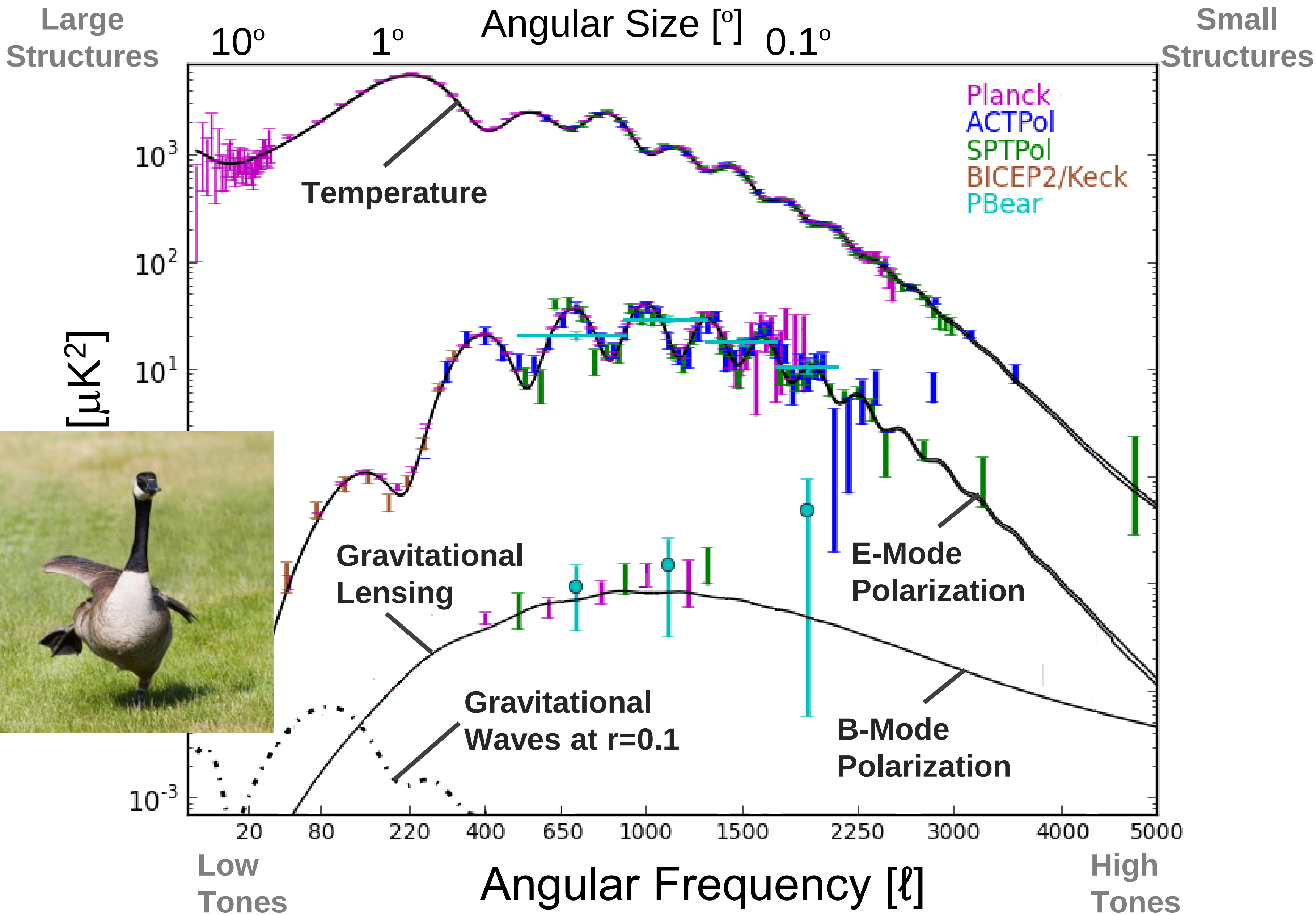
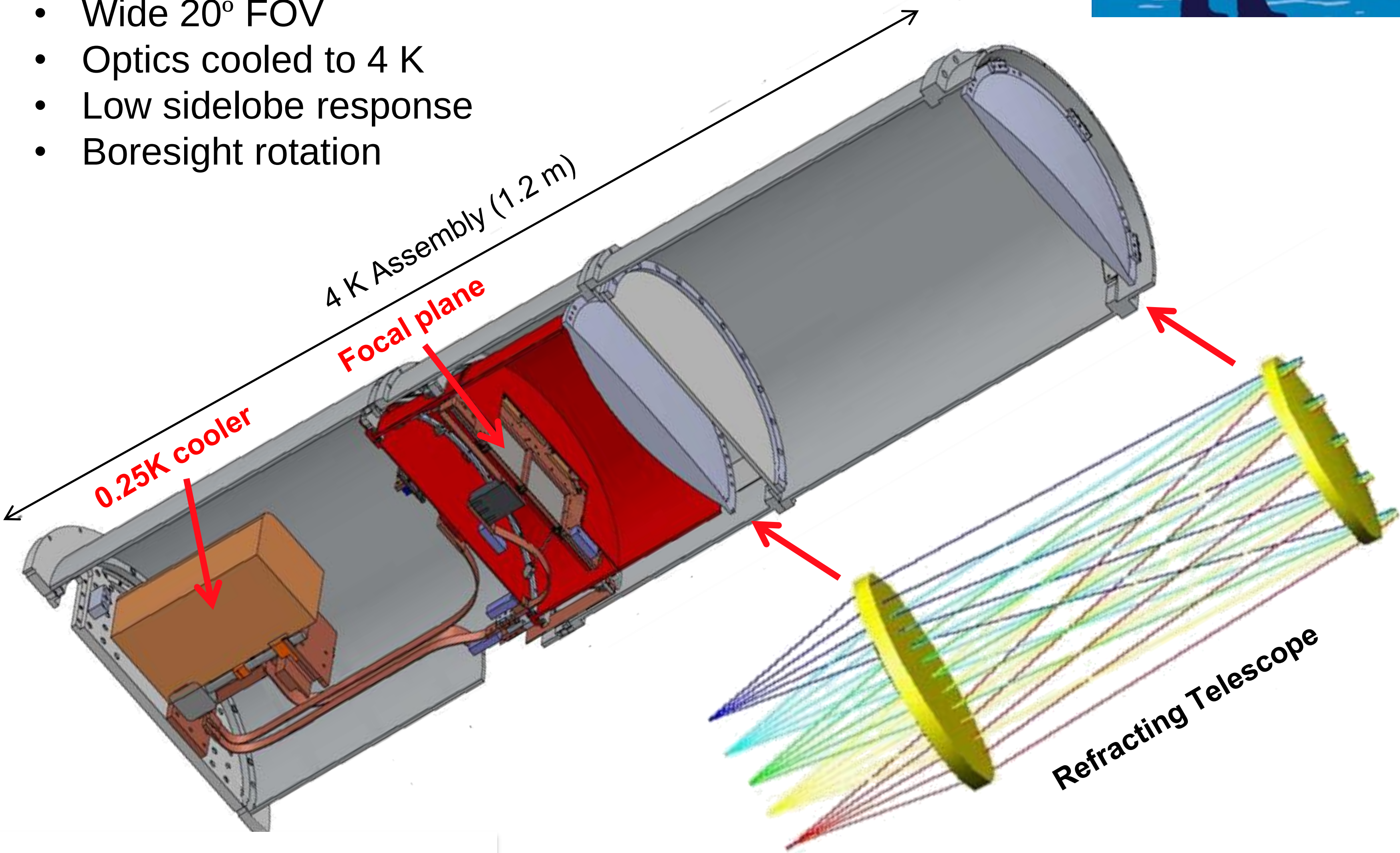
CMB Power Spectra



