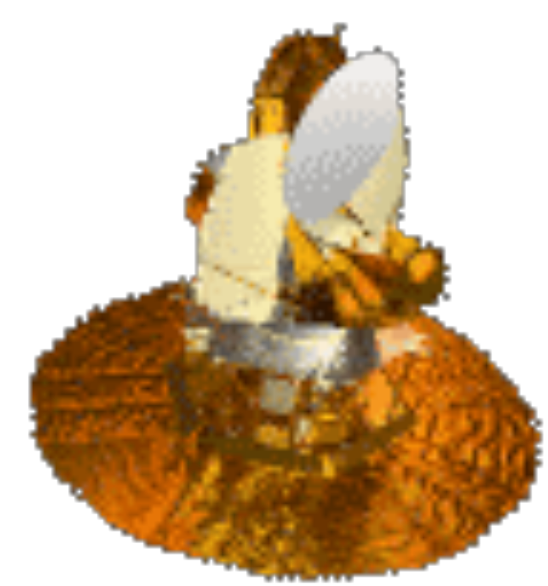
Cosmic Microwave Background: Observational Tests of Theories of the Early Universe

Eiichiro Komatsu, Max-Planck-Institut für Astrophysik
General Relativity and Gravitation: A Centennial Perspective
Penn State University, June 8, 2015



Precision Cosmology

- Precision cosmology requires **both**
  - Precision data
  - Precision theory
- No matter how good the data are, they are not very useful until we figure out how to interpret them accurately
  - **Cosmic Microwave Background (CMB) was revolutionary because *we finally have both***

Inhomogeneous Universe

- Ignoring gravitational waves, the distance between two points in spacetime is given by (in Newtonian gauge):

$$ds^2 = -(1+2\Psi)dt^2 + a^2(t)(1+2\Phi)d\mathbf{x}^2$$

- Einstein's field equations determine the evolution of two potentials Φ and Ψ, given perturbations in the energy contents of the Universe

- These potentials then determine, e.g., how photons lose or gain energy as they propagate through an inhomogeneous universe

Propagation of photons in an inhomogeneous universe

- The geodesic equation for the photon 4-momentum:

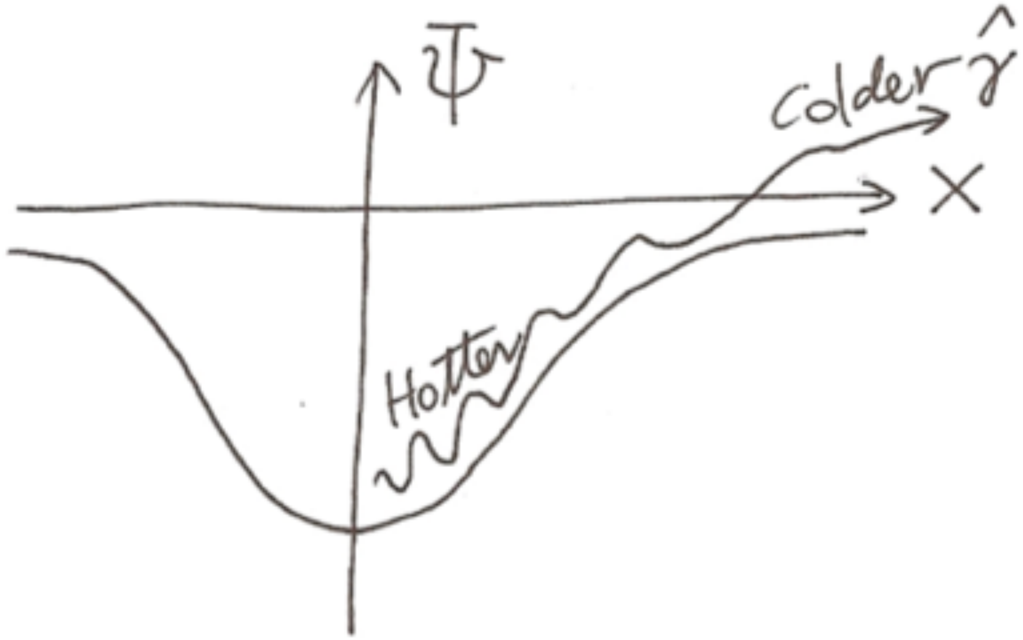
$$\frac{dp^\mu}{d\lambda} + \Gamma^\mu_{\alpha\beta} p^\alpha p^\beta = 0$$

- determines the evolution of the photon energy in an inhomogeneous universe as

$$\frac{1}{p}\frac{dp}{dt} = -\frac{1}{a}\frac{da}{dt} - \frac{d\Psi}{dt} + \frac{\partial\Psi}{\partial t} - \frac{\partial\Phi}{\partial t}$$

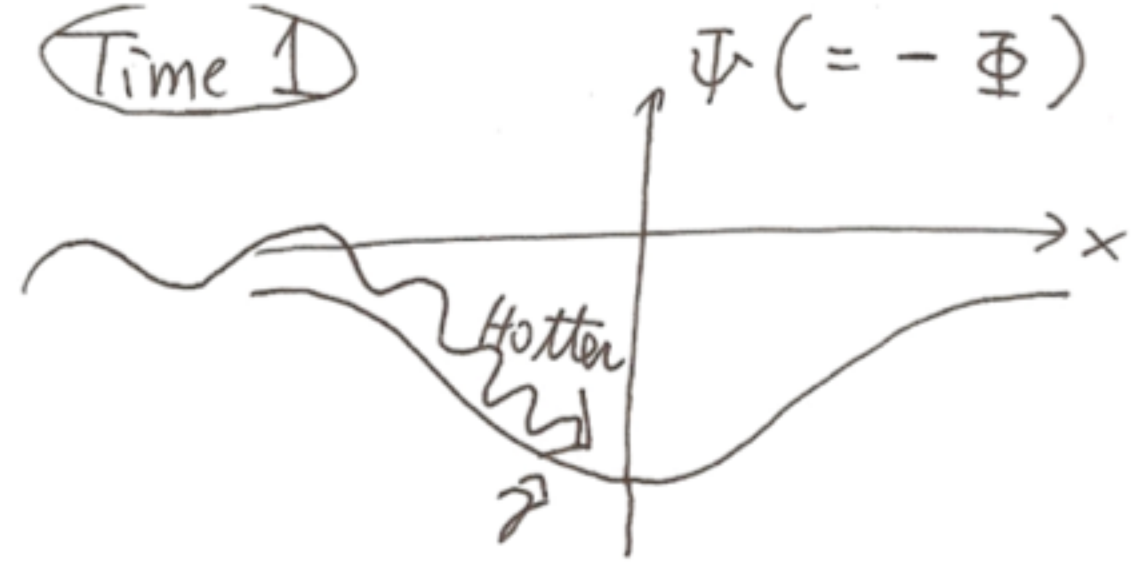
$$\ln(ap)_{\mathcal{O}} = \ln(ap)_{\mathcal{E}} + (\Psi_{\mathcal{E}} - \Psi_{\mathcal{O}}) + \int_{t_{\mathcal{E}}}^{t_{\mathcal{O}}} dt \frac{\partial}{\partial t}(\Psi - \Phi)$$

"$\mathcal{O}$" and "$\mathcal{E}$" denote the observed and emitted epochs

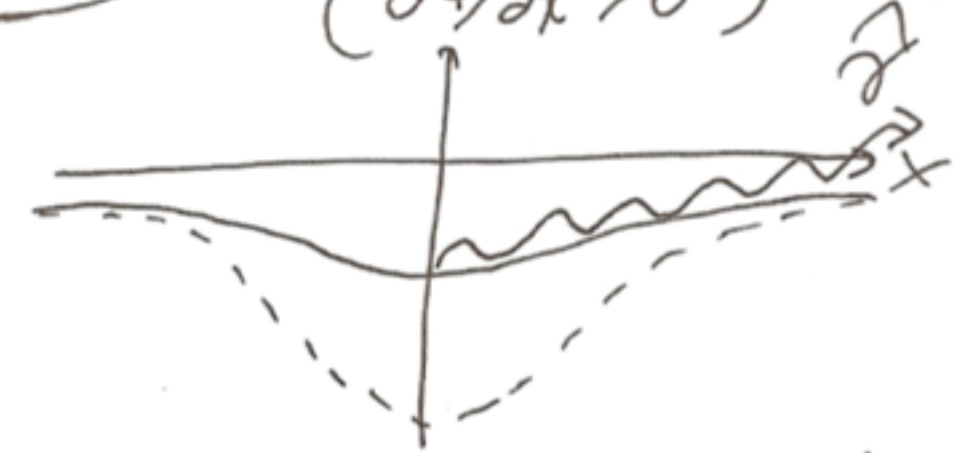


$$\frac{1}{p}\frac{dp}{dt} = -\frac{\gamma^i}{a}\frac{\partial \Psi}{\partial x^i}$$

Time 1

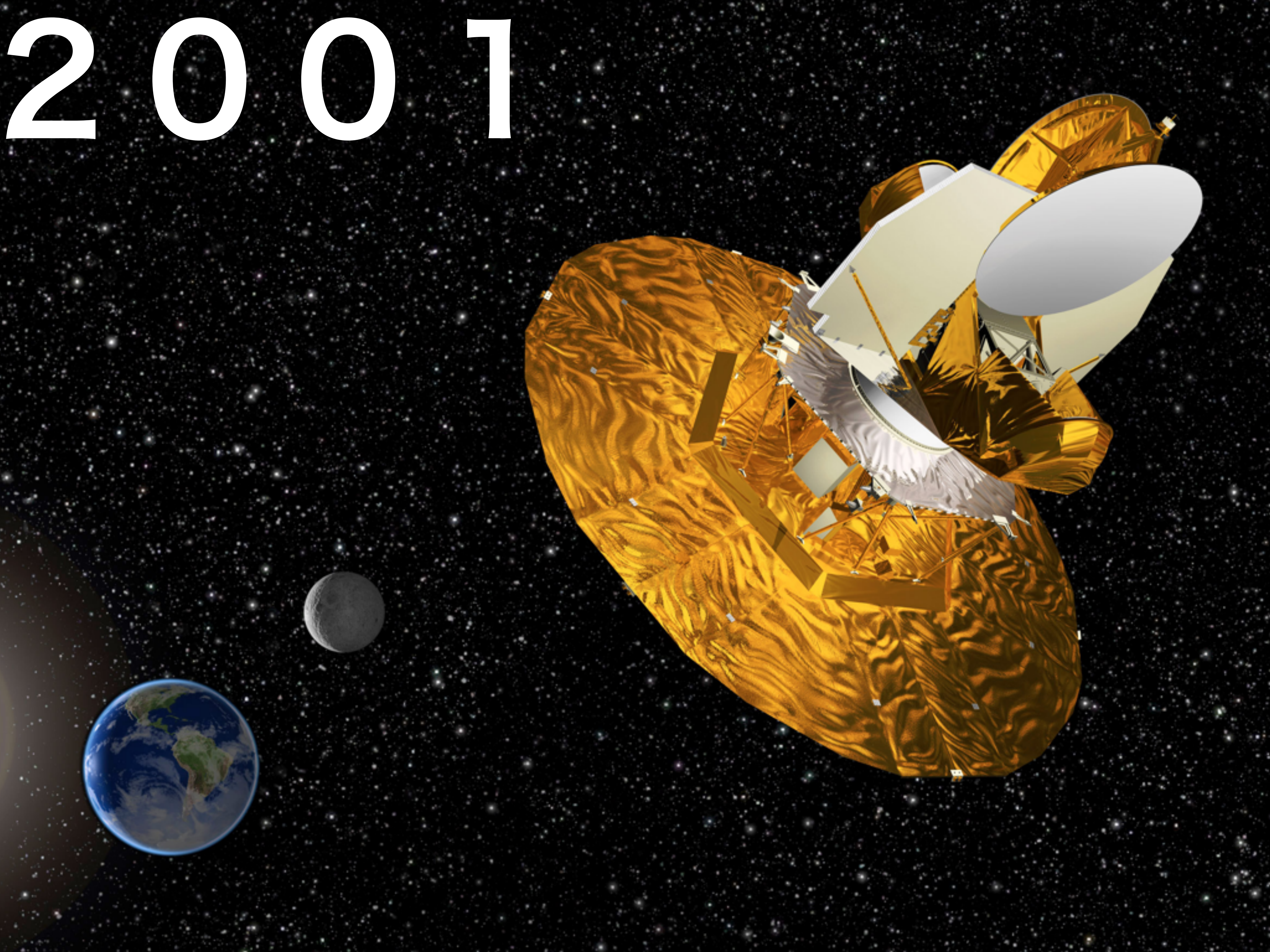


Time 2 potential "decayed" $(\partial\Psi/\partial t > 0)$



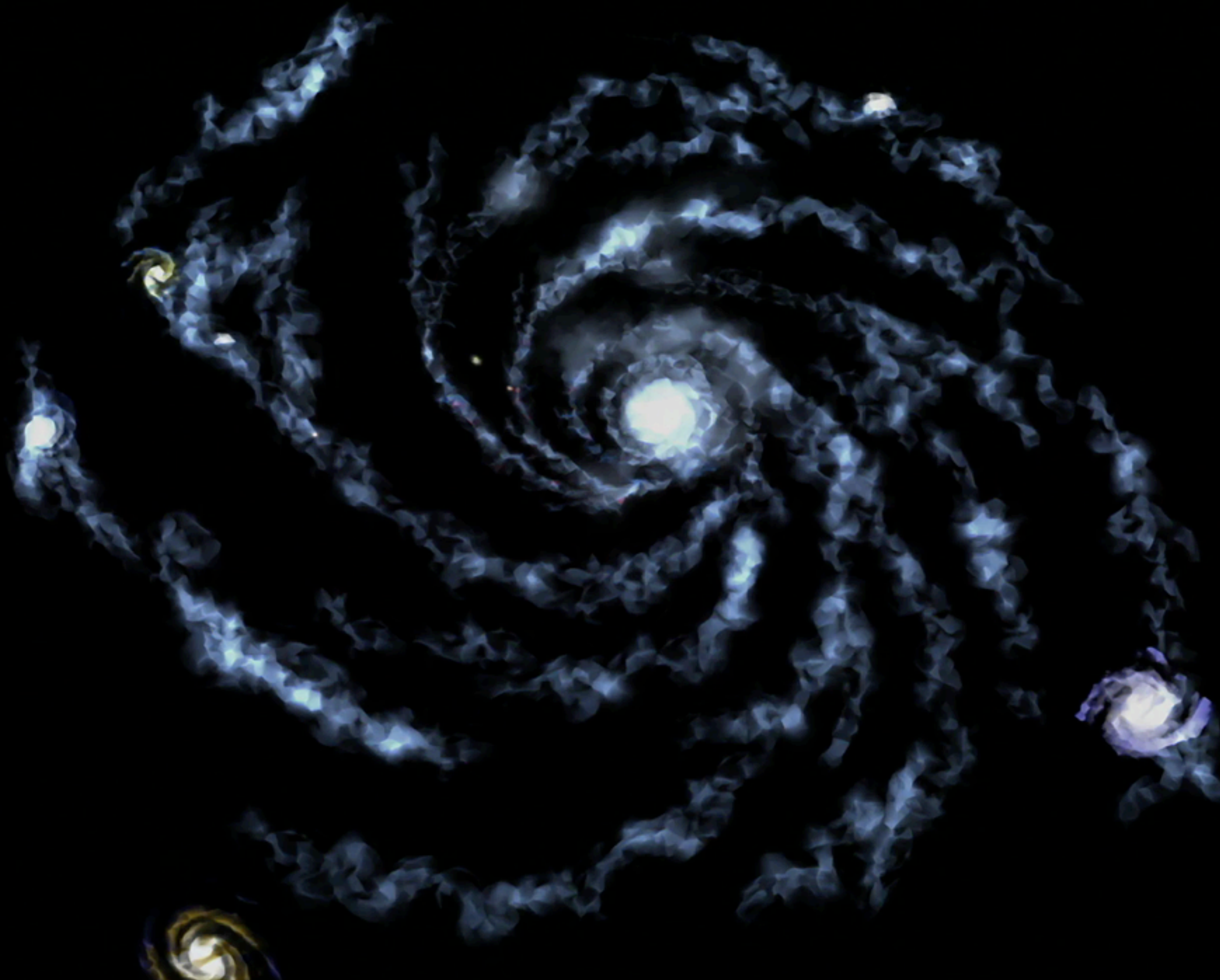
⇒ Net Gain of Energy

$$\frac{1}{p}\frac{dp}{dt} = -\frac{\partial \Phi}{\partial t} = \frac{\partial \Psi}{\partial t}$$

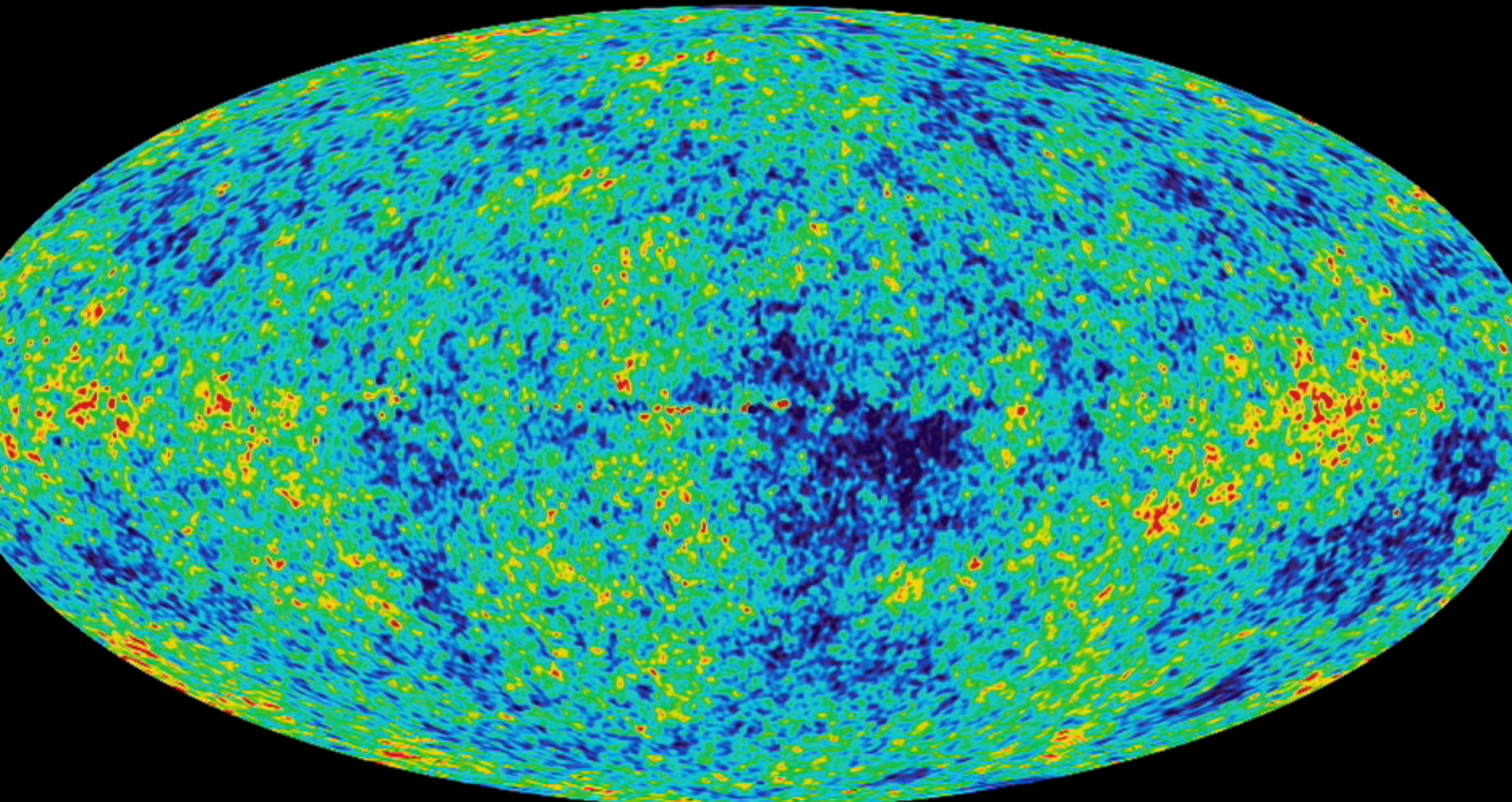

2001

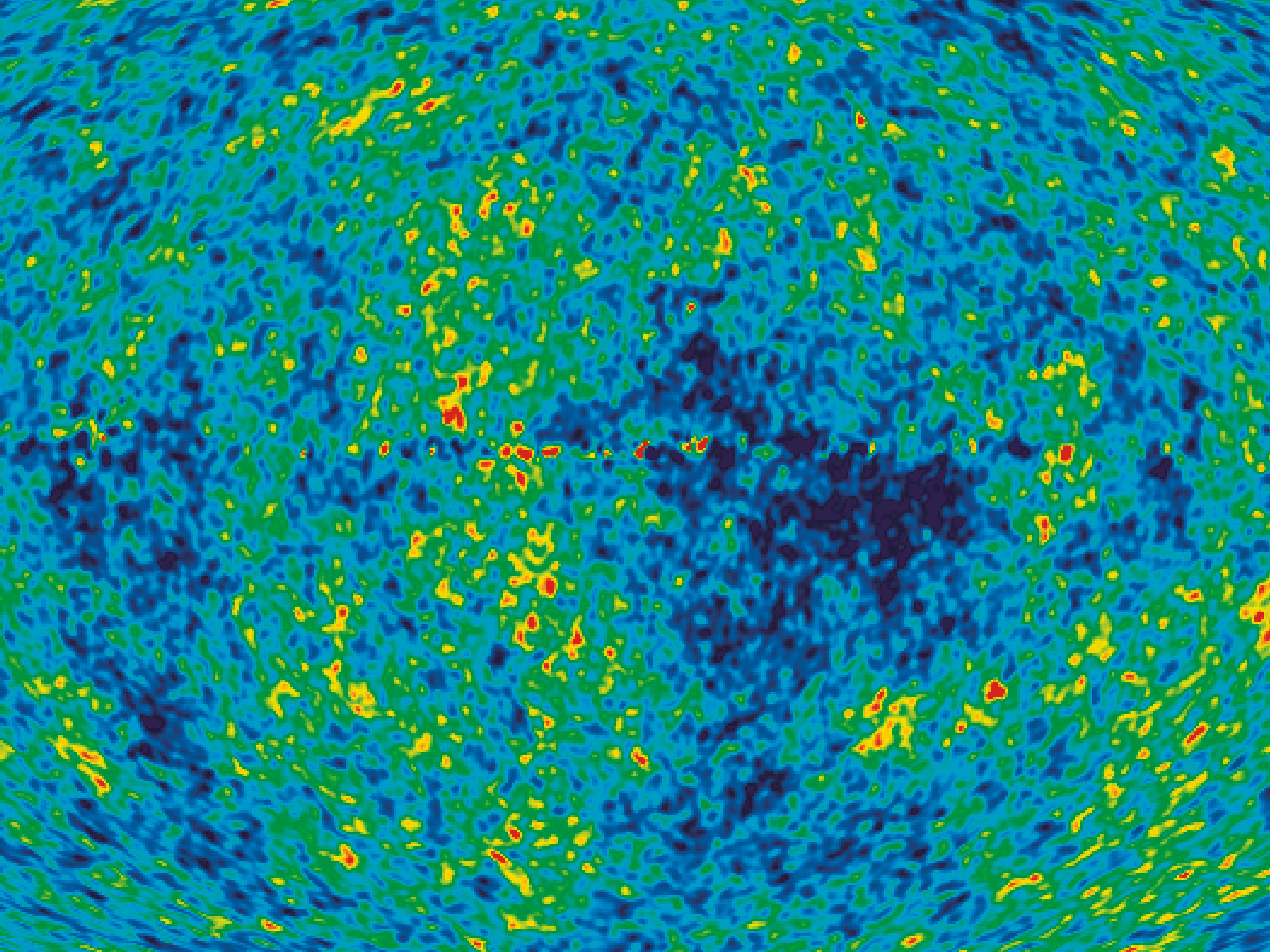
WMAP Science Team
July 19, 2002

- WMAP was launched on June 30, 2001
- The WMAP mission ended after 9 years of operation



Distribution of the density of photons. What about matter?



