Cosmic Microwave Background as a Probe of the Very Early Universe

Eiichiro Komatsu (Texas Cosmology Center, UT Austin)
Physics Seminar, KEK, July 8, 2009

The Question

- How much do we understand our Universe?

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  - How old is it?

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  - What is it made of?

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- How much do we understand our Universe?
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  - How big is it?
  - What shape does it take?
  - What is it made of?
  - How did it begin?

The Question

- How much do we understand our Universe?
  - How old is it?
  - How big is it?
  - What shape does it take?
  - What is it made of?
  - ***How did it begin?***

The Breakthrough

- Now we can **observe** the physical condition of the Universe when it was very young.

Cosmic Microwave Background (CMB)

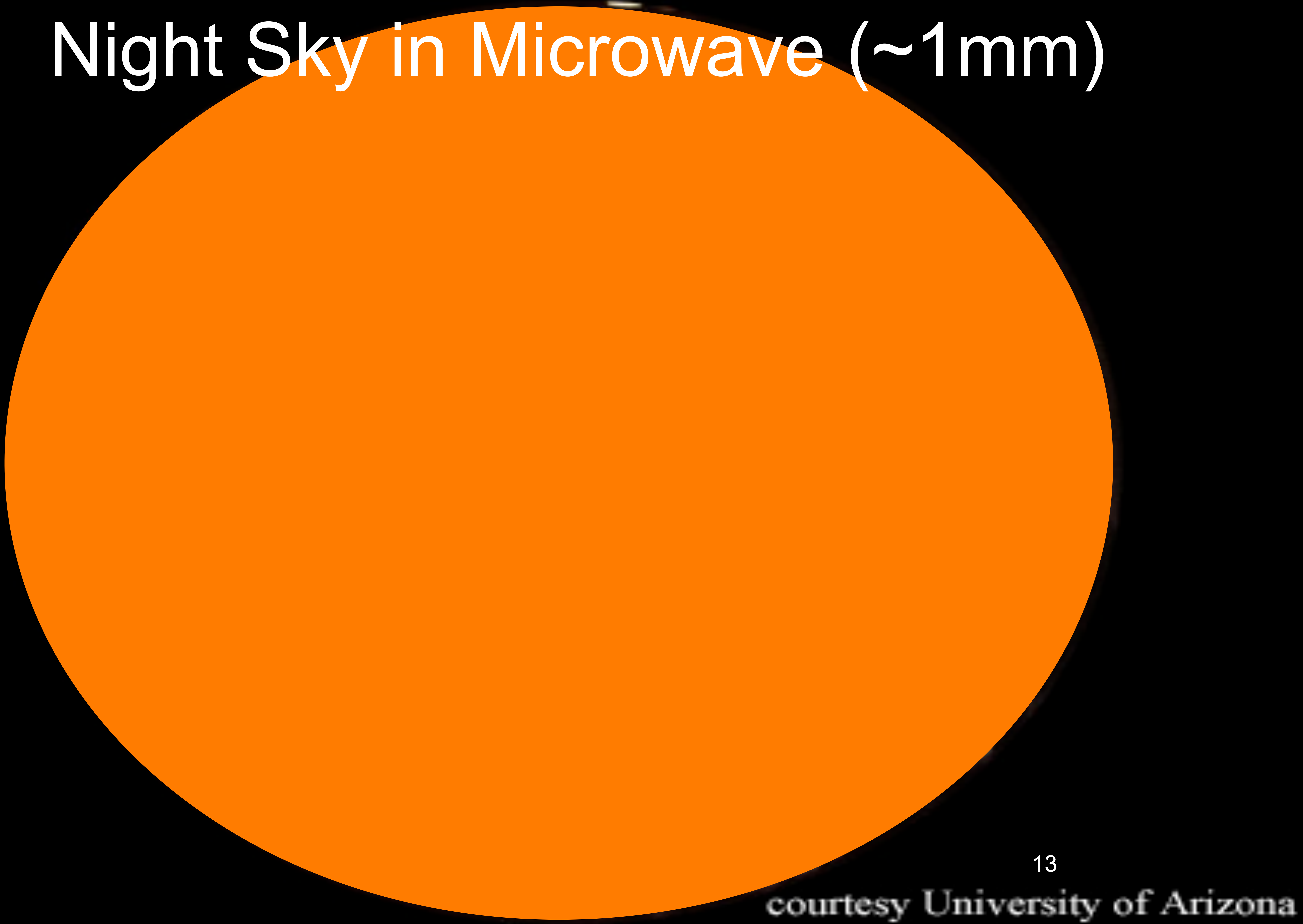
- Fossil light of the Big Bang!

From "Cosmic Voyage"

Night Sky in Optical (~0.5μm)

courtesy University of Arizona

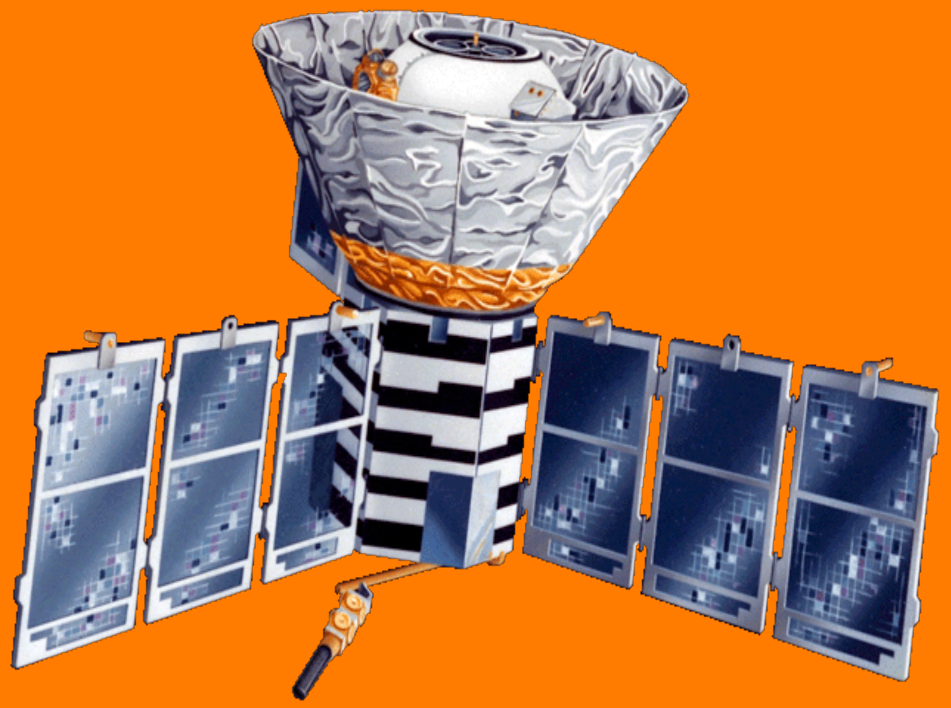
Night Sky in Microwave (~1mm)



courtesy University of Arizona

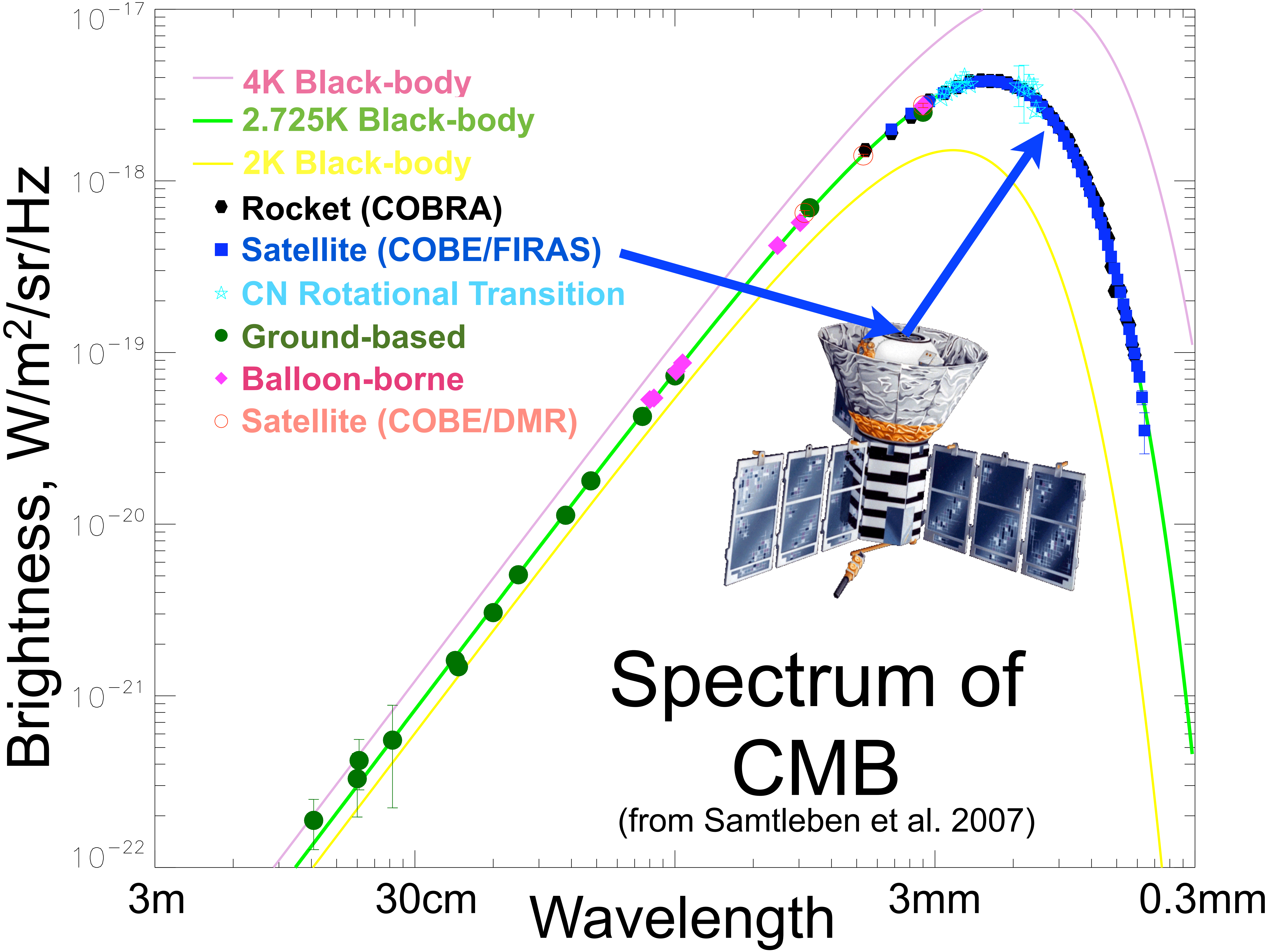
Night Sky in Microwave (~1mm)

$$T_{today}=2.725K$$



COBE Satellite, 1989-1993

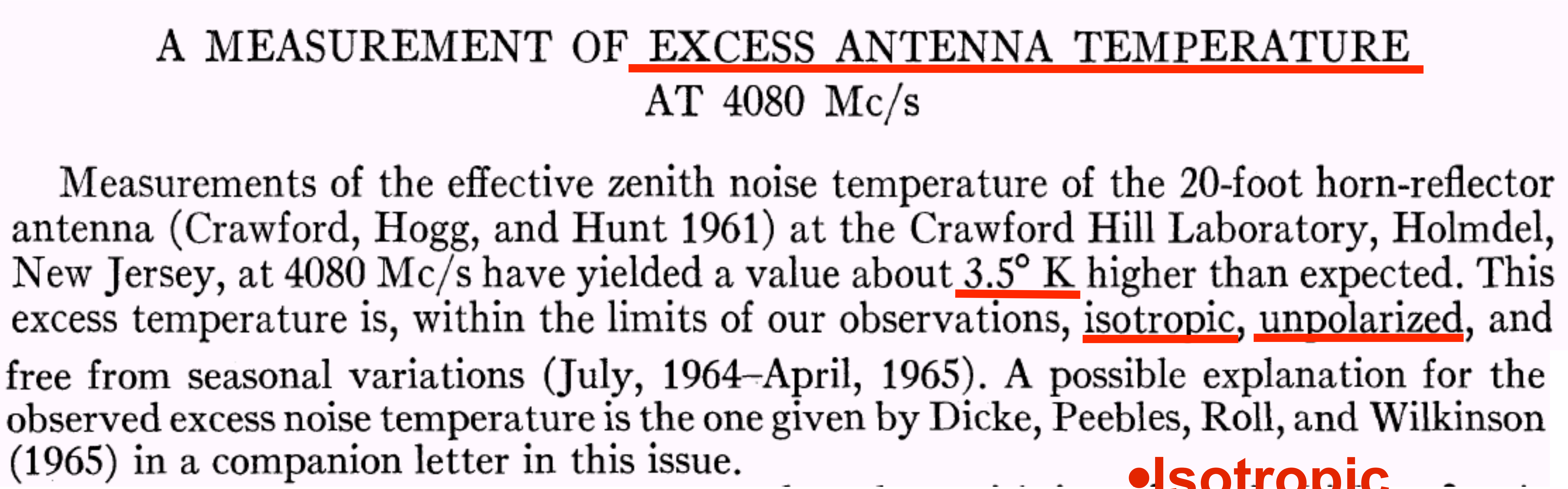
courtesy University of Arizona



Spectrum of CMB

(from Samtleben et al. 2007)

Arno Penzias & Robert Wilson, 1965

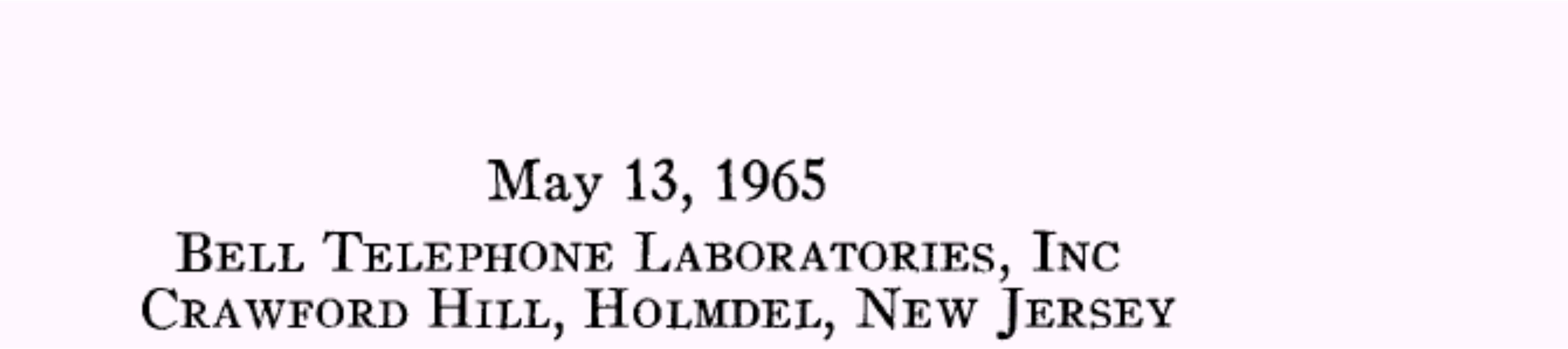


A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

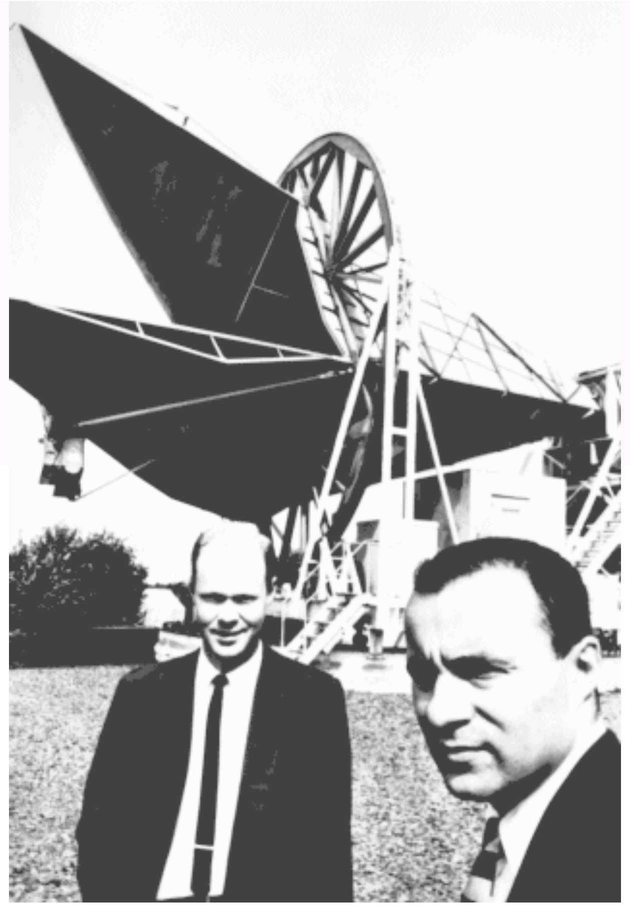
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

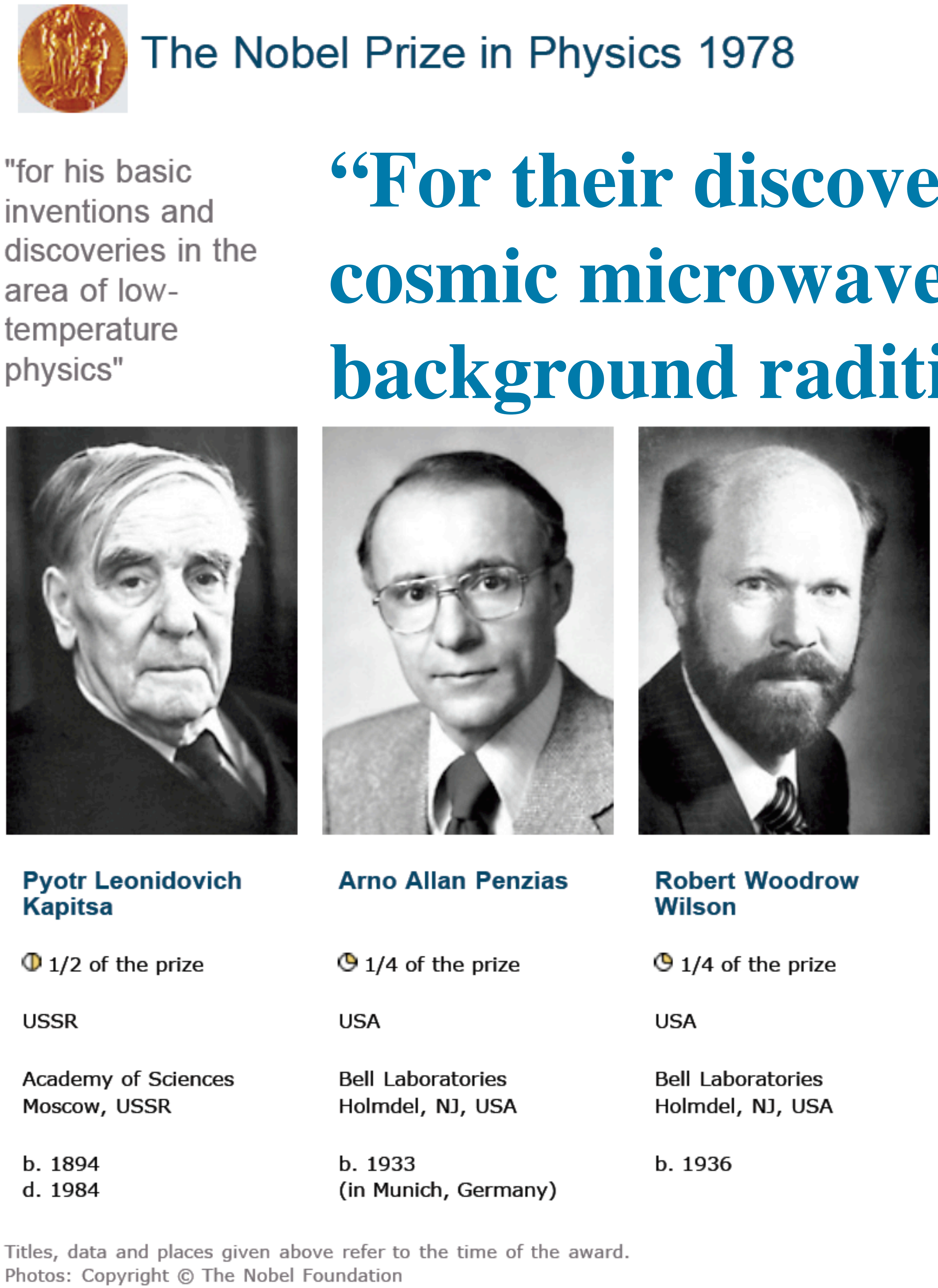
- **Isotropic**
- **Unpolarized**

A. A. Penzias
R. W. Wilson



May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey





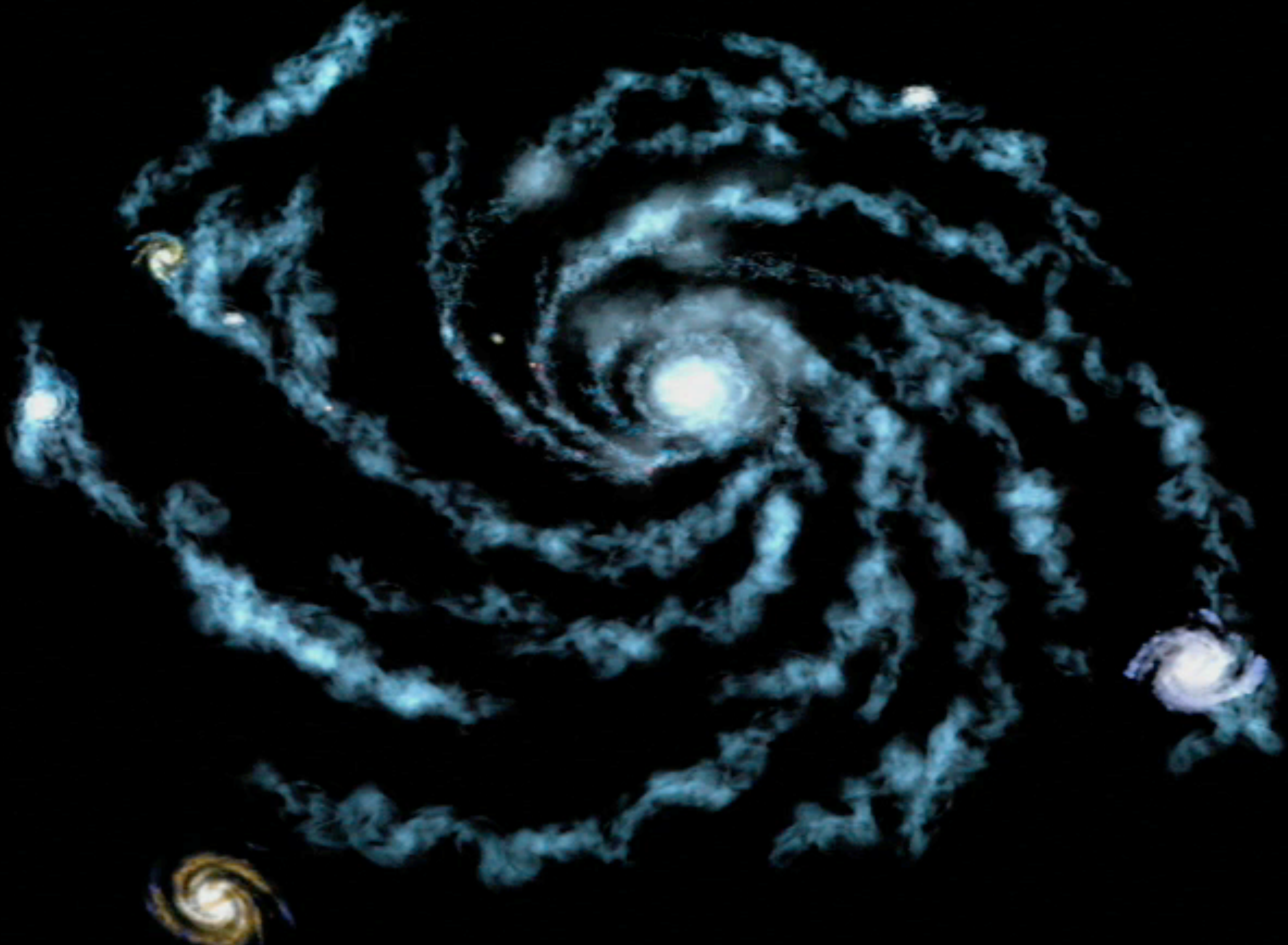
The Nobel Prize in Physics 1978

"for his basic inventions and discoveries in the area of low-temperature physics"