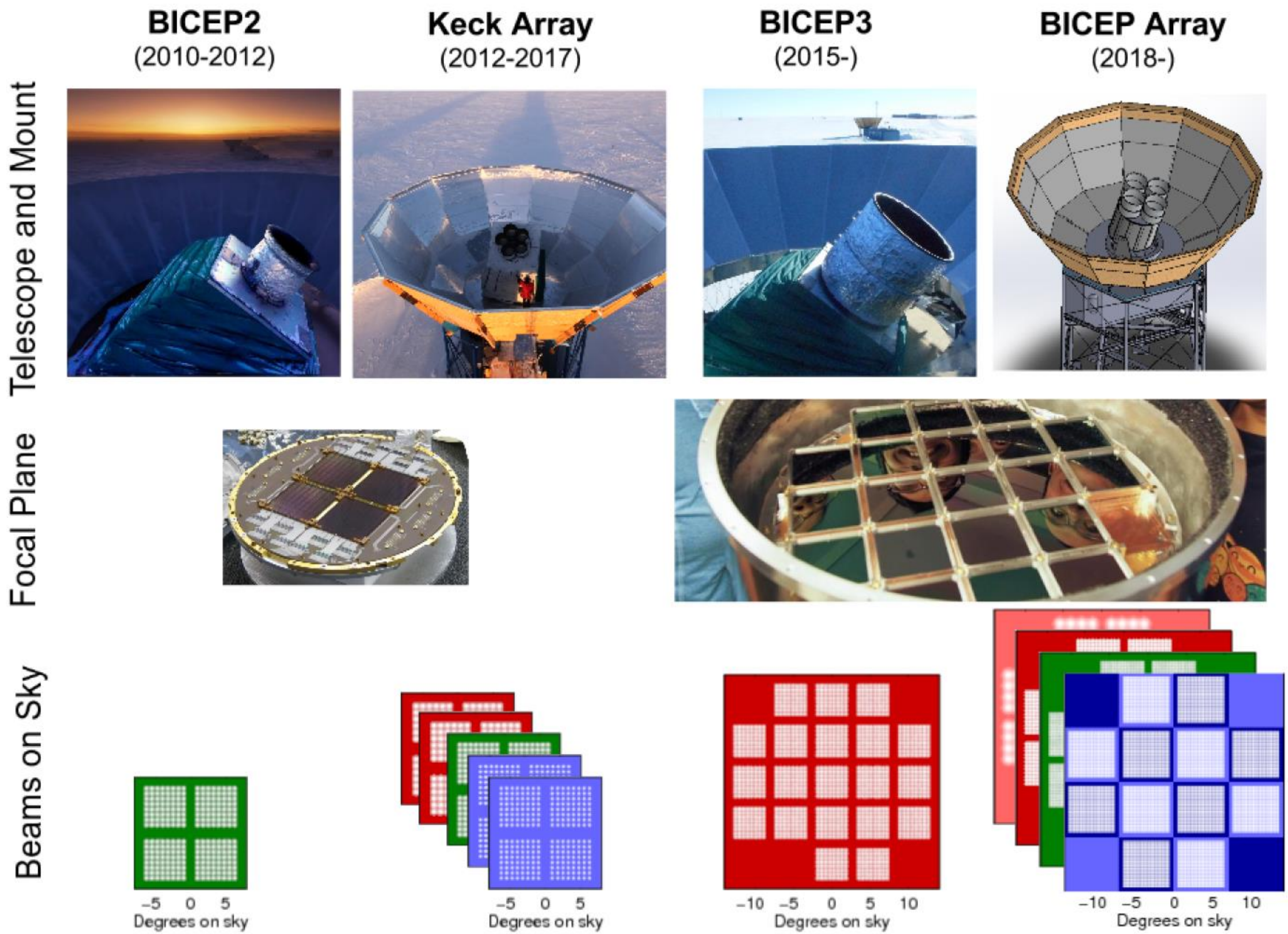
BICEP Concept: Unique Optics

Small-Telescope Design
Invented in 2001

- 26 cm aperture
- Wide 20º FOV
- Optics cooled to 4 K
- Low sidelobe response
- Boresight rotation