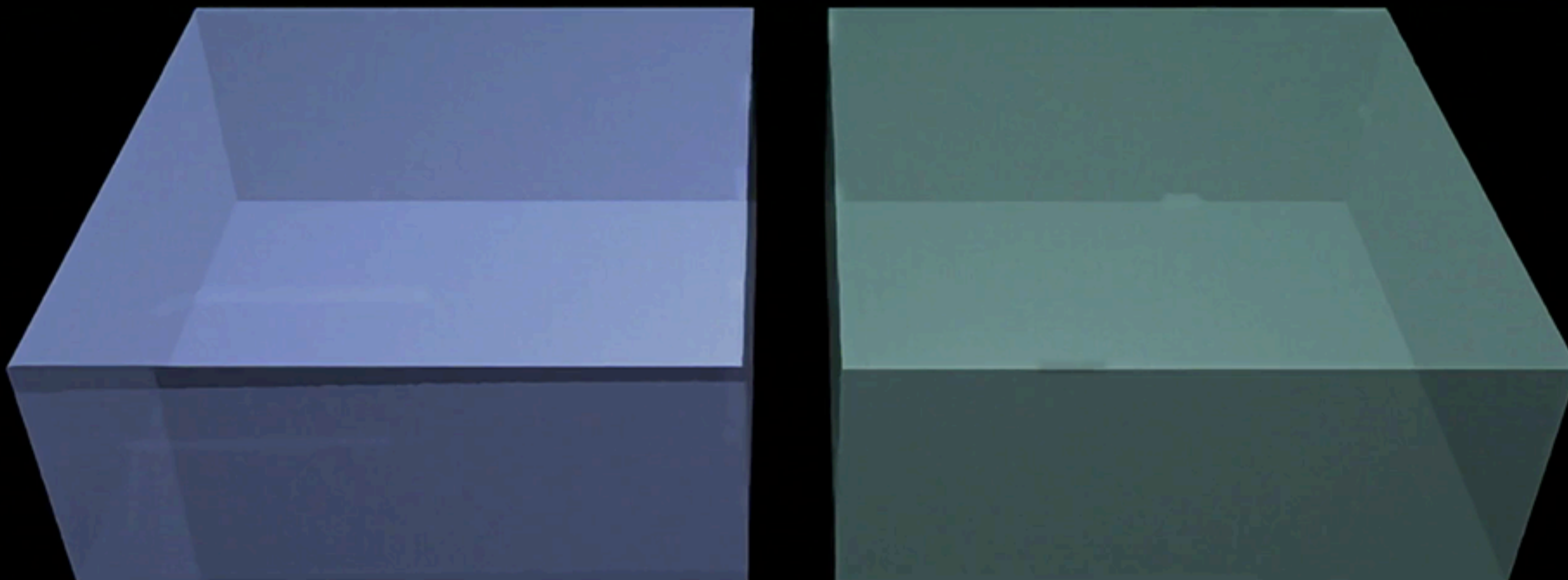


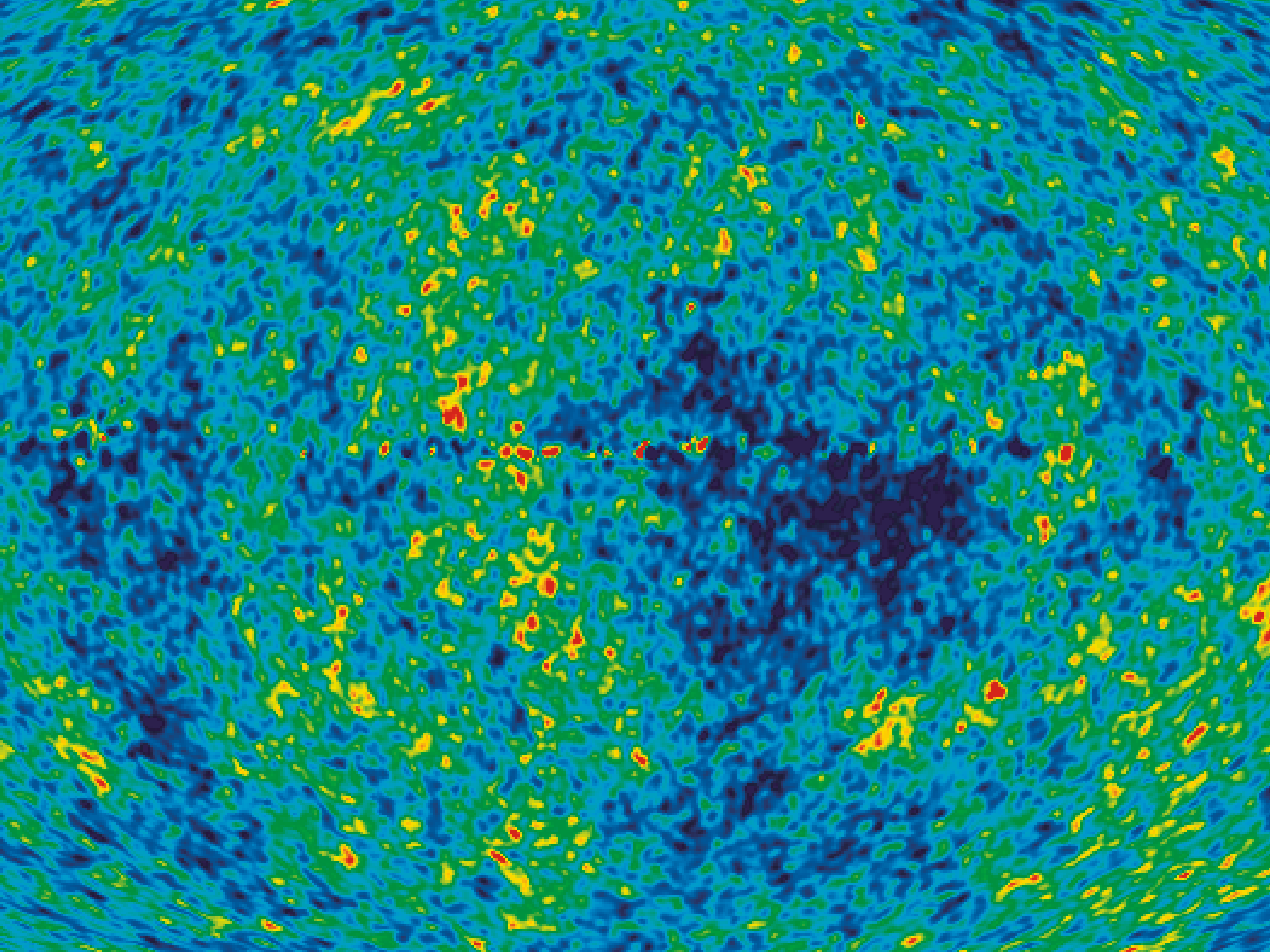
Our Origin

- WMAP taught us that **galaxies, stars, planets, and ourselves originated from tiny fluctuations in the early Universe**

Cosmic Miso Soup

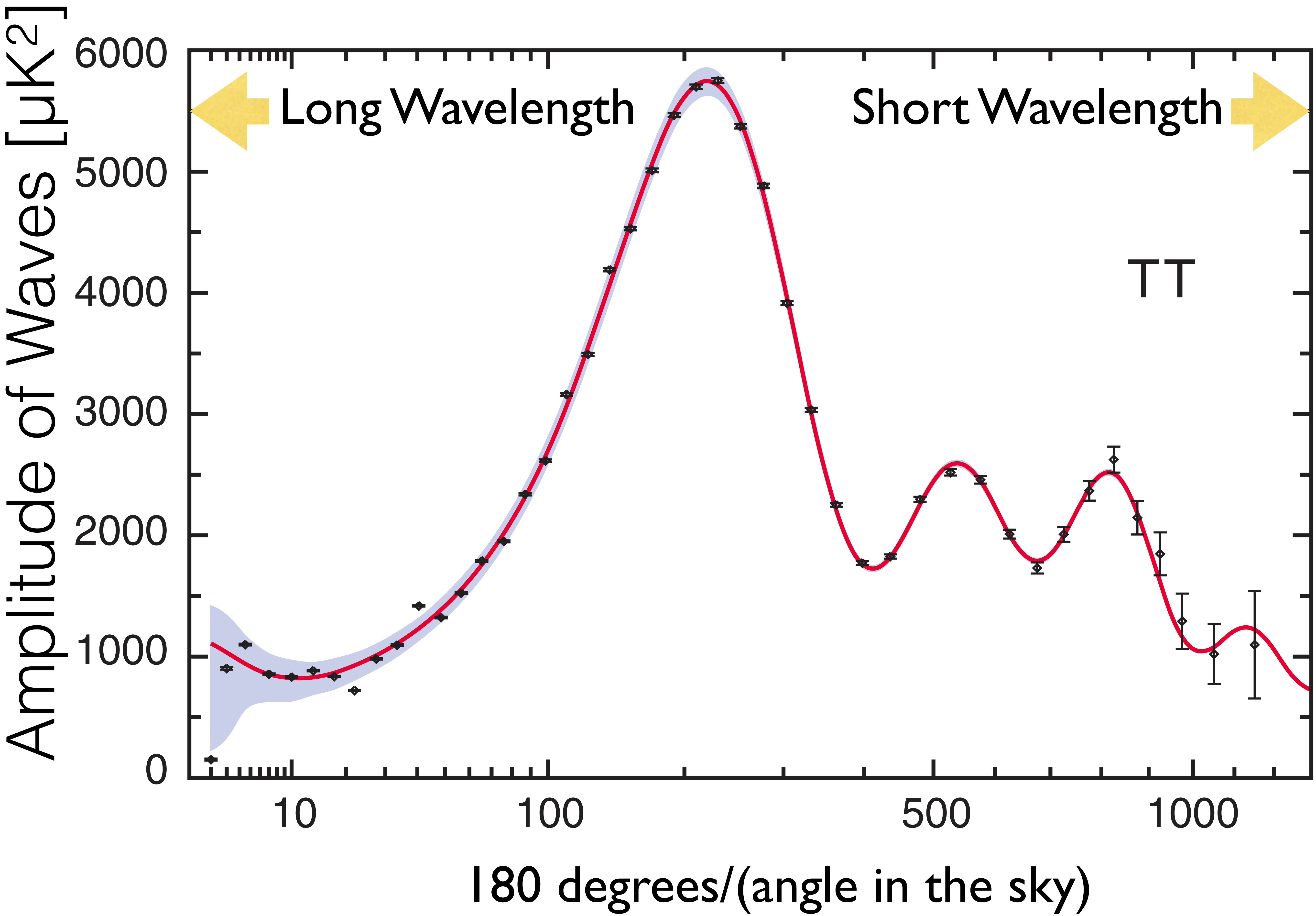
- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup
- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso
- And imagine watching how ripples are created and propagate throughout the soup

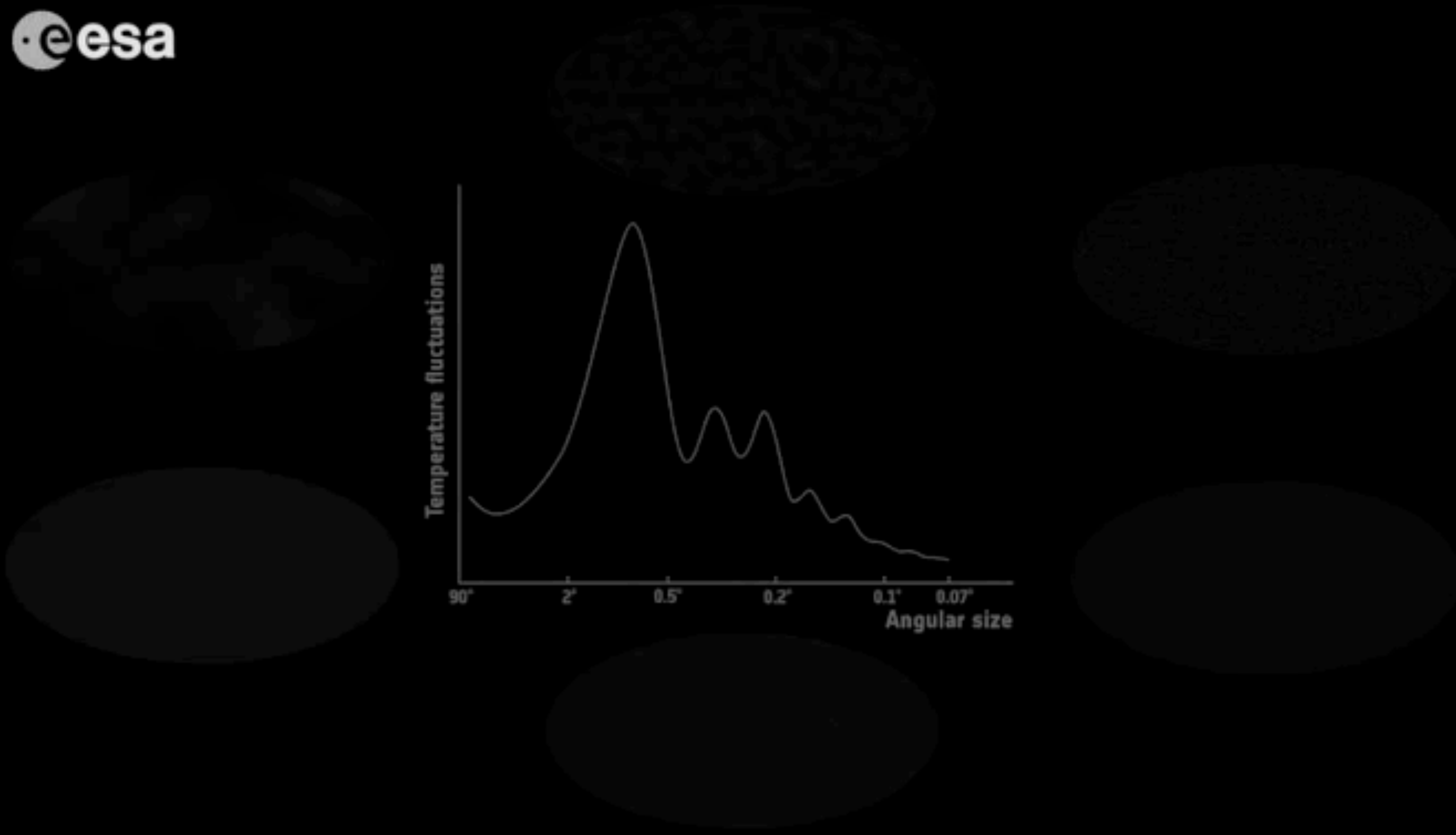




Data Analysis

- Decompose temperature fluctuations in the sky into a set of waves with various wavelengths
- Make a diagram showing the strength of each wavelength


Amplitude of Waves [μK^2]
6000
5000
4000
3000
2000
1000
0
Long Wavelength
Short Wavelength
TT
10
100
500
1000
180 degrees/(angle in the sky)


Temperature fluctuations
90°
2°
0.5°
0.2°
0.1°
0.07°
Angular size

How baryons and photons move together

- "Baryons" = protons and helium nuclei

$$\dot{\delta}_B = -\frac{k}{a}V_B - 3\dot{\Phi},$$

$$\dot{\delta}_\gamma = -\frac{4}{3}\frac{k}{a}V_\gamma - 4\dot{\Phi}, \qquad R \equiv 3\rho_B/(4\rho_\gamma)$$

$$\dot{V}_B = -\frac{\dot{a}}{a}V_B + \frac{k}{a}\Psi + \frac{\sigma_T n_e}{R}(V_\gamma - V_B),$$

$$\dot{V}_\gamma = \frac{1}{4}\frac{k}{a}\delta_\gamma + \frac{k}{a}\Psi + \sigma_T n_e(V_B - V_\gamma),$$

Combine three equations into one and simplify using

$$\Psi = -\Phi \text{ and } \dot{\Phi} = 0$$

$$\ddot{\delta}_\gamma + \frac{1+2R}{1+R}\frac{\dot{a}}{a}\dot{\delta}_\gamma + \frac{1}{3(1+R)}\frac{k^2}{a^2}\delta_\gamma = \frac{4}{3}\frac{k^2}{a^2}\Phi$$

$$R \equiv 3\rho_B/(4\rho_\gamma)$$

- Wave equation! With the “speed of sound” given by the speed of light times $1/\sqrt{3(1+R)}$

Solution:
The Acoustic Oscillation!

$$\frac{\partial^2}{\partial t^2}\left[\frac{1}{4}\delta_\gamma - (1+R)\Phi\right] + \frac{k^2 c_s^2}{a^2}\left[\frac{1}{4}\delta_\gamma - (1+R)\Phi\right] = 0$$

c_s is the speed of sound, $c_s^2 \equiv 1/[3(1+R)]$

$$\frac{1}{4}\delta_\gamma = (1+R)\Phi + A\cos(kr_s) + B\sin(kr_s)$$

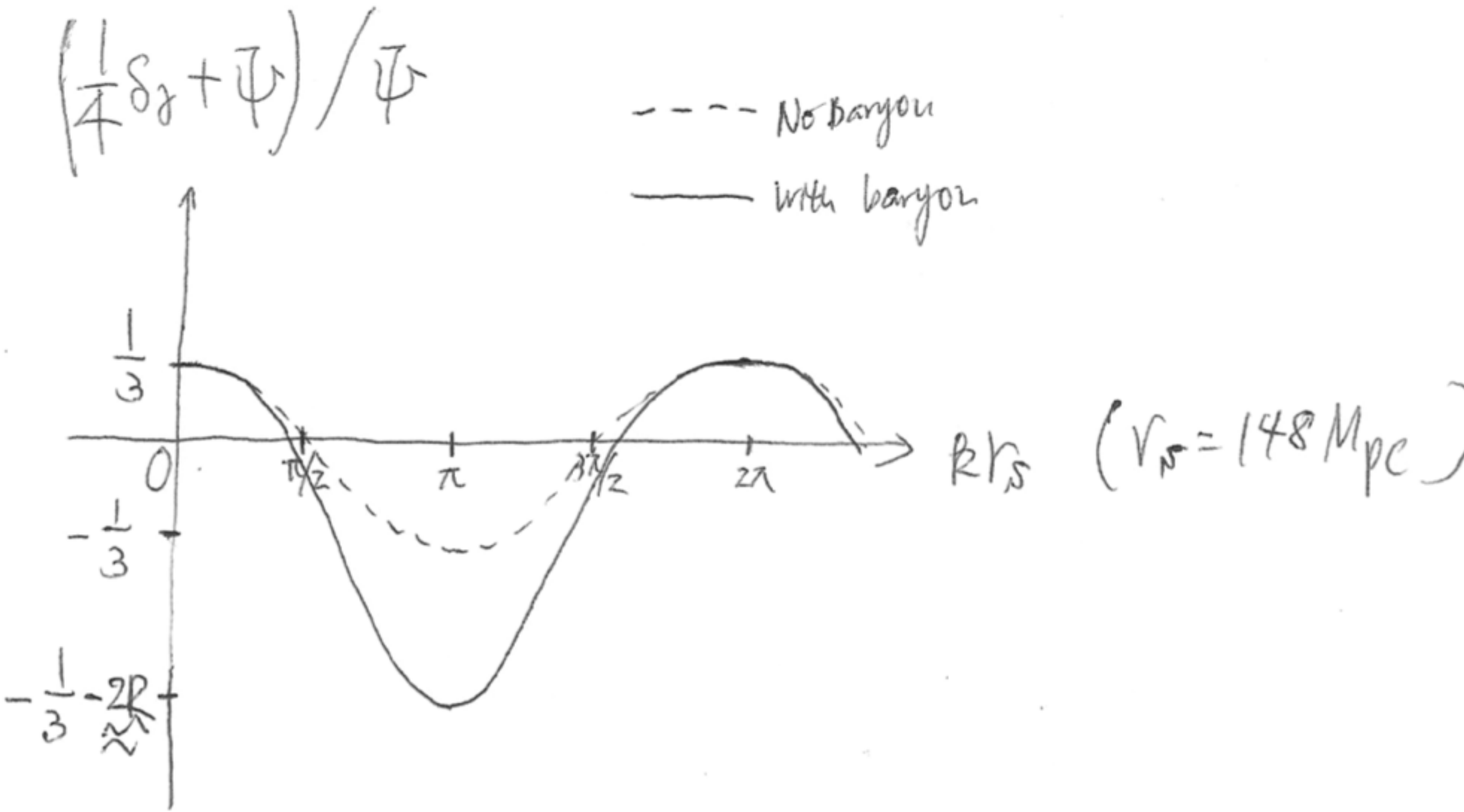
r_s is the "sound horizon" defined by $r_s \equiv \int_0^{t_*} c_s \frac{dt}{a} = 147$ Mpc