“For their discovery of cosmic microwave background radition”

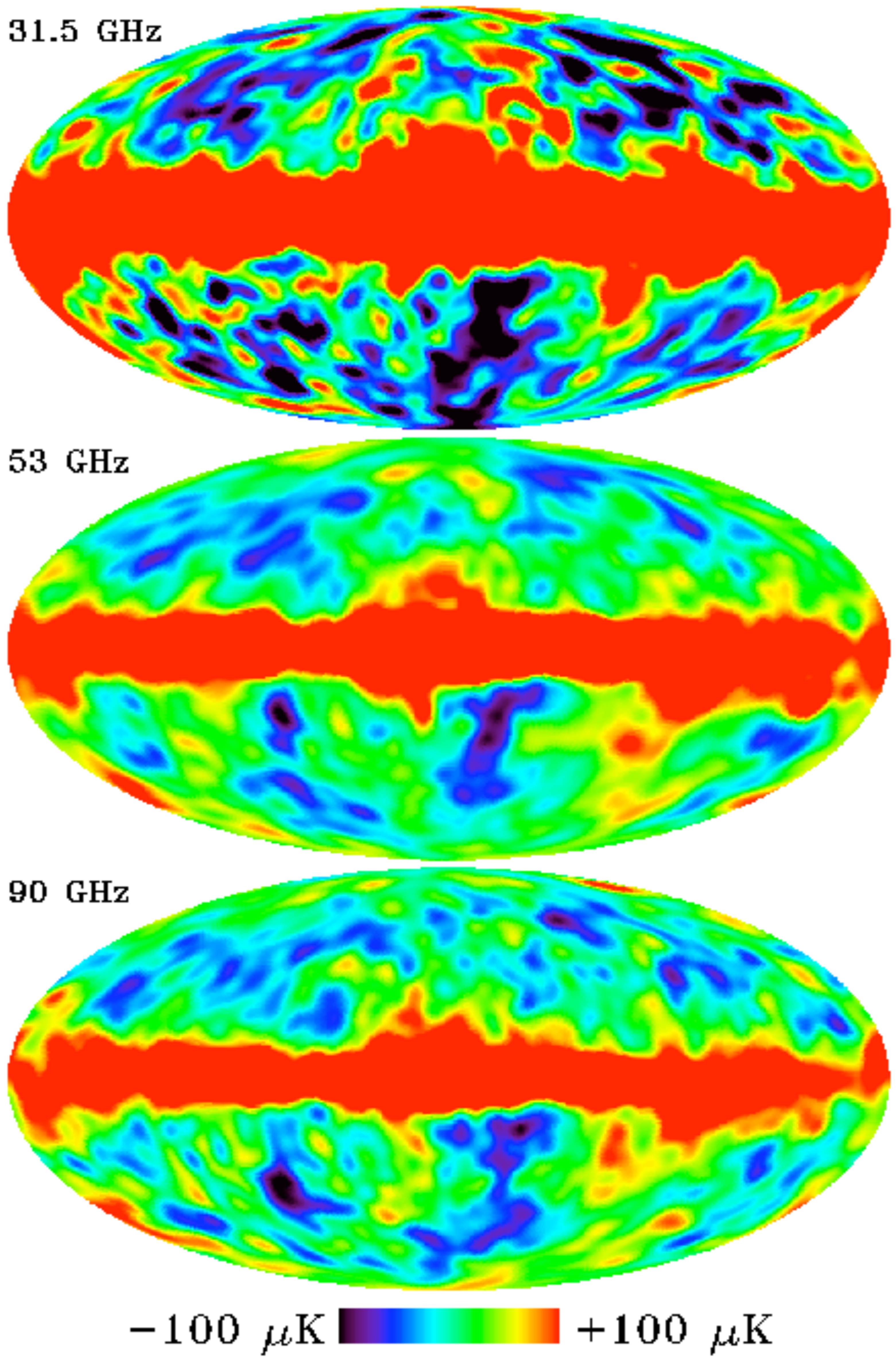
Pyotr Leonidovich Kapitsa	**Arno Allan Penzias**	**Robert Woodrow Wilson**
◑ 1/2 of the prize	◔ 1/4 of the prize	◔ 1/4 of the prize
USSR	USA	USA
Academy of Sciences Moscow, USSR	Bell Laboratories Holmdel, NJ, USA	Bell Laboratories Holmdel, NJ, USA
b. 1894 d. 1984	b. 1933 (in Munich, Germany)	b. 1936

Titles, data and places given above refer to the time of the award.



COBE/DMR, 1992

Smoot et al. (1992)



- **Isotropic?**
- **CMB is anisotropic! (at the 1/100,000 level)**

The Nobel Prize in Physics 2006

"For their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

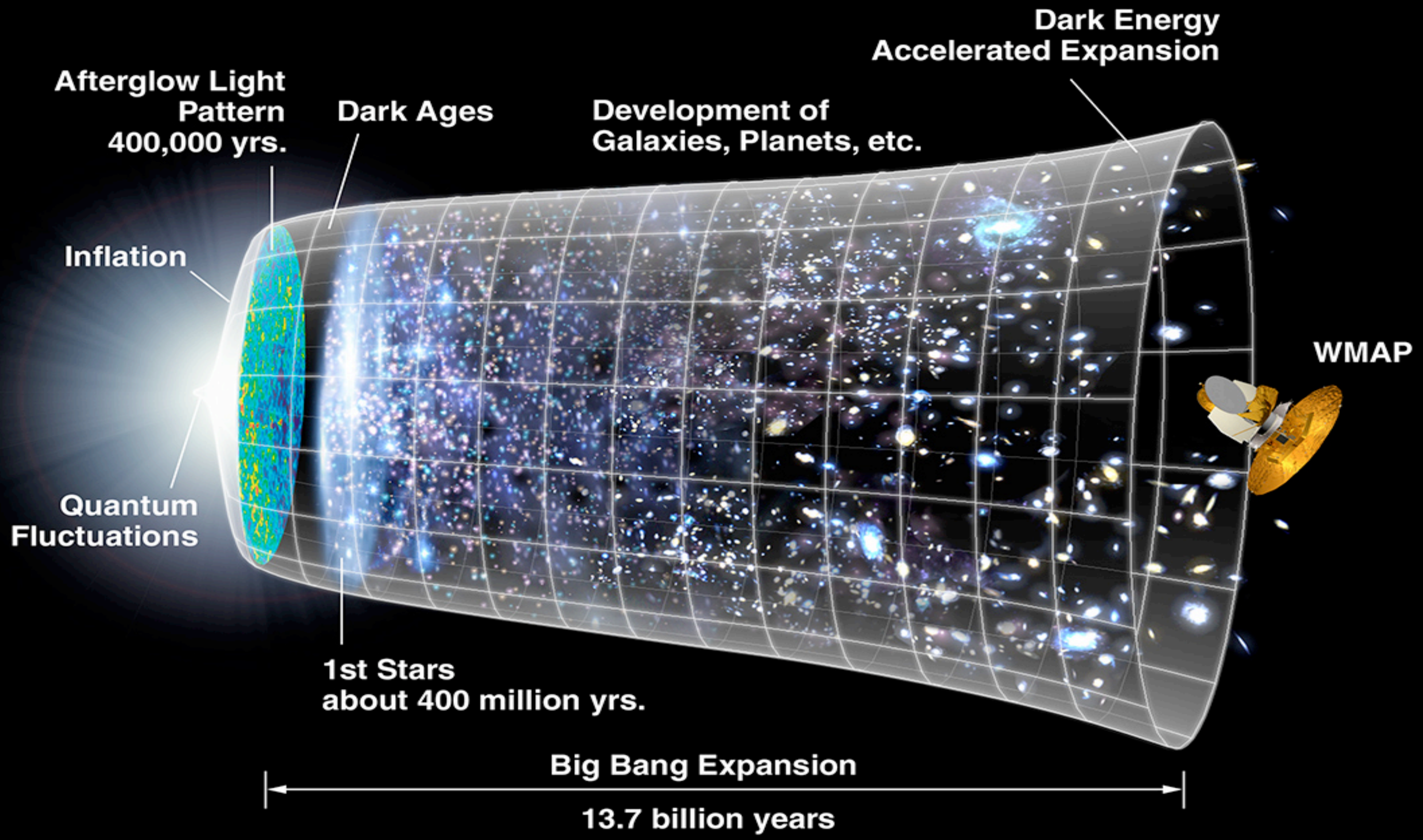
Photo: NASA

Photo: R. Kaltschmidt/LBNL

John C. Mather	**George F. Smoot**
◑ 1/2 of the prize	◑ 1/2 of the prize
USA	USA
NASA Goddard Space Flight Center Greenbelt, MD, USA	University of California Berkeley, CA, USA
b. 1946	b. 1945

Titles, data and places given above refer to the time of the award.
Photos: Copyright © The Nobel Foundation

CMB: The Farthest and Oldest Light That We Can Ever Hope To Observe Directly



- When the Universe was 3000K (~380,000 years after the Big Bang), electrons and protons were combined to form neutral hydrogen.

NASA/WMAP Science Team

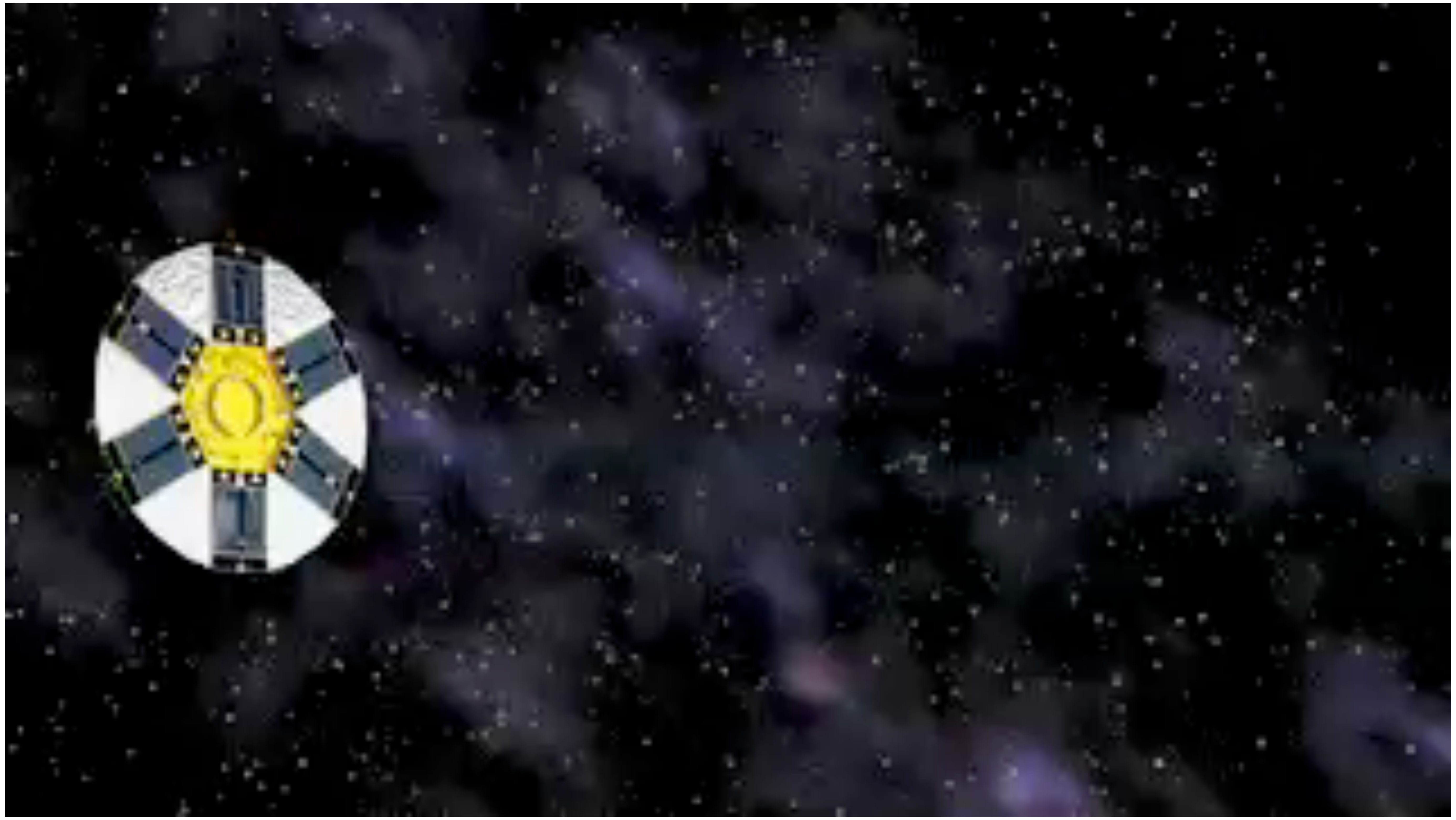
WMAP at Lagrange 2 (L2) Point

June 2001:
WMAP launched!

February 2003:
The first-year data release

March 2006:
The three-year data release

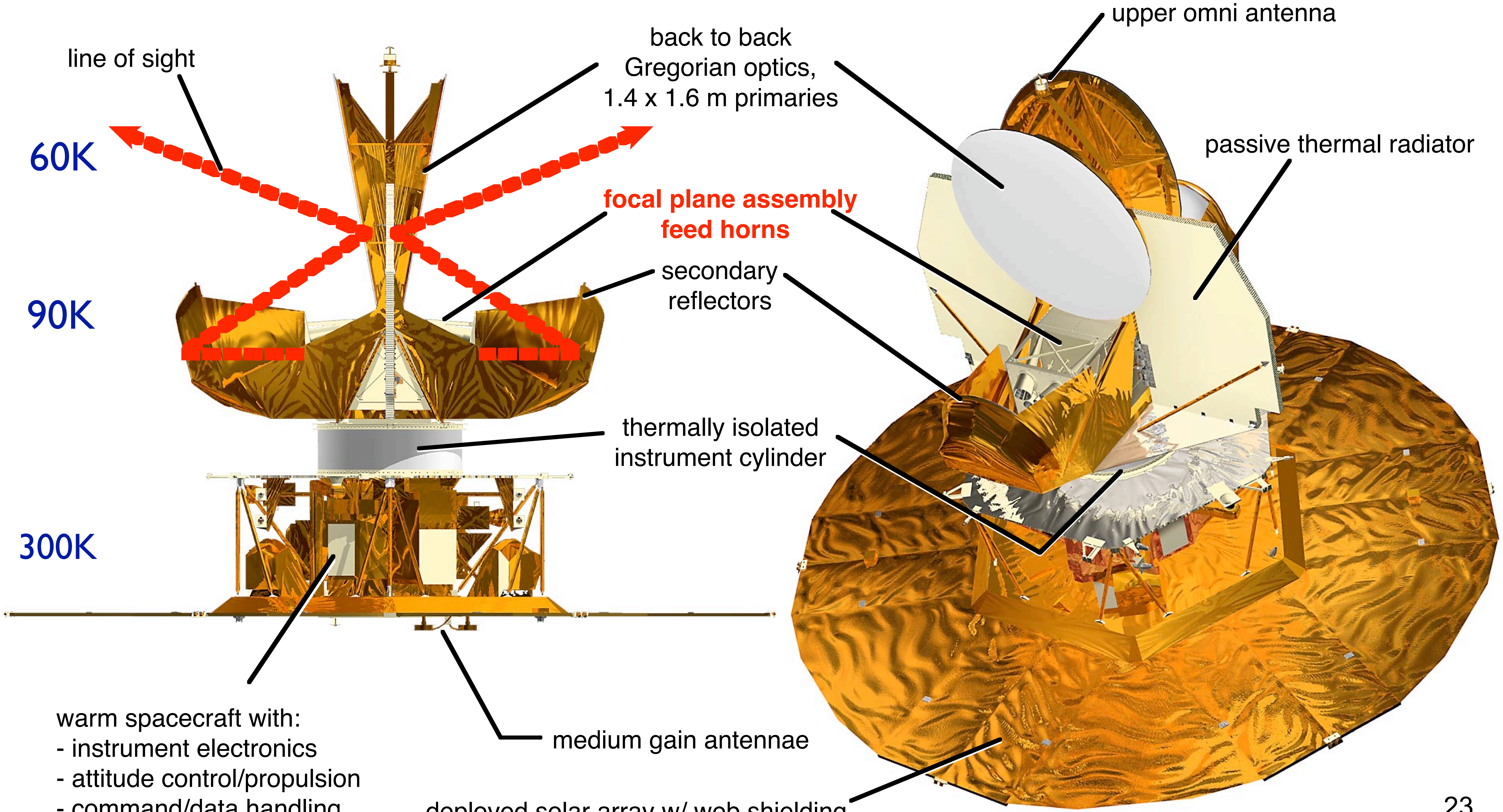
March 2008:
The five-year data release



- L2 is a million miles from Earth
- WMAP leaves Earth, Moon, and Sun behind it to avoid radiation from them

WMAP Spacecraft

Radiative Cooling: No Cryogenic System



line of sight

60K

90K

300K

back to back
Gregorian optics,
1.4 x 1.6 m primaries

focal plane assembly
feed horns

secondary
reflectors

thermally isolated
instrument cylinder

upper omni antenna

passive thermal radiator

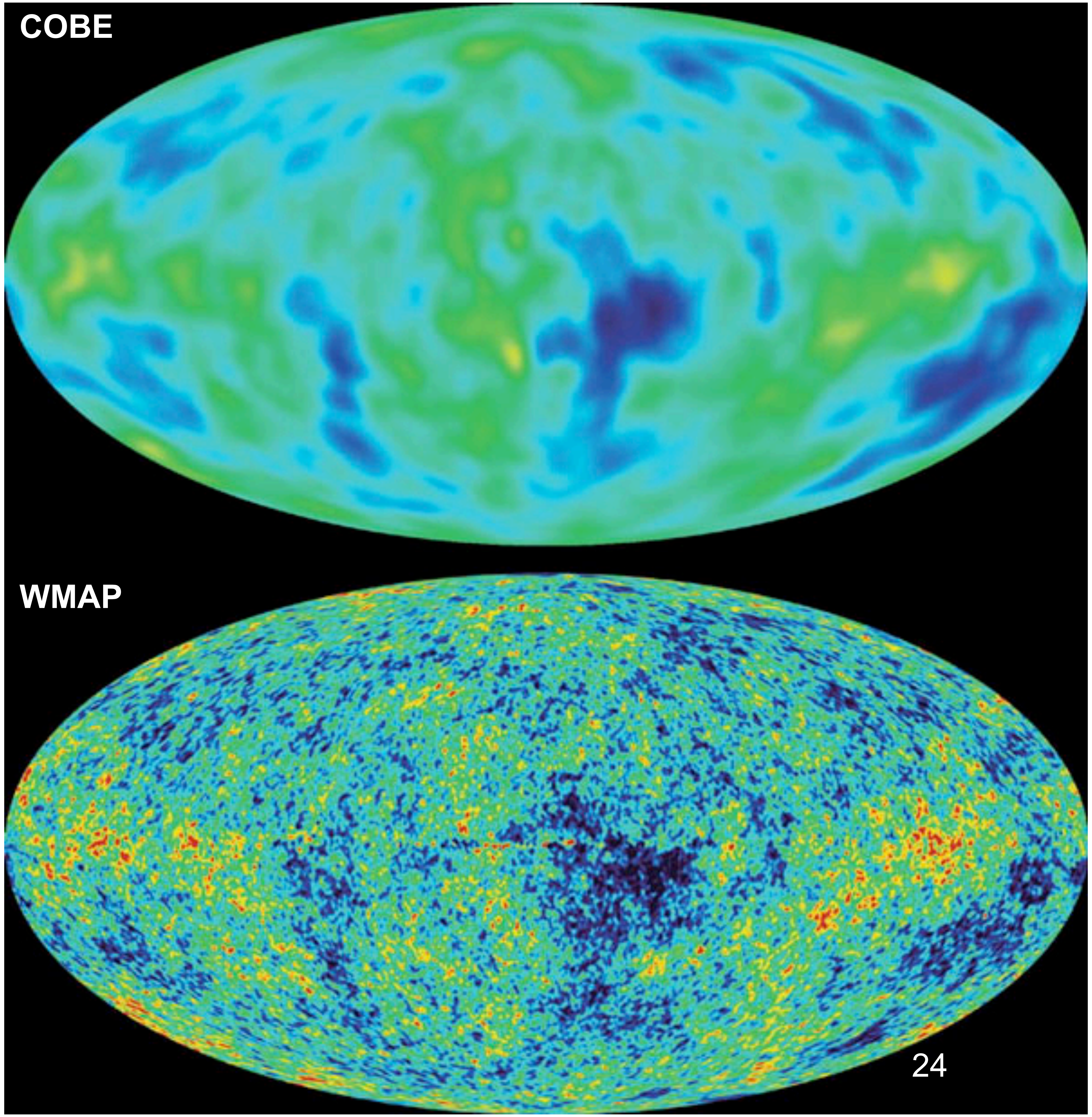
warm spacecraft with:
- instrument electronics
- attitude control/propulsion
- command/data handling
- battery and power control

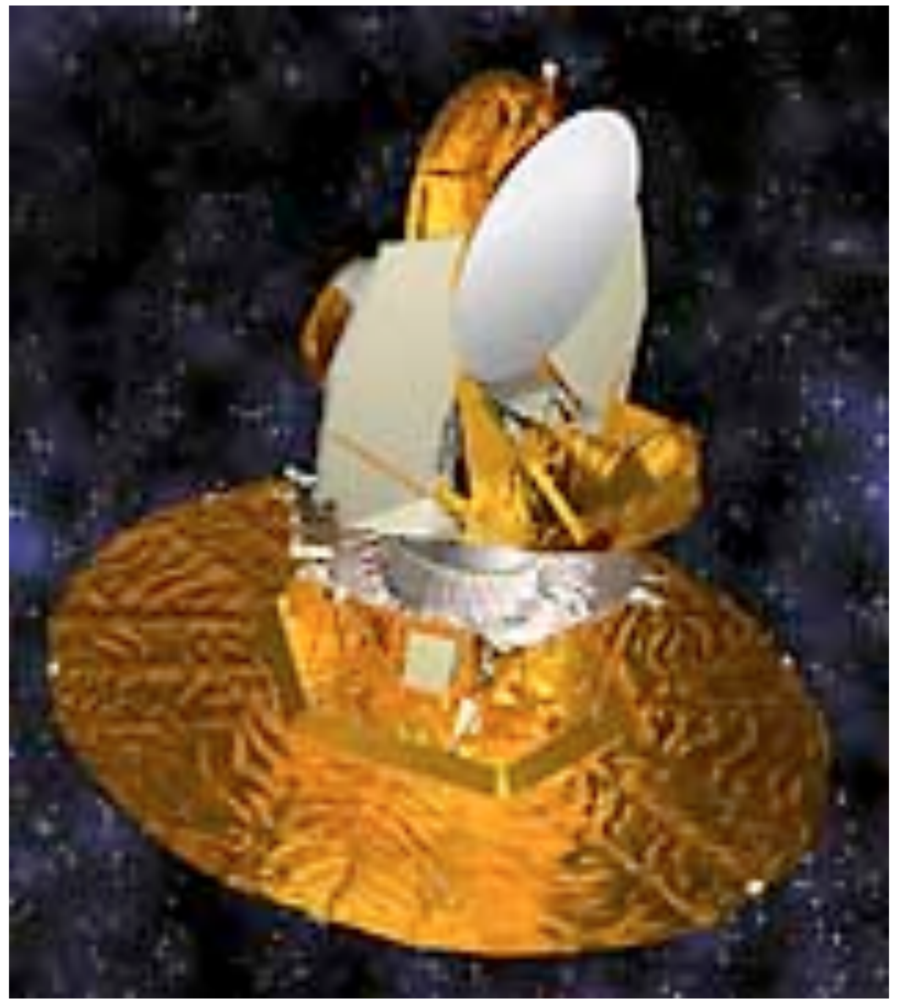
medium gain antennae

deployed solar array w/ web shielding

COBE to WMAP (x35 better resolution)

COBE
1989





WMAP
2001

WMAP First Year Science Team

- WMAP is currently planned to complete 9 years of full-sky survey, ending its mission in ~2010–2011.