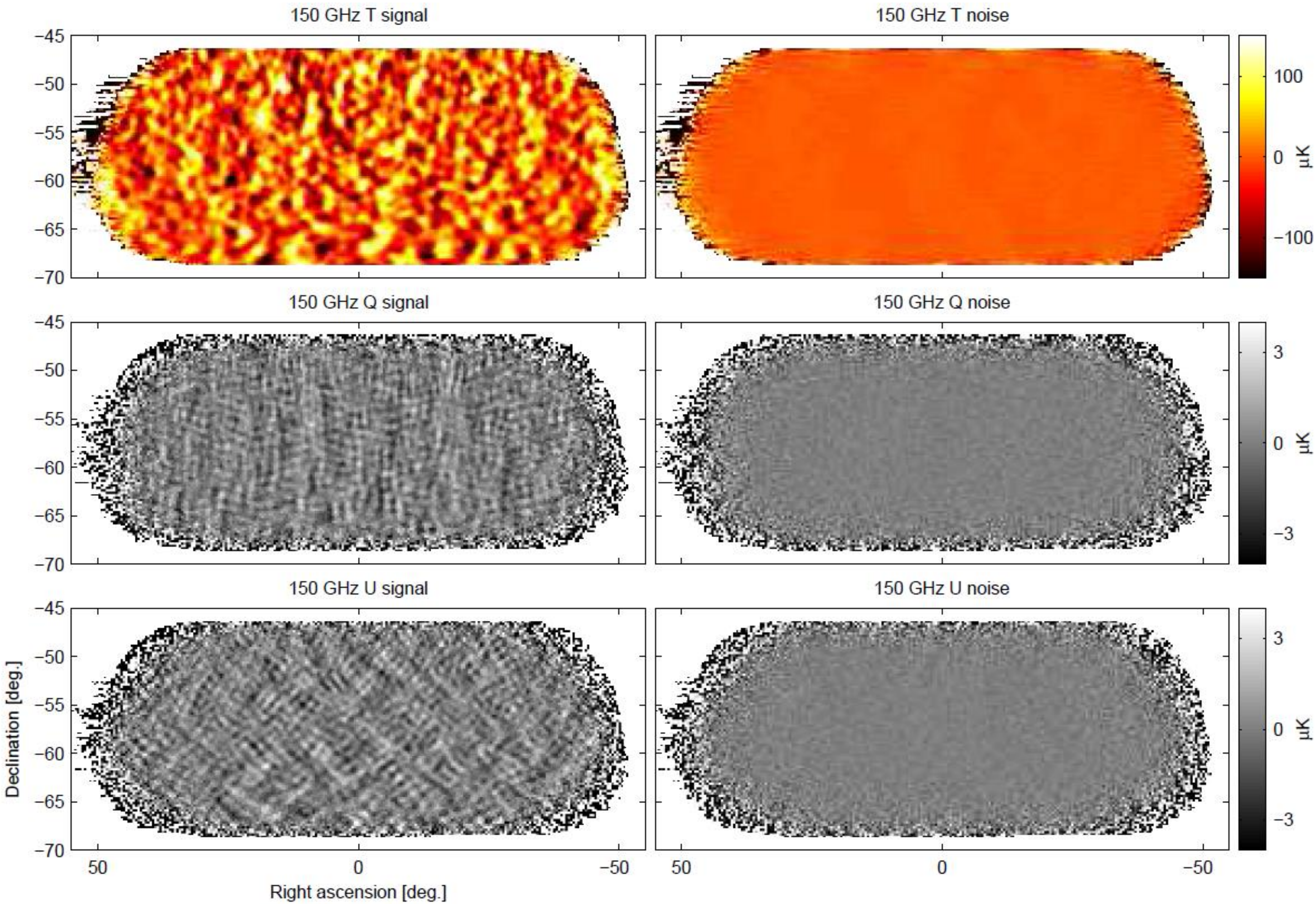
BICEP/Keck: A Staged Program



The South Pole: The Best Place ^for cosmology^ on Earth

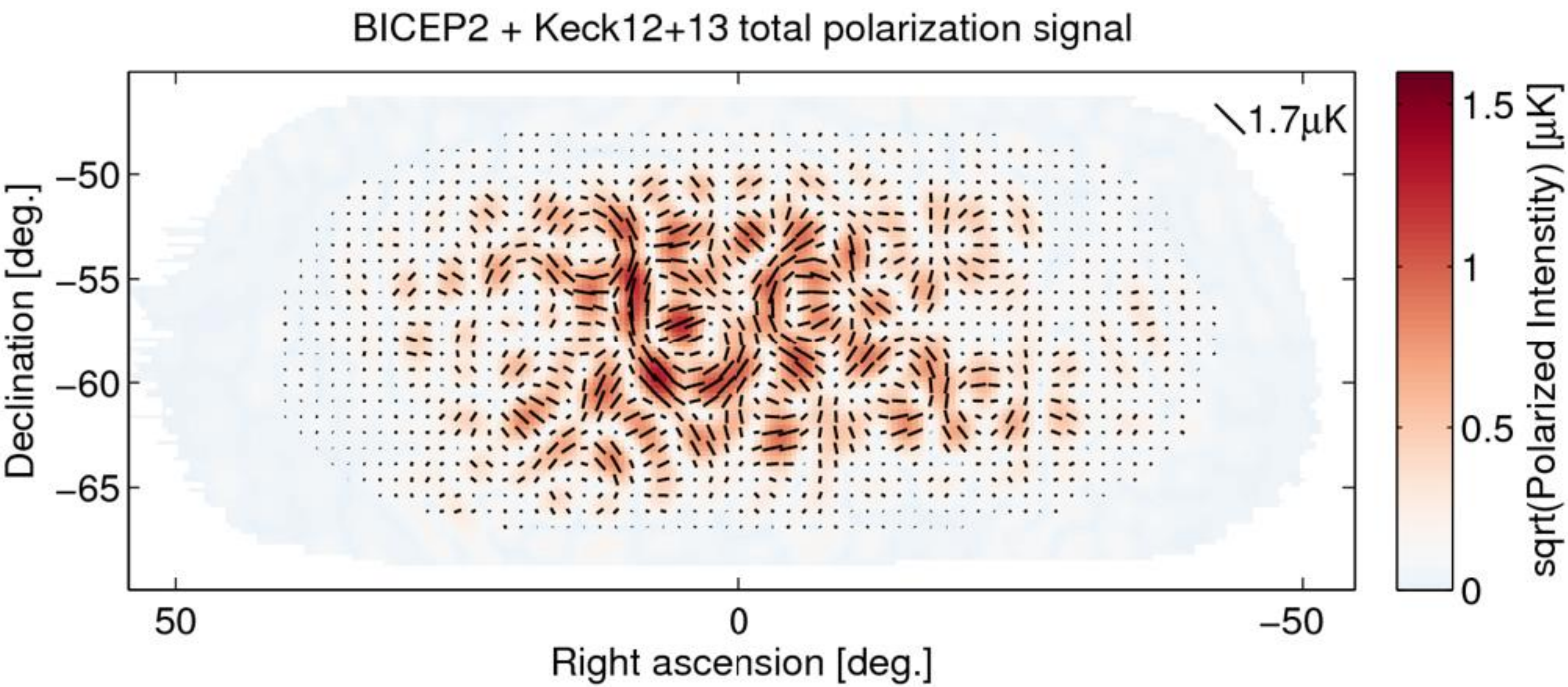
Relentless Observing