Adiabatic Initial Condition

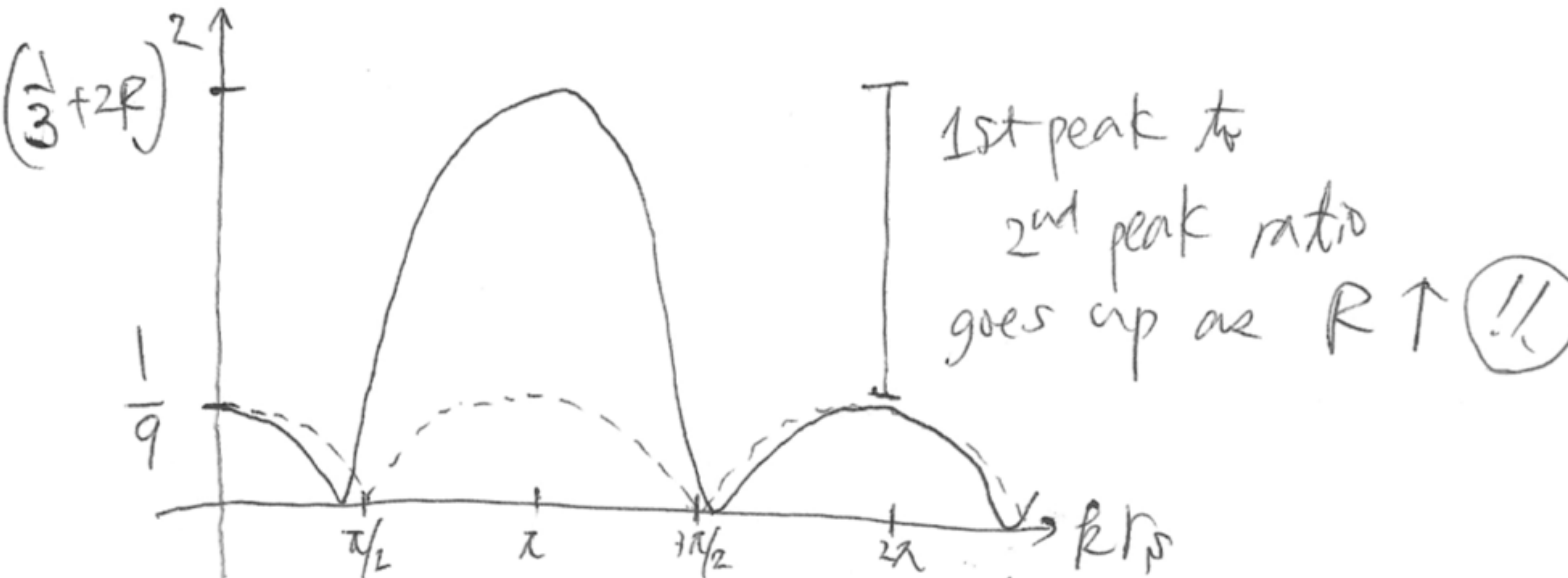
- On "super horizon scales", where the wavelength of fluctuations is larger than the horizon size, the fluctuations are set by the initial conditions
- Adiabatic initial condition: $\frac{1}{4}\delta_\gamma = \frac{1}{3}\delta_m = \frac{2}{3}\Phi$
- Thus:

$$\frac{1}{4}\delta_\gamma = (1+R)\Phi - \left(\frac{1}{3}+R\right)\Phi\cos(kr_s)$$

How baryons affect photon density fluctuations

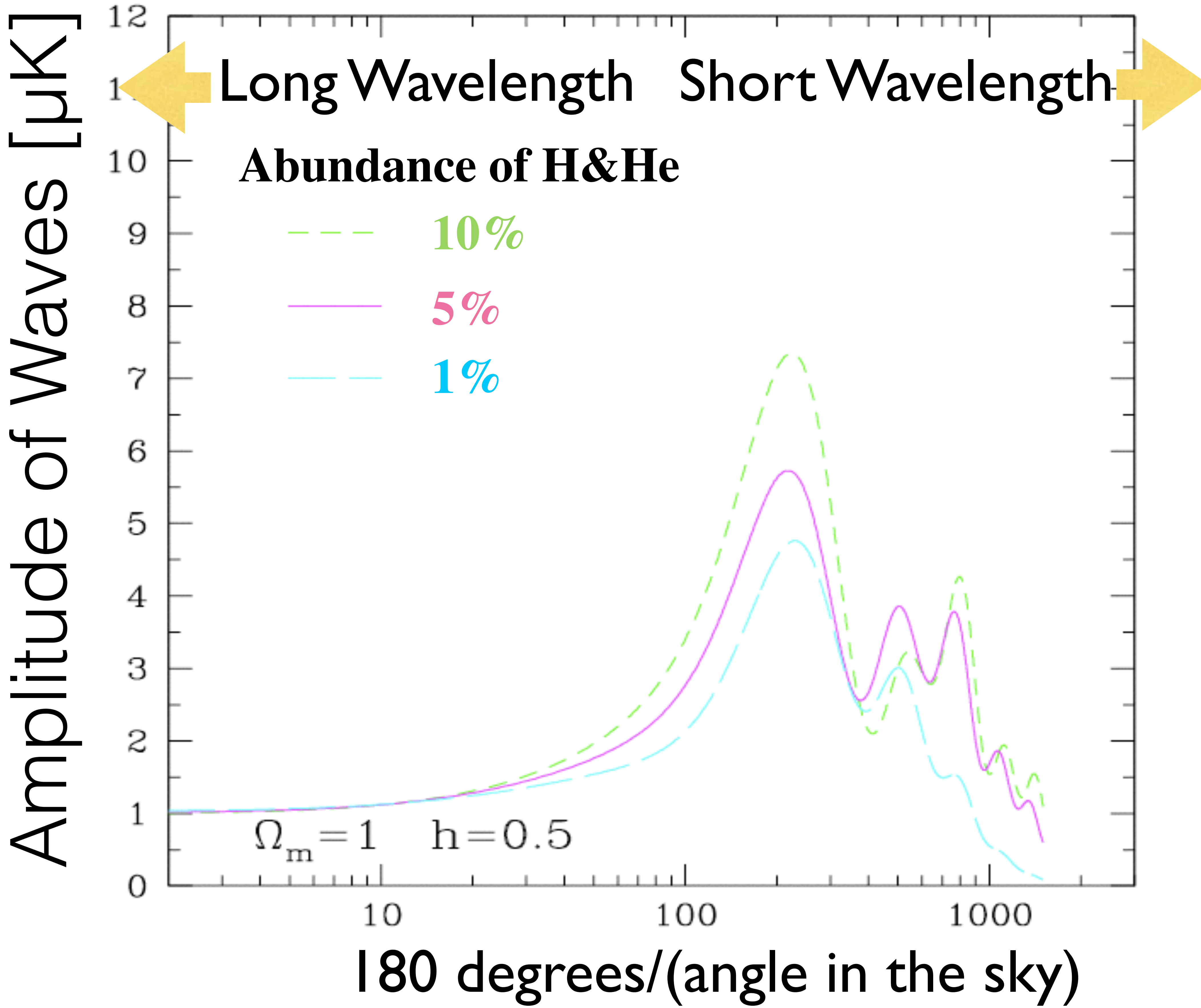


How baryons affect [photon density fluctuations]^2

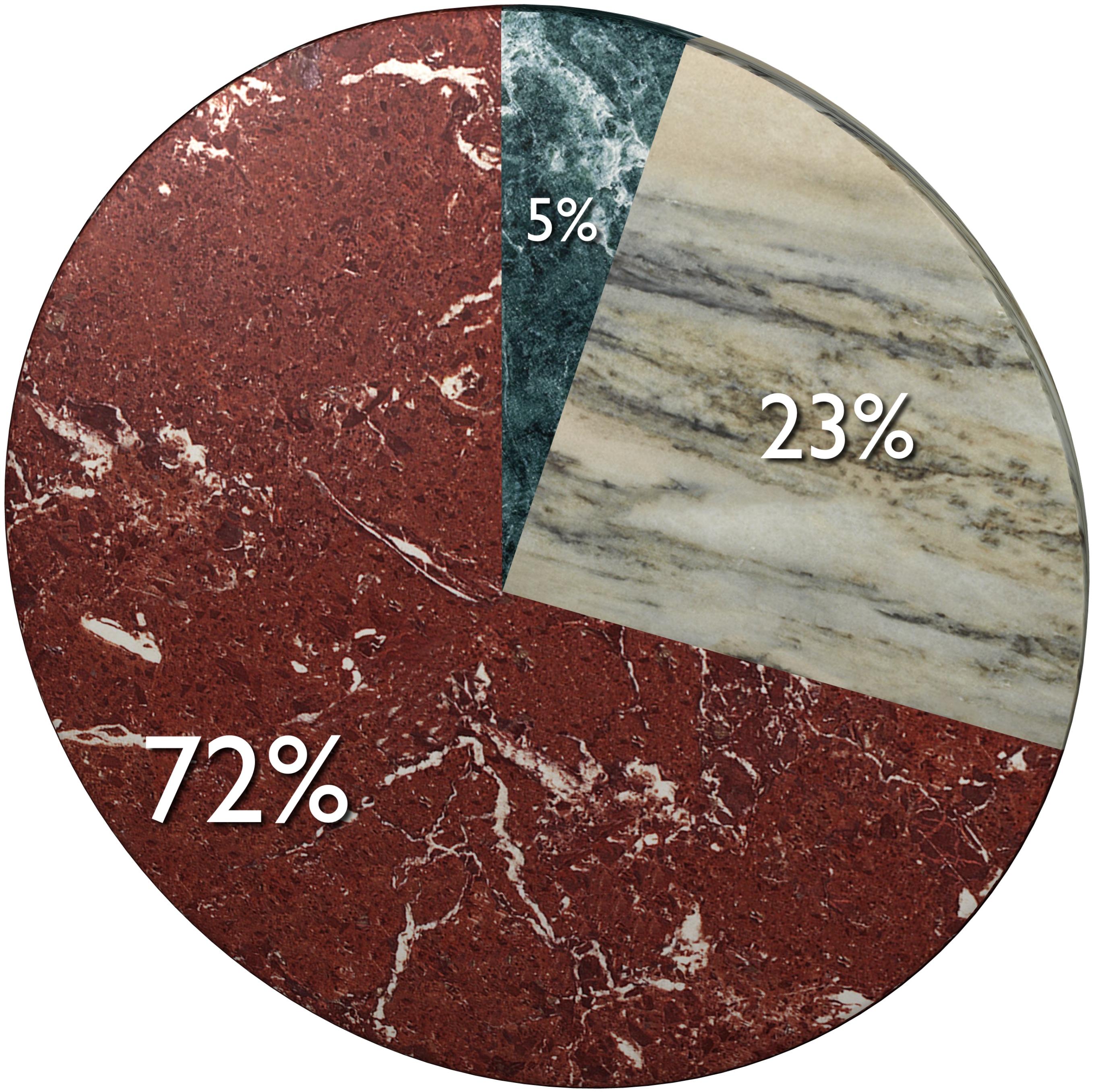


$$\left[\begin{array}{l} l_{1st} = k_{1st}\, d_A = \pi \dfrac{d_A}{r_s} \approx 300 \\ l_{2nd} = k_{2nd}\, d_A = 2\pi \dfrac{d_A}{r_s} \approx 600 \end{array}\right.$$

Measuring Abundance of H&He



Cosmic Pie Chart

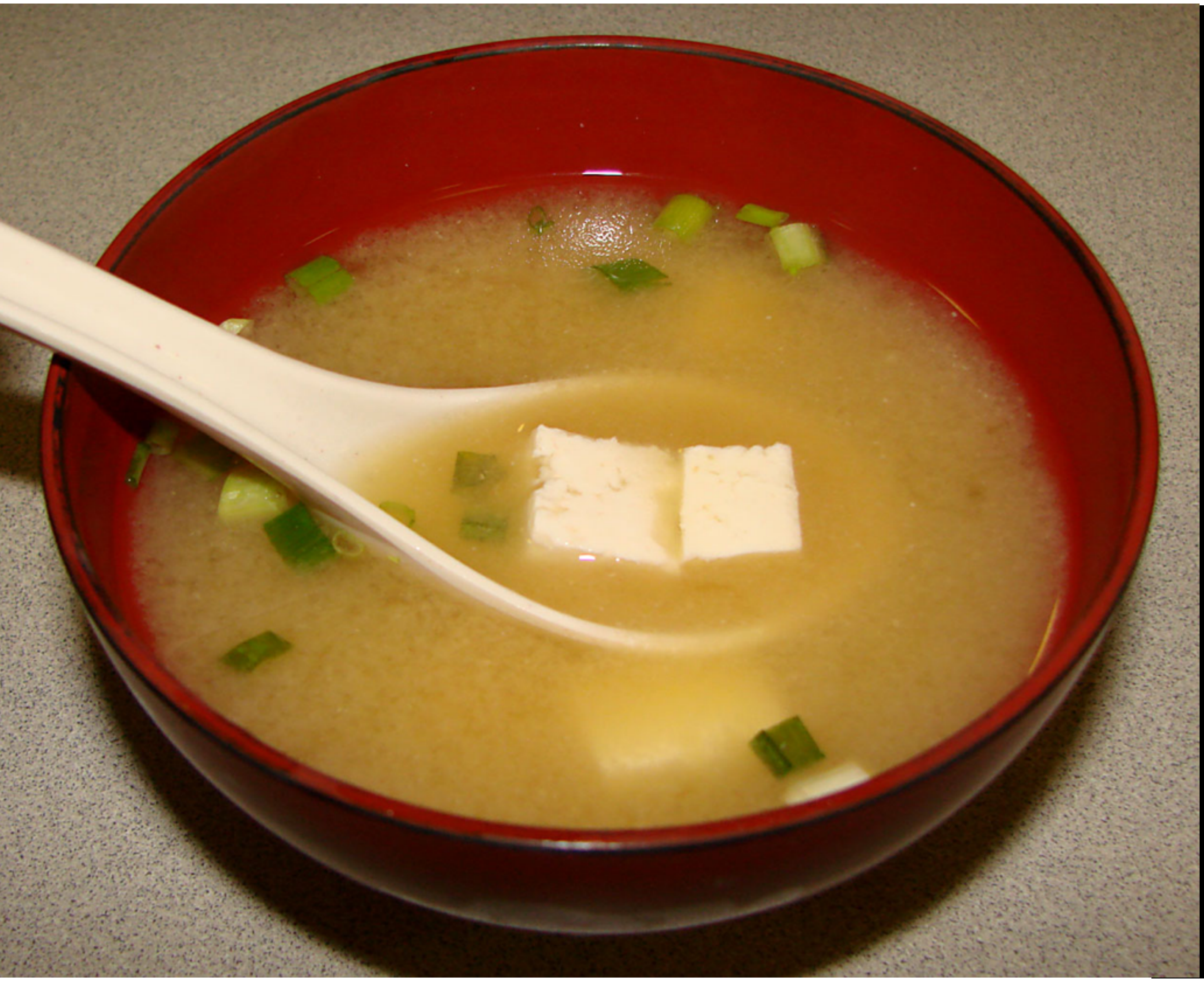


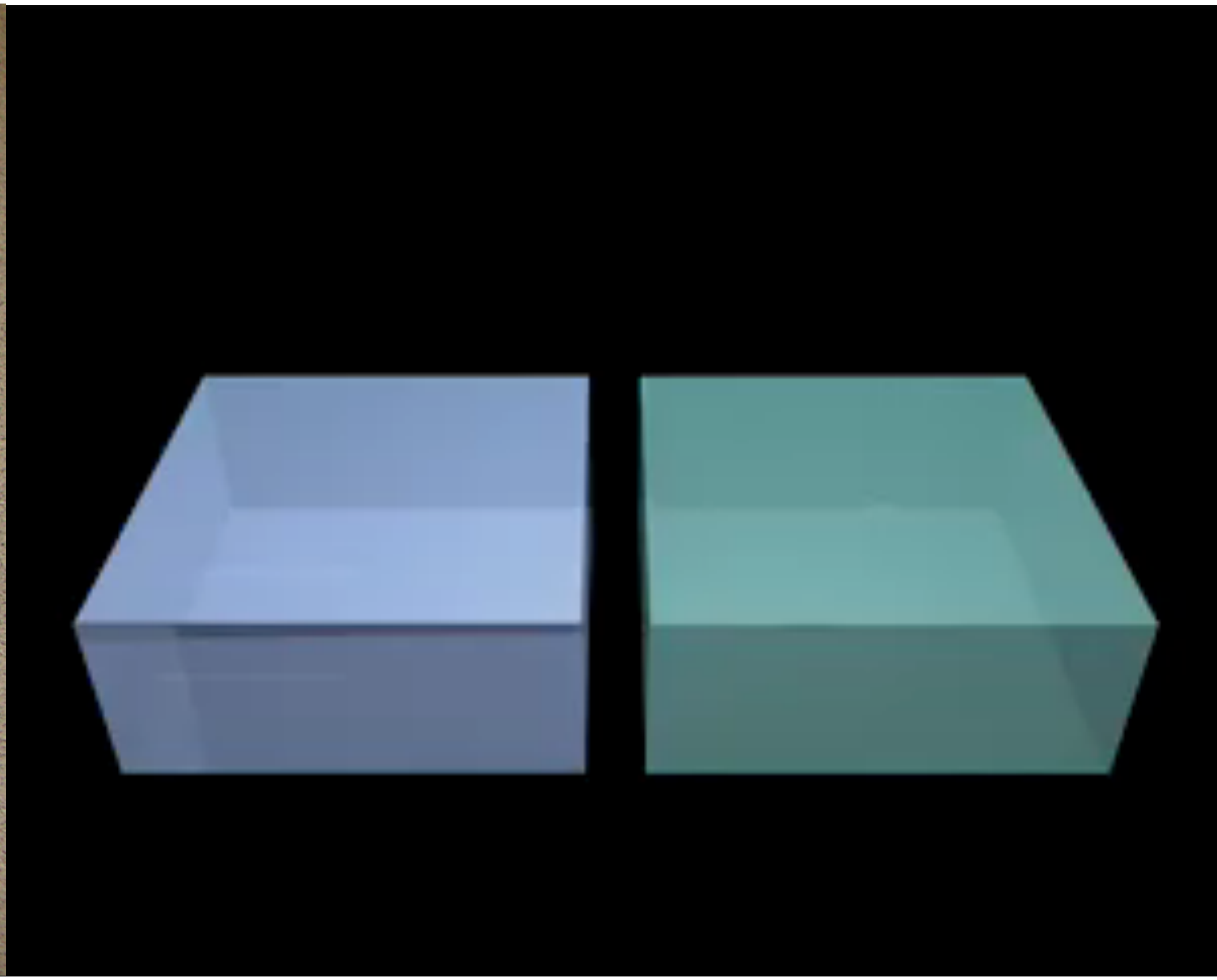
- WMAP determined the abundance of various components in the Universe
- As a result, **we came to realise that we do not understand 95% of our Universe…**

H&He
Dunkle Materie
Dunkle Energie

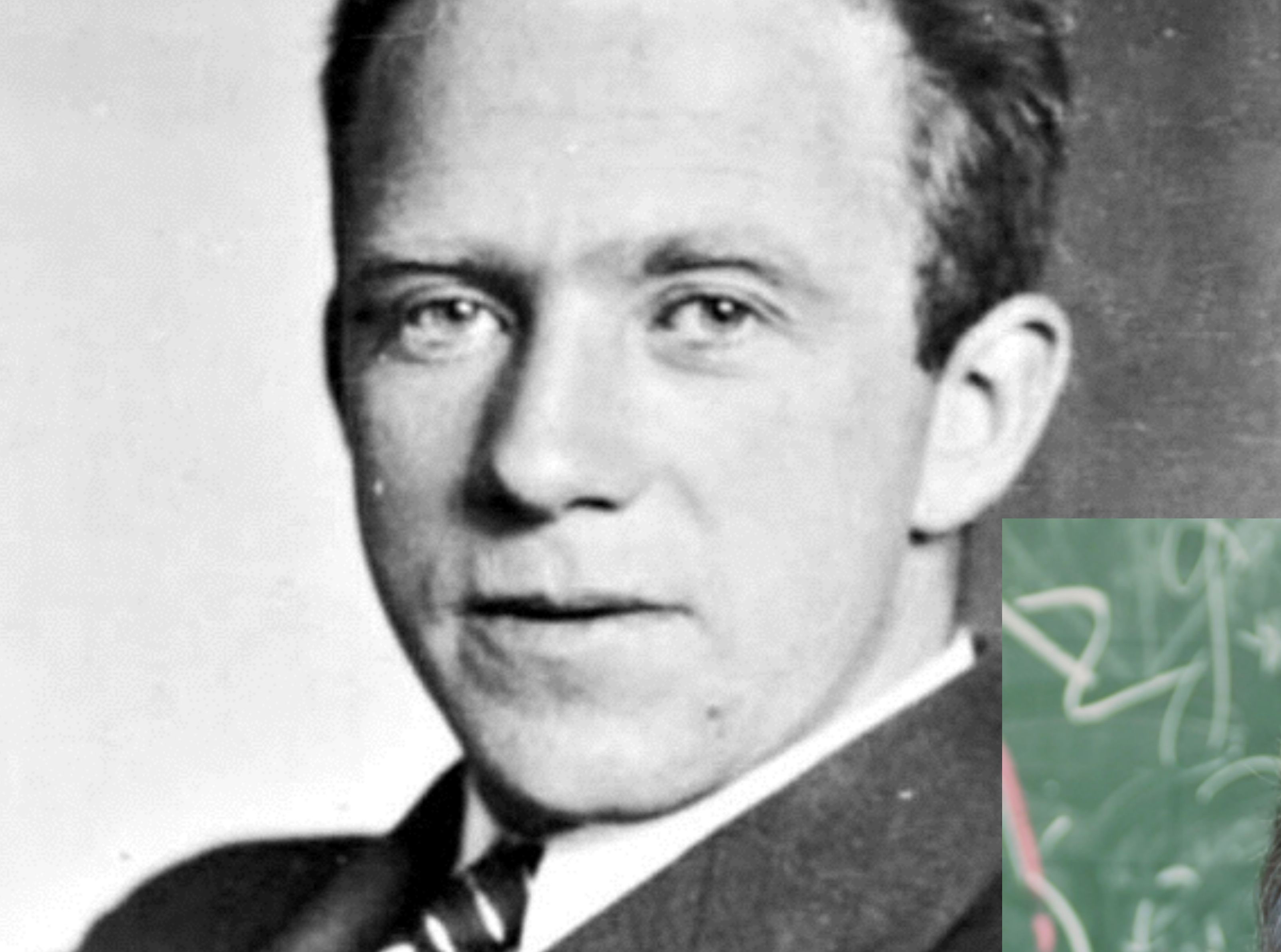
Origin of Fluctuations

- Who dropped those Tofus into the cosmic Miso soup?





Slava Mukhanov
[Munich University]



Werner Heisenberg
(1901–1976)

Leading Idea

- **Quantum Mechanics at work in the early Universe**
  (Mukhanov & Chibisov, 1981)
- **Werner Heisenberg's Uncertainty Principle:**
  - **[Energy you can borrow] x [Time you borrow] ~ h**
  - **Time was very short in the early Universe =**
    You could borrow a lot of energy
- **Those energies became the origin of fluctuations**
- How did quantum fluctuations on the microscopic scales become macroscopic fluctuations over cosmological sizes?