WMAP First Year Science Team

Principal Investigator: ***Charles L. Bennett***

- WMAP is currently planned to complete 9 years of full-sky survey, ending its mission in ~2010–2011.

WMAP 5-Year Science Team

- C.L. Bennett
- G. Hinshaw
- N. Jarosik
- S.S. Meyer
- L. Page
- D.N. Spergel
- E.L. Wright

- M.R. Greason
- M. Halpern
- R.S. Hill
- A. Kogut
- M. Limon
- N. Odegard
- G.S. Tucker

- J. L. Weiland
- E. Wollack
- J. Dunkley
- B. Gold
- E. Komatsu
- D. Larson
- M.R. Nolta

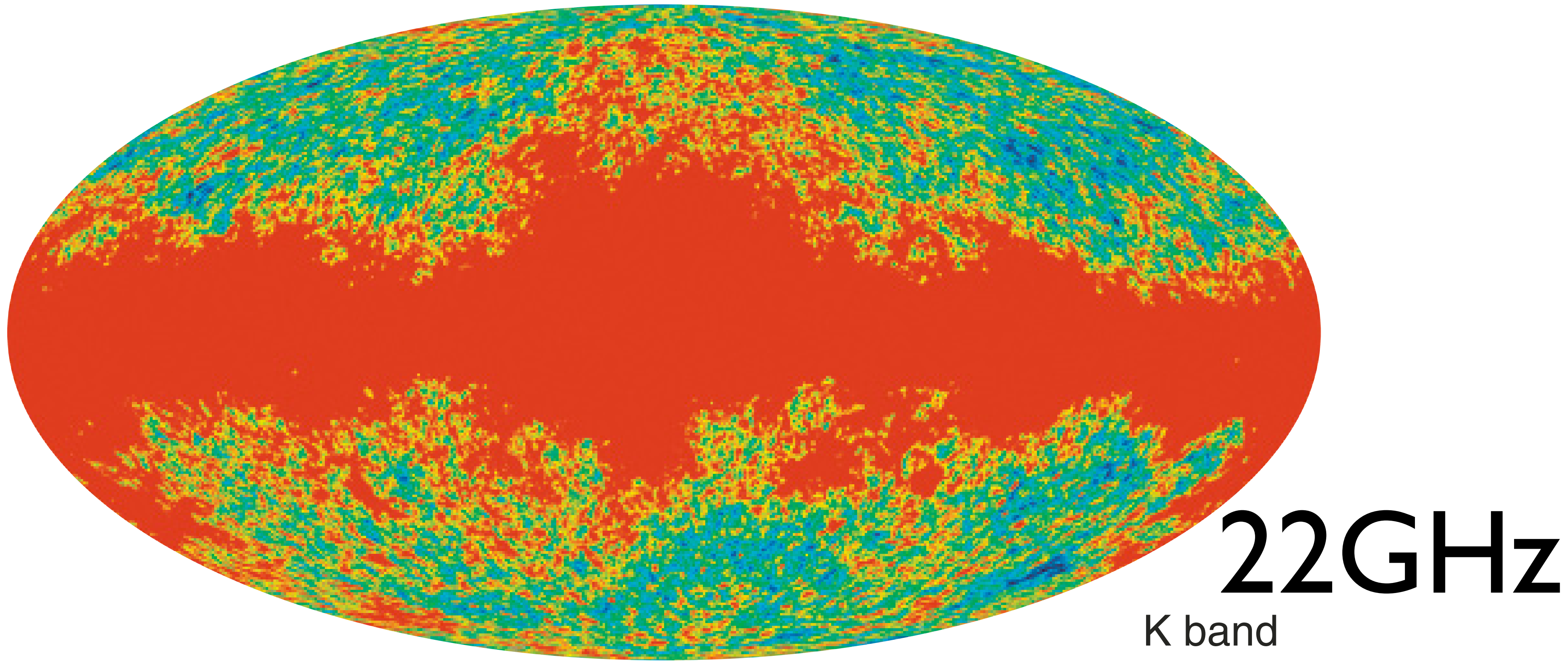
Special Thanks to
WMAP
Graduates!

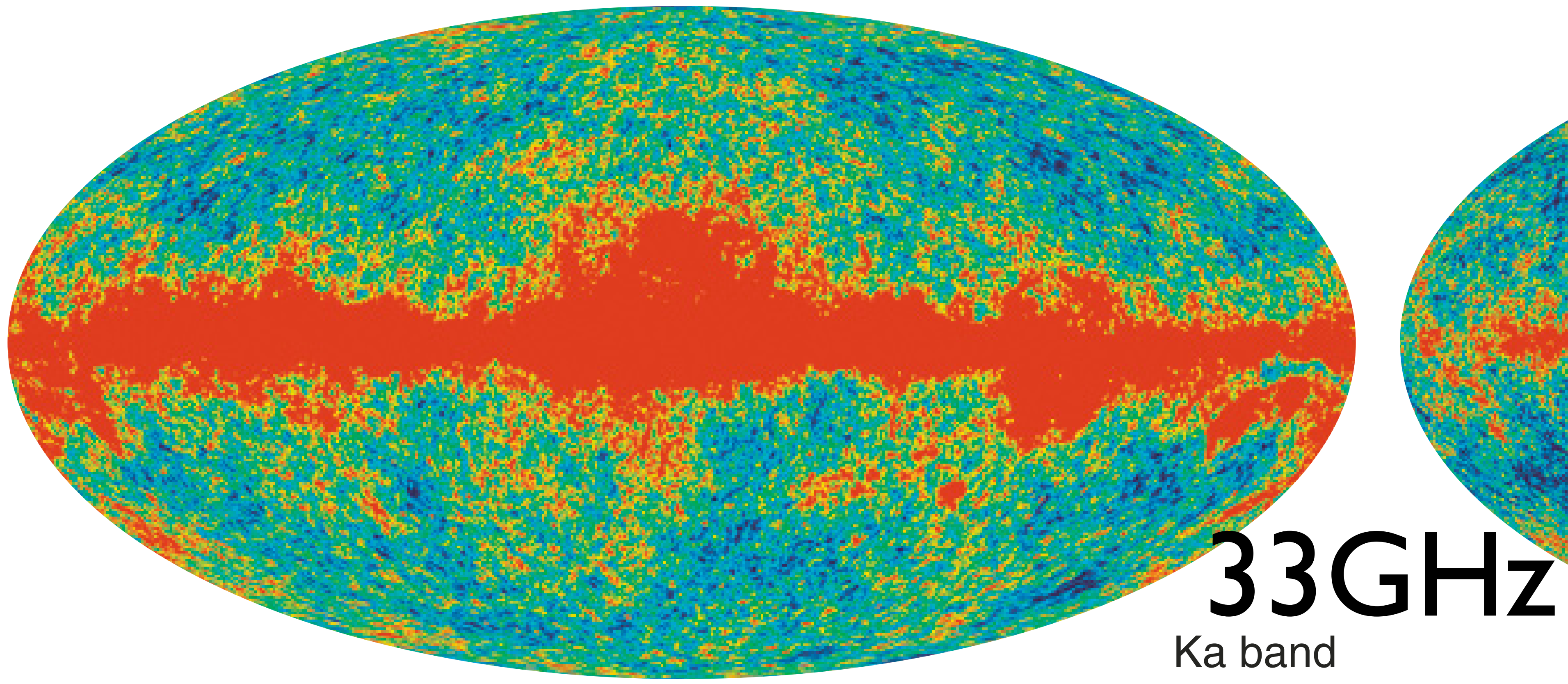
- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde

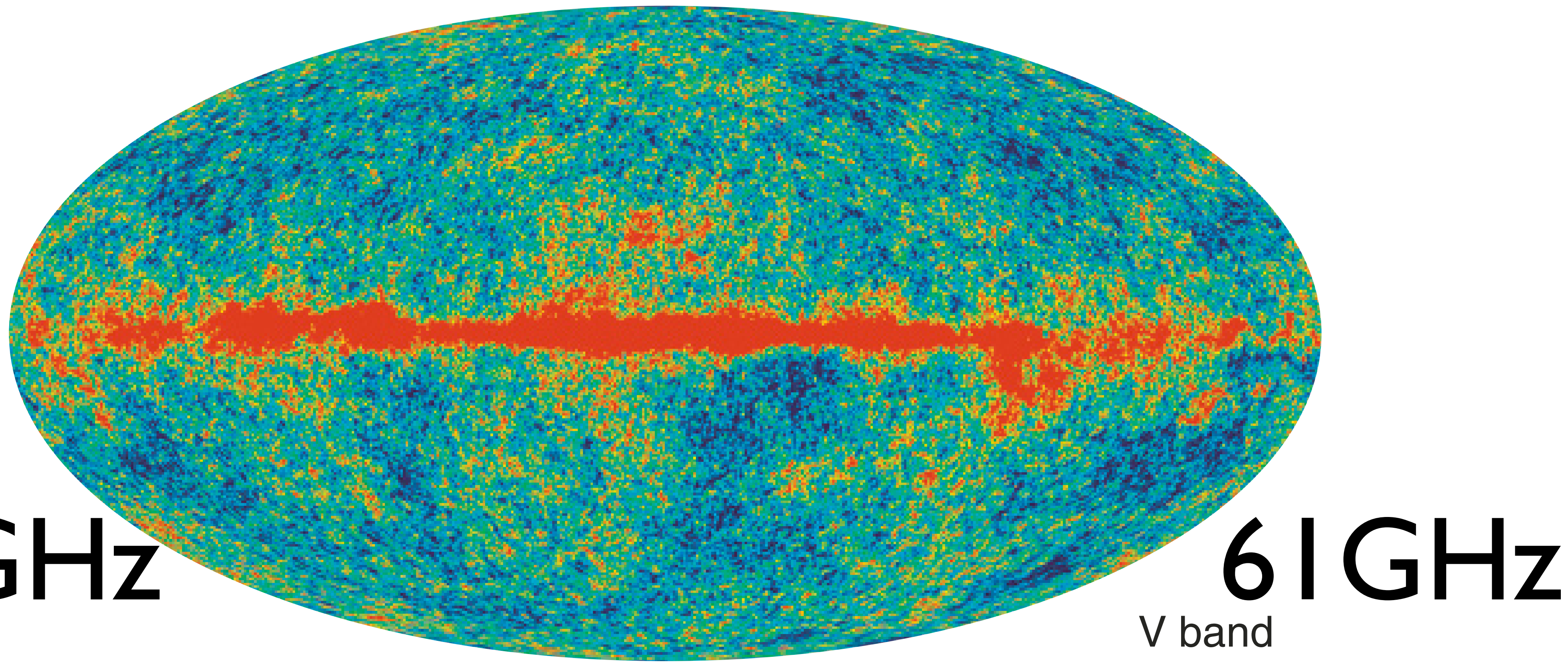
WMAP 5-Year Papers

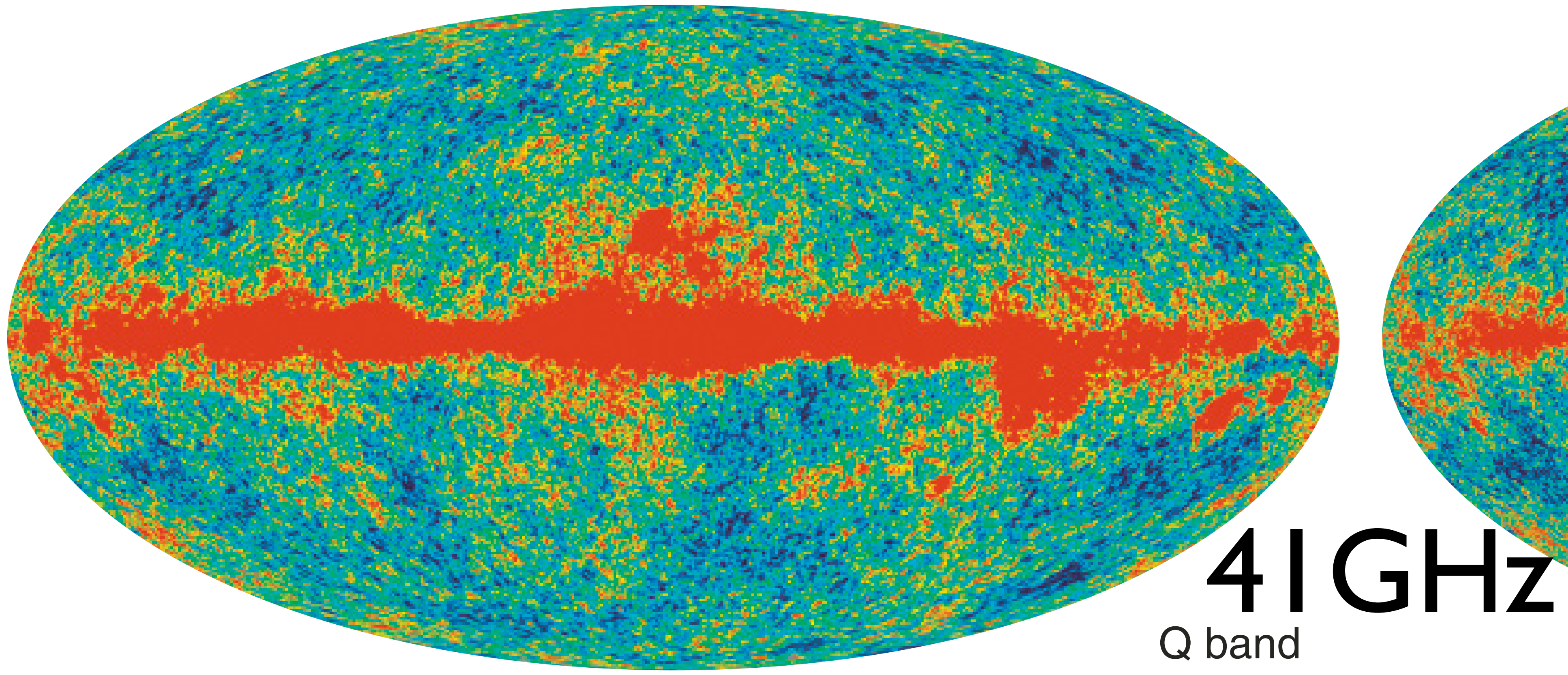
- **Hinshaw et al.**, "*Data Processing, Sky Maps, and Basic Results*" ApJS, 180, 225 (2009)
- **Hill et al.**, "*Beam Maps and Window Functions*" ApJS, 180, 246
- **Gold et al.**, "*Galactic Foreground Emission*" ApJS, 180, 265
- **Wright et al.**, "*Source Catalogue*" ApJS, 180, 283
- **Nolta et al.**, "*Angular Power Spectra*" ApJS, 180, 296
- **Dunkley et al.**, "*Likelihoods and Parameters from the WMAP data*" ApJS, 180, 306
- **Komatsu et al**., "*Cosmological Interpretation*" ApJS, 180, 330

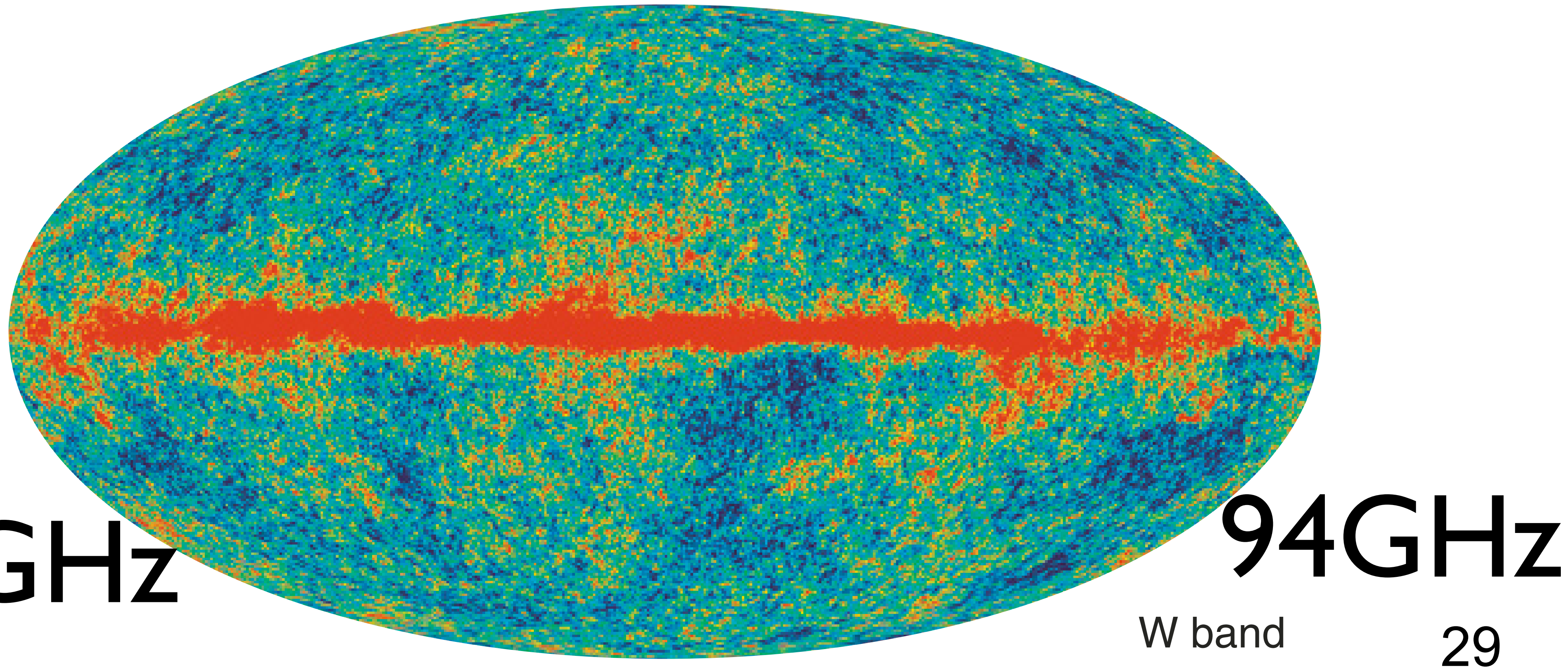
Temperature Anisotropy (Unpolarized)