BICEP-Keck Maps at 150 GHz



Total Polarization Map

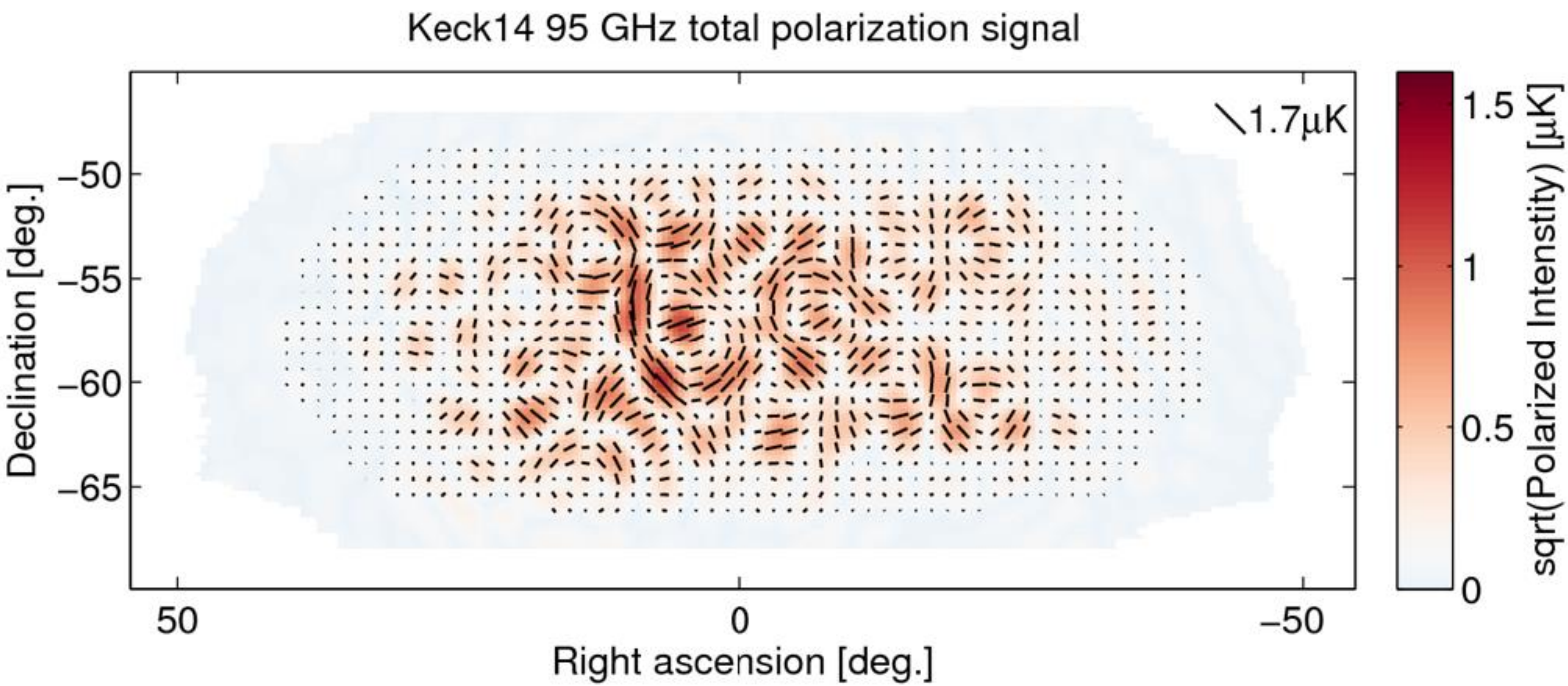
150 GHz



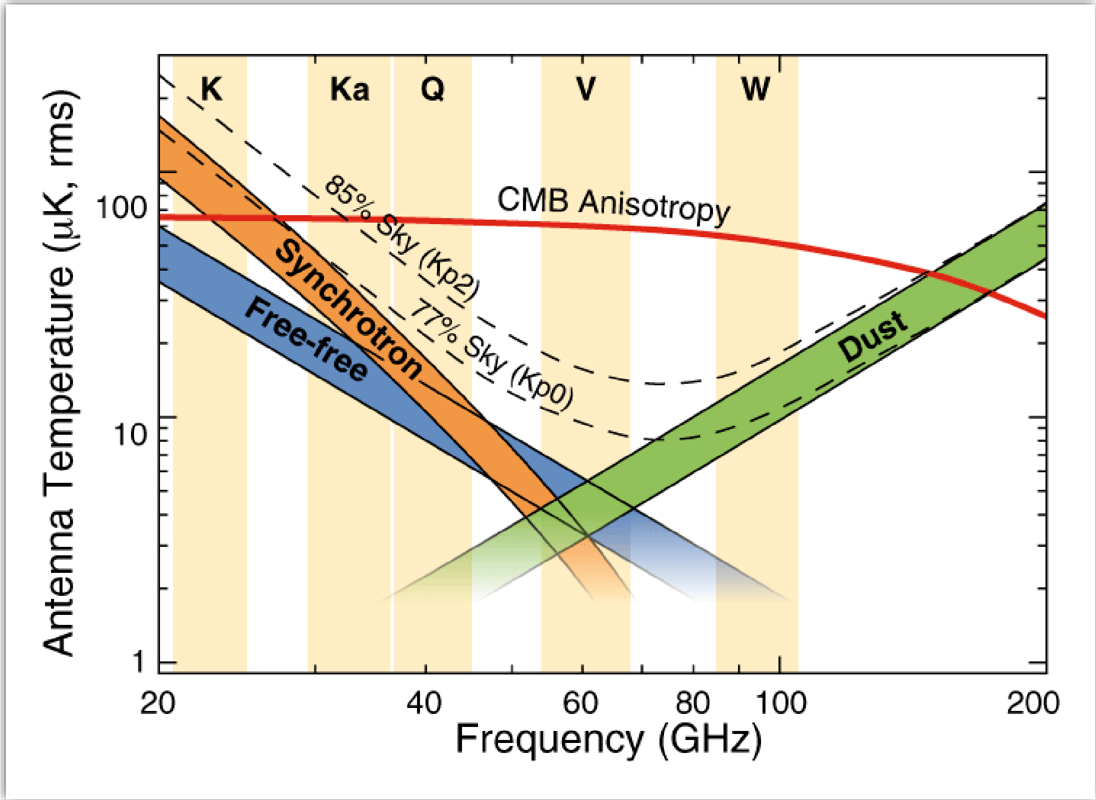
B-modes constitute about 15 % of the total polarization signal