Outstanding Questions

- Where does anisotropy in CMB temperature come from?
  - This is the origin of galaxies, stars, planets, and everything else we see around us, including ourselves
- The leading idea: **quantum fluctuations in vacuum, stretched to cosmological length scales** by a rapid exponential expansion of the universe called "*cosmic inflation*" in the very early universe

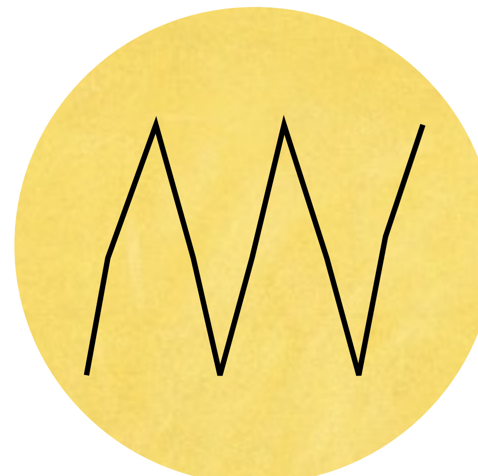
Starobinsky (1980); Sato (1981); Guth (1981); Linde (1982); Albrecht & Steinhardt (1982)

Cosmic Inflation

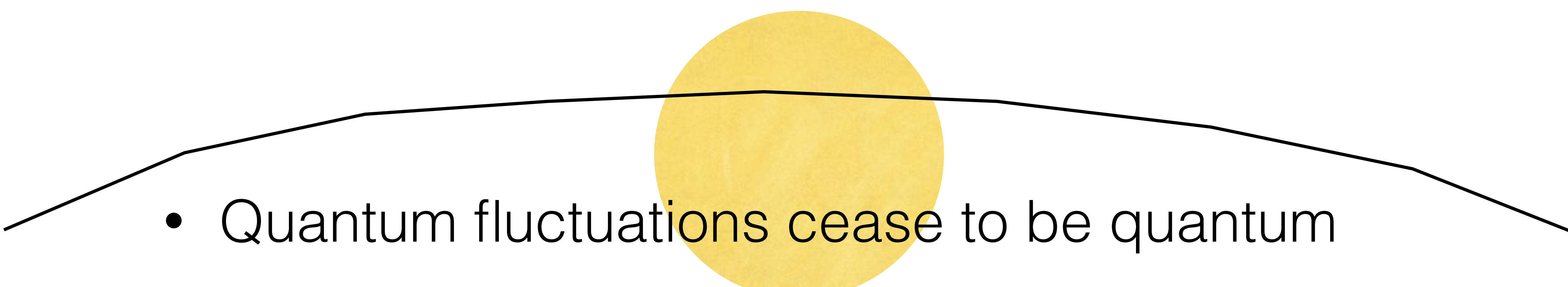
- In a tiny fraction of a second, the size of an atomic nucleus became the size of the Solar System
    - In 10^{-36} second, space was stretched by at least a factor of 10^{26}

Stretching Micro to Macro

Quantum fluctuations on microscopic scales



Inflation!



- Quantum fluctuations cease to be quantum
- Become macroscopic, classical fluctuations

Scalar and Tensor Modes

- A distance between two points in space

$$d\ell^2 = a^2(t)[1 + 2\zeta(\mathbf{x}, t)][\delta_{ij} + h_{ij}(\mathbf{x}, t)]dx^i dx^j$$

- ζ: "curvature perturbation" (scalar mode)
    - Perturbation to the determinant of the spatial metric
- h_{ij}: "gravitational waves" (tensor mode)
    - Perturbation that does not change the determinant (area)

$$\sum_i h_{ii} = 0$$

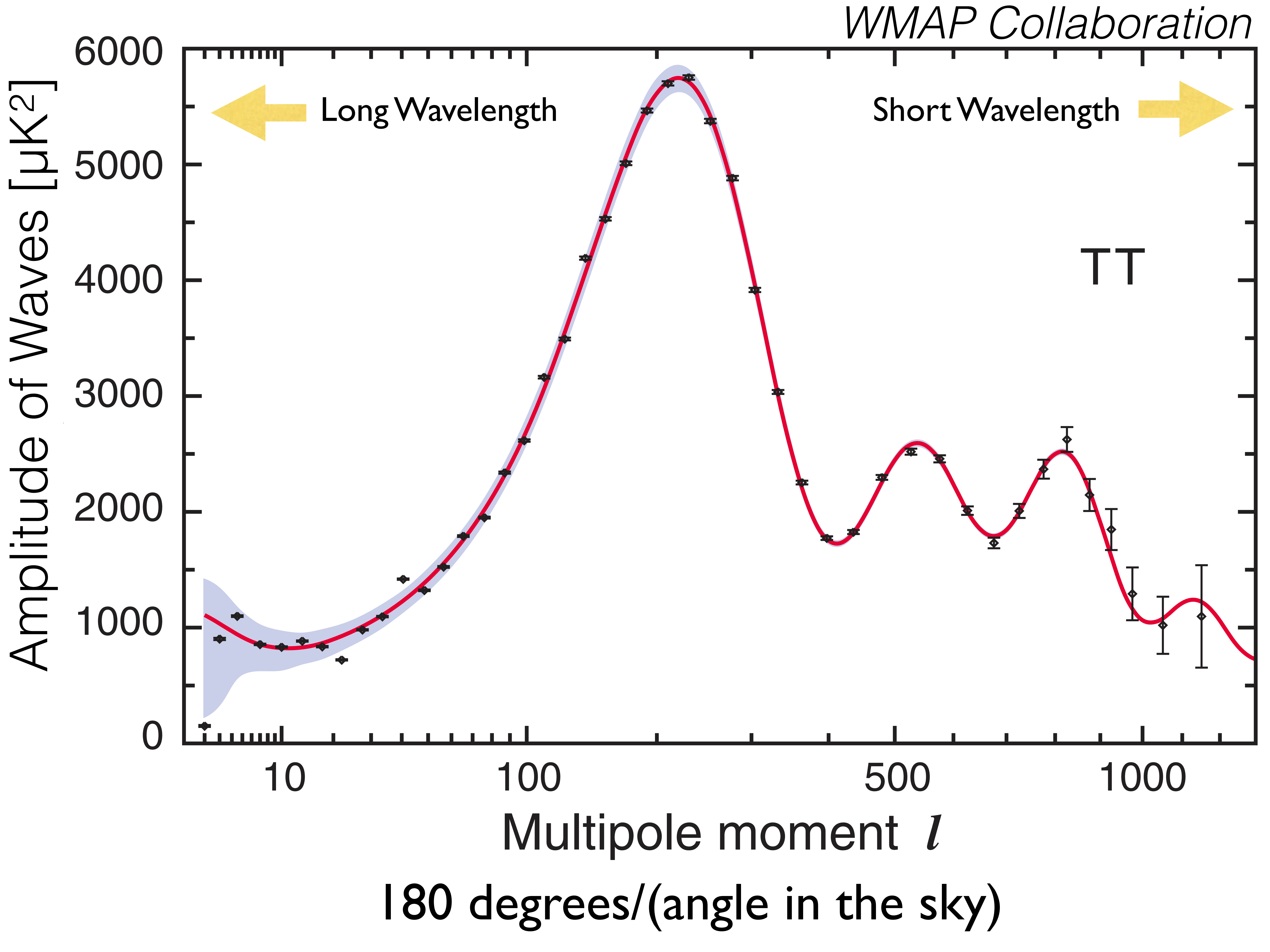
Tensor-to-scalar Ratio

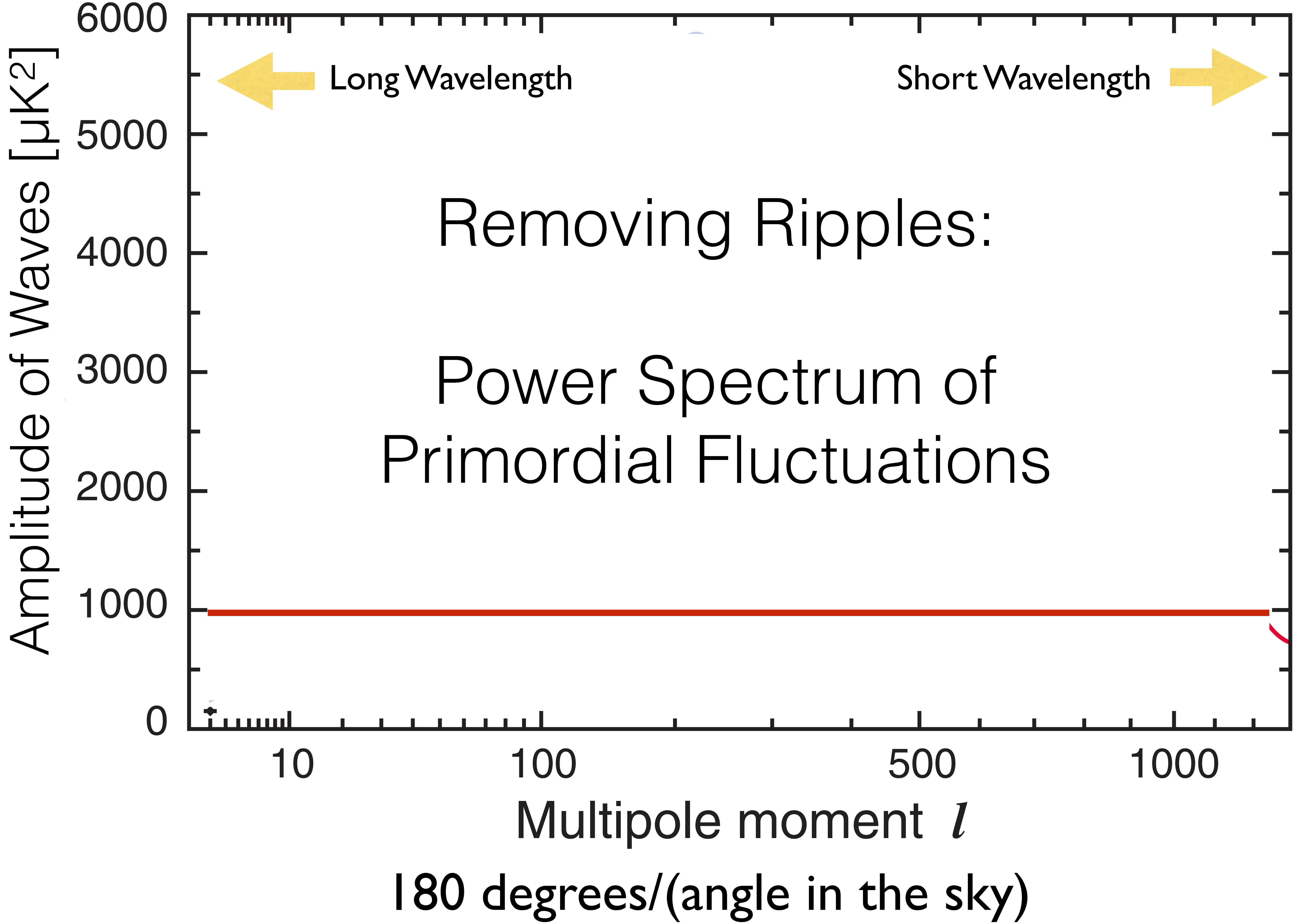
$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

- We really want to find this quantity!
- **The upper bound from the temperature anisotropy data: r<0.1** [WMAP & Planck]

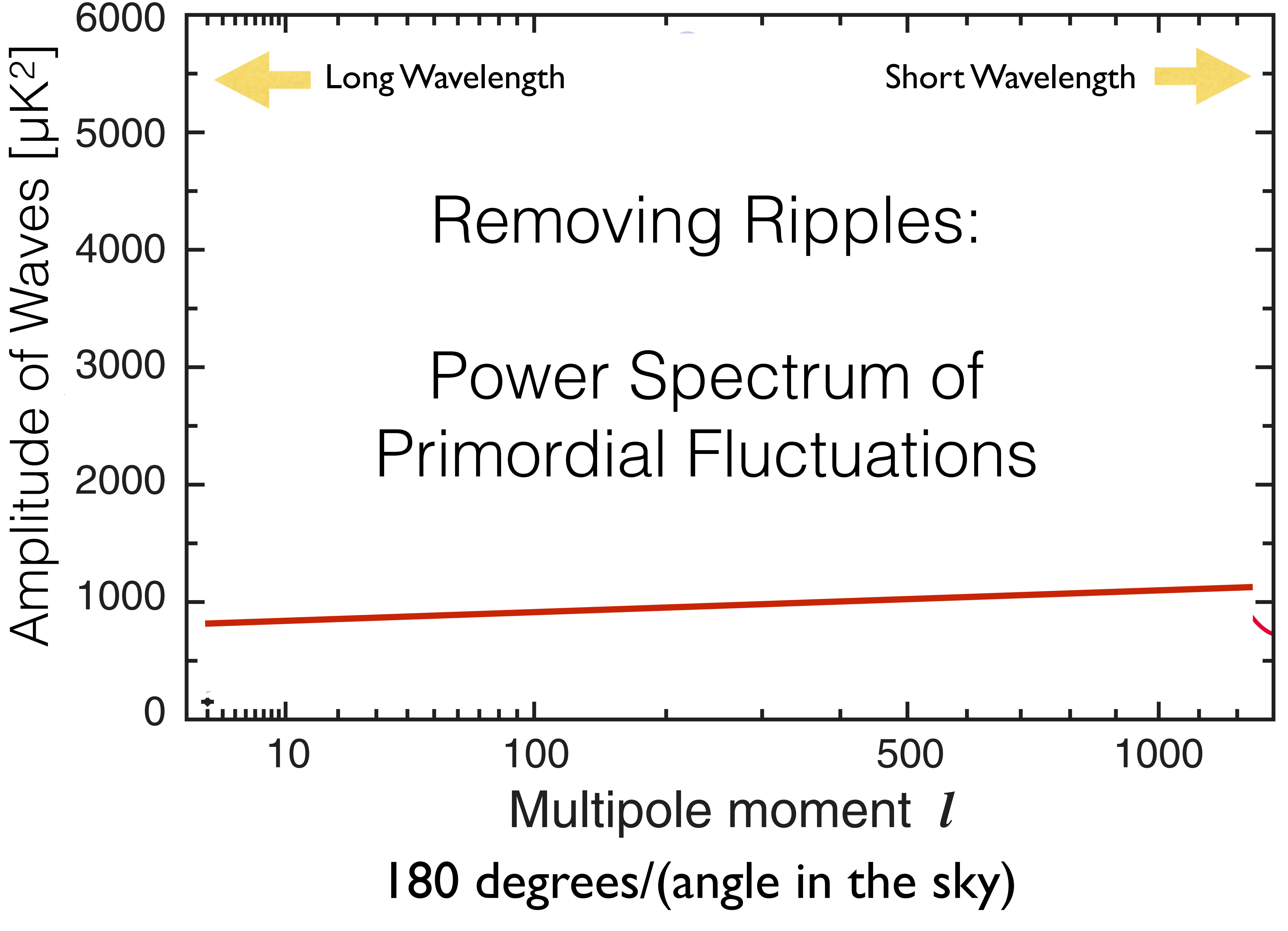
Fluctuations are proportional to H

- [Energy you can borrow] x [Time you borrow] = constant
- $H \equiv \frac{\dot{a}}{a}$ [This has units of 1/time]
- Then, **both ζ and h_{ij} are proportional to H**
- Inflation occurs in 10^{-36} second - this is such a short period of time that you can borrow a lot of energy! **H during inflation in energy units is 10^{14} GeV**


WMAP Collaboration
Long Wavelength
Short Wavelength
TT
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)



Removing Ripples:
Power Spectrum of Primordial Fluctuations
Long Wavelength
Short Wavelength
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)


Removing Ripples:
Power Spectrum of Primordial Fluctuations
Long Wavelength
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Amplitude of Waves [μK²]
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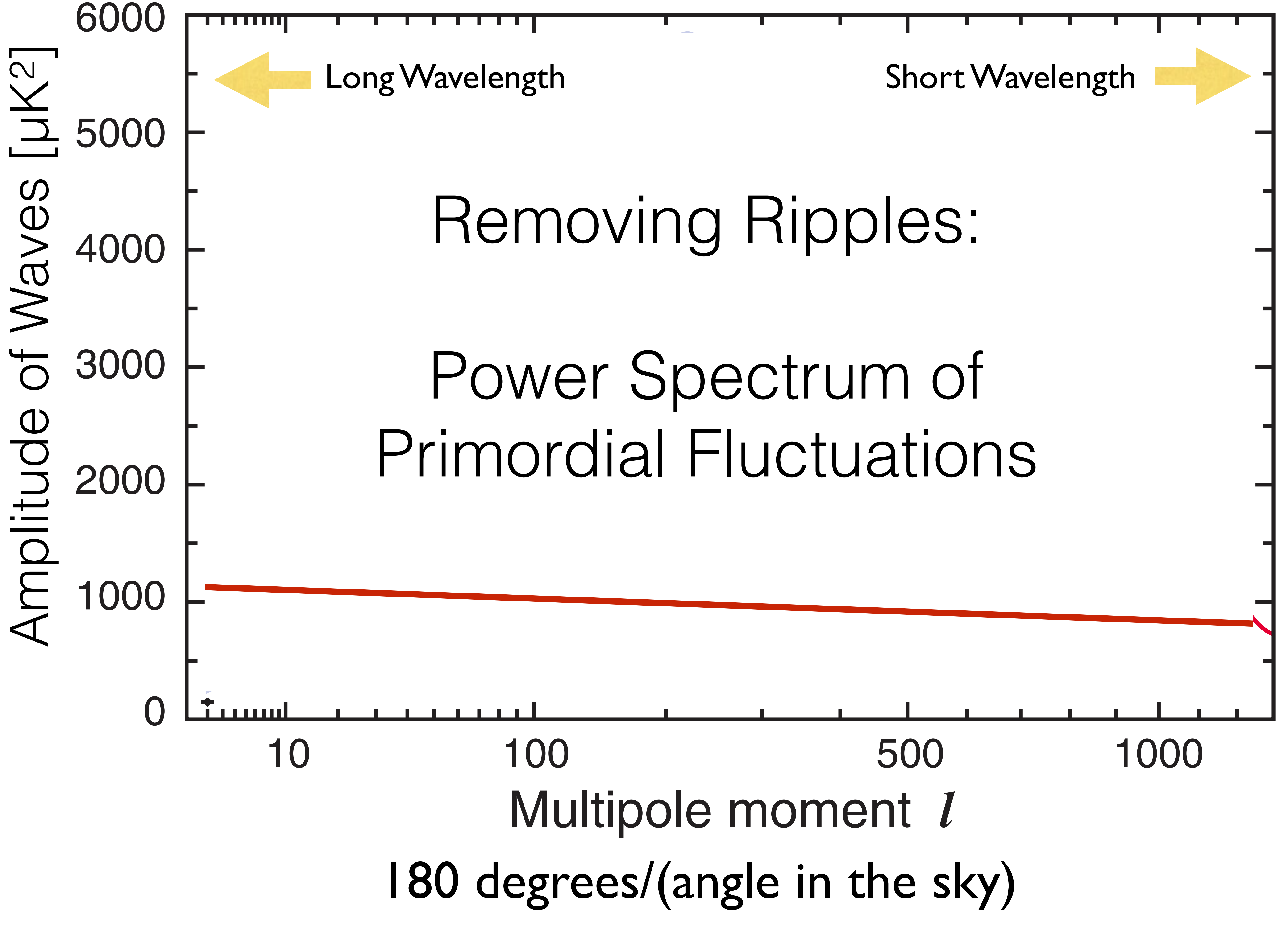
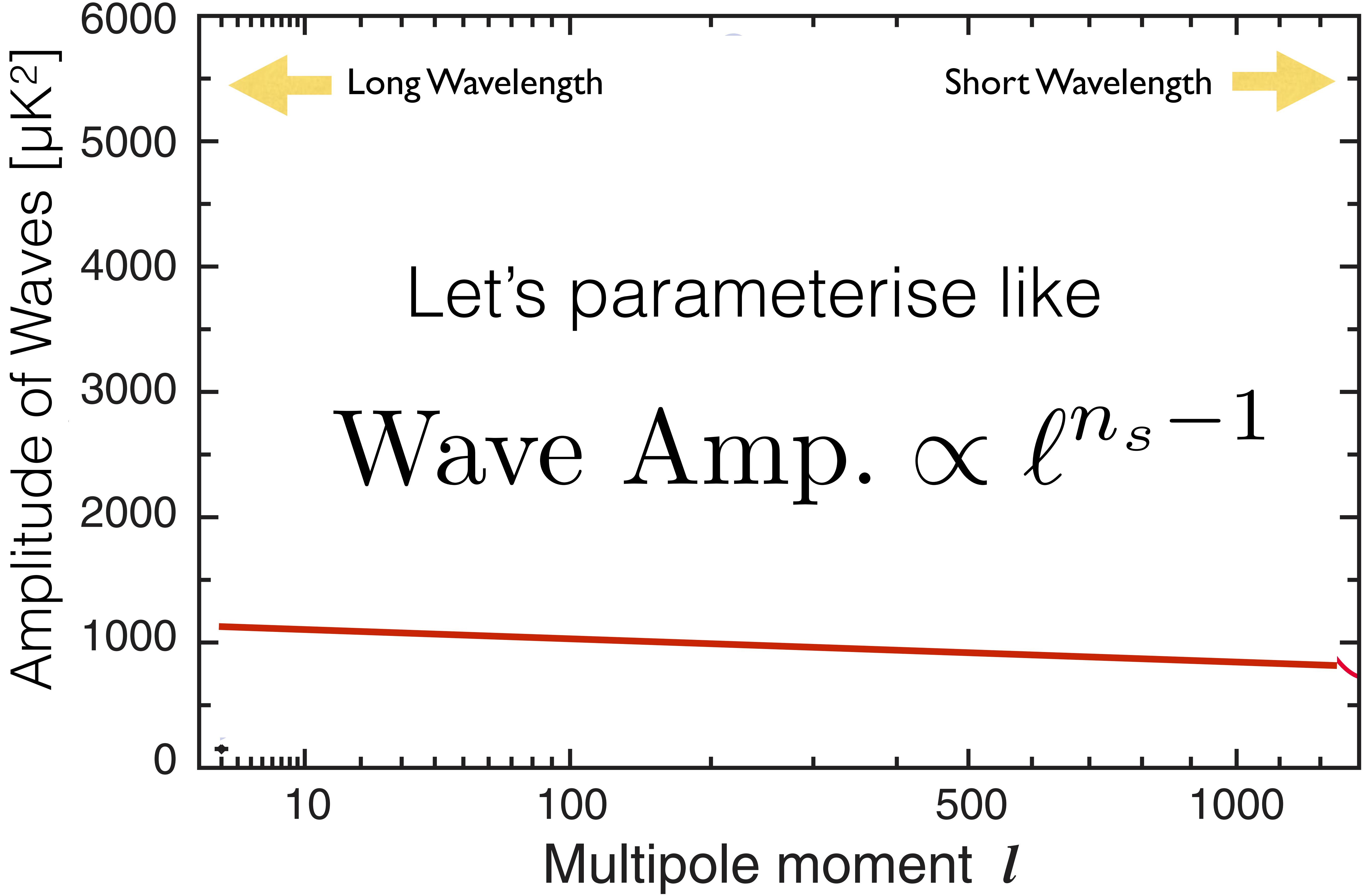
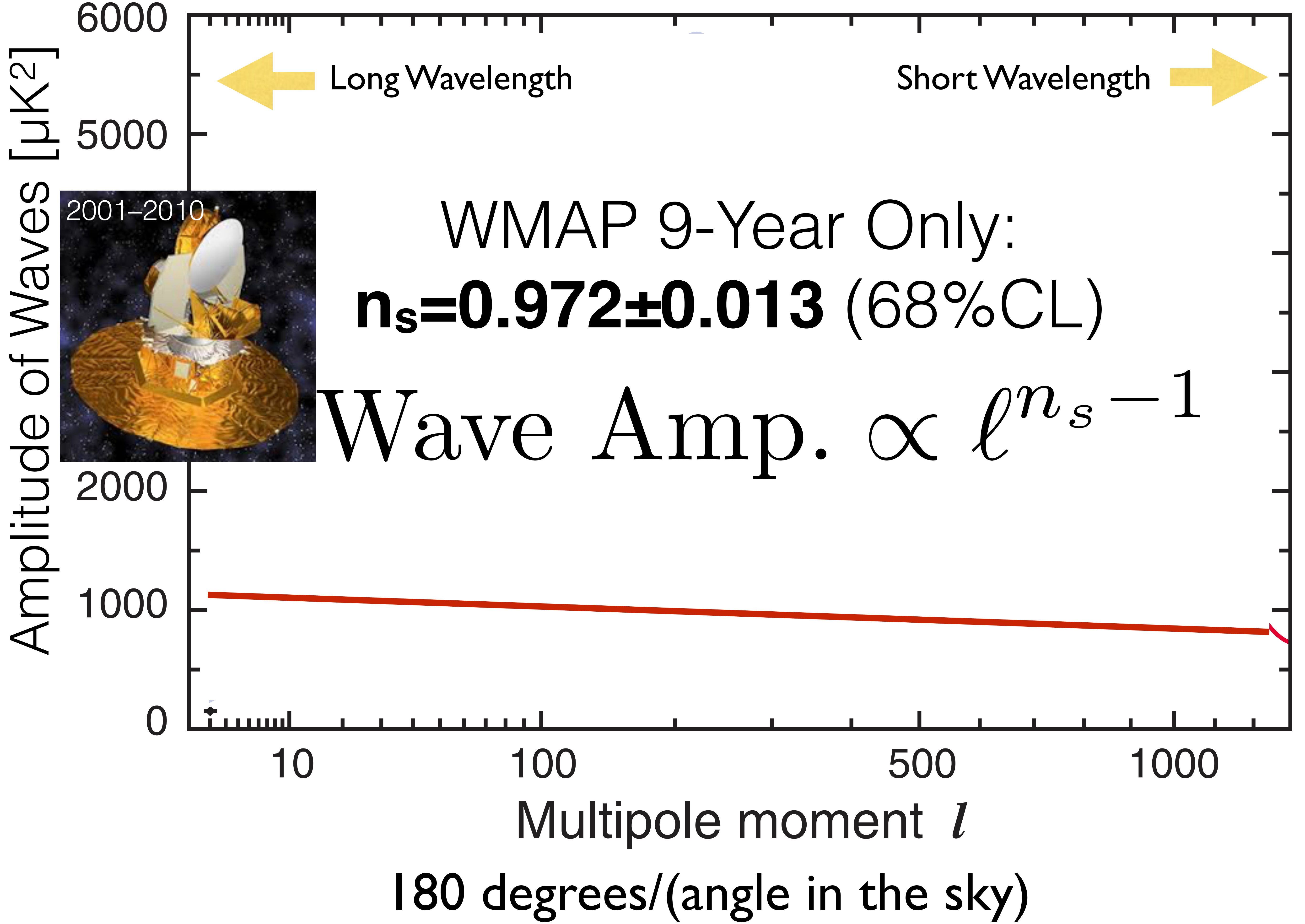
180 degrees/(angle in the sky)