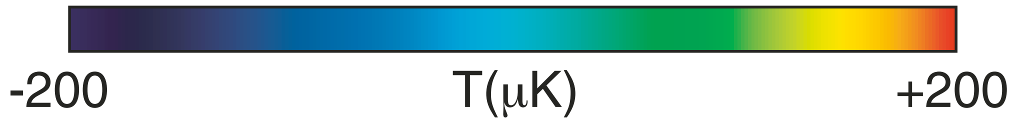




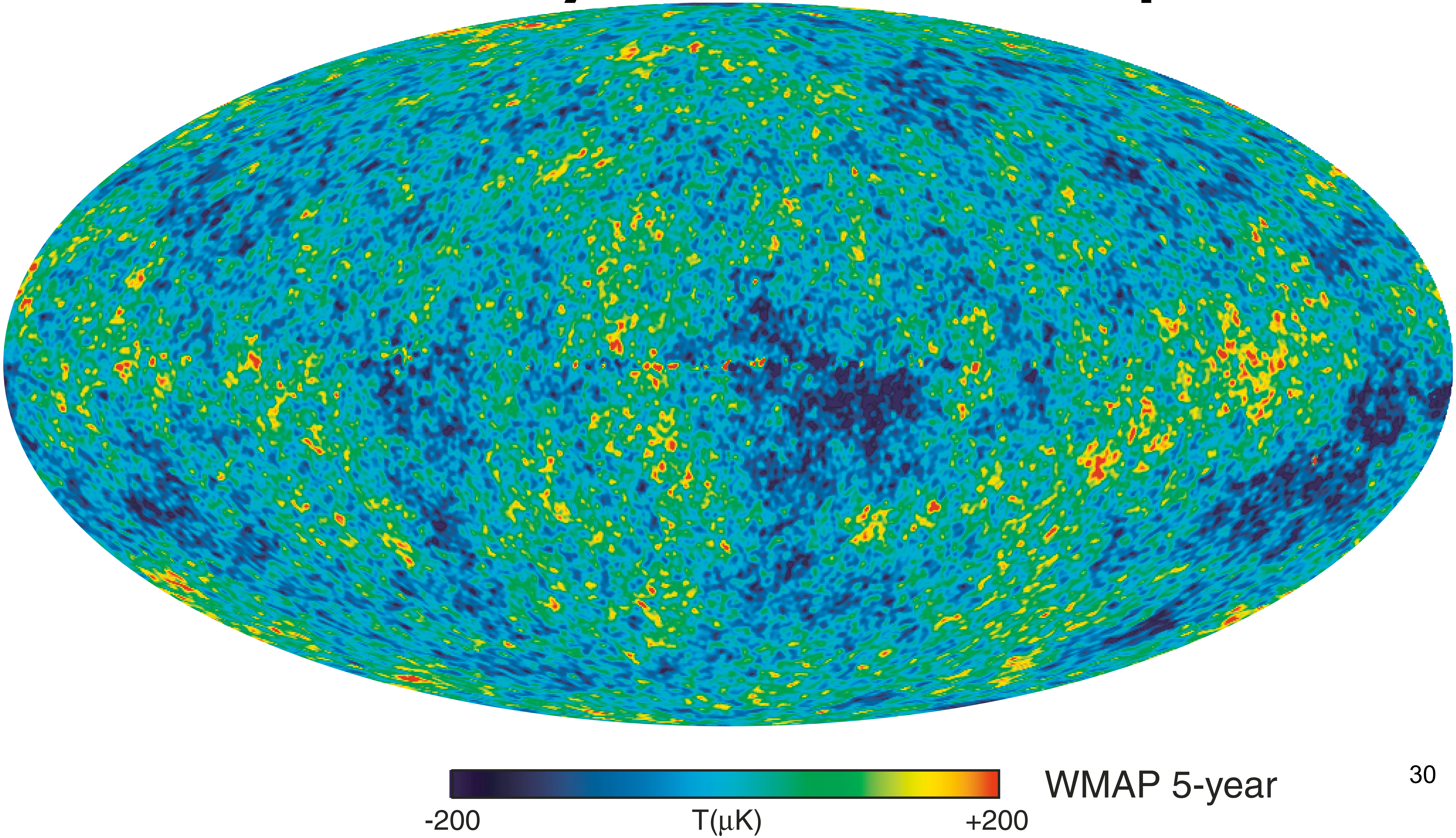




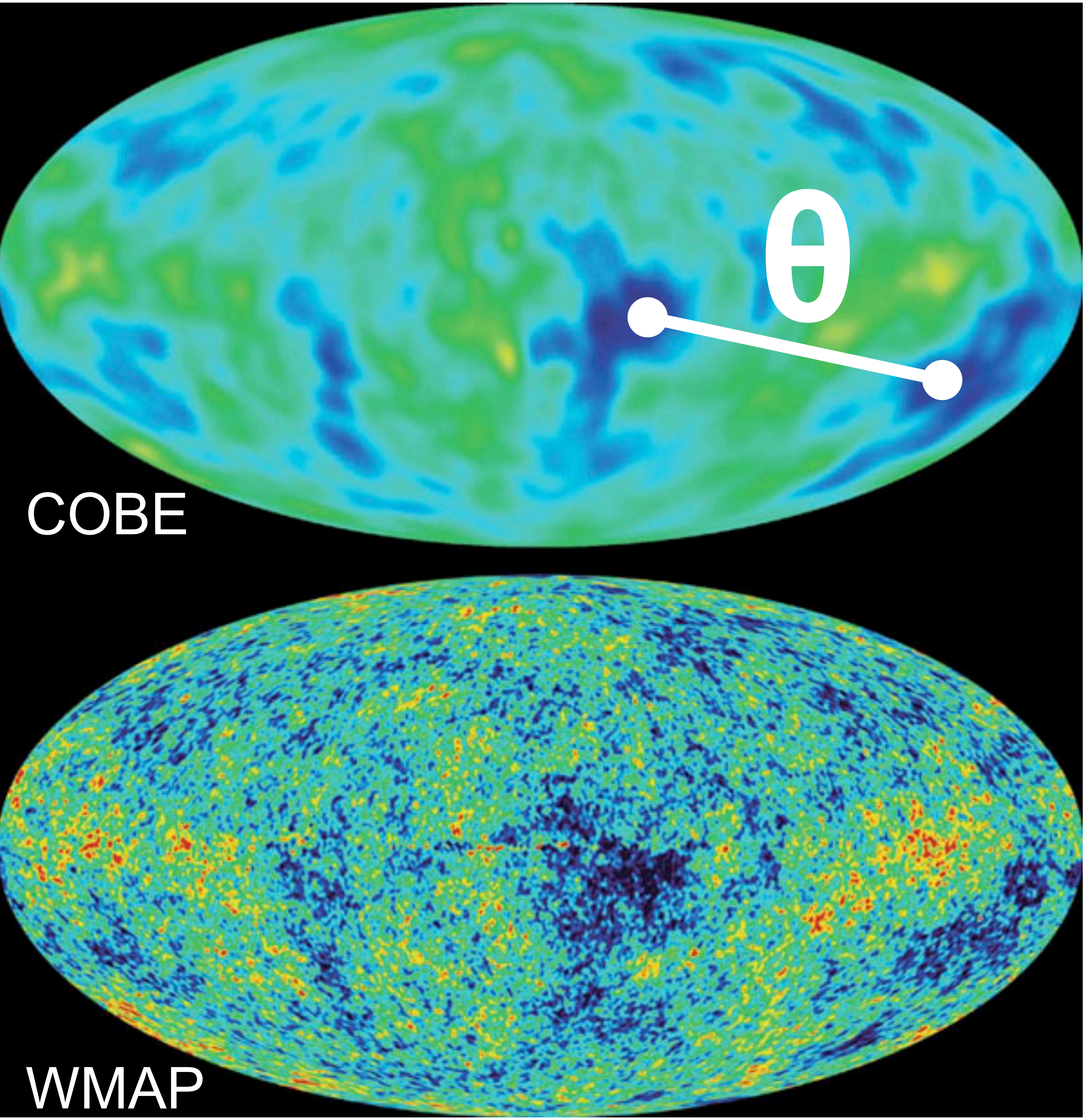




Galaxy-cleaned Map

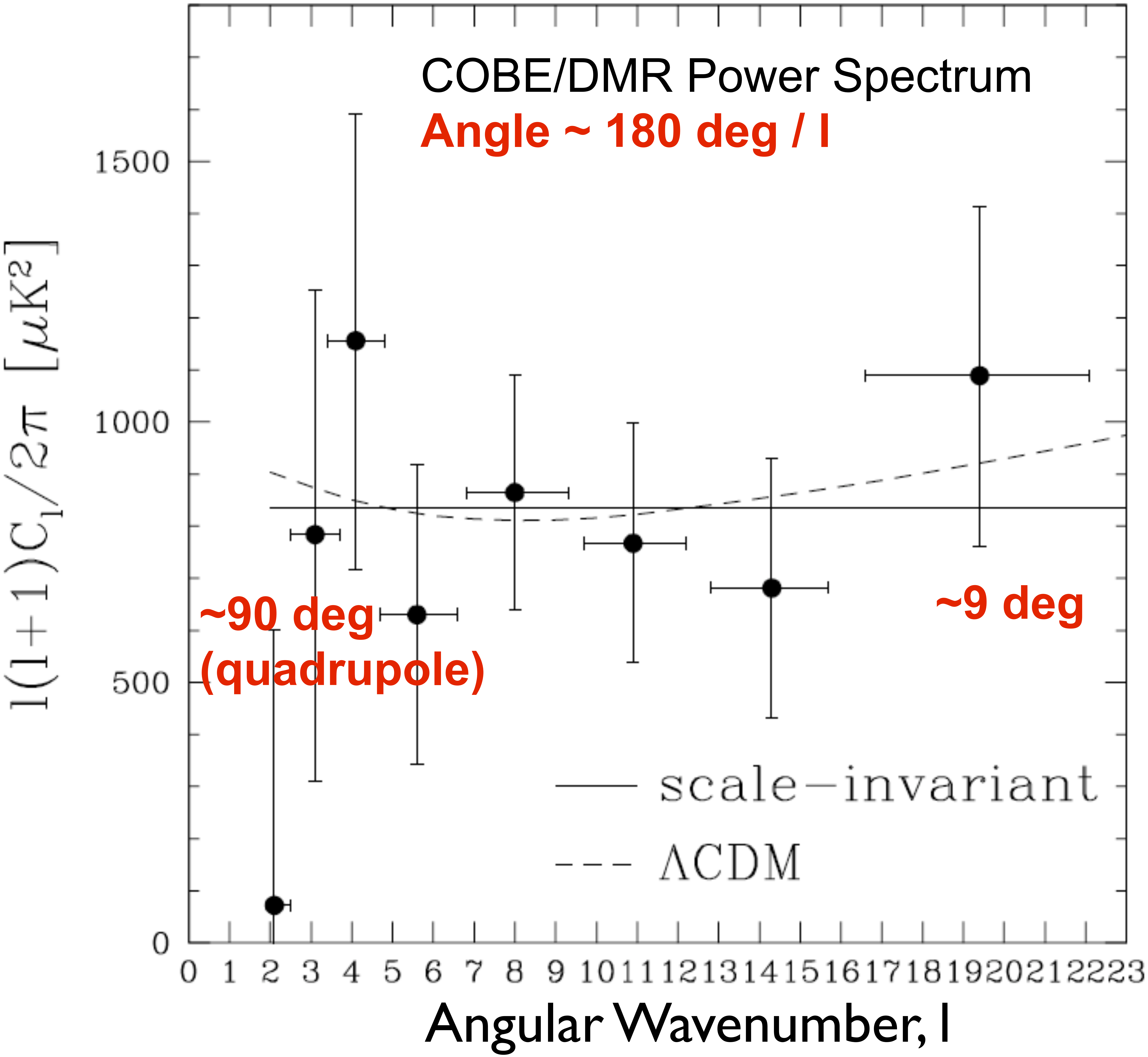


WMAP 5-year



Analysis: 2-point Correlation

- $C(\theta)=(1/4\pi)\sum(2l+1)C_l P_l(\cos\theta)$
- How are temperatures on two points on the sky, separated by θ, are correlated?
- **"Power Spectrum," C_l**
  - How much fluctuation power do we have at a given angular scale?
  - **$l \sim 180$ degrees / θ**

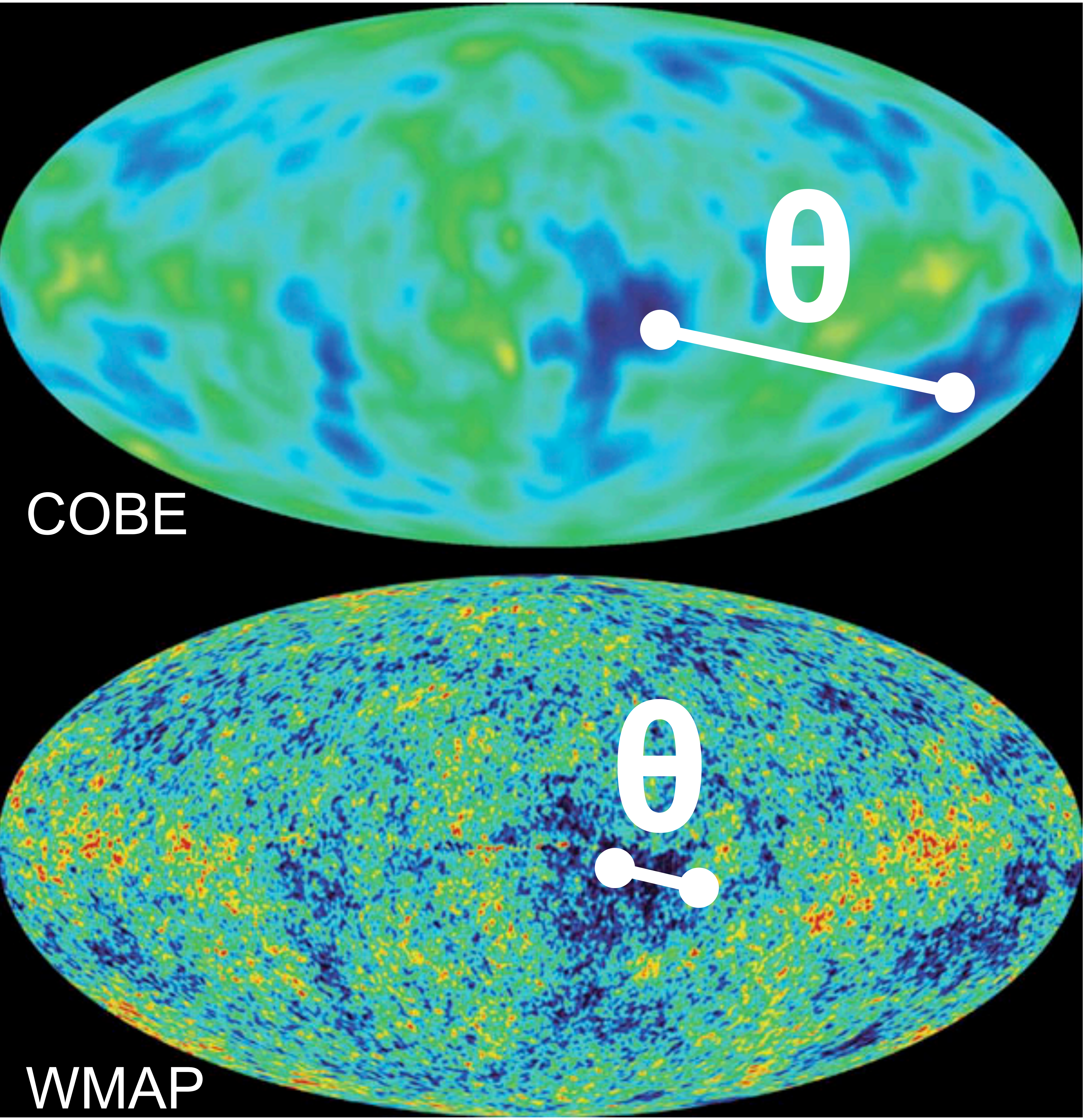


COBE/DMR Power Spectrum

Angle ~ 180 deg / l

~90 deg (quadrupole)

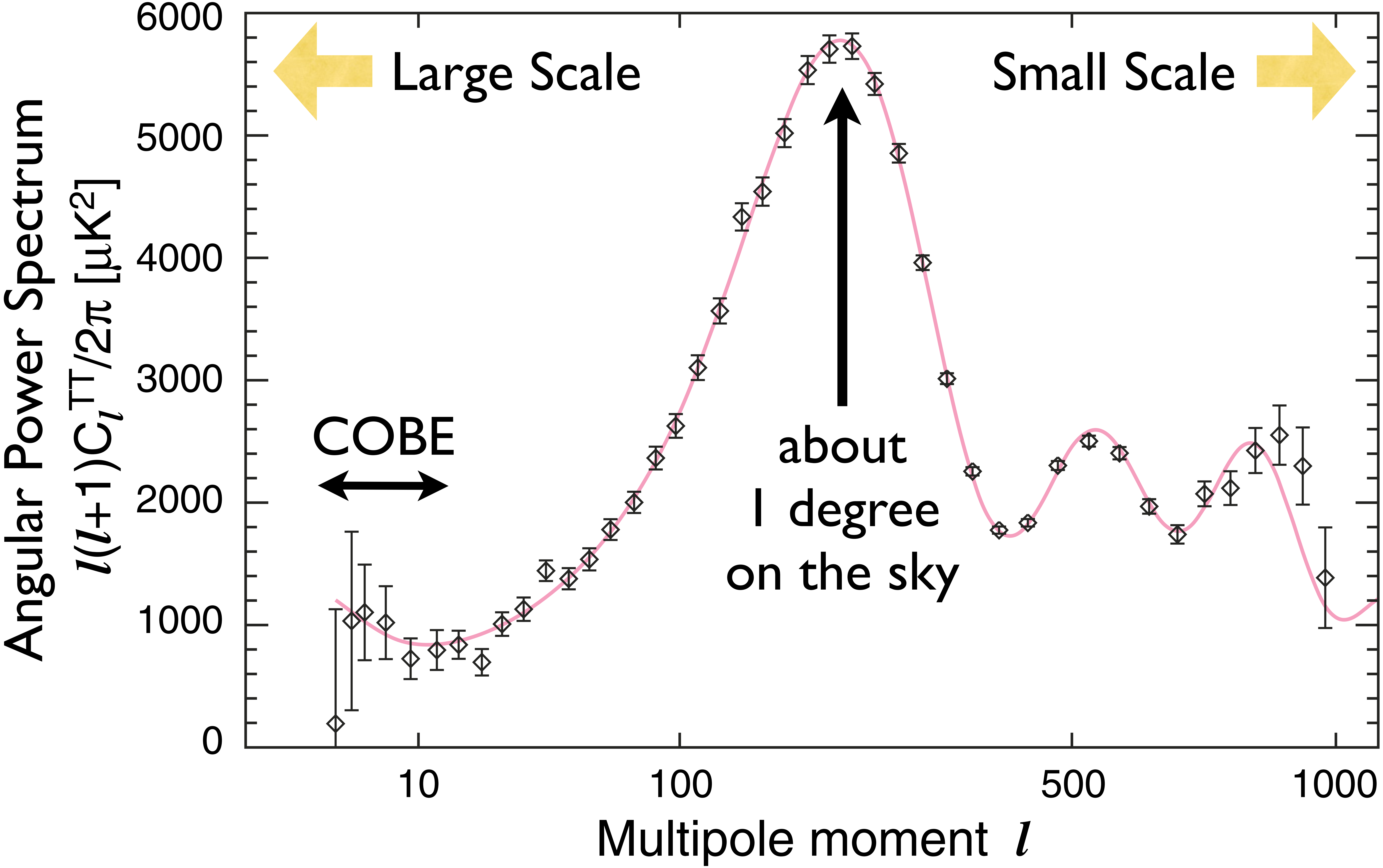
~9 deg



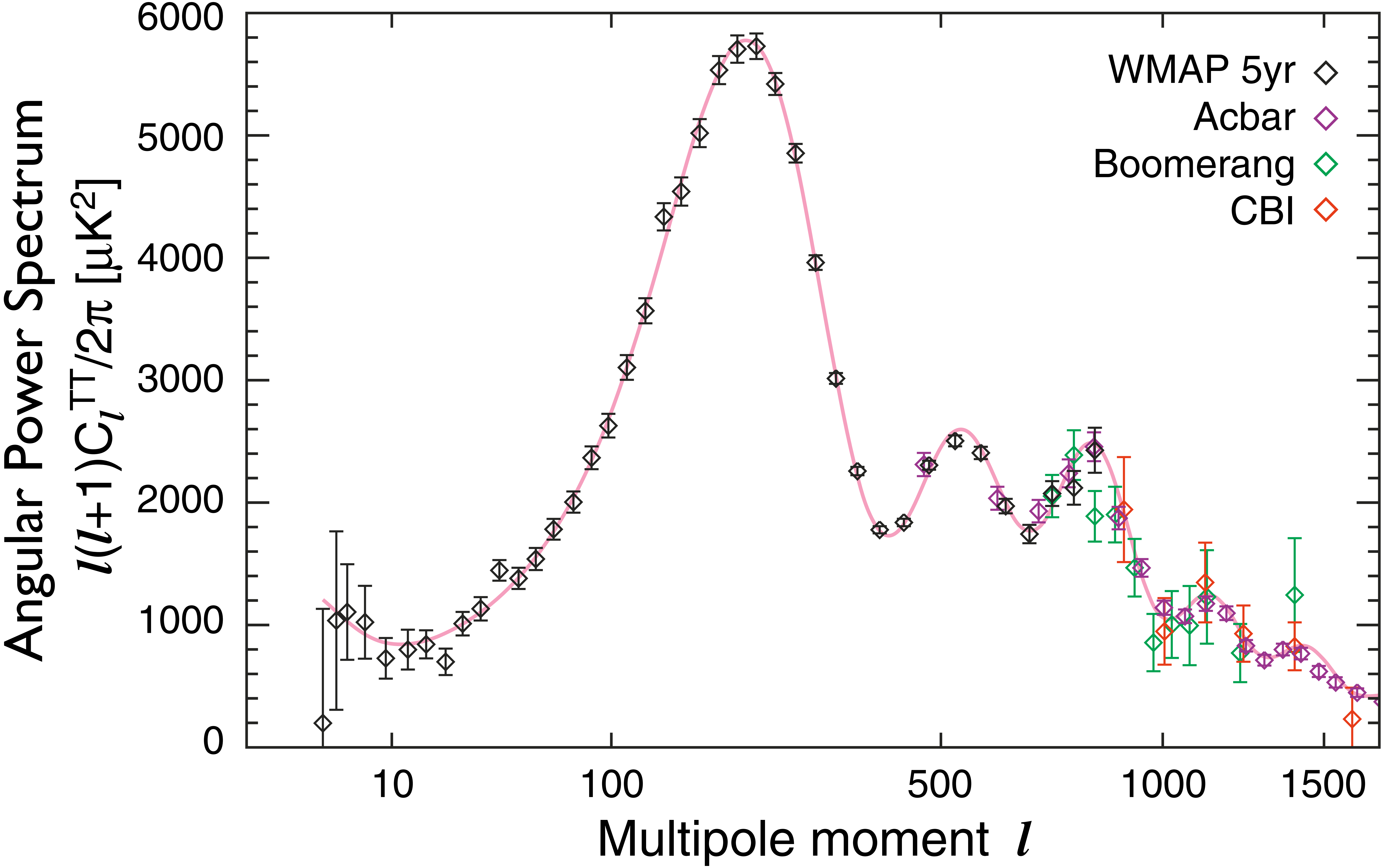
COBE To WMAP

- COBE is unable to resolve the structures below ~7 degrees
- WMAP's resolving power is 35 times better than COBE.
- What did WMAP see?