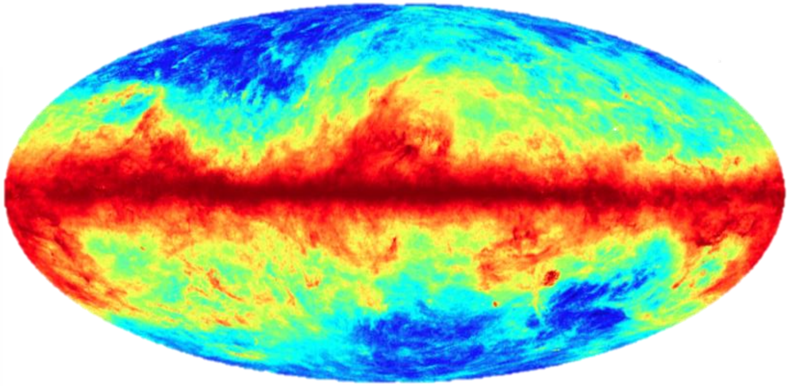
Total Polarization Map

95 GHz

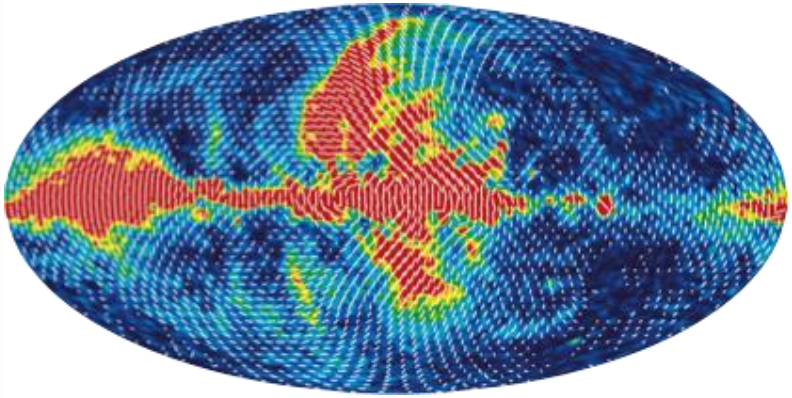


Galactic Emission





Model of Polarized Dust Emission

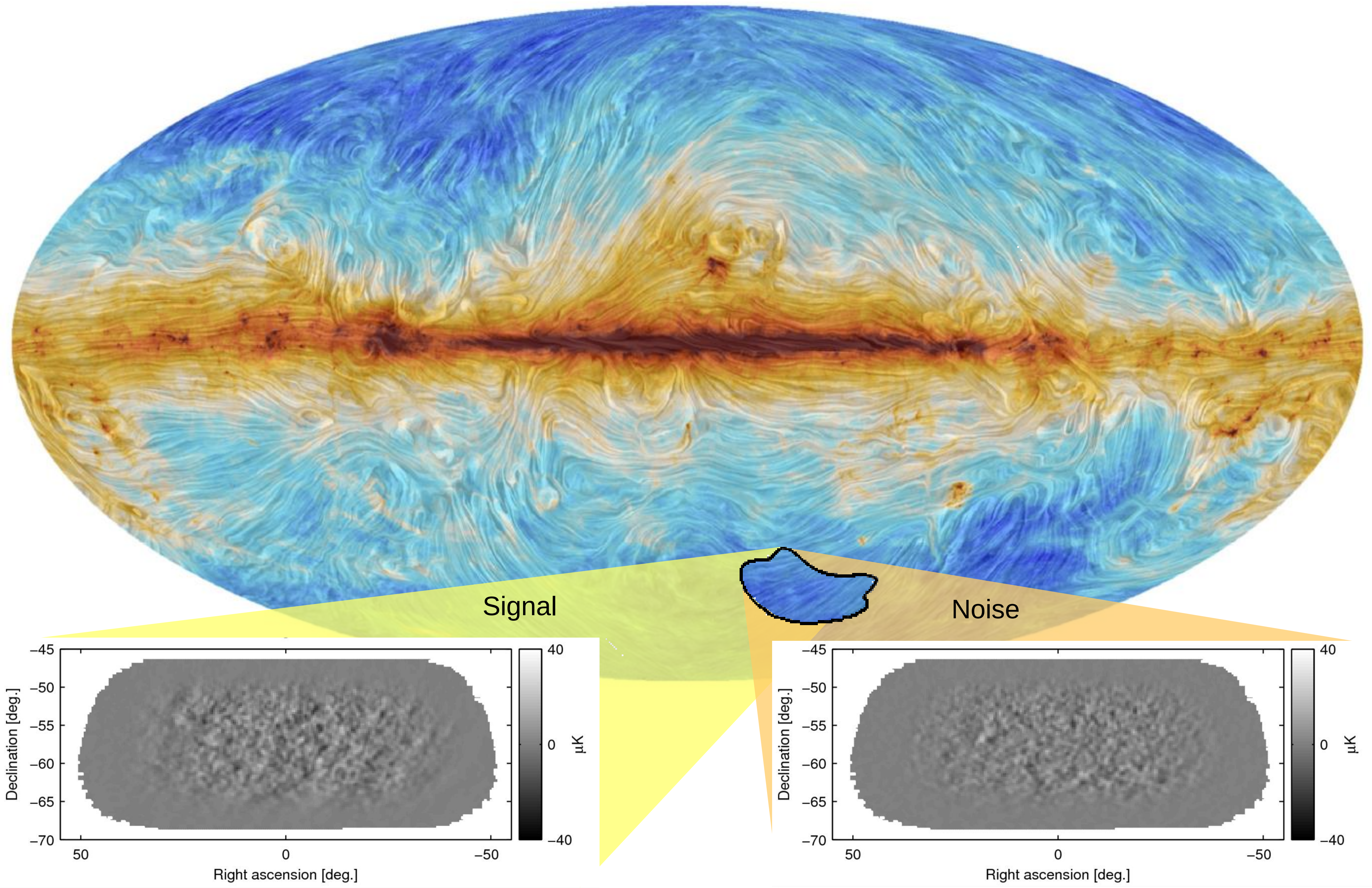