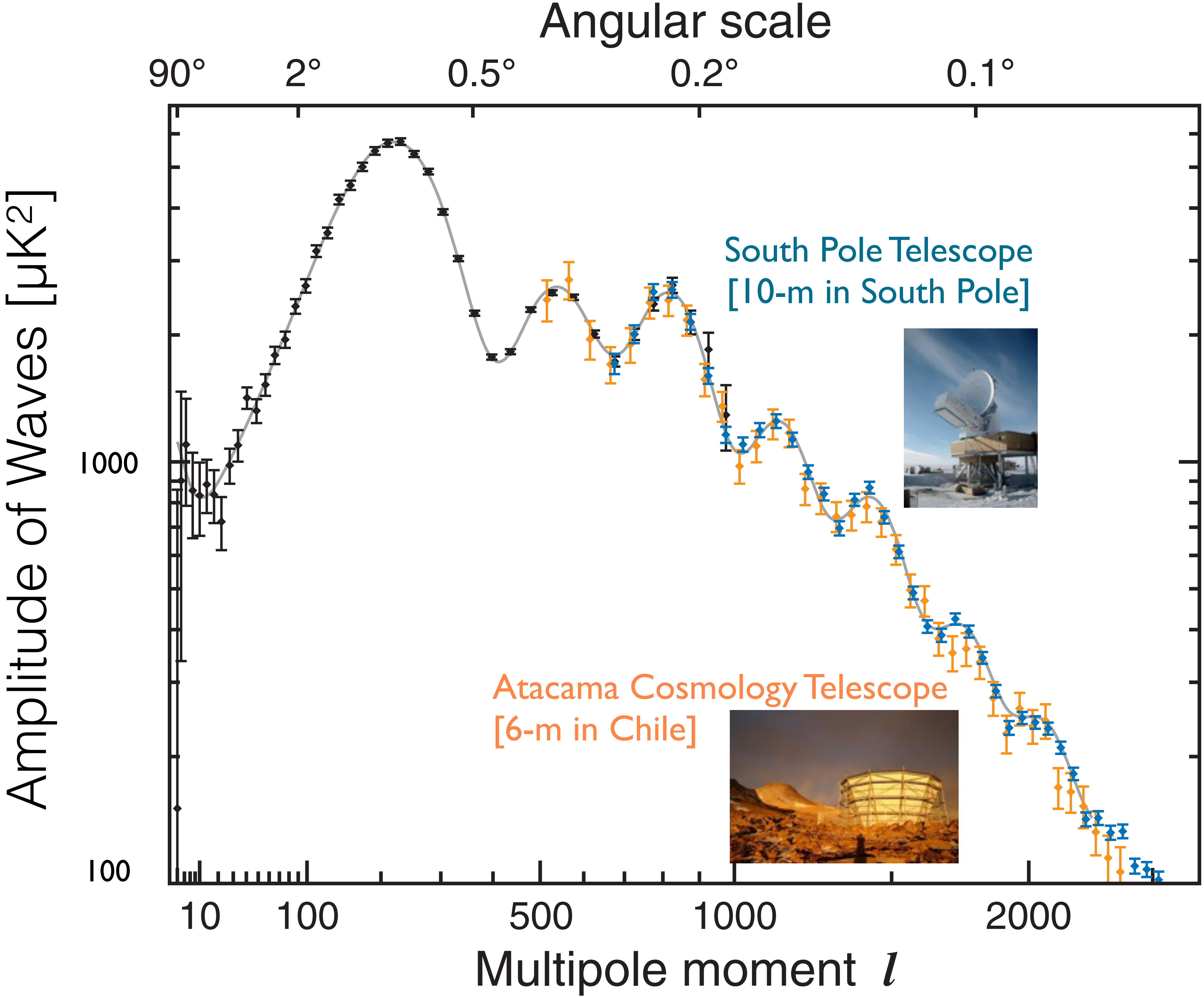
Amplitude of Waves [μK²]
6000
5000
4000
3000
2000
1000
0
Long Wavelength
Short Wavelength
Removing Ripples:
Power Spectrum of Primordial Fluctuations
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)



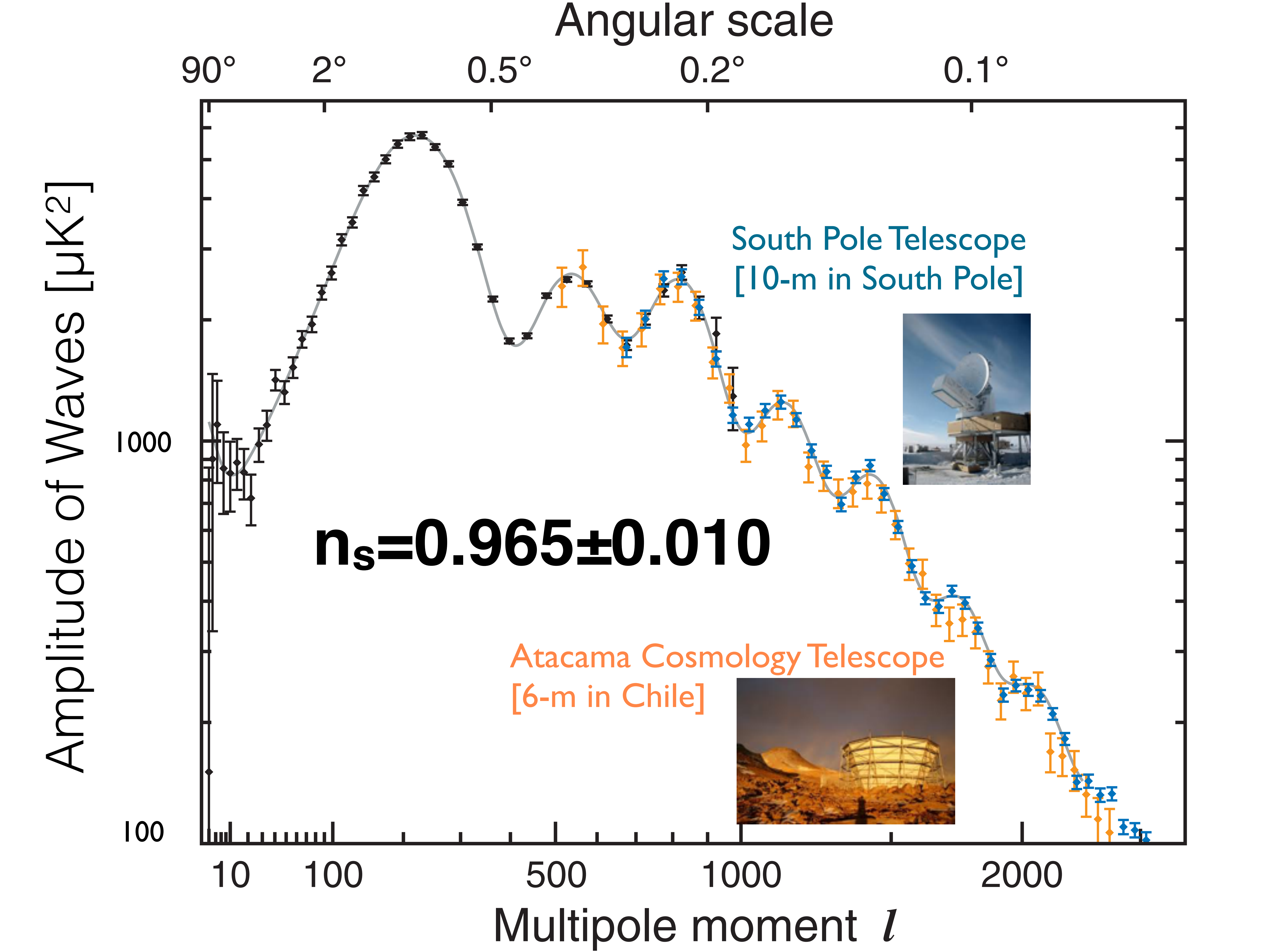
180 degrees/(angle in the sky)



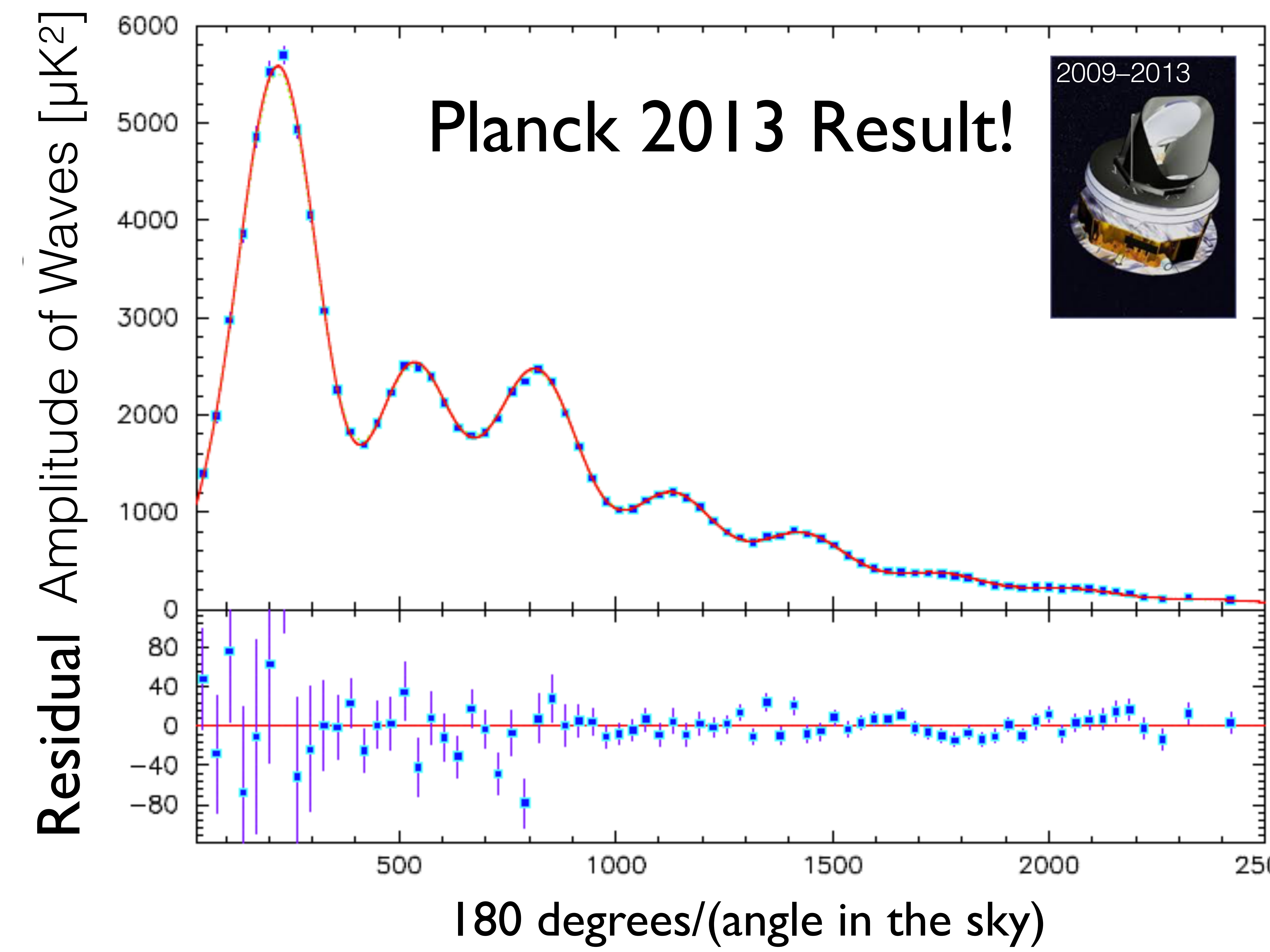
Long Wavelength
Short Wavelength
2001–2010
WMAP 9-Year Only:
n_s=0.972±0.013 (68%CL)
$$\text{Wave Amp.} \propto \ell^{n_s - 1}$$
Amplitude of Waves [μK²]
6000
5000
2000
1000
0
10
100
500
1000
Multipole moment l
180 degrees/(angle in the sky)

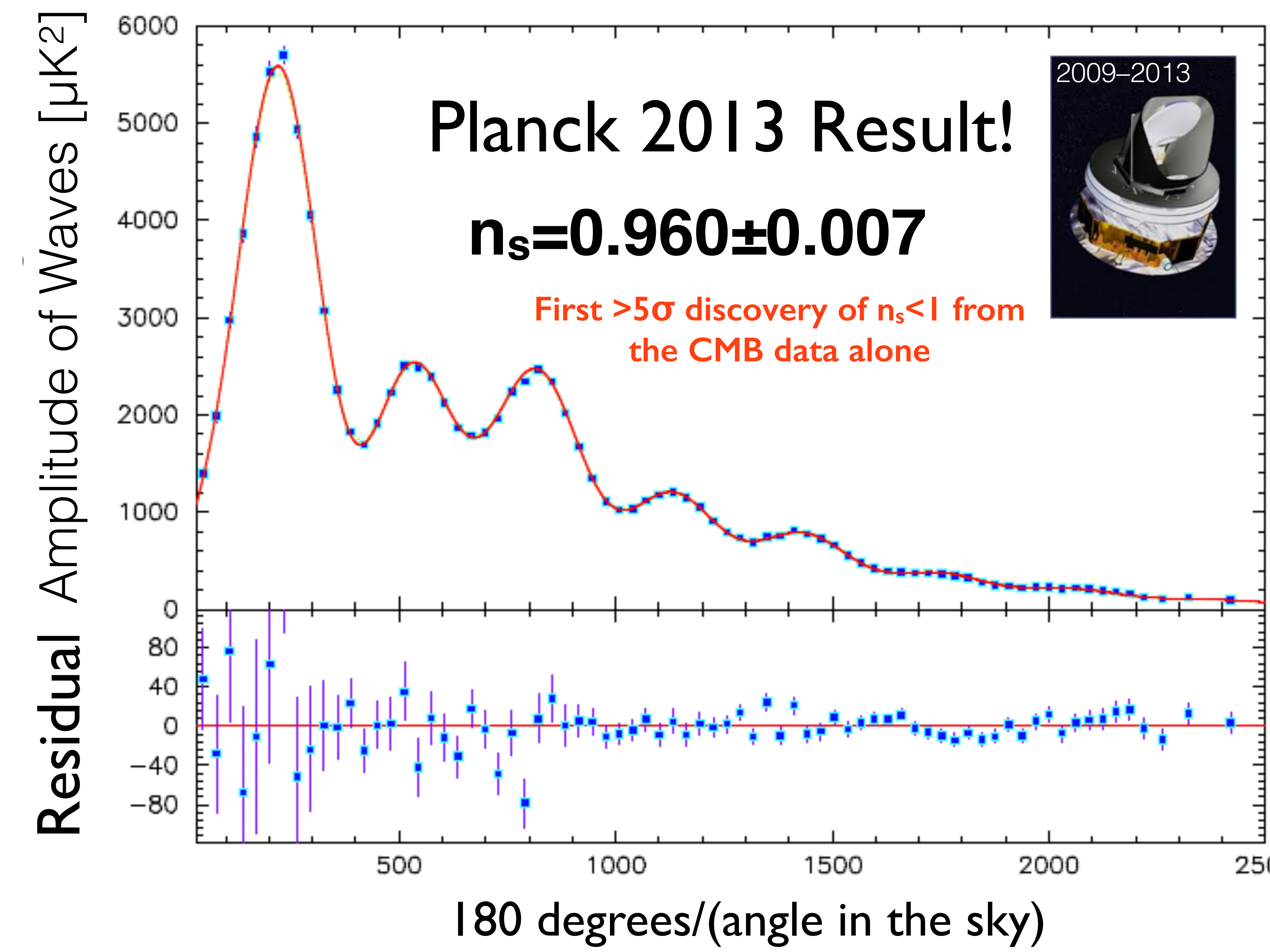


Angular scale
90°
2°
0.5°
0.2°
0.1°
Amplitude of Waves [μK^2]
1000
100
10
100
500
1000
2000
Multipole moment l
South Pole Telescope
[10-m in South Pole]
Atacama Cosmology Telescope
[6-m in Chile]



Angular scale
90°
2°
0.5°
0.2°
0.1°
Amplitude of Waves [μK²]
1000
100
South Pole Telescope
[10-m in South Pole]
n_s=0.965±0.010
Atacama Cosmology Telescope
[6-m in Chile]
10
100
500
1000
2000
Multipole moment l


Planck 2013 Result!
2009–2013
Amplitude of Waves [μK²]
Residual
180 degrees/(angle in the sky)
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000



Planck 2013 Result!
n_s=0.960±0.007
First >5σ discovery of n_s<1 from the CMB data alone
2009–2013
Amplitude of Waves [μK^2]
Residual
180 degrees/(angle in the sky)
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000

Predicted in 1981. Finally discovered in 2013 by WMAP and Planck

- Inflation must end
- Inflation predicts $n_s \sim 1$, but not exactly equal to 1. Usually $n_s < 1$ is expected
- **The discovery of $n_s < 1$ has been the dream of cosmologists since 1992,** when the CMB anisotropy was discovered and $n_s \sim 1$ (to within 10%) was indicated

Slava Mukhanov said in his 1981 paper that n_s should be less than 1

Nearly de Sitter Space

- When ε<<1, the universe expands quasi-exponentially.
$$\epsilon \equiv -\frac{\dot{H}}{H^2} < 1$$
- If ε=0, space-time is exactly de Sitter:

$$ds^2 = -dt^2 + e^{2Ht}d\mathbf{x}^2$$

- *But, inflation never ends if ε=0.* When ε<<1, space-time is nearly, but not exactly, de Sitter:

$$ds^2 = -dt^2 + e^{2\int dt' H(t')}d\mathbf{x}^2$$

Symmetry of de Sitter Space

$$ds^2 = -dt^2 + e^{2Ht} d\mathbf{x}^2$$

- De Sitter spacetime is invariant under 10 isometries (transformations that keep ds^2 invariant):

- Time translation, followed by space dilation

$$t \to t - \lambda/H \,, \quad \mathbf{x} \to e^{\lambda}\mathbf{x}$$

- Spatial rotation, $\mathbf{x} \to R\mathbf{x}$
- Spatial translation, $\mathbf{x} \to \mathbf{x} + c$
- Three more transformations irrelevant to this talk

$\varepsilon \neq 0$ breaks space dilation invariance

$$ds^2 = -dt^2 + e^{2Ht} d\mathbf{x}^2$$

- De Sitter spacetime is invariant under 10 isometries (transformations that keep ds^2 invariant):