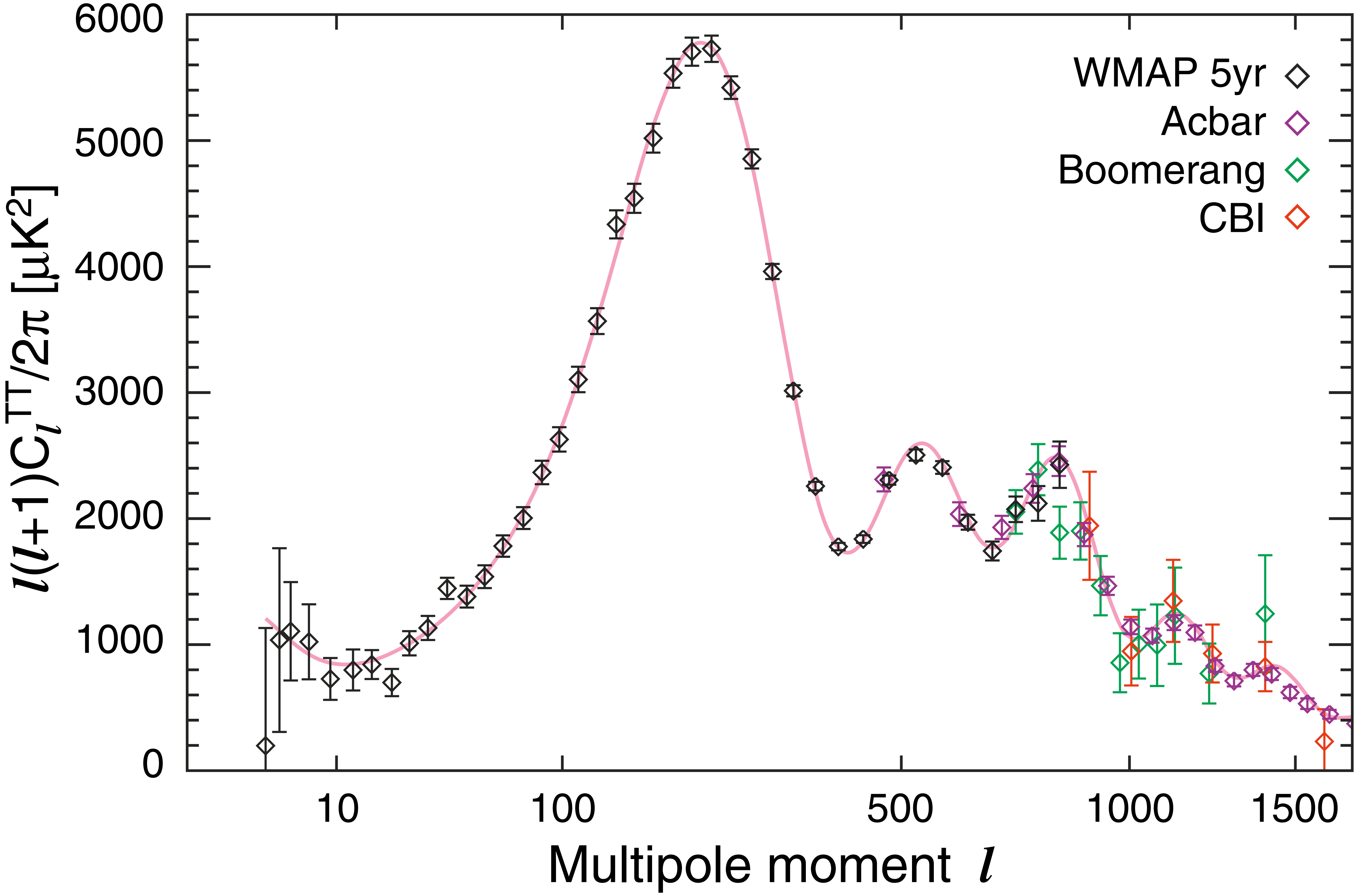
WMAP Power Spectrum

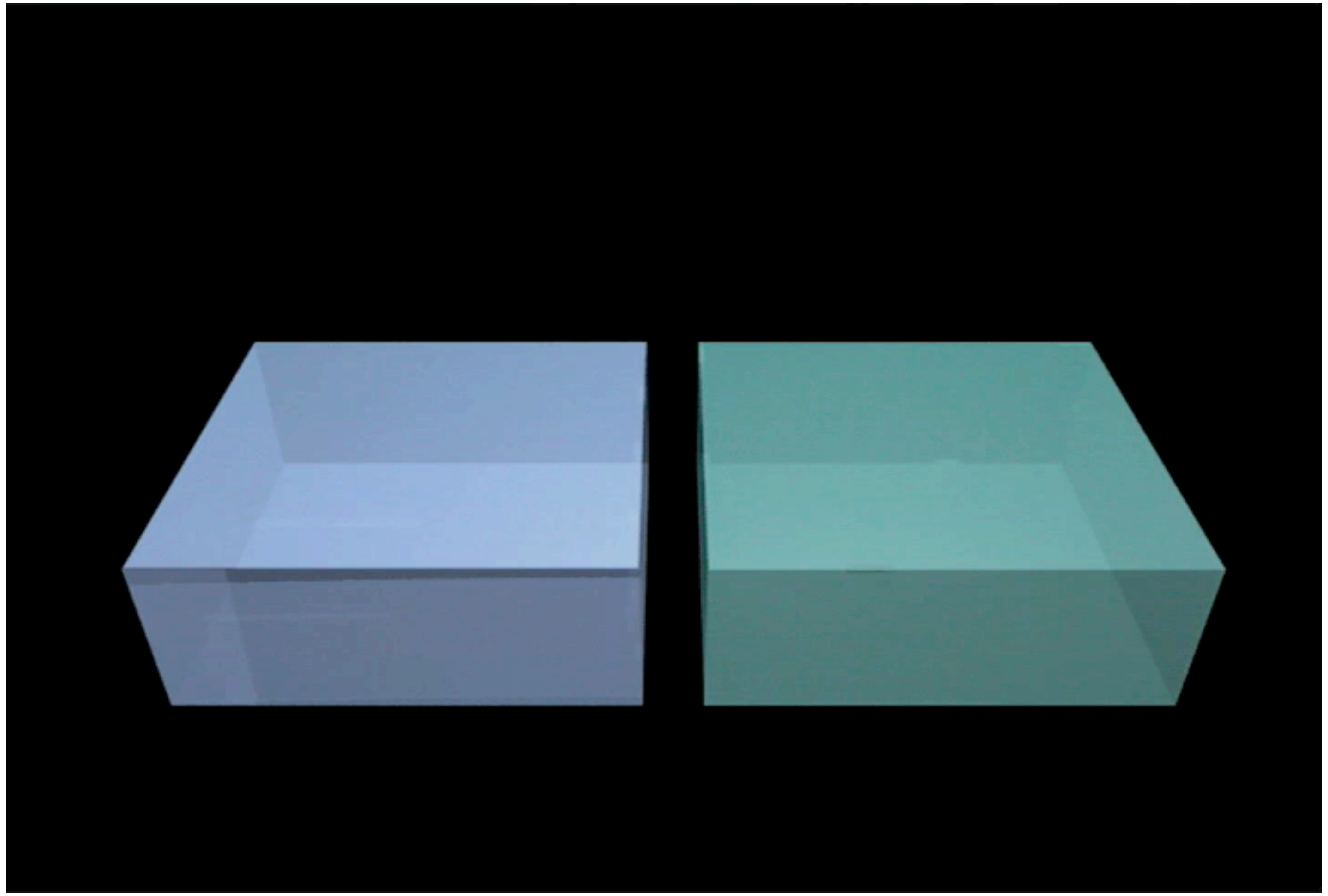


The Cosmic Sound Wave



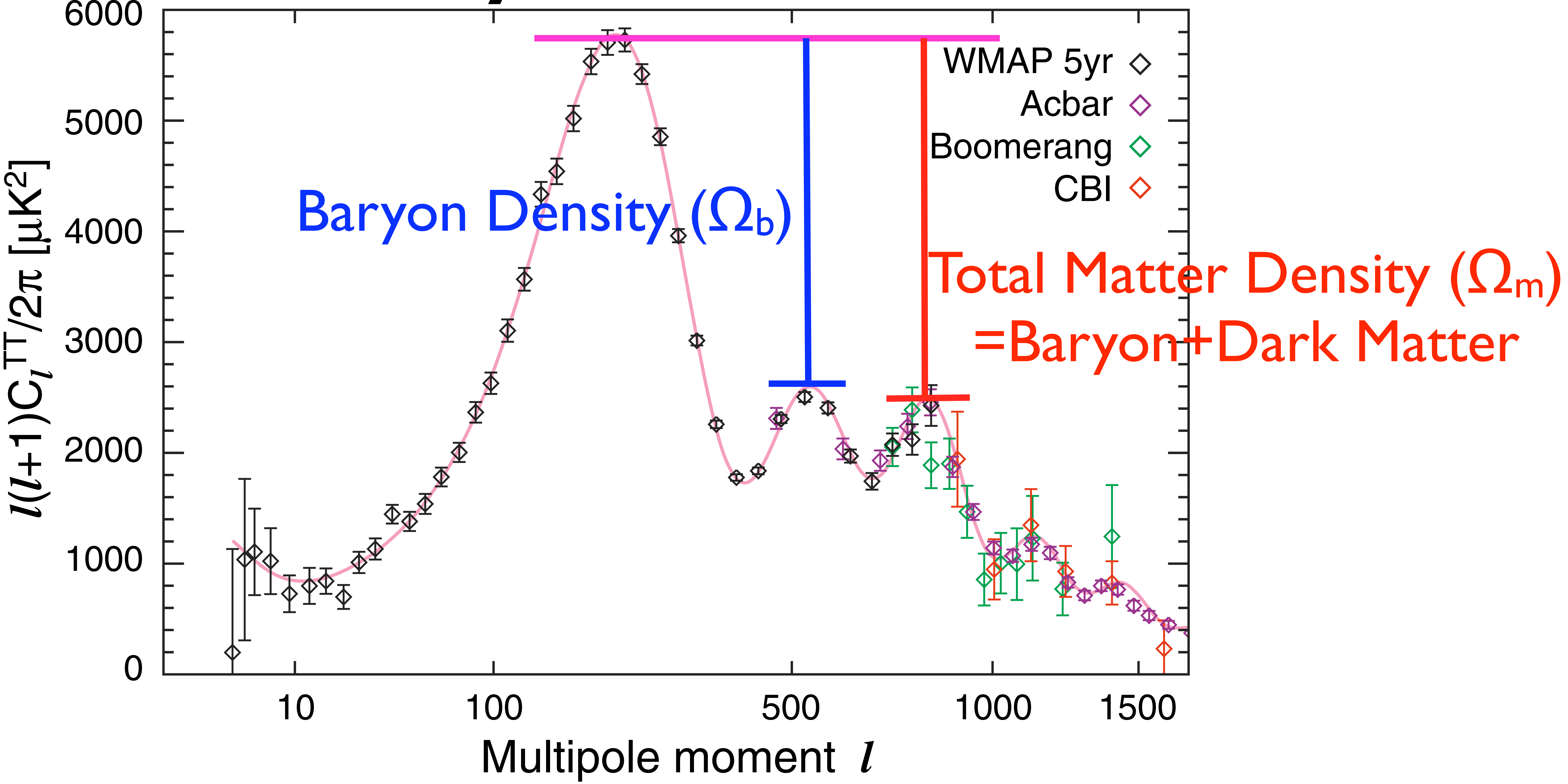
The Cosmic Sound Wave





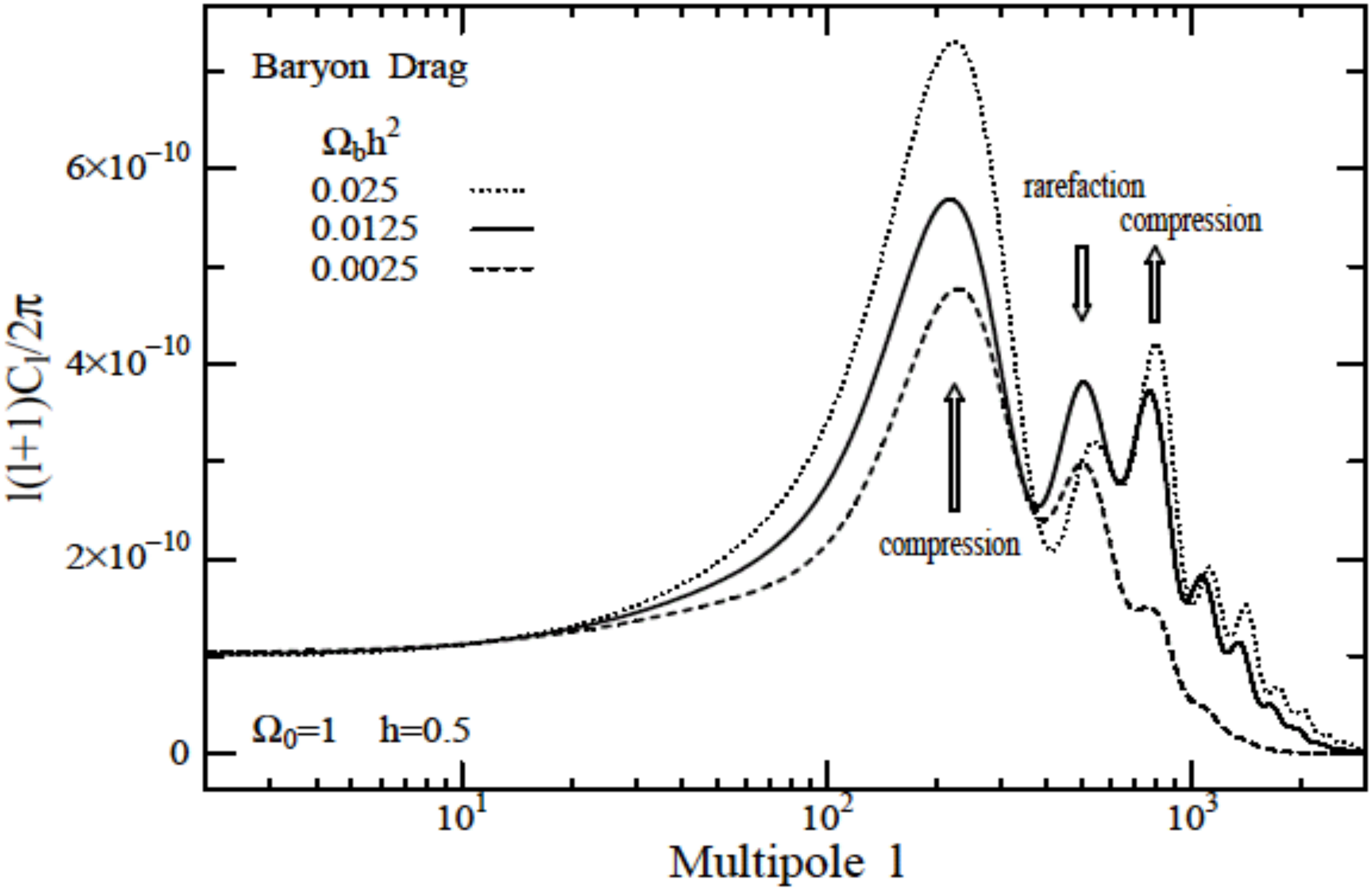
- *"The Universe as a Miso soup"*
    - *Main Ingredients: protons, helium nuclei, electrons, photons*
- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves.

CMB to Baryon & Dark Matter

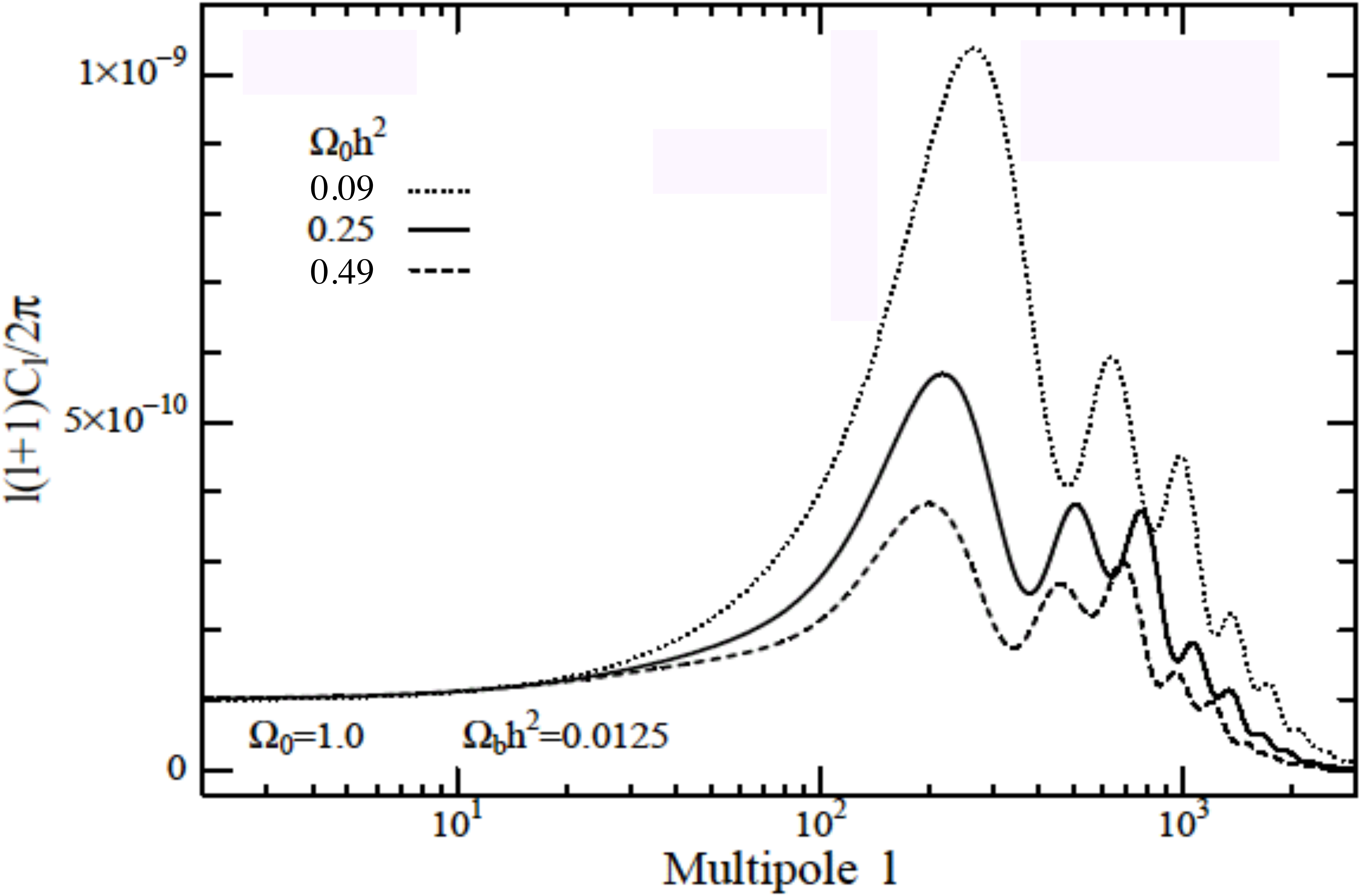


- 1-to-2: baryon-to-photon ratio
- 1-to-3: matter-to-radiation ratio

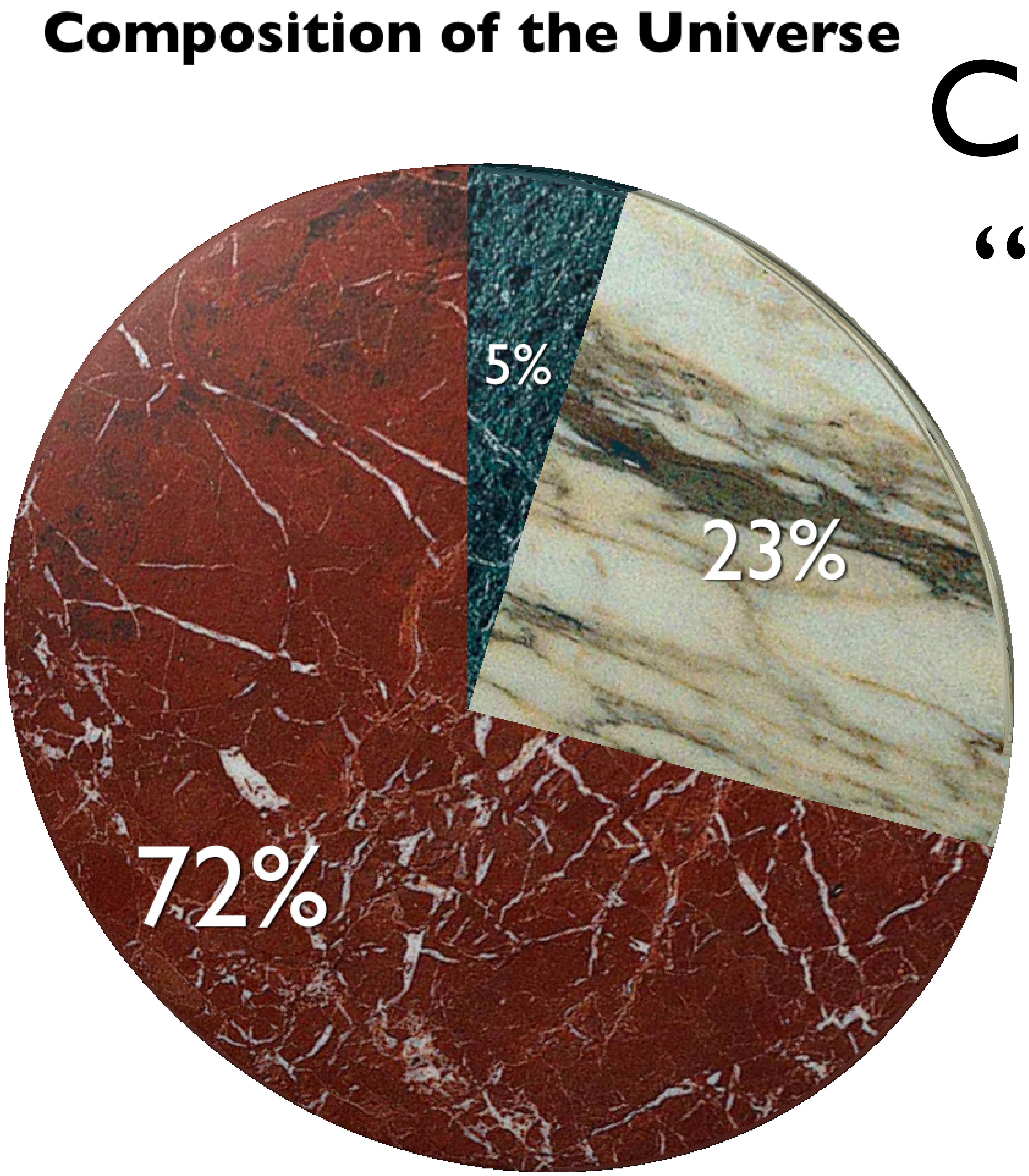
Determining Baryon Density From C_l



Determining Dark Matter Density From C_l

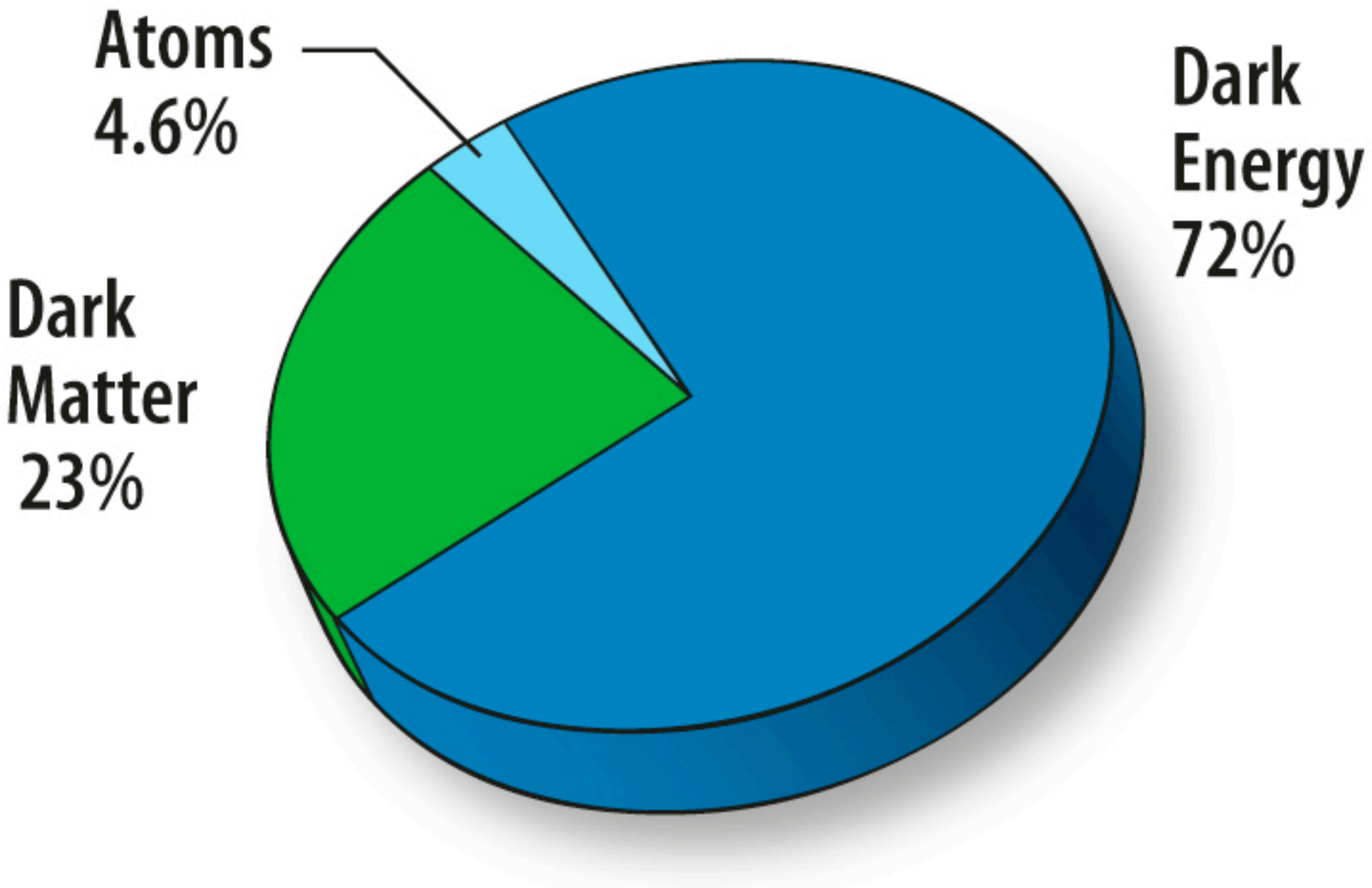


Cosmic Pie Chart
“ΛCDM” Model

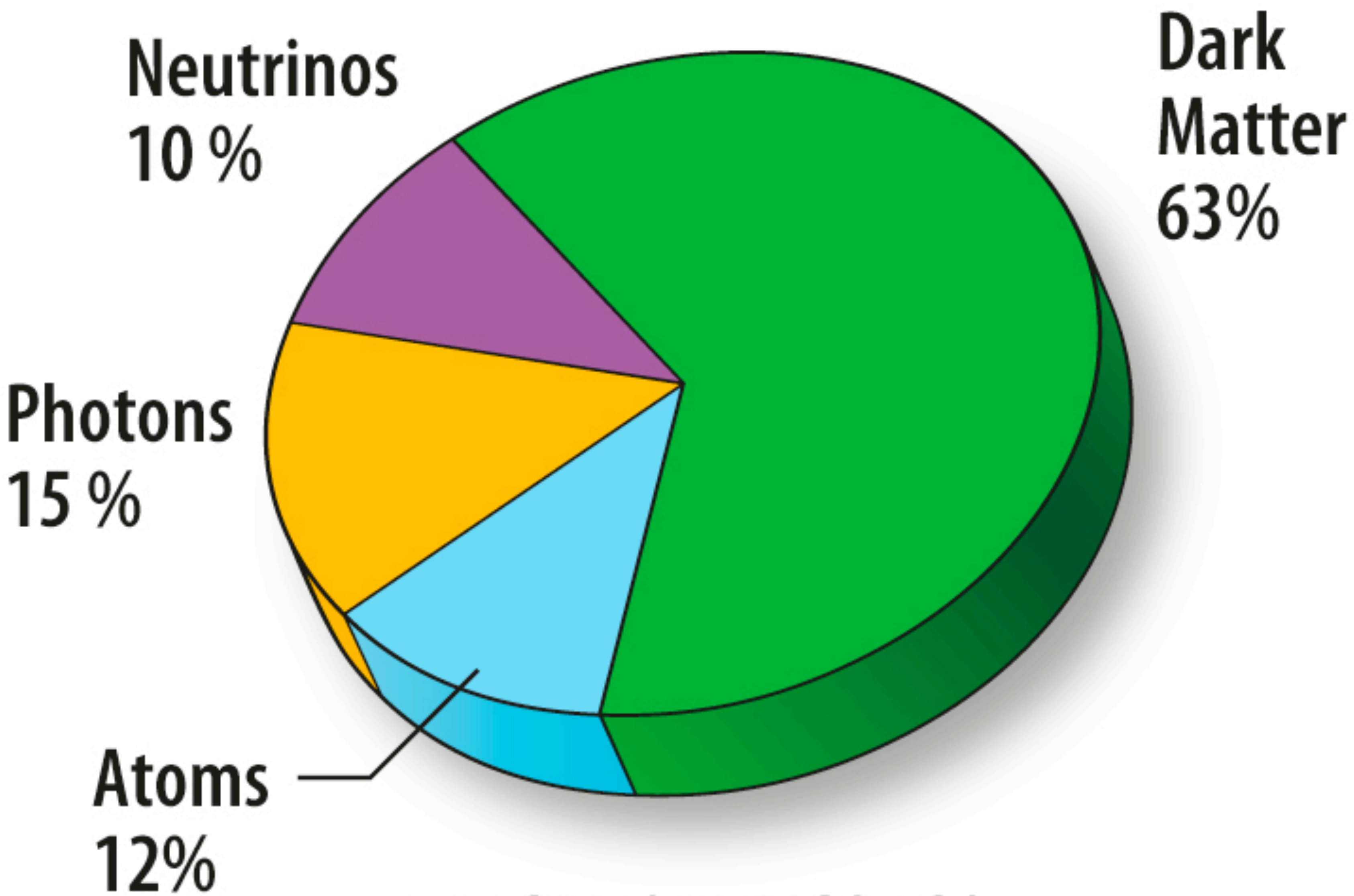


- Cosmological observations (CMB, galaxies, supernovae) over the last decade told us that **we don’t understand much of the Universe**.