Map of Polarized Synchrotron Emission

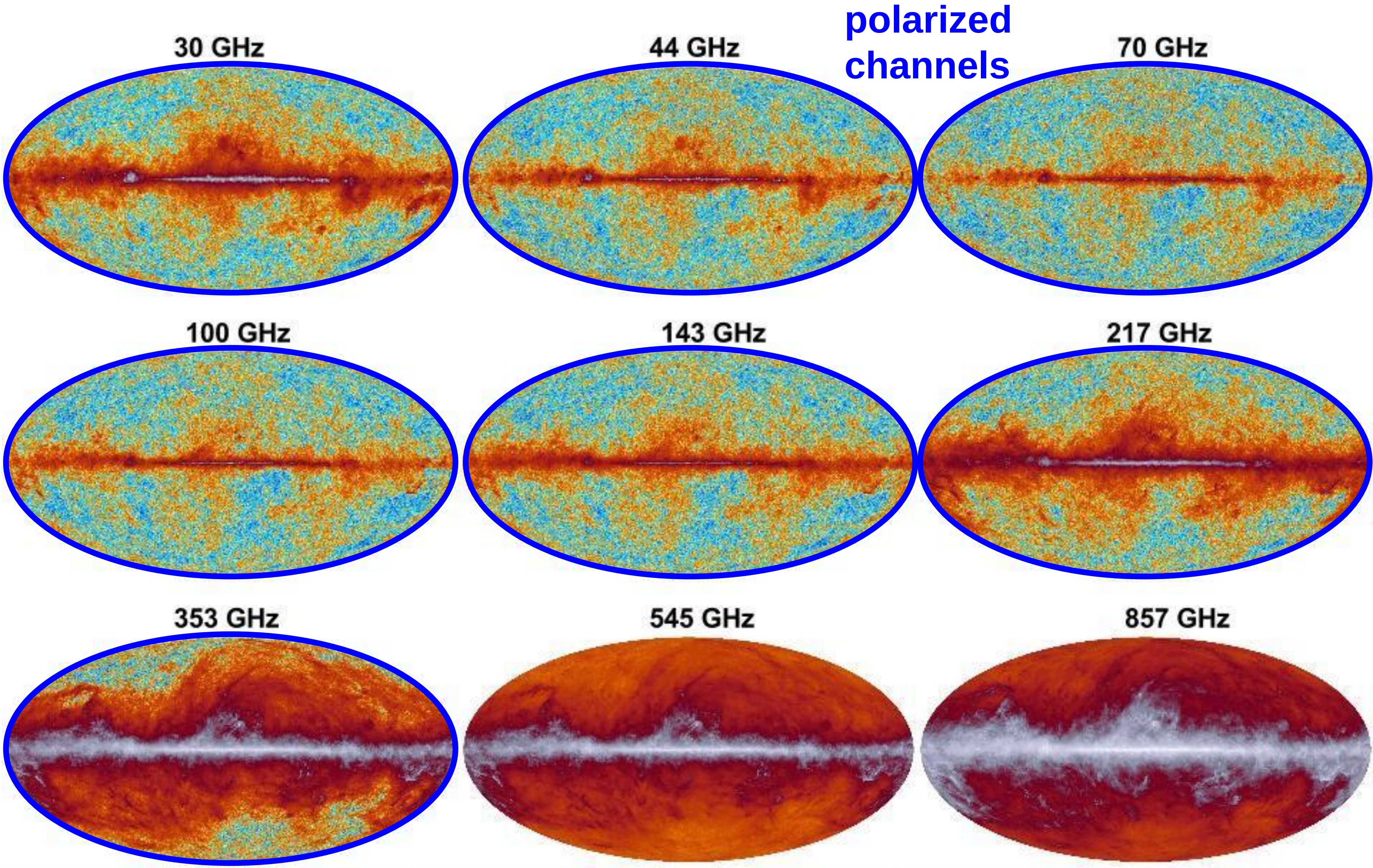
Synchrotron	Spiraling electrons	Emission α (Frequency)$^{-3}$
Dust	Galactic dust grains	Emission α (Frequency)$^{1.75}$