- Time translation, followed by space dilation

$$t \to t - \lambda/H\,, \quad \mathbf{x} \to e^{\lambda}\mathbf{x}$$

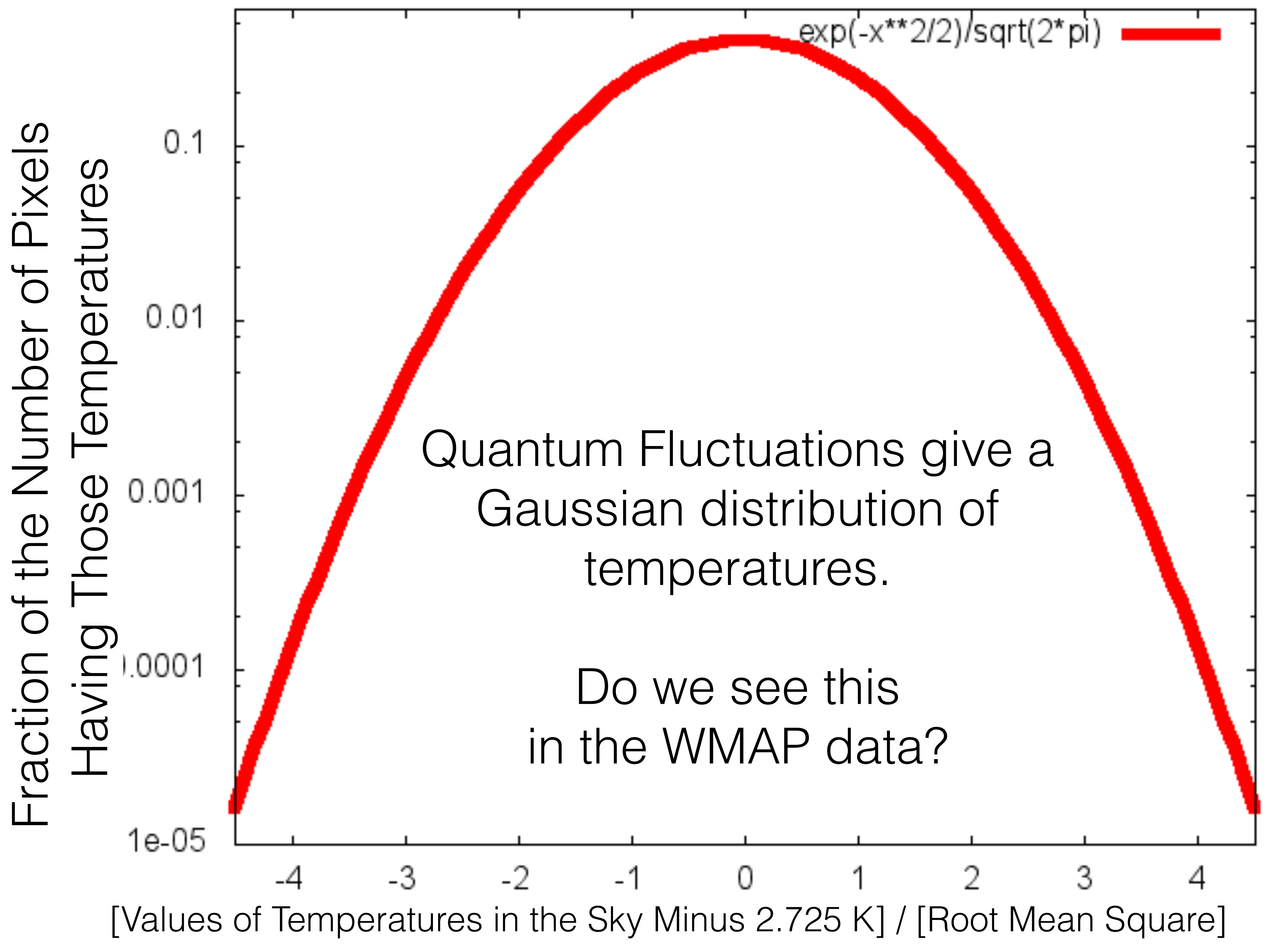
- Spatial rotation, $\mathbf{x} \to R\mathbf{x}$

- Spatial translation, $\mathbf{x} \to \mathbf{x} + c$

- And three more transformations

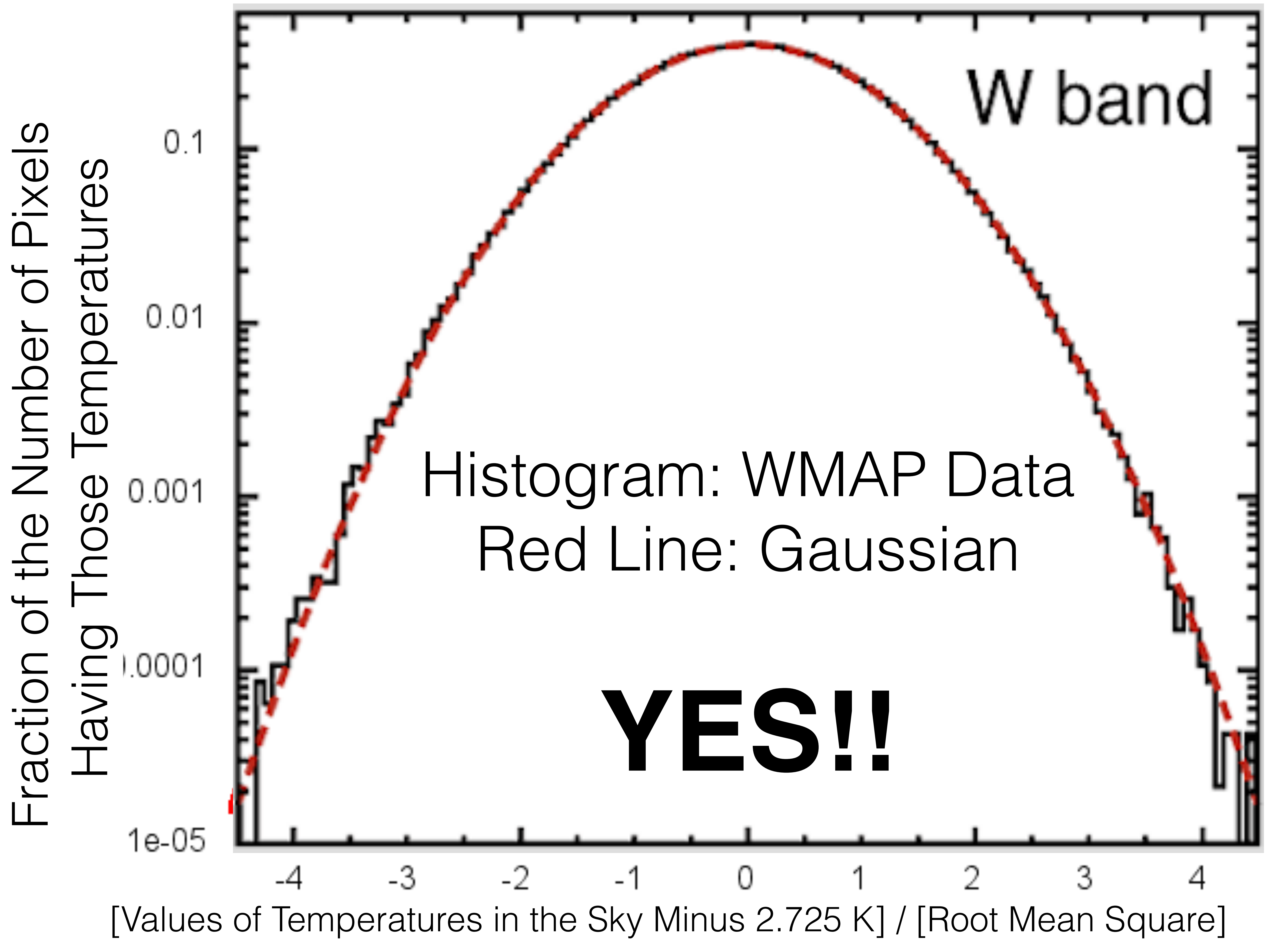
Thus, n_s<1 is fairly generic to inflation

How do we know that primordial fluctuations were of *quantum mechanical origin*?

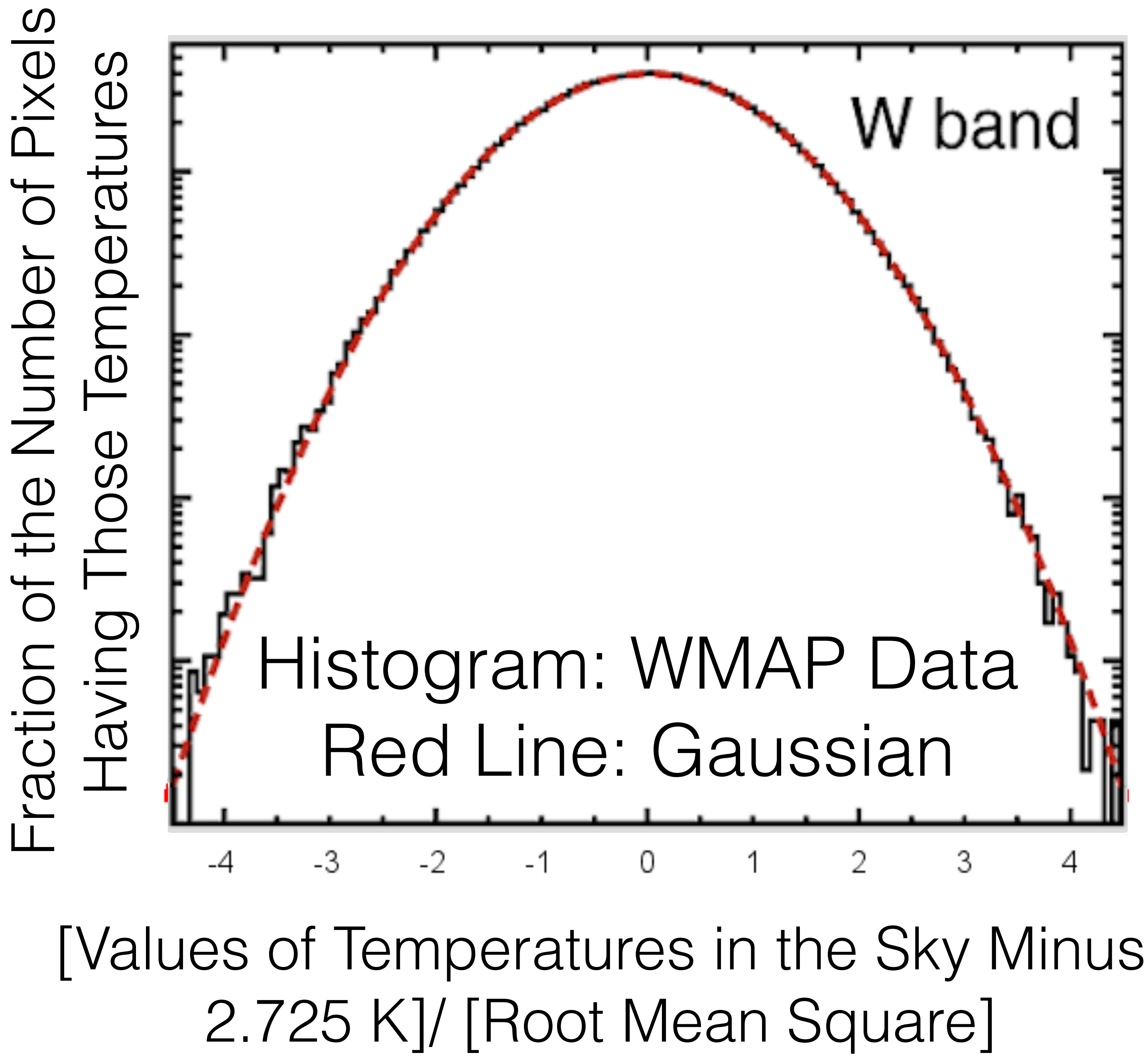


Quantum Fluctuations give a Gaussian distribution of temperatures.

Do we see this in the WMAP data?


W band
Histogram: WMAP Data
Red Line: Gaussian
YES!!
Fraction of the Number of Pixels
Having Those Temperatures
0.1
0.01
0.001
1e-05
-4
-3
-2
-1
0
1
2
3
4
[Values of Temperatures in the Sky Minus 2.725 K] / [Root Mean Square]

Testing Gaussianity



Since a Gauss distribution is symmetric, it must yield a vanishing **3-point function**

$$\langle \delta T^3 \rangle \equiv \int_{-\infty}^{\infty} d\delta T \; P(\delta T) \delta T^3$$

More specifically, we measure this using temperatures at three different locations and average:

$$\langle \delta T(\hat{n}_1) \delta T(\hat{n}_2) \delta T(\hat{n}_3) \rangle$$

Non-Gaussianity:

A Powerful Test of Quantum Fluctuations

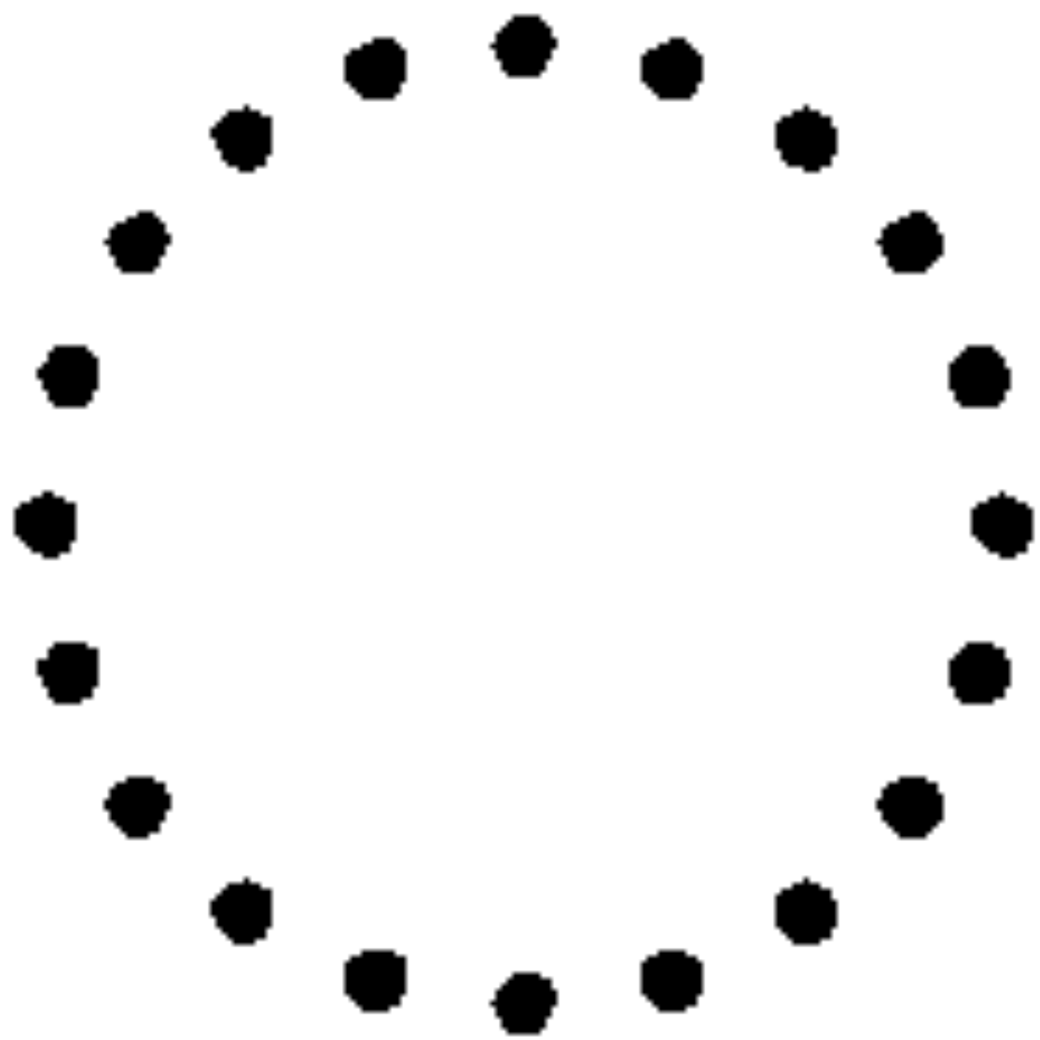
- The WMAP data show that the distribution of temperature fluctuations of CMB is **very precisely** Gaussian
  - with an upper bound on a deviation of **0.2%**
- With improved data provided by the Planck mission, the upper bound is now **0.03%**

CMB Research: Next Frontier

Primordial Gravitational Waves

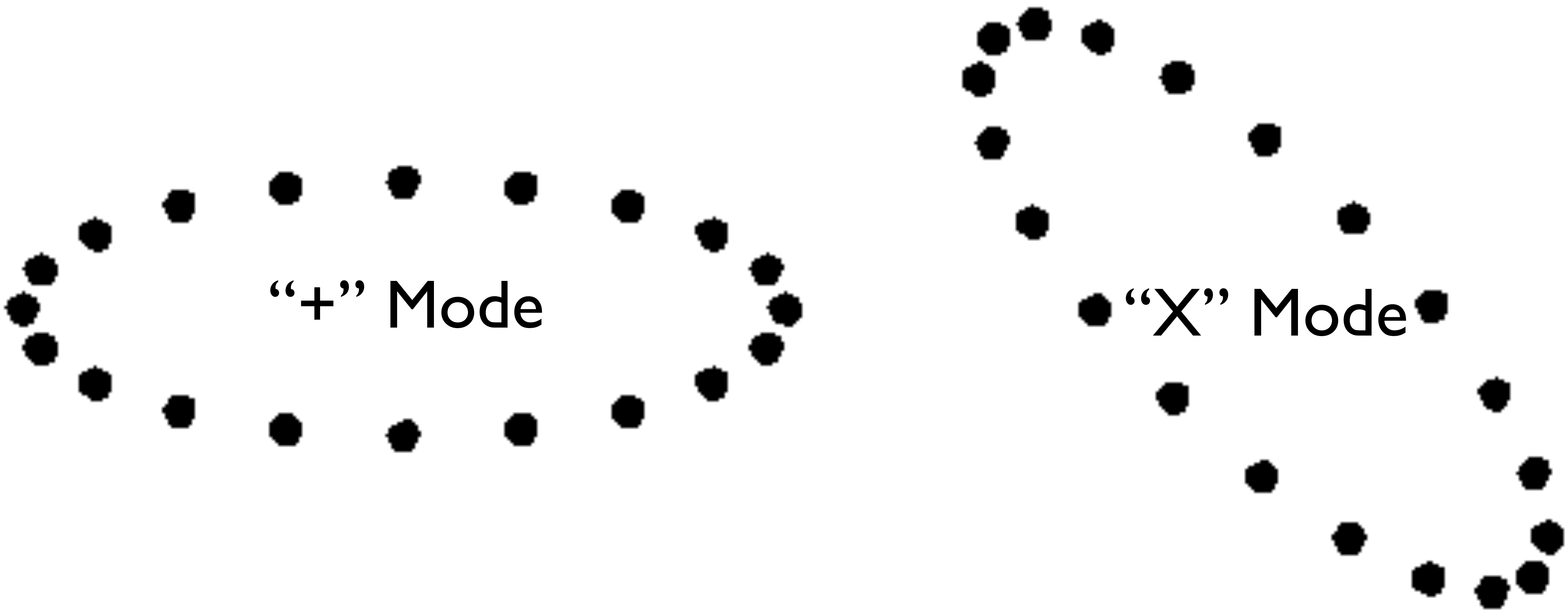
Extraordinary claims require extraordinary evidence. The same quantum fluctuations could also generate gravitational waves, and we wish to find them

Gravitational Waves Are Coming Toward You!



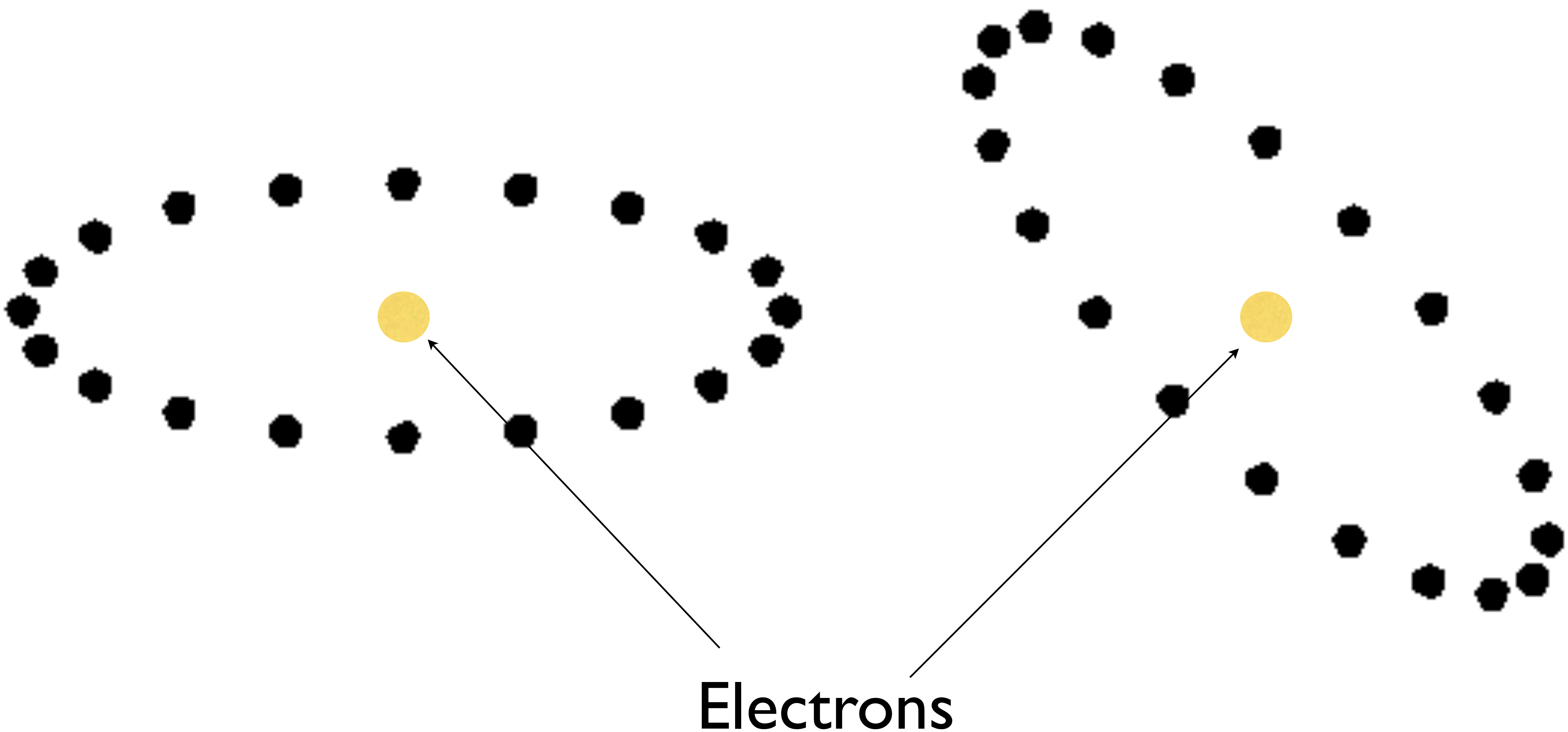
Gravitational waves stretch and contract space, moving particles

Two Modes

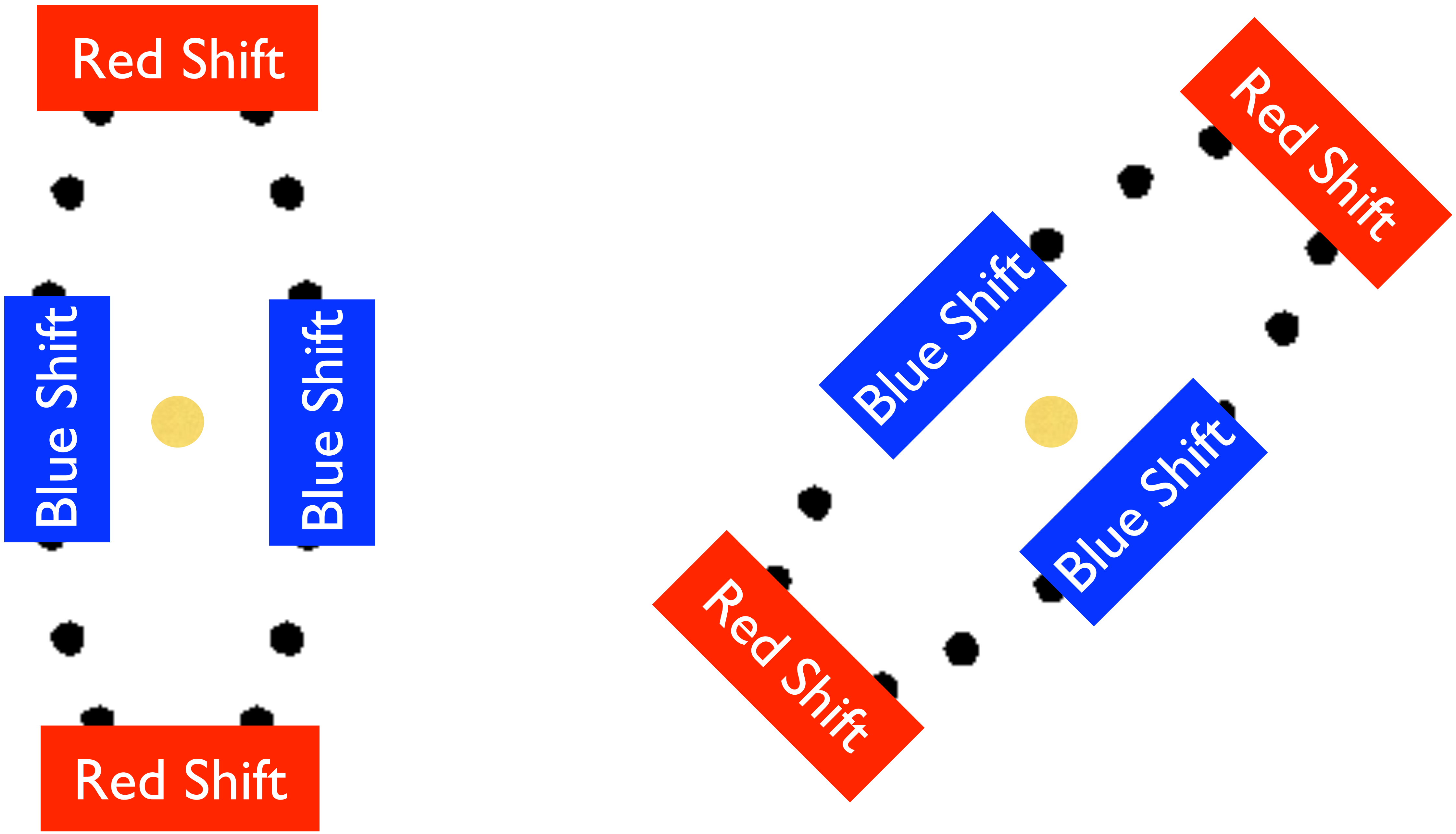


How do they change temperatures?