● Hydrogen & Helium
● Dark Matter
● Dark Energy



TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

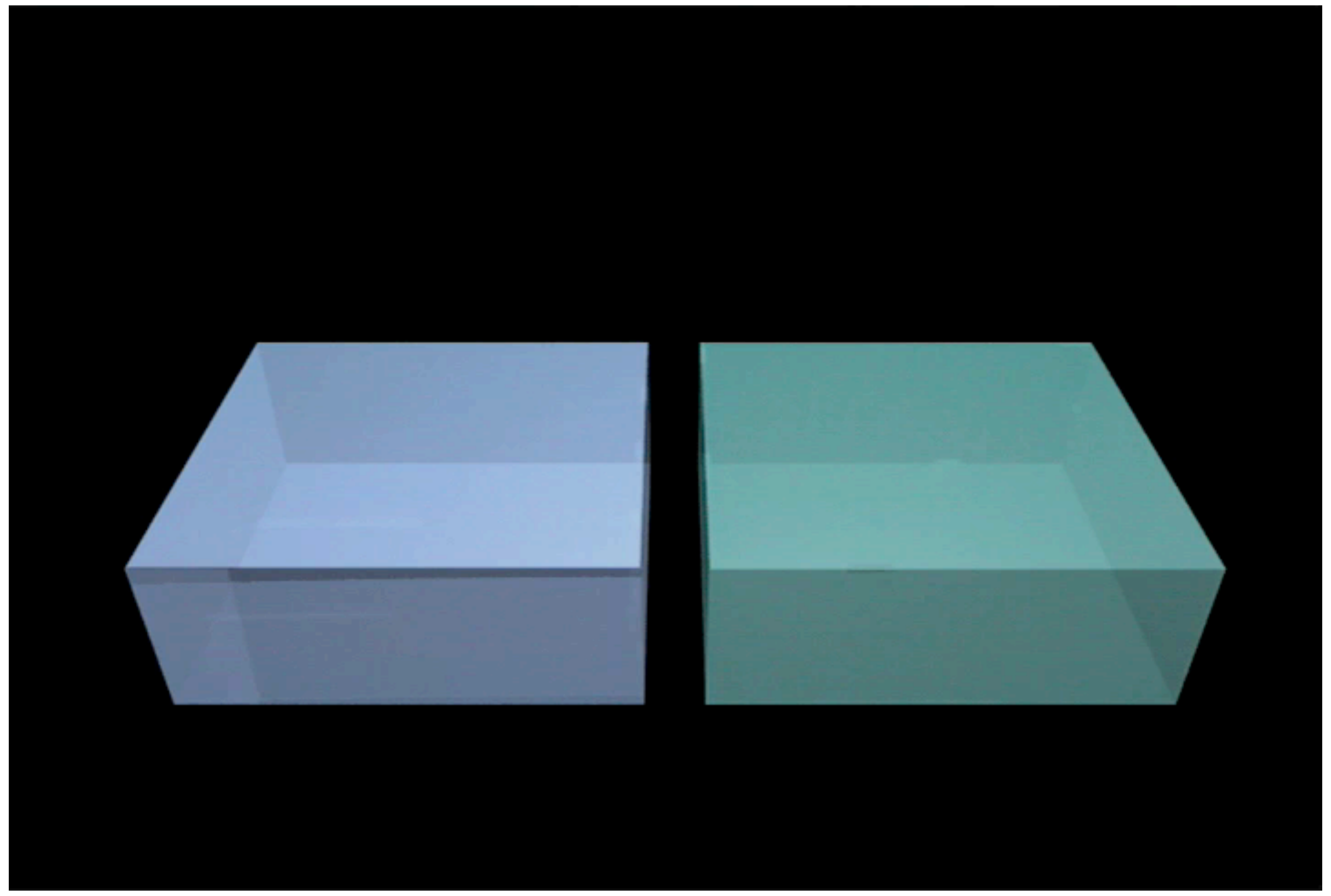
~WMAP 5-Year~ Pie Chart Update!

- Universe today
  - Age: **13.72 ± 0.12** billion years
  - Atoms: **4.56 ± 0.15 %**
  - Dark Matter: **22.8 ± 1.3%**
  - Vacuum Energy: **72.6 ± 1.5%**
- When CMB was released 13.7 B yrs ago
  - A significant contribution from the *cosmic neutrino background*

Golden Age of Cosmology

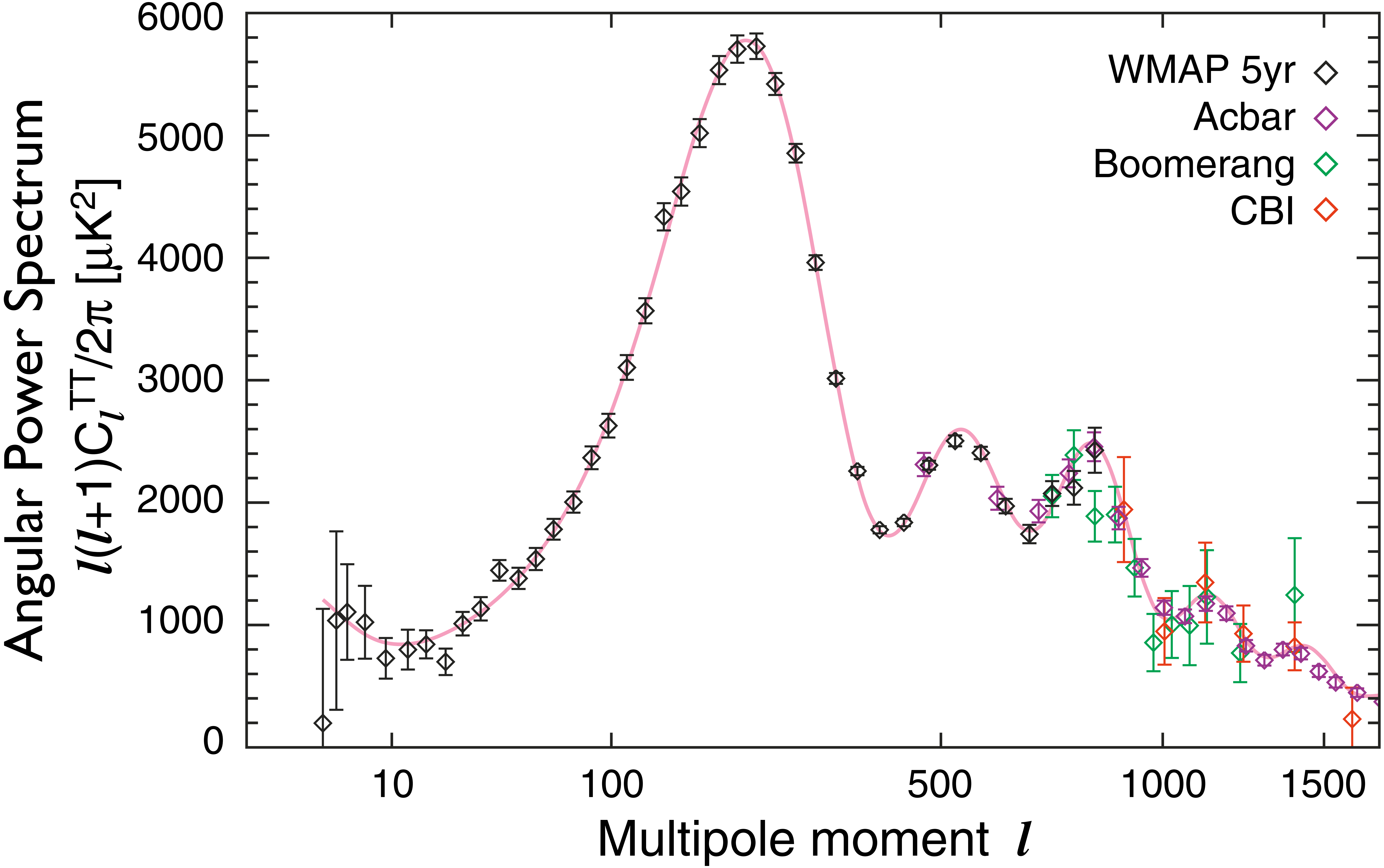
- **Q. Why Golden Age?**
- **A. Because we are facing extraordinary challenges.**
  - What is Dark Matter?
  - What is Dark Energy?

Even More Challenging

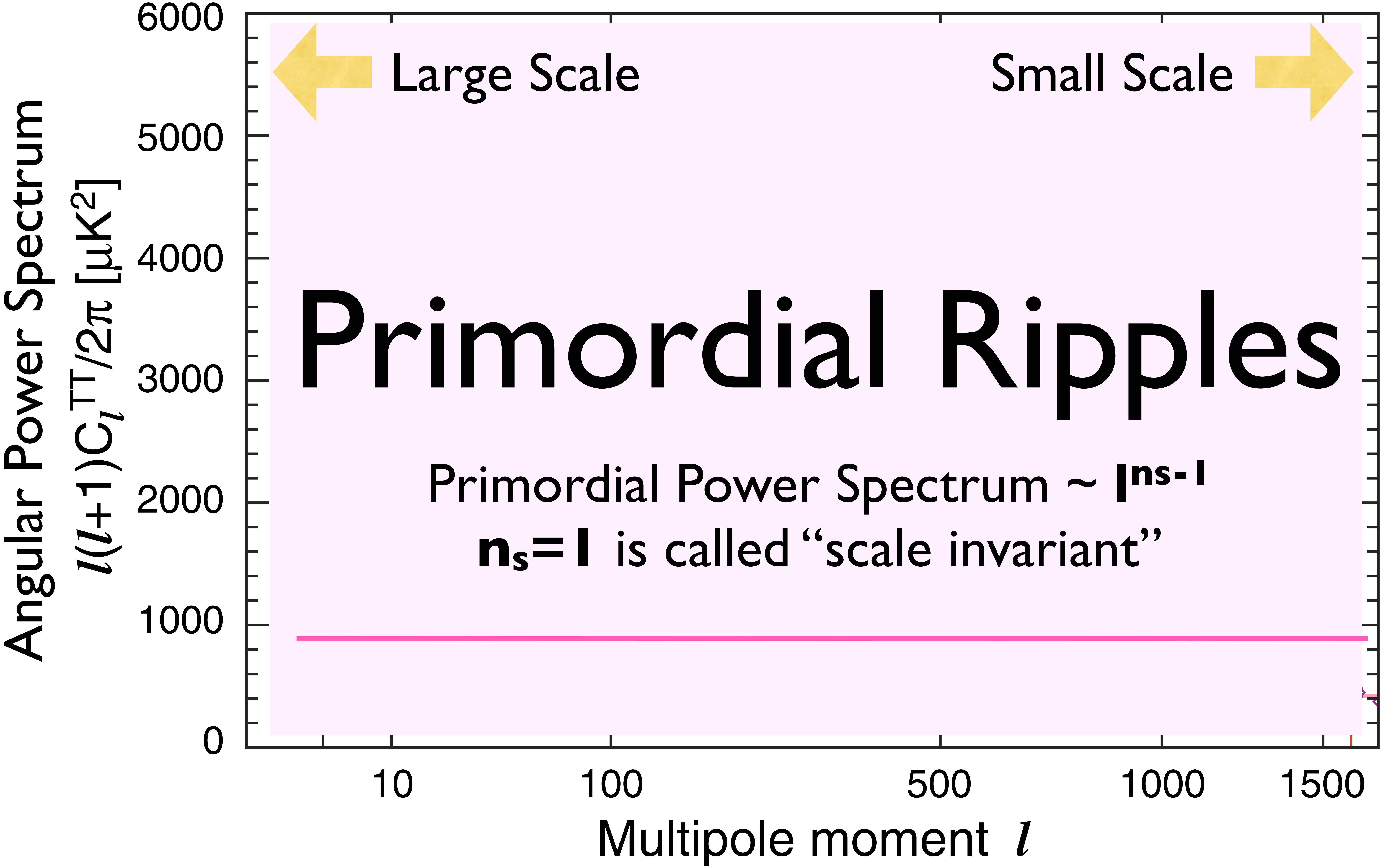


- OK, back to the cosmic waterzooi.
- The sound waves were created when we perturbed it.
- “We”? **Who?**
- Who actually dropped a spoon in the cosmic waterzooi?
- **Who generated the original (seed) ripples?**
  - ***We must go farther back in time to answer this question!***

Decoding the Primordial Ripples



Getting rid of the Sound Waves

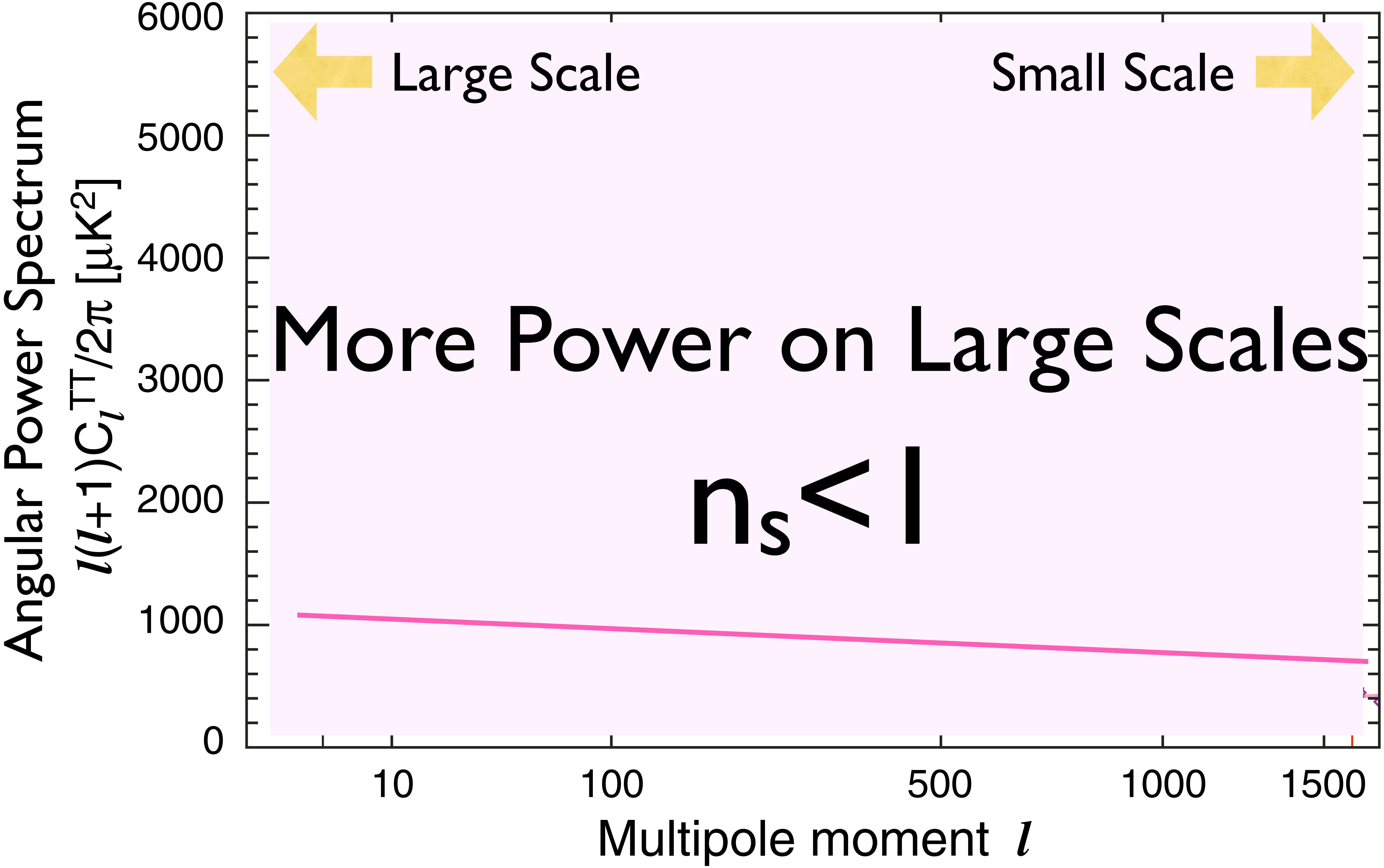


Primordial Ripples

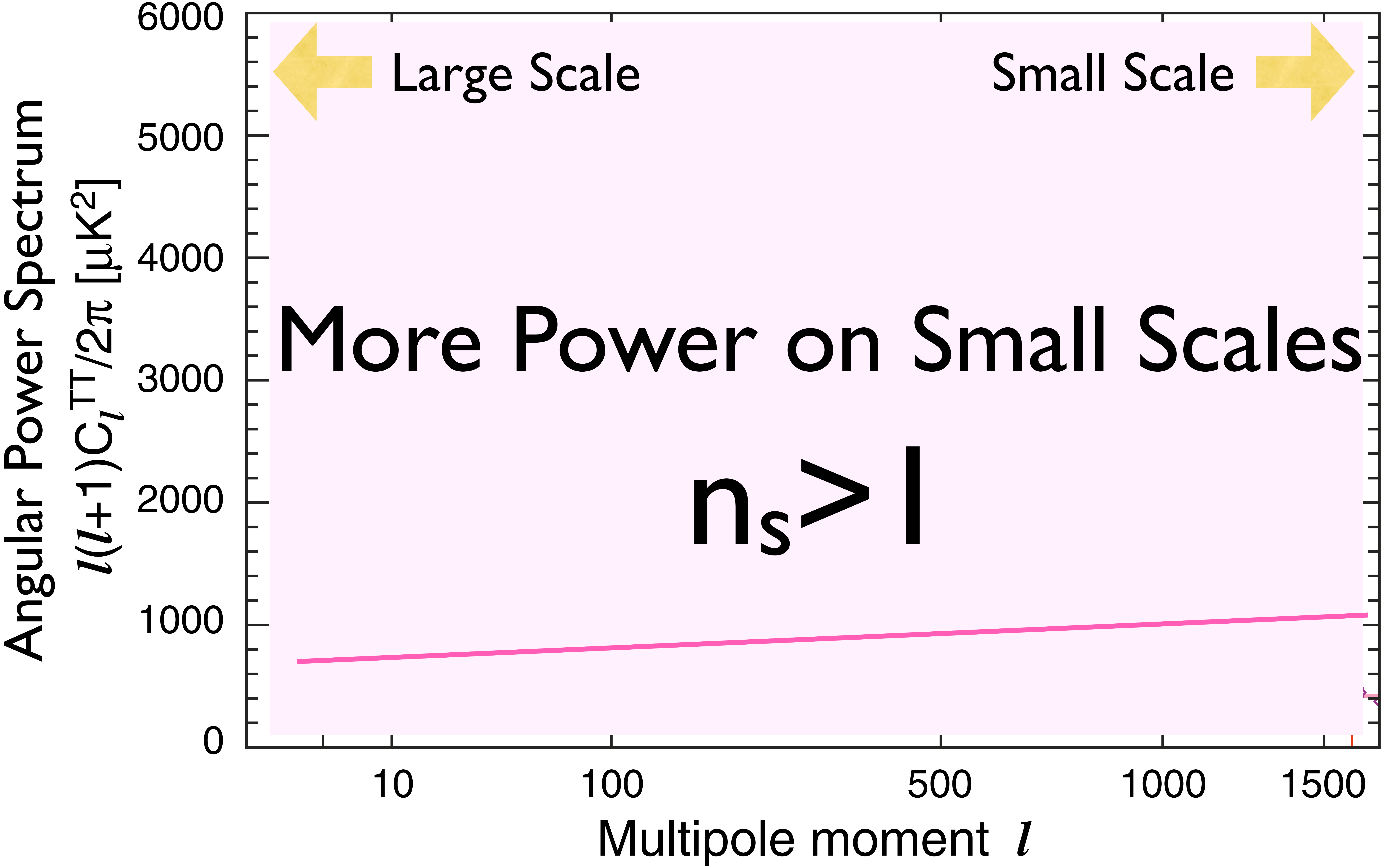
Primordial Power Spectrum ~ l^{n_s-1}

$n_s=1$ is called “scale invariant”

The Early Universe Could Have Done This Instead



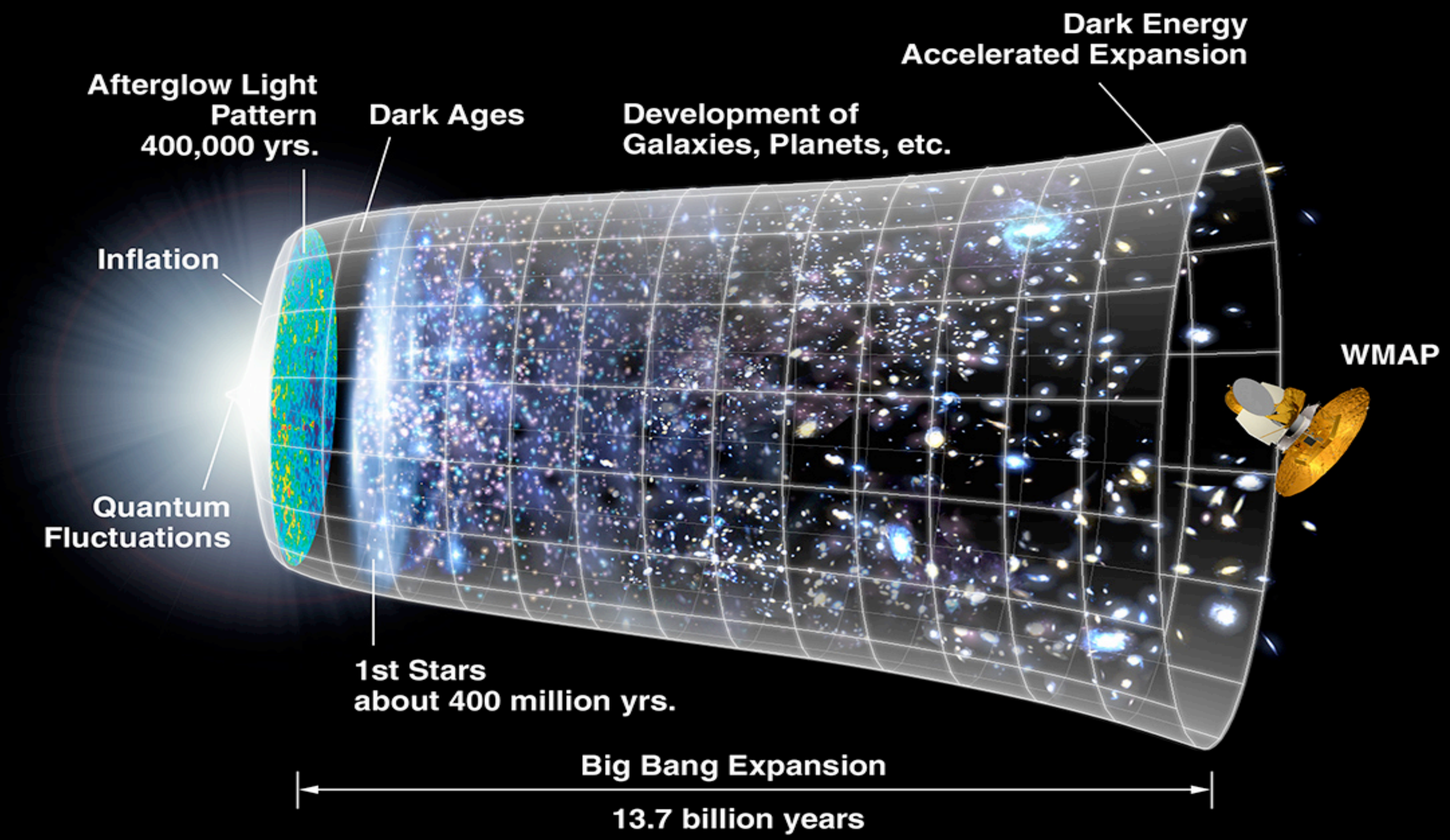
...or, This.