Planck Visualization of Polarized Dust Emission

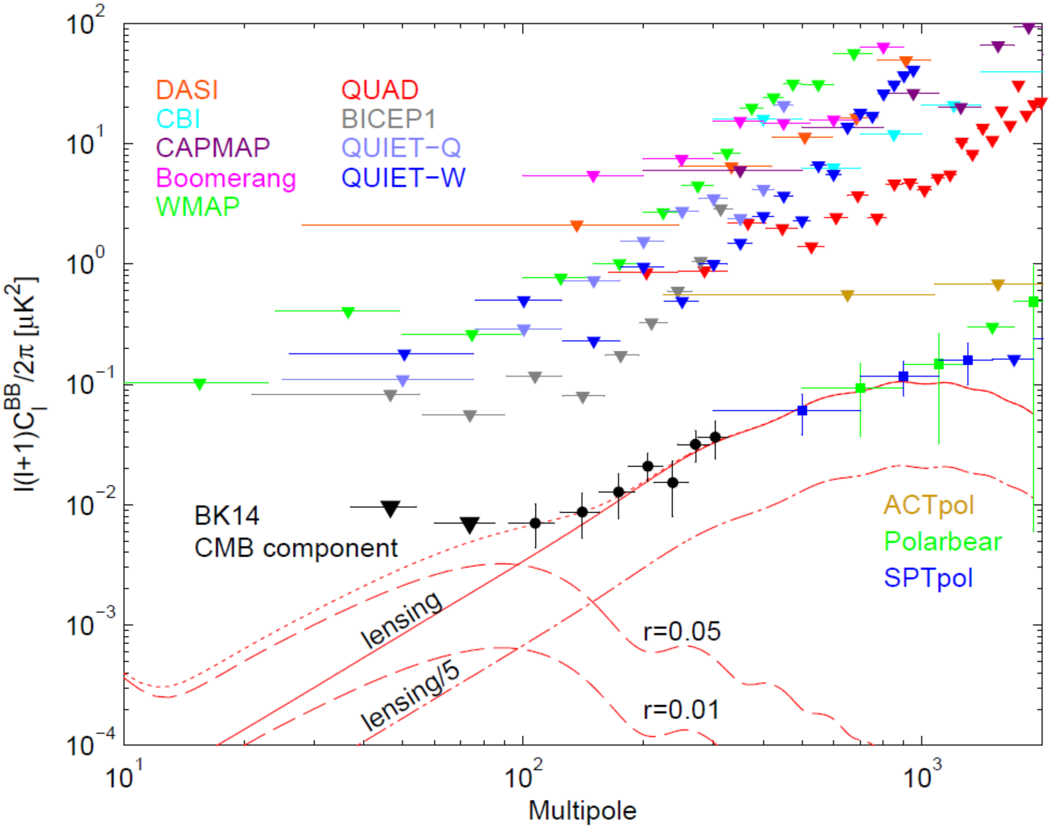
With apologies to Vincent van Gogh

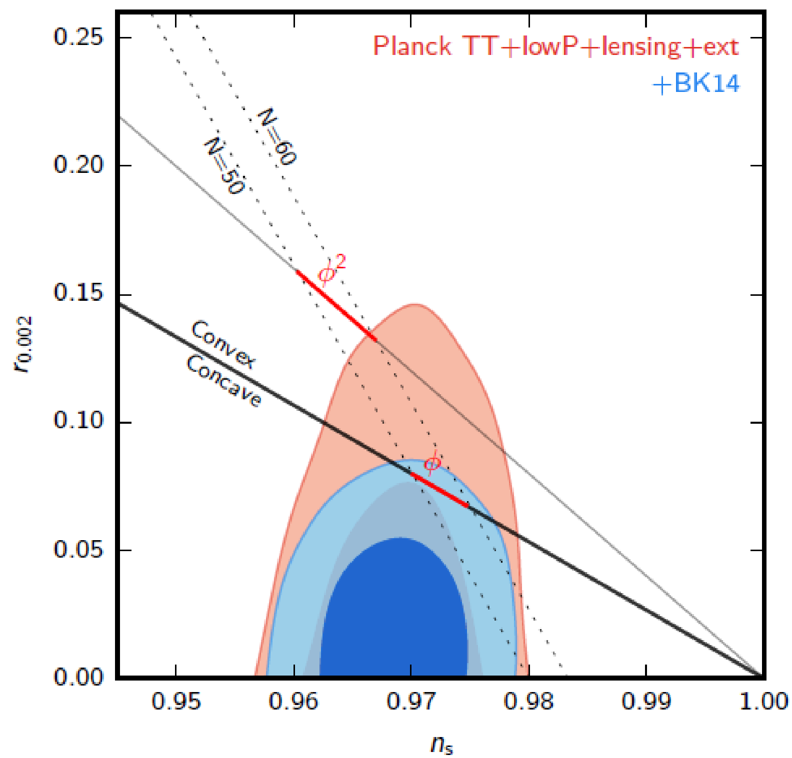


All-Sky Maps from the Planck Satellite



Latest Constraints on the Inflationary Gravitational Wave Background





<u>BICEP/Keck 2014 data + Planck</u>

$r = 0.028^{+0.026}_{-0.025}$

r < 0.09 (95 % CF)

Phys Rev. Lett. (2016) 116, 1302B.

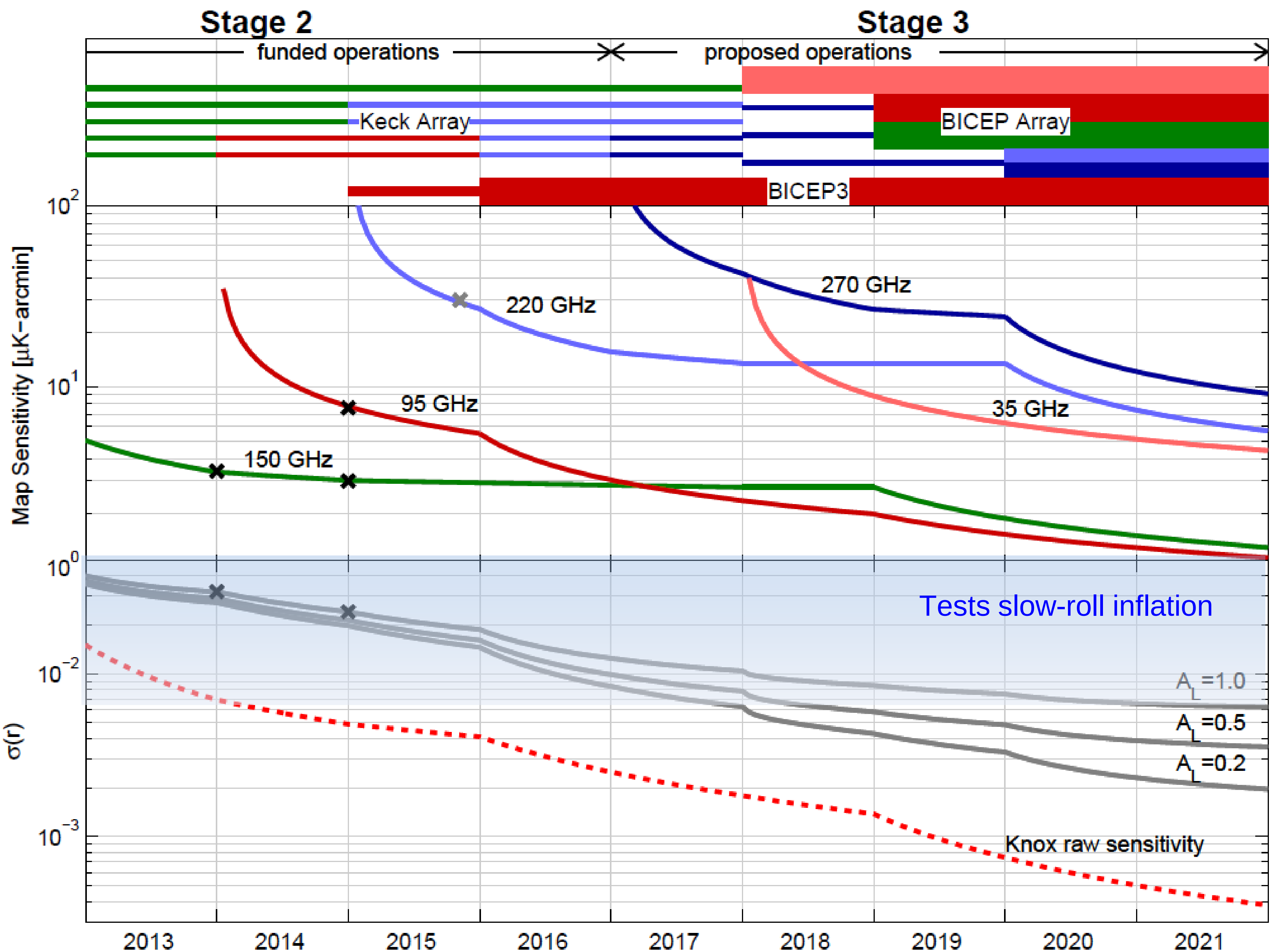
Best constraints on GWs now come from B-mode polarization (as predicted in the 1990s)