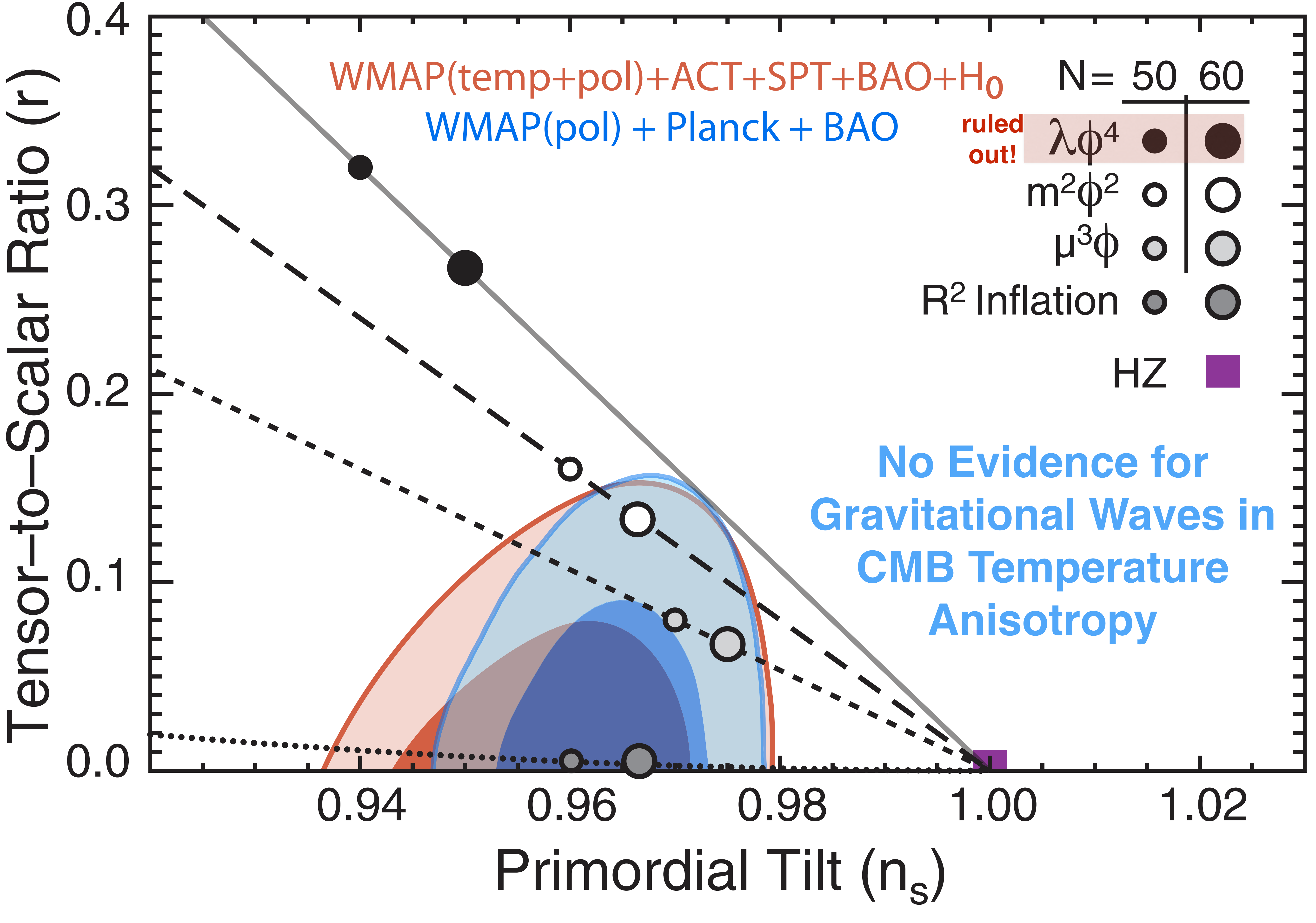
Gravitational Waves to Temperature Fluctuations



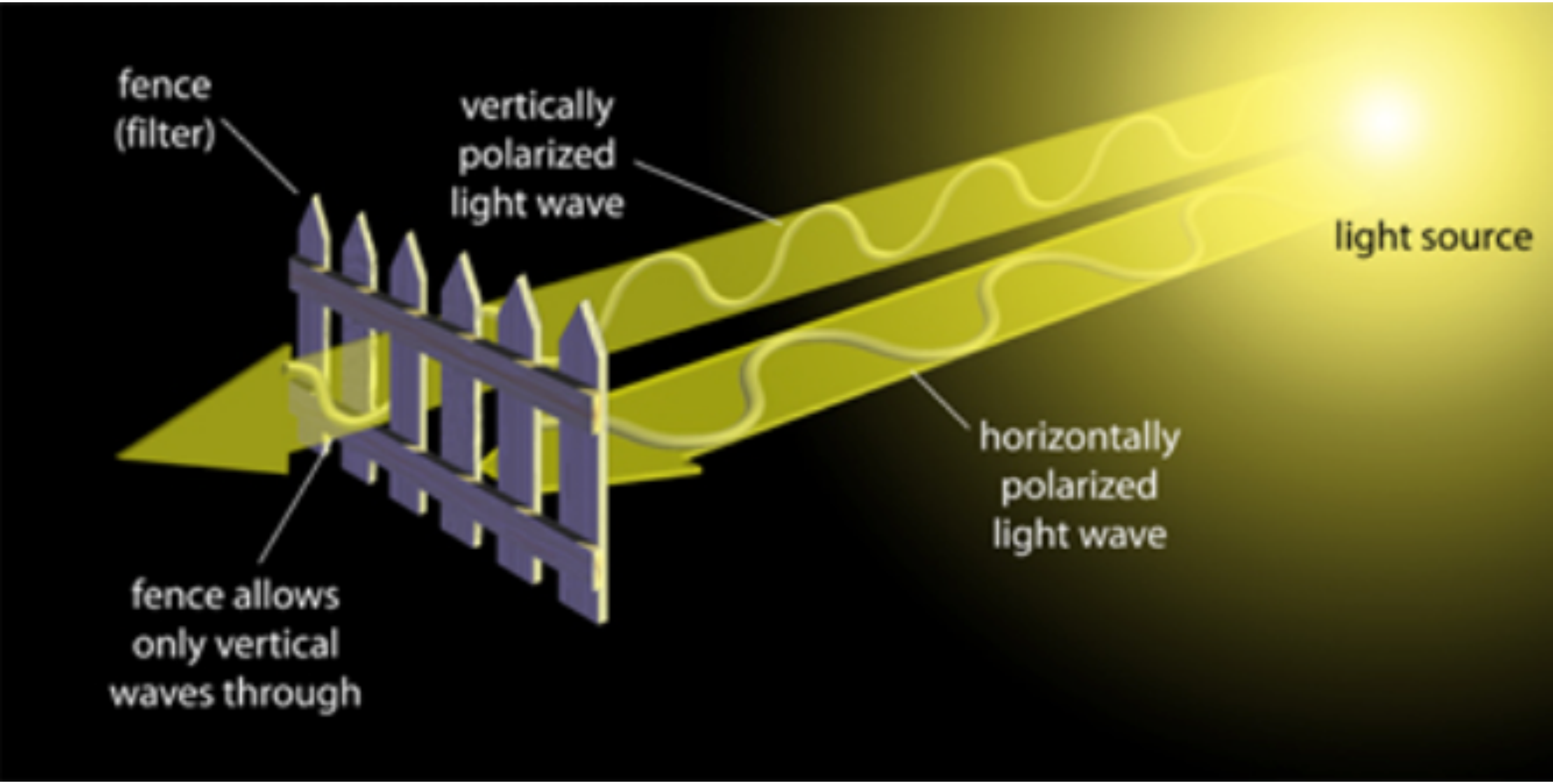
Gravitational Waves to Temperature Fluctuations



Courtesy of David Larson

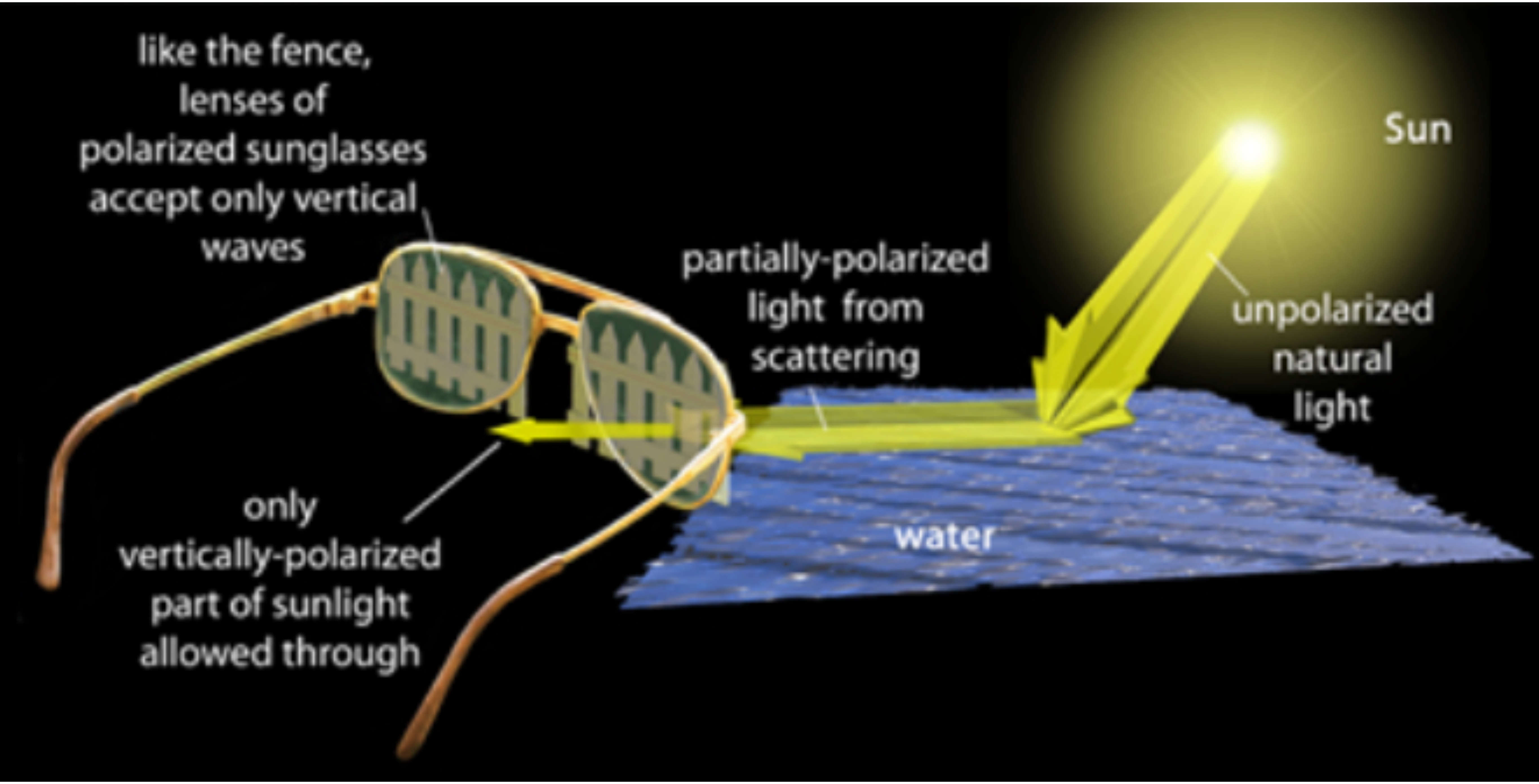

WMAP(temp+pol)+ACT+SPT+BAO+H0
WMAP(pol) + Planck + BAO
N= 50 60
ruled out!
λφ4
m2φ2
μ3φ
R2 Inflation
HZ
No Evidence for Gravitational Waves in CMB Temperature Anisotropy
Tensor–to–Scalar Ratio (r)
0.0
0.1
0.2
0.3
0.4
Primordial Tilt (ns)
0.94
0.96
0.98
1.00
1.02

Polarisation of Light



Light waves oscillate in various directions. We say “light is polarised,” when one particular direction dominates

Ex. 1: Reflection by Sea

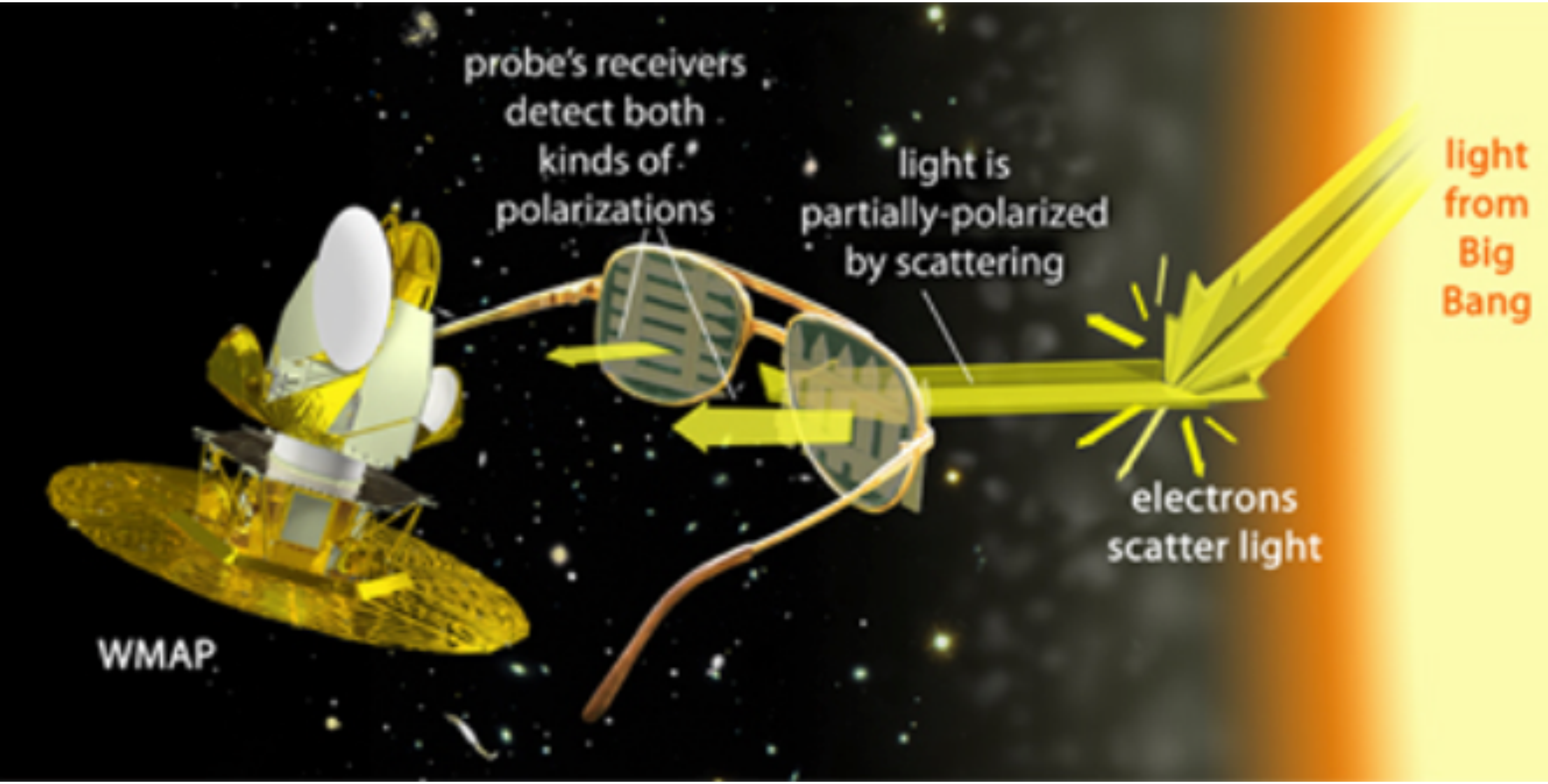


Sun light reflected by the surface of the sea is polarised horizontally. Using sunglasses transmitting only vertical polarisation eliminates the reflected sun light

Ex. 2: Windshield

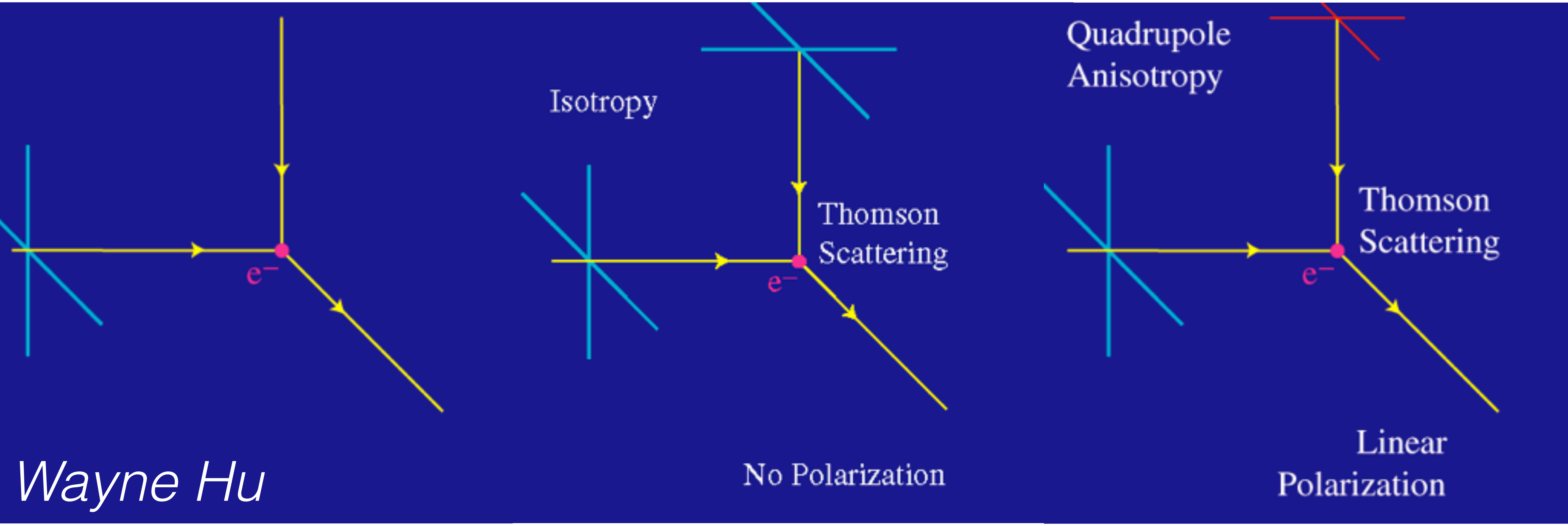
We can see through the interior of a car with polarised sunglasses transmitting only vertical polarisation

Ex. 3: CMB



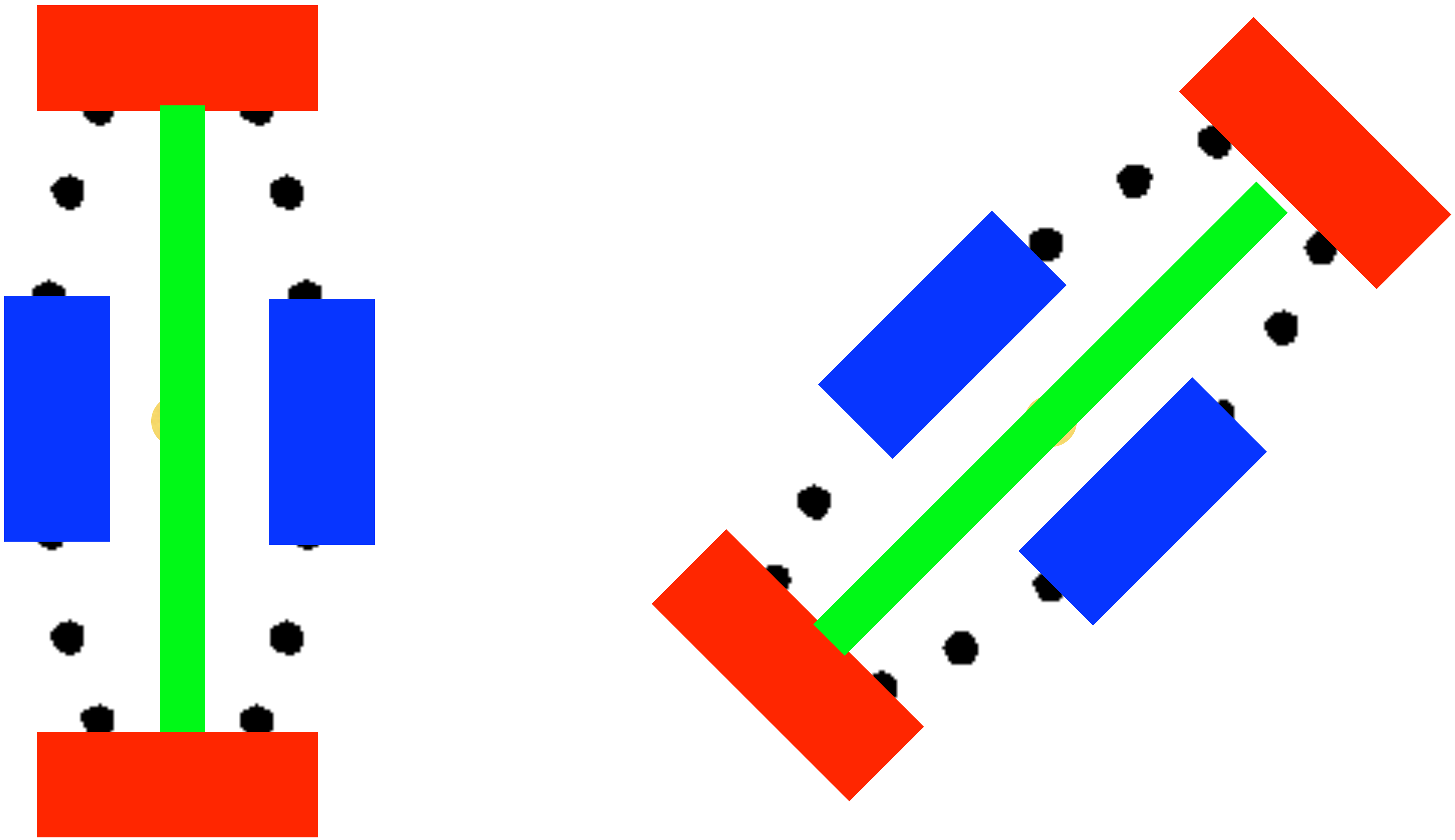
Scattering by electrons makes CMB polarised in various directions

Physics of Polarisation



Polarisation is generated when light is scatted by an electron

Gravitational Waves to Polarisation!

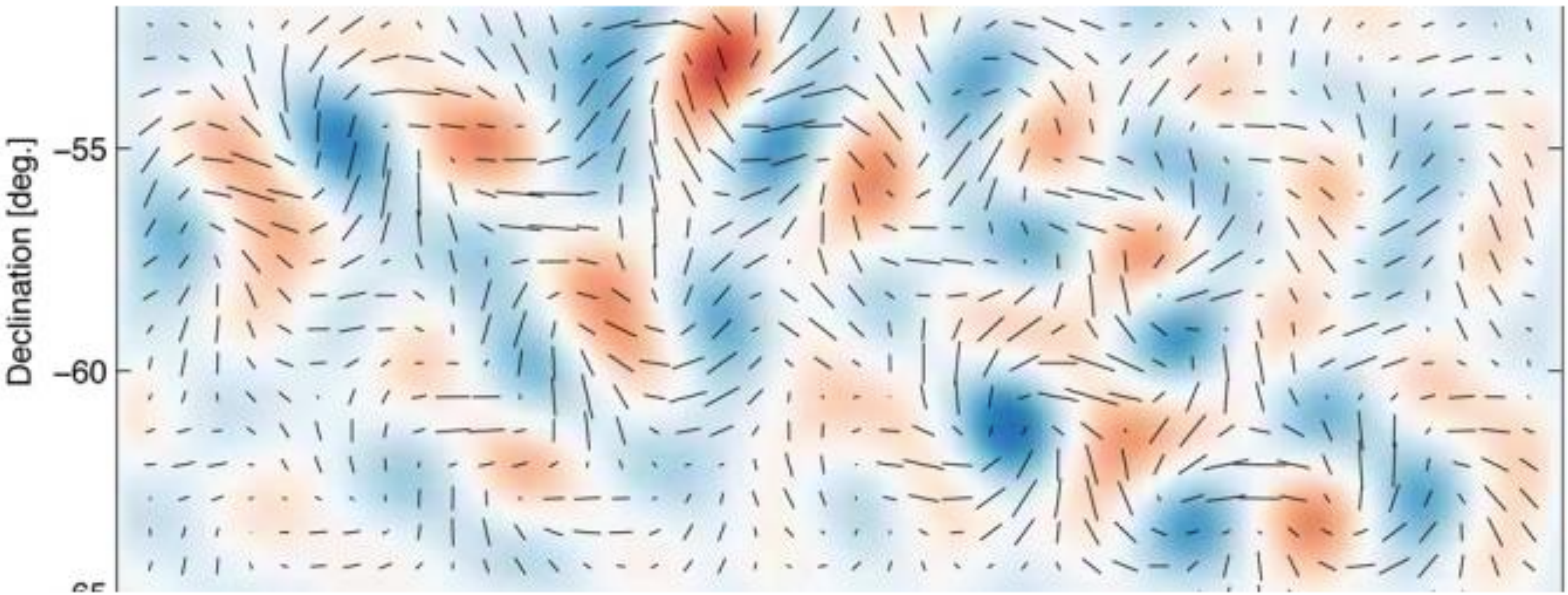


March 17, 2014

BICEP2's announcement

First Direct Evidence of Cosmic Inflation

Release No.: 2014-05
For Release: Monday, March 17, 2014 - 10:45am



Cambridge, MA - Almost 14 billion years ago, the universe we inhabit burst into existence in an extraordinary event that initiated the Big Bang. In the first fleeting fraction of a second, the universe expanded exponentially, stretching far beyond the view of our best telescopes. All this, of course, was just theory.

SPACE & COSMOS

The New York Times

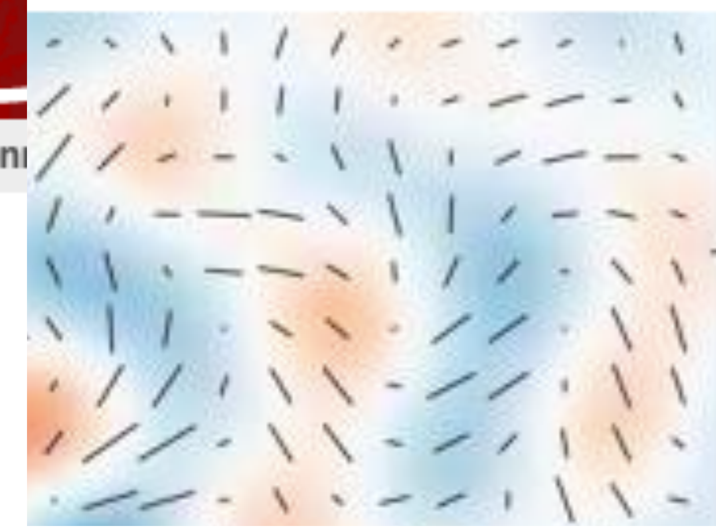
Space Ripples Reveal Big Bang's Smoking Gun

By DENNIS OVERBYE MARCH 17, 2014

BBC

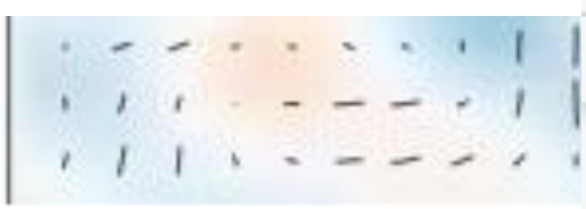
NEWS SCIENCE & ENVIRONMENT

17 March 2014 Last updated at 14:46 GMT



Cosmic inflation: 'Spectacular' discovery hailed

By Jonathan Amos
Science correspondent, BBC News



Cambridge, MA - Almost 14 billic
that initiated the Big Bang. In the
far beyond the view of our best tel

Süddeutsche.de Wissen

17. März 2014, 17:34 Gravitationswellen

Signale aus der Geburtsstunde des Universums

Von Patrick Illinger

January 30, 2015

Joint Analysis of BICEP2 data and Planck data

SCIENCE

The New York Times

Speck of Interstellar Dust Obscures Glimpse of Big Bang

By DENNIS OVERBYE JAN. 30, 2015

BBC

News Sport Weather Earth Future Shop

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30 January 2015 Last updated at 20:54 GMT

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Cosmic inflation: New study says BICEP claim was wrong

By Jonathan Amos
Science correspondent, BBC News

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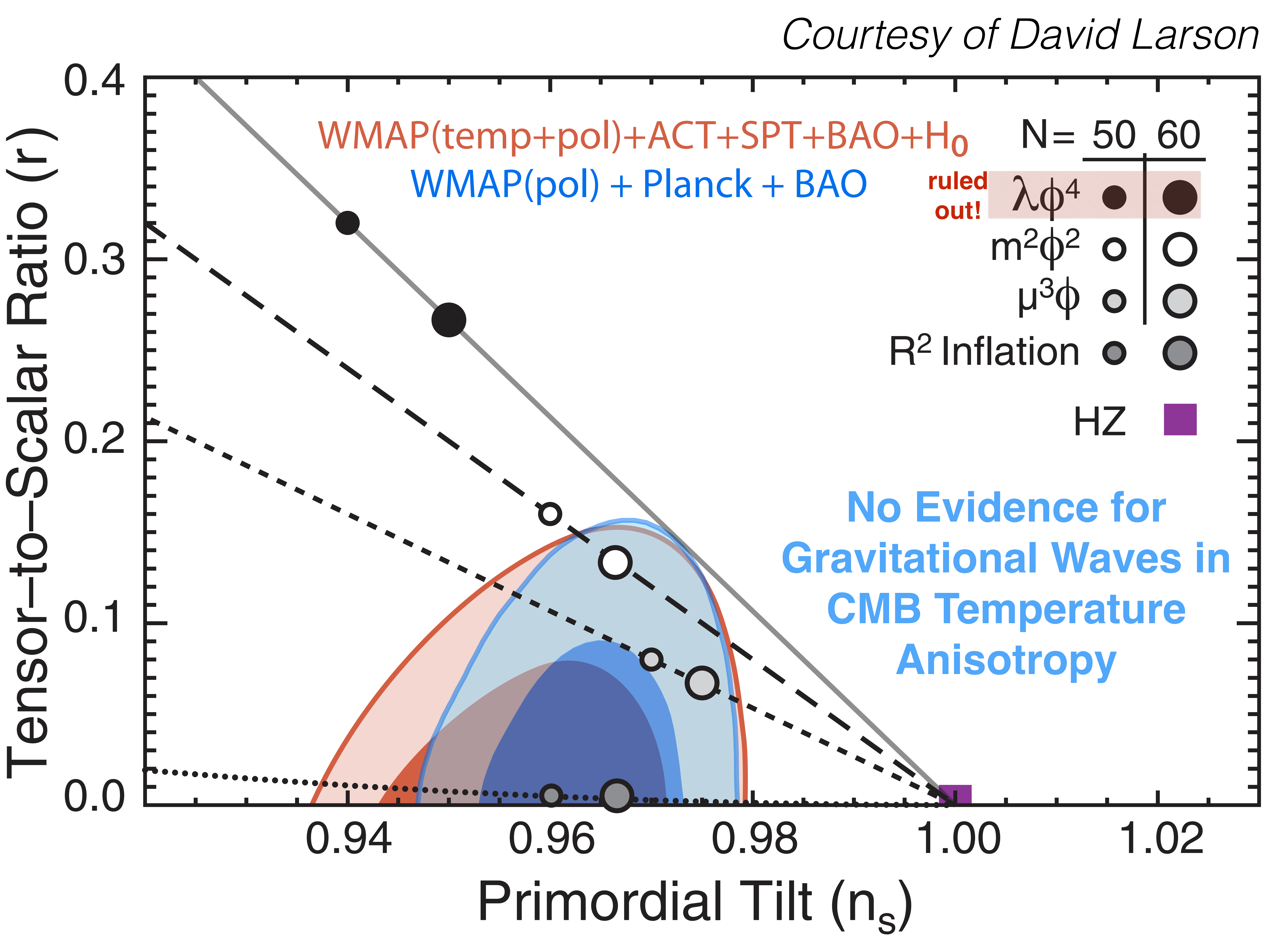
Süddeutsche.de als Startseite einrichten Hir

1. Februar 2015, 22:19 Kosmologie

Urknall-Forscher gestehen Irrtum ein

Von Marlene Weiß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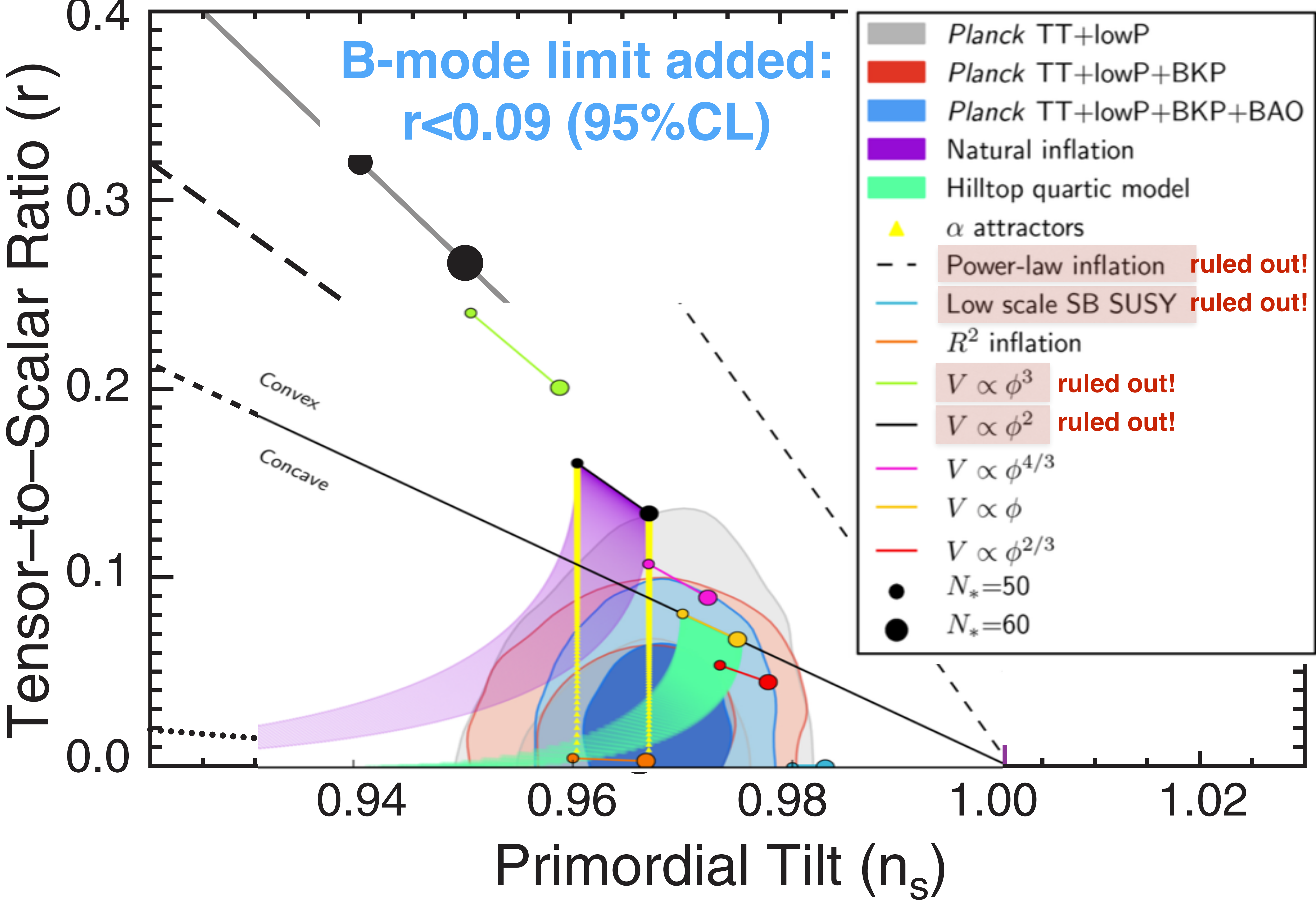
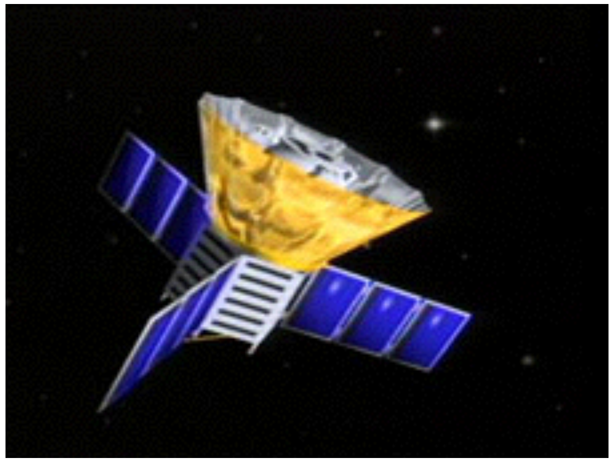
BICEP2/Keck Array & Planck Collaboration (2015)

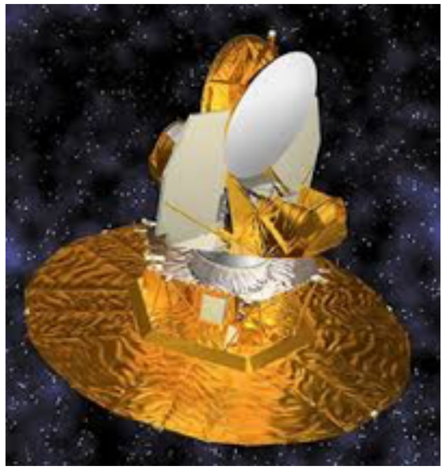


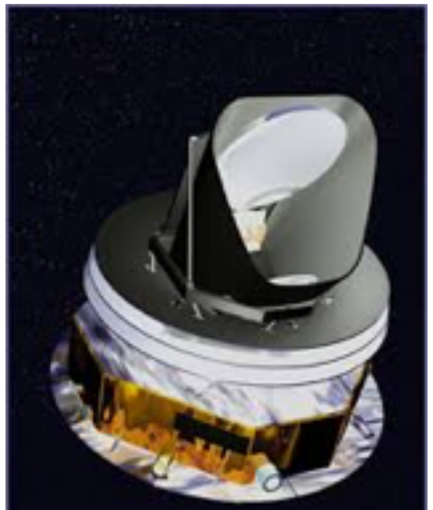
Current Situation

- Planck shows the evidence that the detected signal is not cosmological, but is due to dust
- No strong evidence that the detected signal is cosmological

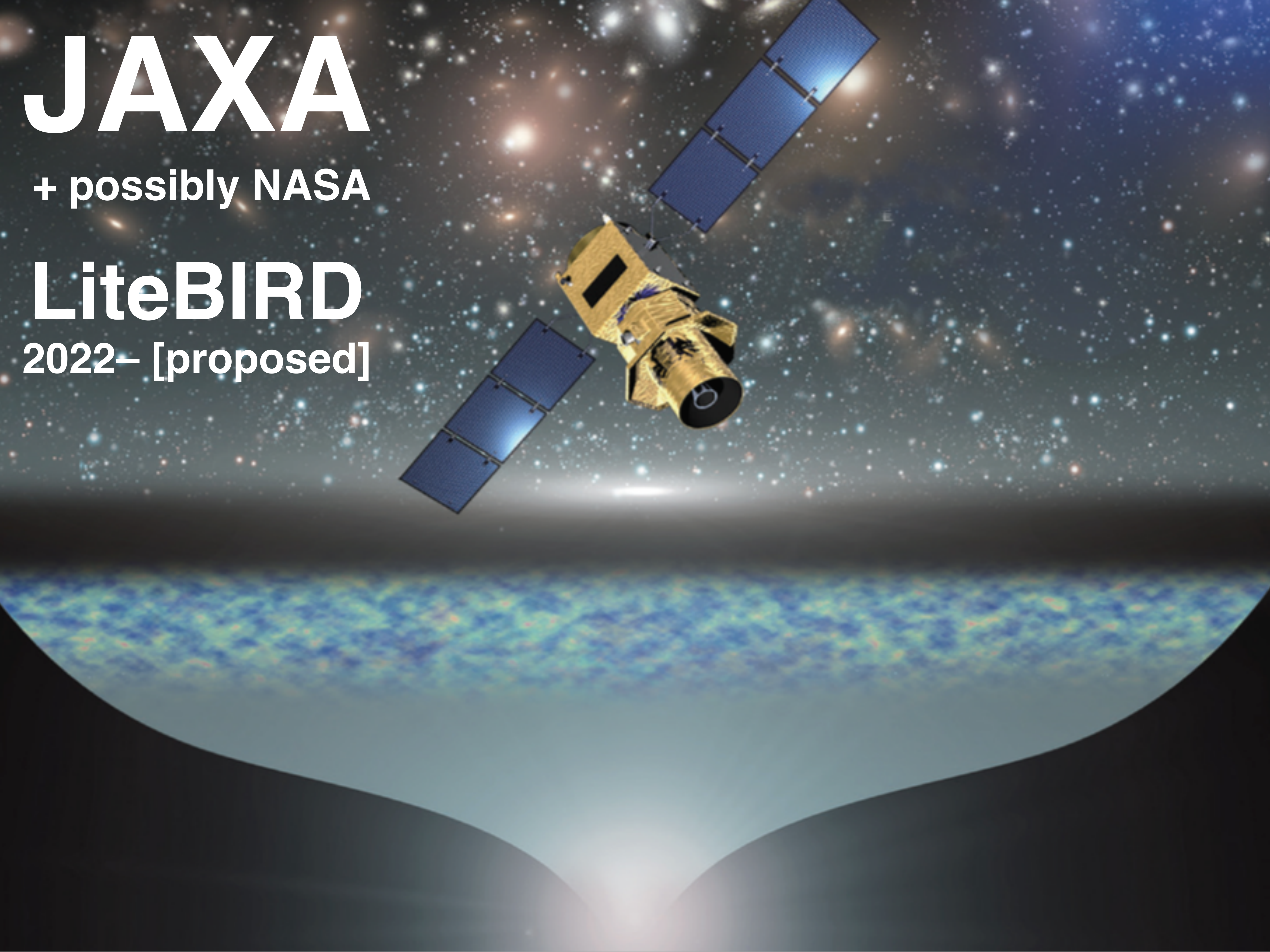
The search continues!!


1989–1993


2001–2010


2009–2013


202X–


JAXA
+ possibly NASA
LiteBIRD
2022– [proposed]

Conclusion

- The CMB data provide the precise and accurate determinations of the composition of the universe, and **provide strong evidence for inflation**

- The next goal: unambiguous measurement of the primordial B-mode polarisation from inflation

- **LiteBIRD** proposal: a CMB polarisation satellite in early 2020. Fingers crossed!