New Data Coming - Keck220 and BICEP3

2015 season
95 GHz depth doubles
First observations at 220 GHz
BICEP3 commissioned

2016 upgrades
220 GHz receivers: 2 → 4
BICEP3 reaches full power
= 10 Keck Array receivers

Next Step: the BICEP-Array



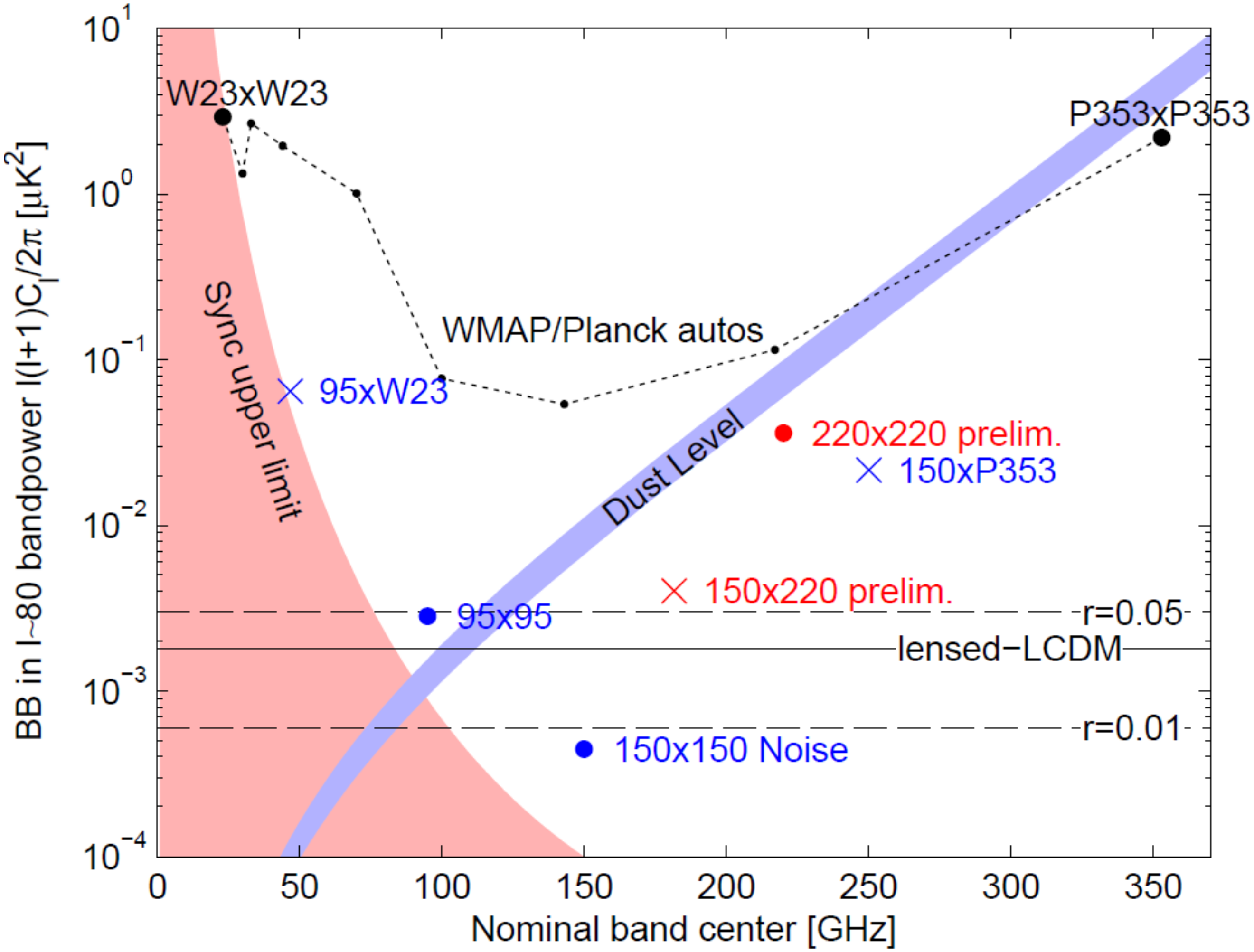
So What Does All This Mean?

Gravitational waves can tell us what powered inflation
- Inflation requires new physics at high energies
- Connects Einstein's gravity to quantum mechanics
- Only ***some*** inflation models make copious waves

New analysis from 2015 Keck Array data
- Gravitational wave amplitude $r < 0.09$
- Polarization data have now overtaken temperature data
- Limited by errors in foreground removal

Program will push down to $\delta r = 1\ \%$ (3σ) in several years
- Stay tuned!

Spectral Constraints from Auto- and Cross-Spectra



Dominant error comes from dust subtraction

- CMB: 150x150 sensitivity $\Delta r < 1$ %
- Dust: best information from 150xP353
- Sync: not yet detected
- New: Keck data provides dust measurement in 95x150