Large Scale
Small Scale
More Power on Small Scales
$n_s > 1$
Angular Power Spectrum
$l(l+1)C_l^{TT}/2\pi$ [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
Multipole moment l

Theory of the Very Early Universe

- The leading theoretical idea about the primordial Universe, called "***Cosmic Inflation***," predicts:
  (Guth 1981; Linde 1982; Albrecht & Steinhardt 1982; Starobinsky 1980)
  - The expansion of our Universe ***accelerated*** in a tiny fraction of a second after its birth.
  - Just like Dark Energy accelerating today's expansion: the acceleration also happened at very, very early times!
- **Inflation stretches "*micro to macro*"**
  - In a tiny fraction of a second, the size of an atomic nucleus (~10^{-15}m) would be stretched to 1 A.U. (~10^{11}m), at least.

Cosmic Inflation = Very Early Dark Energy



NASA/WMAP Science Team

Theory Says...

- The leading theoretical idea about the primordial Universe, called "***Cosmic Inflation***," predicts:
  - The expansion of our Universe ***accelerated*** in a tiny fraction of a second after its birth.
  - the primordial ripples were created by ***quantum fluctuations*** during inflation, and
  - how the power is distributed over the scales is determined by the **expansion history during cosmic inflation**.
- Detailed observations give us **this** remarkable information!

Quantum Fluctuations

- You may borrow a lot of **energy** from vacuum if you promise to return it to the vacuum immediately.
- The amount of **energy** you can borrow is inversely proportional to the time for which you borrow the **energy** from the vacuum.
- This is the so-called Heisenberg's Uncertainty Principle, which is the foundation of Quantum Mechanics.

Mukhanov & Chibisov (1981); Guth & Pi (1982); Starobinsky (1982); Hawking (1982); Bardeen, Turner & Steinhardt (1983)

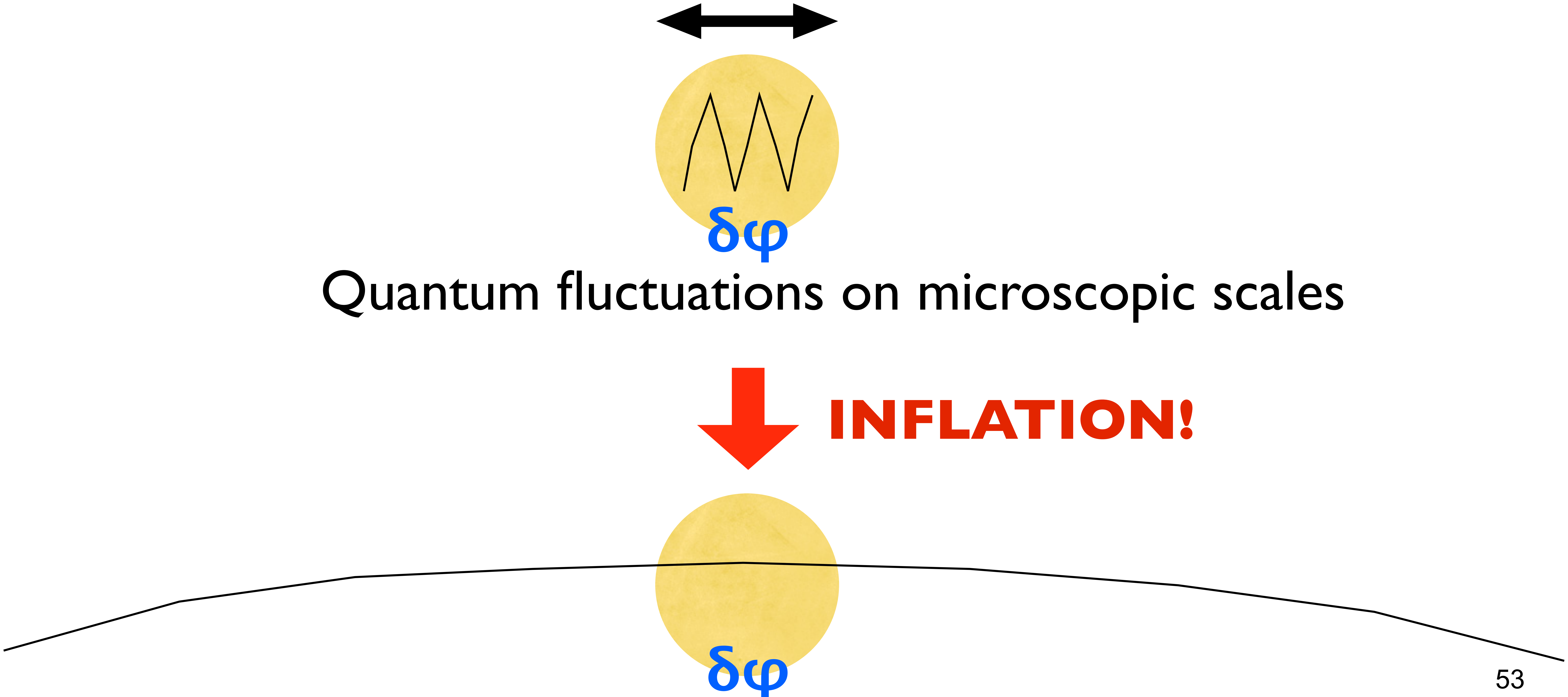
(Scalar) Quantum Fluctuations

$\delta\varphi$ = (Expansion Rate)/(2π) [in natural units]

- Why is this relevant?
- The cosmic inflation (probably) happened when the Universe was a tiny fraction of second old.
  - Something like 10^{-36} second old
  - (Expansion Rate) ~ 1/(Time)
    - which is a big number! (~10^{12}GeV)
  - *Quantum fluctuations were important during inflation!*

Stretching Micro to Macro

Macroscopic size at which gravity becomes important



Quantum fluctuations on microscopic scales

INFLATION!

Quantum fluctuations cease to be quantum, and become observable!

Inflation Offers a Magnifier for Microscopic World

- Using the *power spectrum of primordial fluctuations* imprinted in CMB, we can observe the quantum phenomena at the ultra high-energy scales that would never be reached by the particle accelerator.

Starobinsky (1979)

(Tensor) Quantum Fluctuations, a.k.a. Gravitational Waves

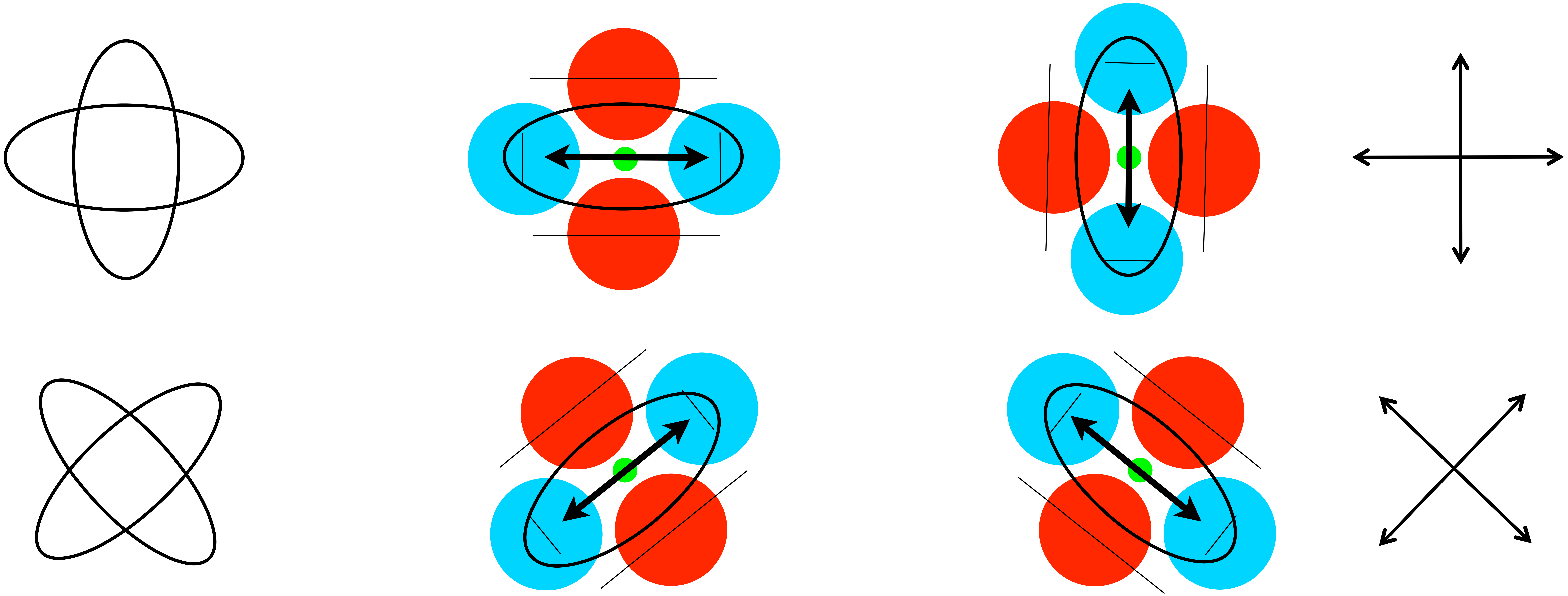
$h = (\text{Expansion Rate})/(2^{1/2}\pi M_{\text{planck}})$ [in natural units]

[h = “strain”]

- Quantum fluctuations also generate ripples in space-time, i.e., gravitational waves, by the same mechanism.
- Primordial gravitational waves generate temperature anisotropy in CMB, as well as polarization in CMB with a distinct pattern called “**B-mode polarization**.”

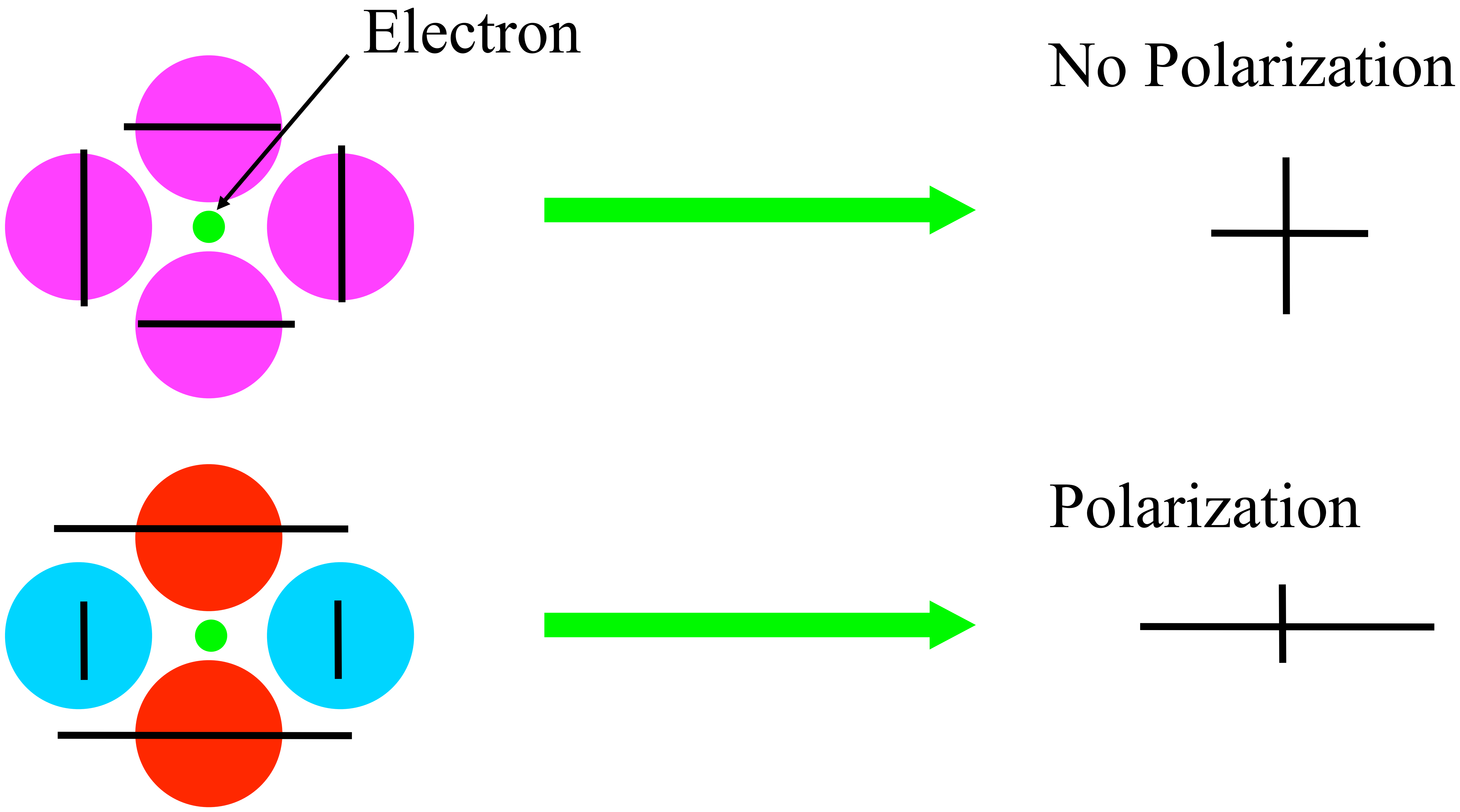
Gravitational Waves & Quadrupole

- As GW propagates in space, it stretches/contracts space.
  - –Stretch -> Redshift -> **Lower temperature**
  - –Contraction -> Blueshift -> **Higher temperature**



CMB Polarization

- Polarization is generated from an electron scattering, coupled with the quadrupolar radiation pattern around the electron.



No Quadrupole

Electron

No Polarization

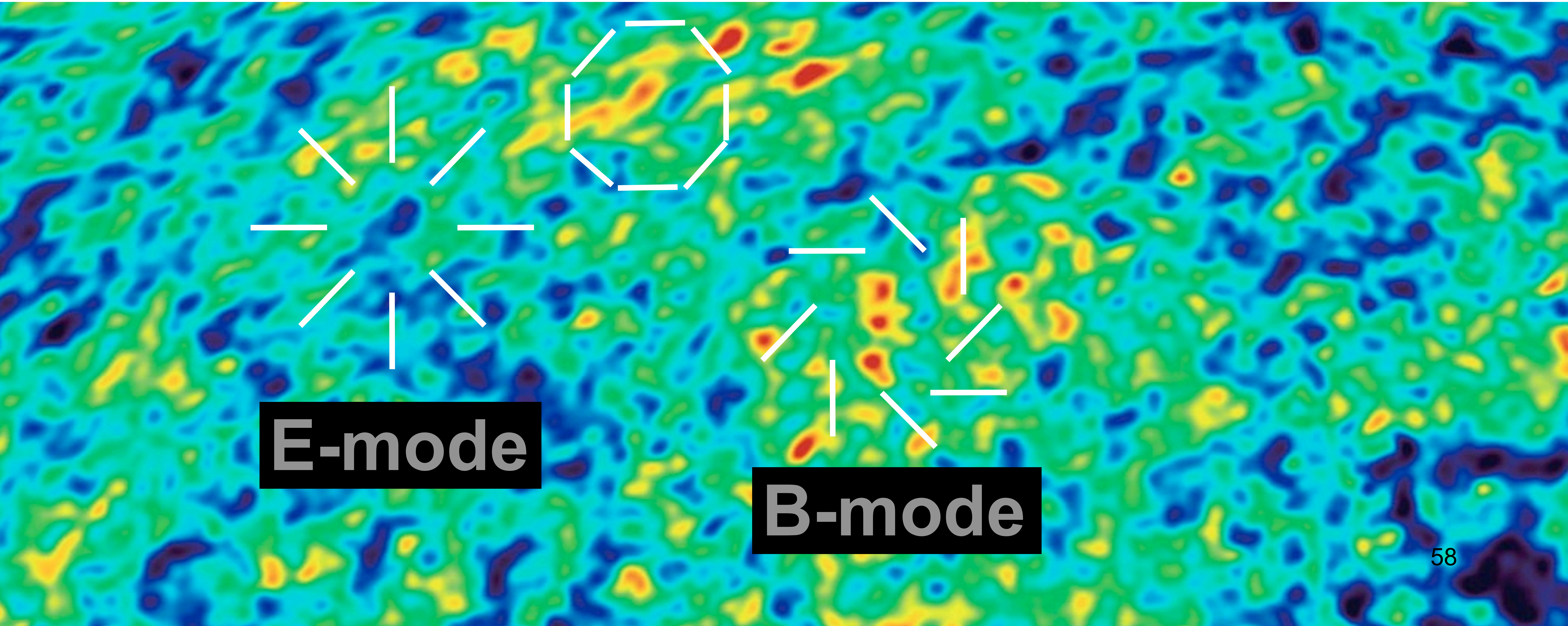
Quadrupole

Polarization

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky, Stebbins (1997)

E-mode and B-mode Polarization

- Polarization has directions.
- One can decompose it into a divergence-like "E-mode" and a vorticity-like "B-mode".



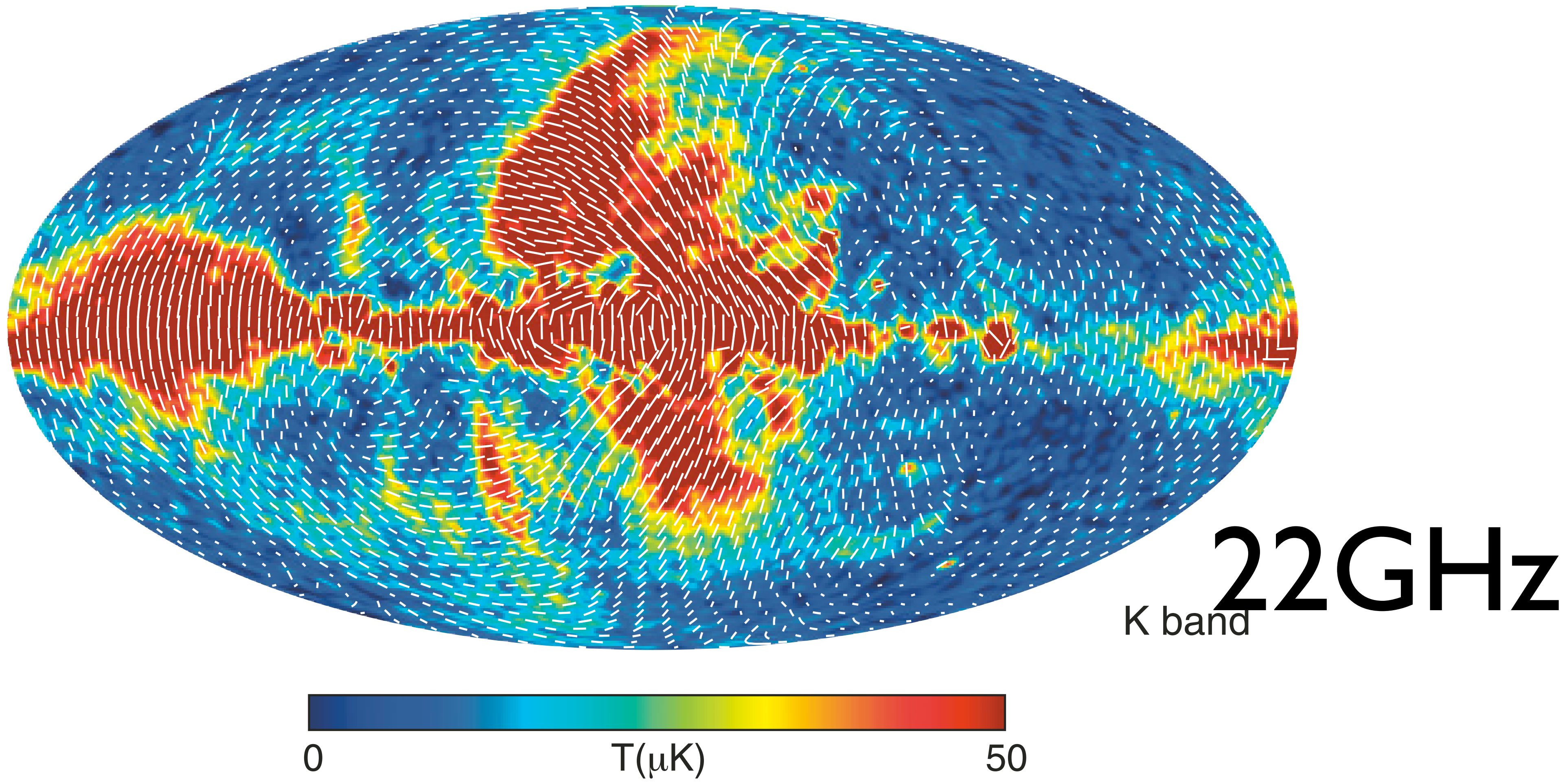
Polarization Anisotropy

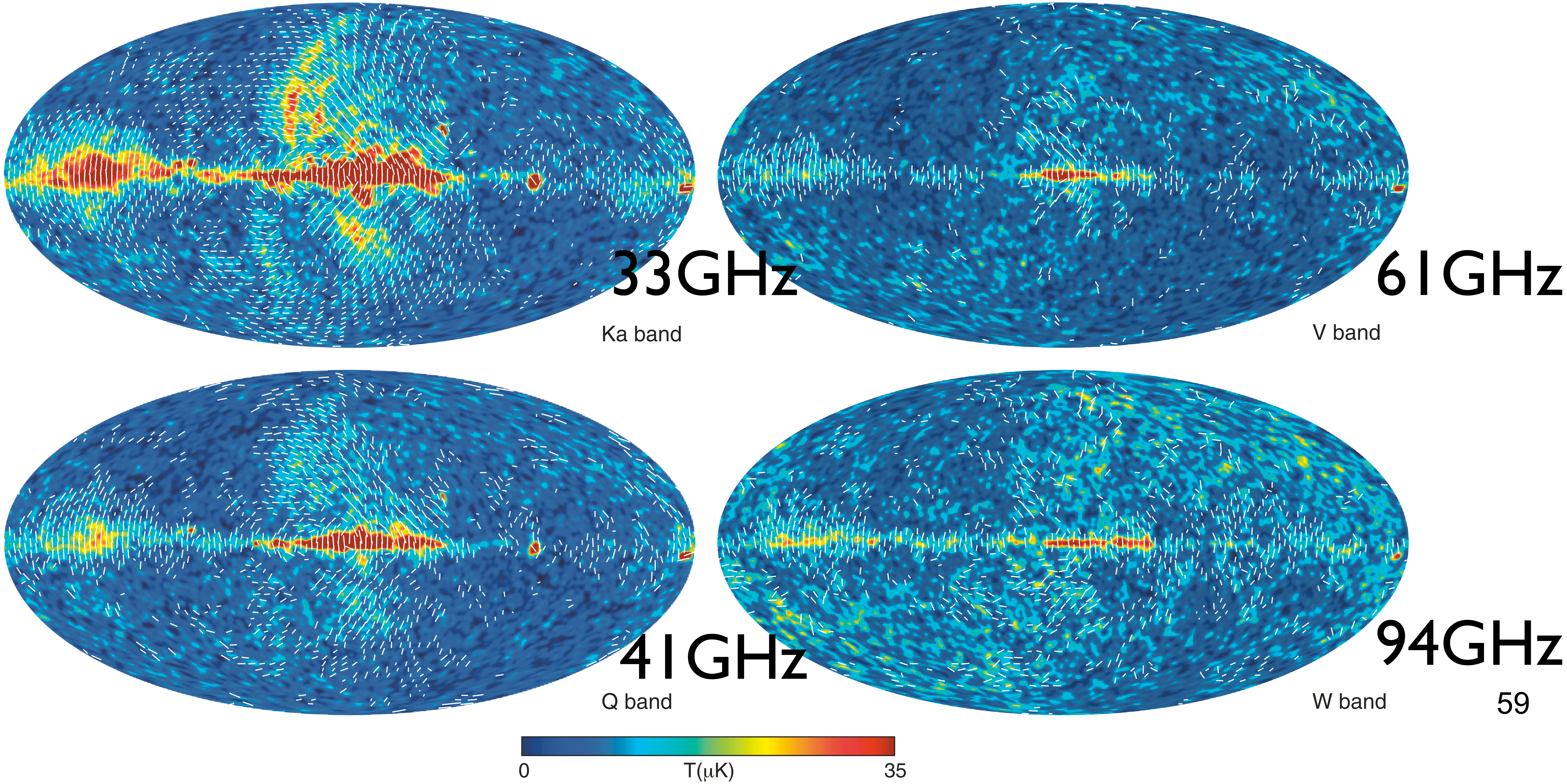
Color:

Polarization Intensity

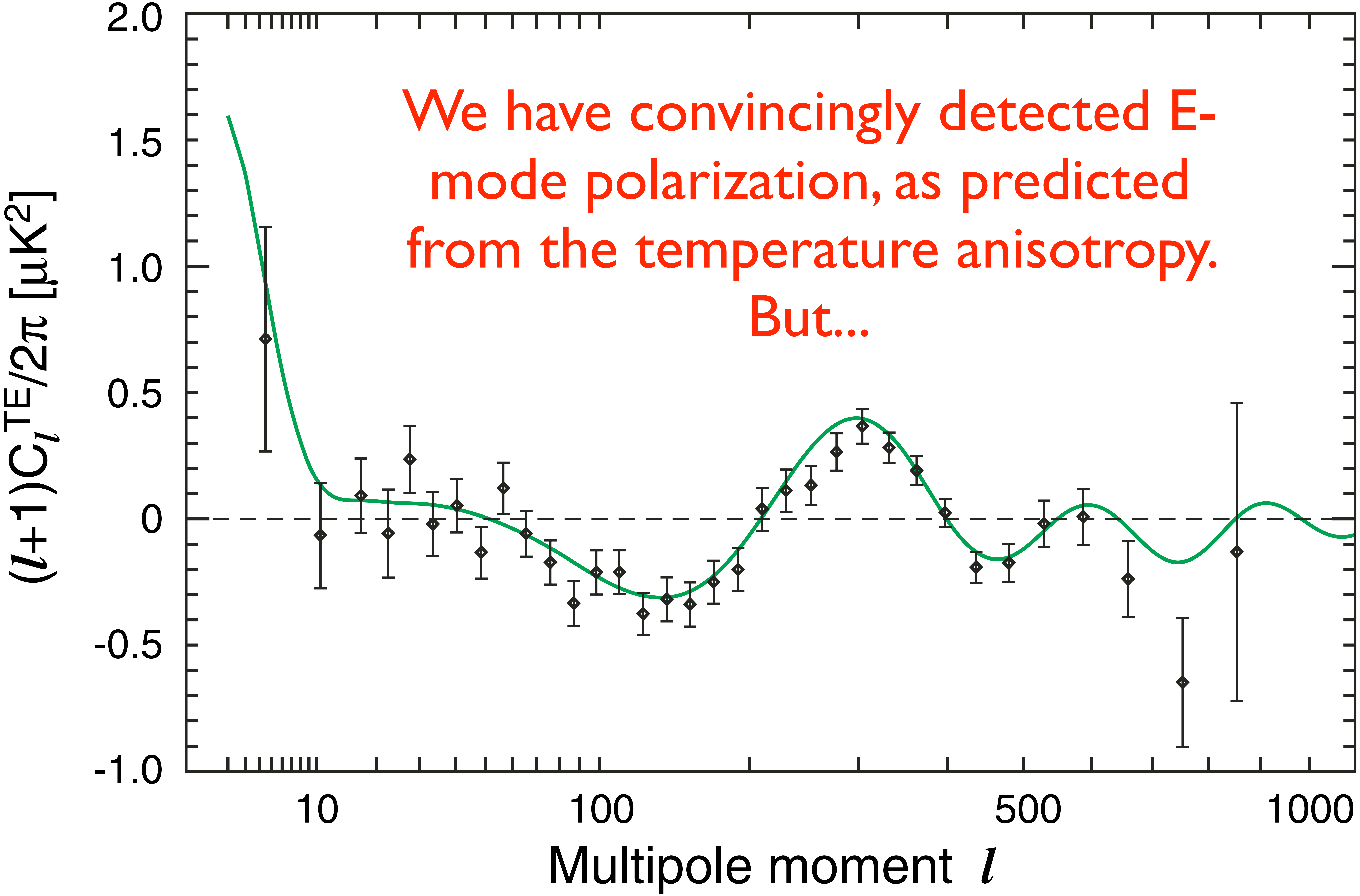
Line:

Polarization Direction



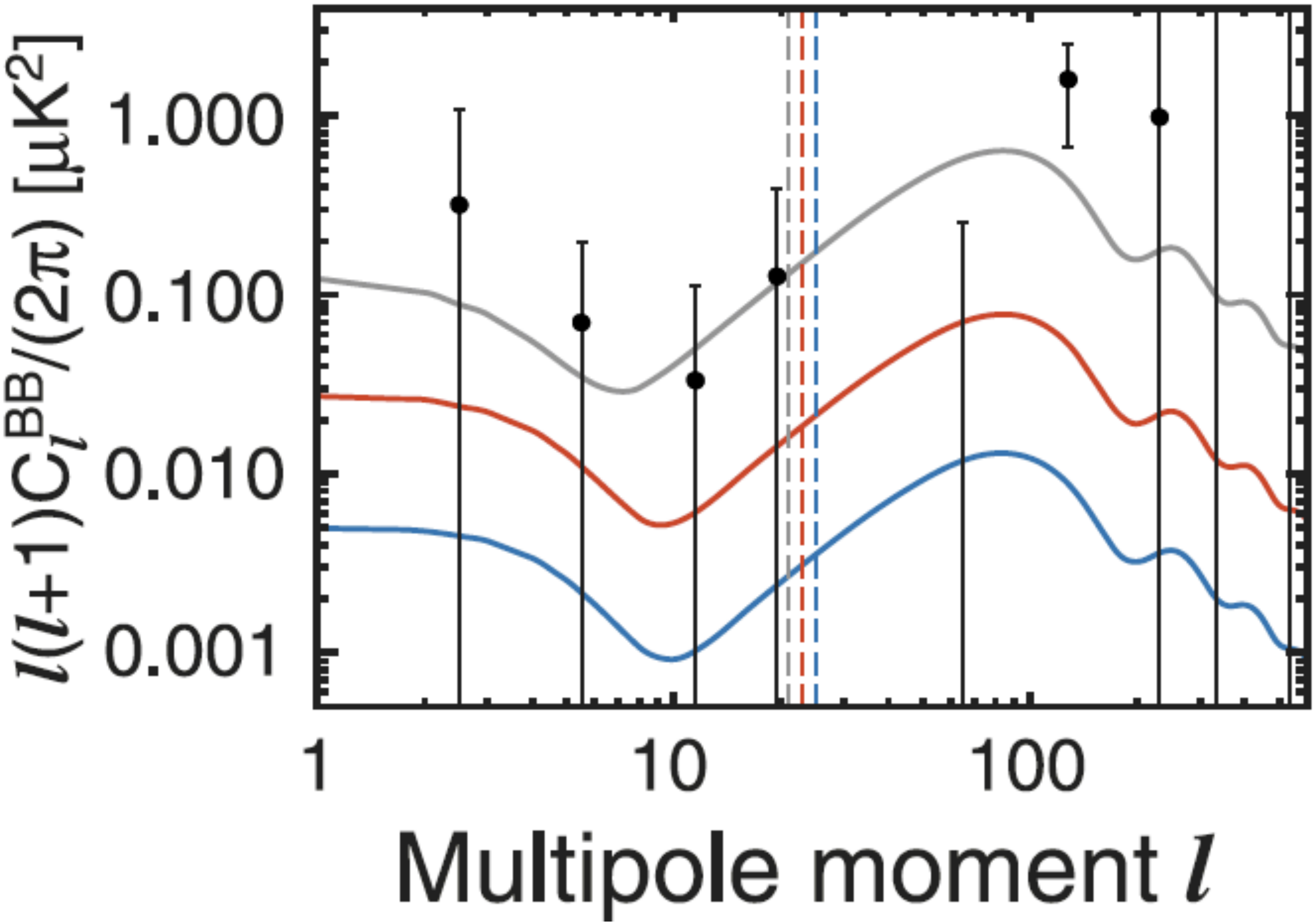


5-Year TxE Power Spectrum



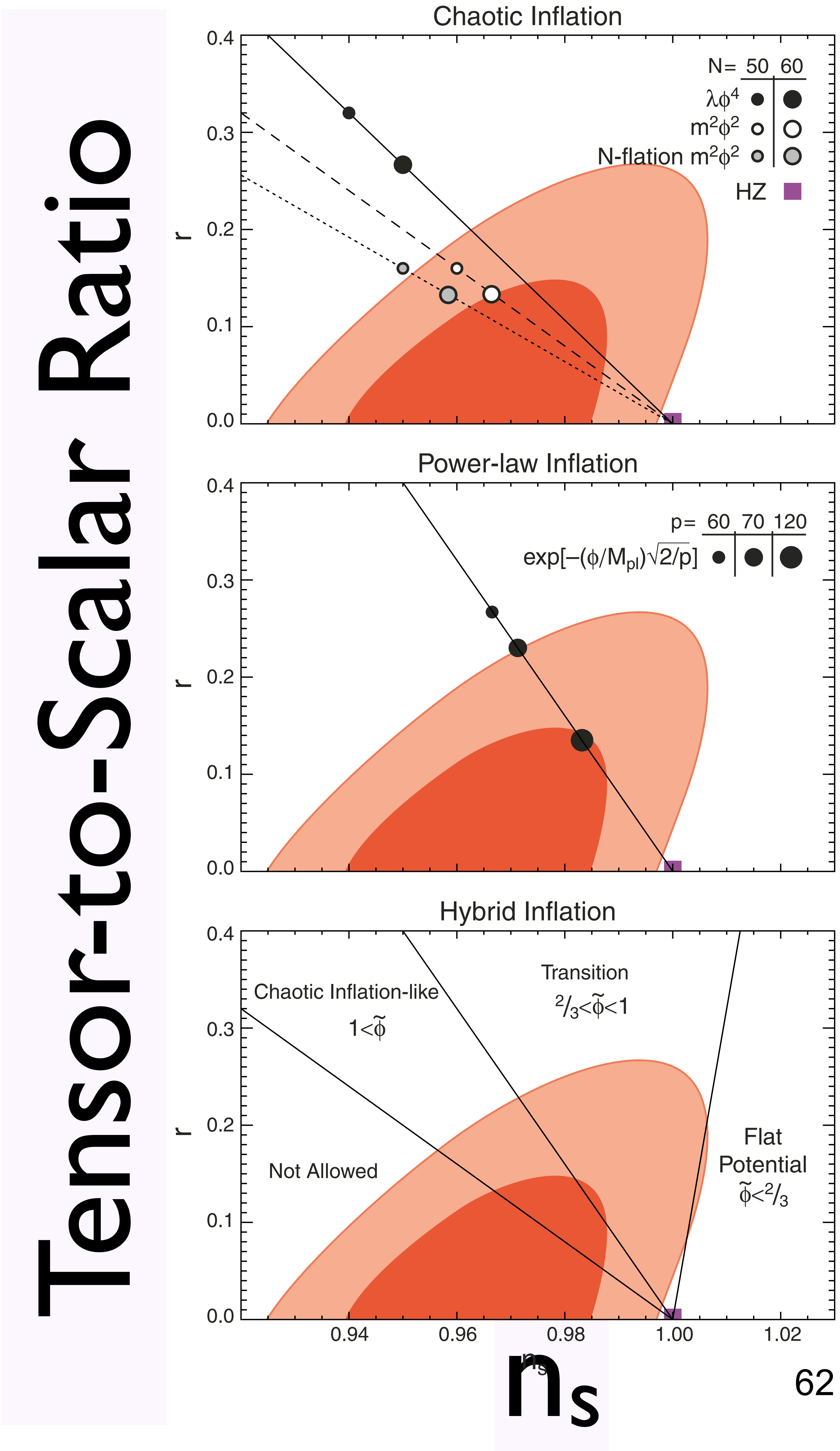
We have convincingly detected E-mode polarization, as predicted from the temperature anisotropy. But...

No Detection of B-modes (Yet)



Testing Inflation

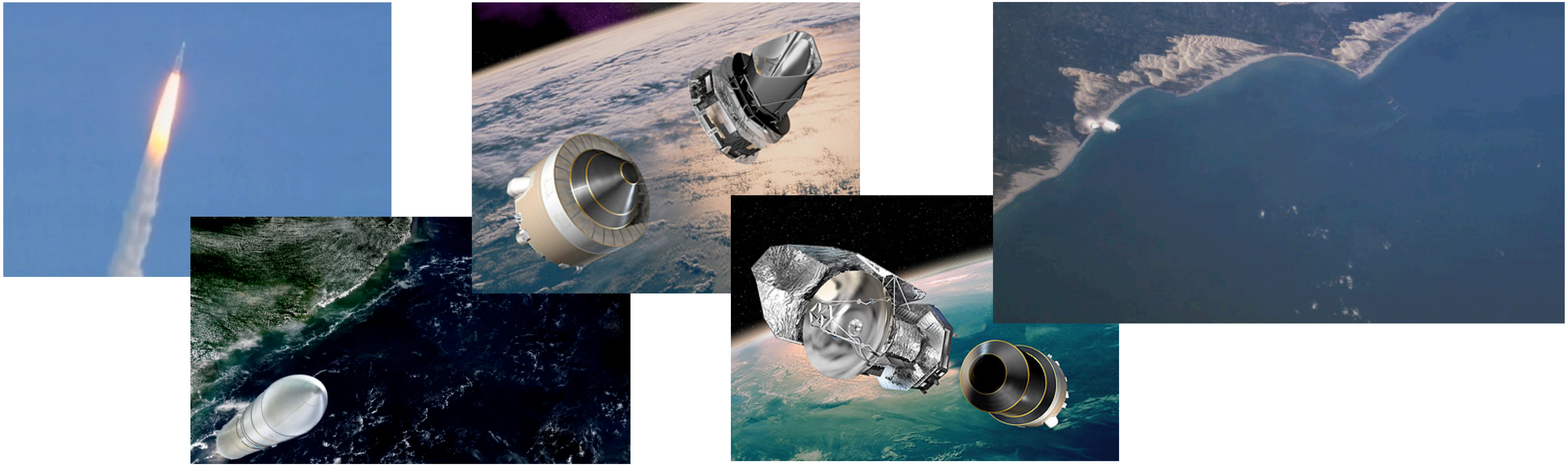
- **n_s=0.960 ± 0.013 (68%CL)**
  - 3σ away from the exact scale invariance (which is favoured by many inflation models)
- **Tensor-to-scalar Ratio < 0.22 (95%CL)**
- Many inflationary models are still compatible with the current data.
- Many models have been excluded also: ***observational*** *test of inflation!*



Summary

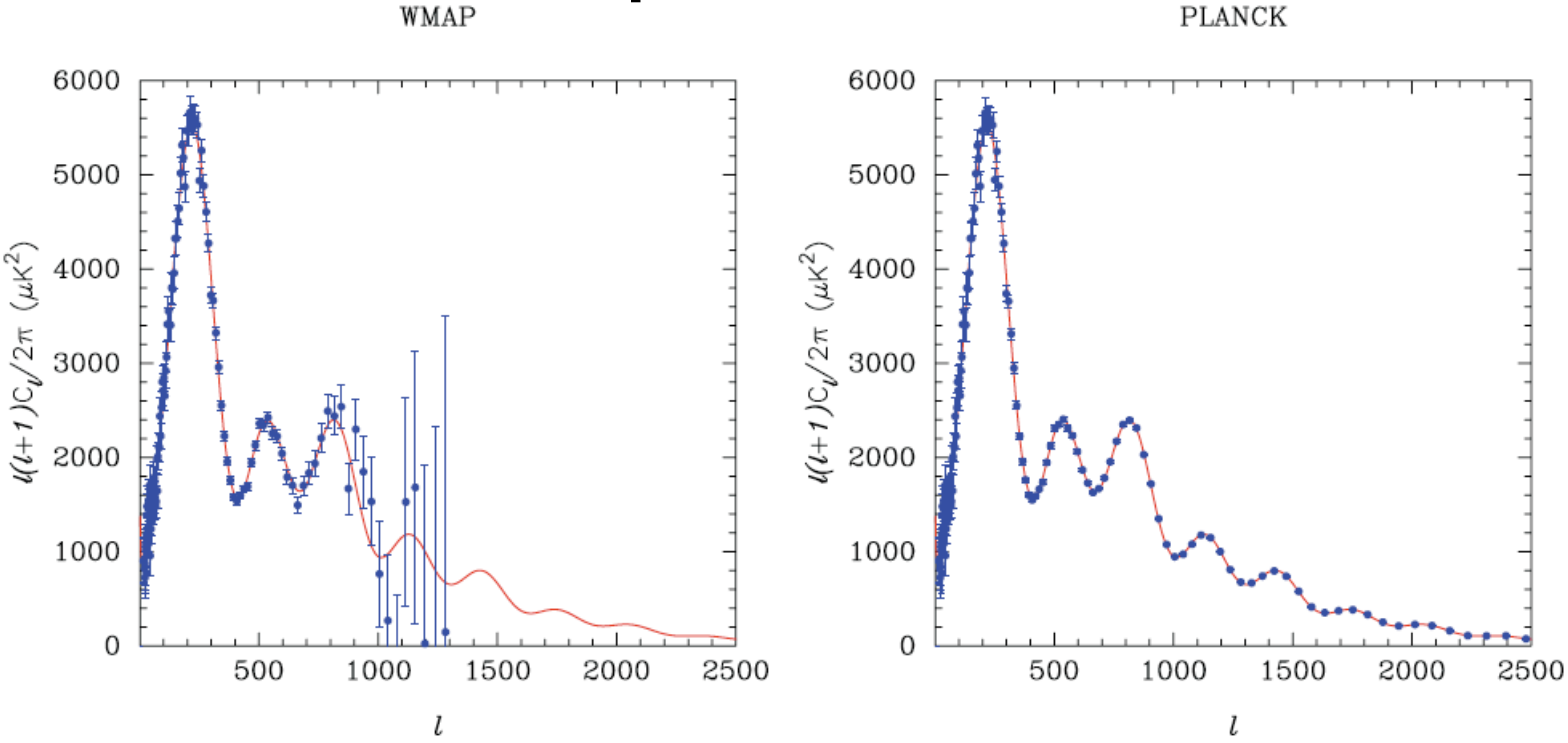
- CMB is the fossil light of the Big Bang.
- We could determine the age, composition, expansion rate, etc., from CMB.
- We could even push the boundary farther back in time, probing the origin of fluctuations in the very early Universe: inflationary epoch at ultra-high energies.
- Next Big Thing(s): **Primordial gravitational waves**, and 3-point function (or more generally, we call it "**non-Gaussianity**".)

Planck Launched!



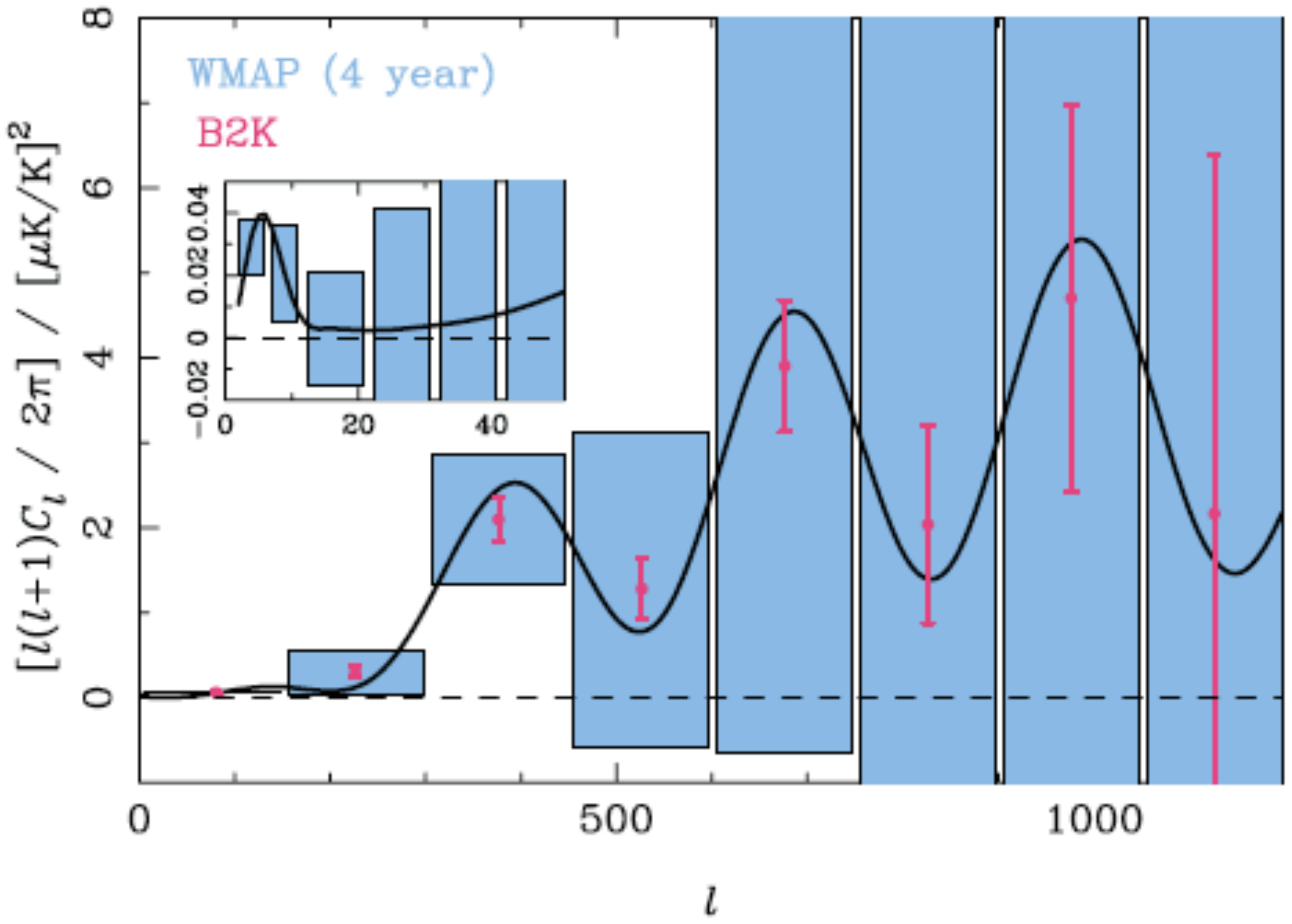
- The Planck satellite was successfully launched from French Guiana on May 14.
- Separation from the Herschell satellite was also successful.
- Both Planck and Hershell are on their ways to L2.

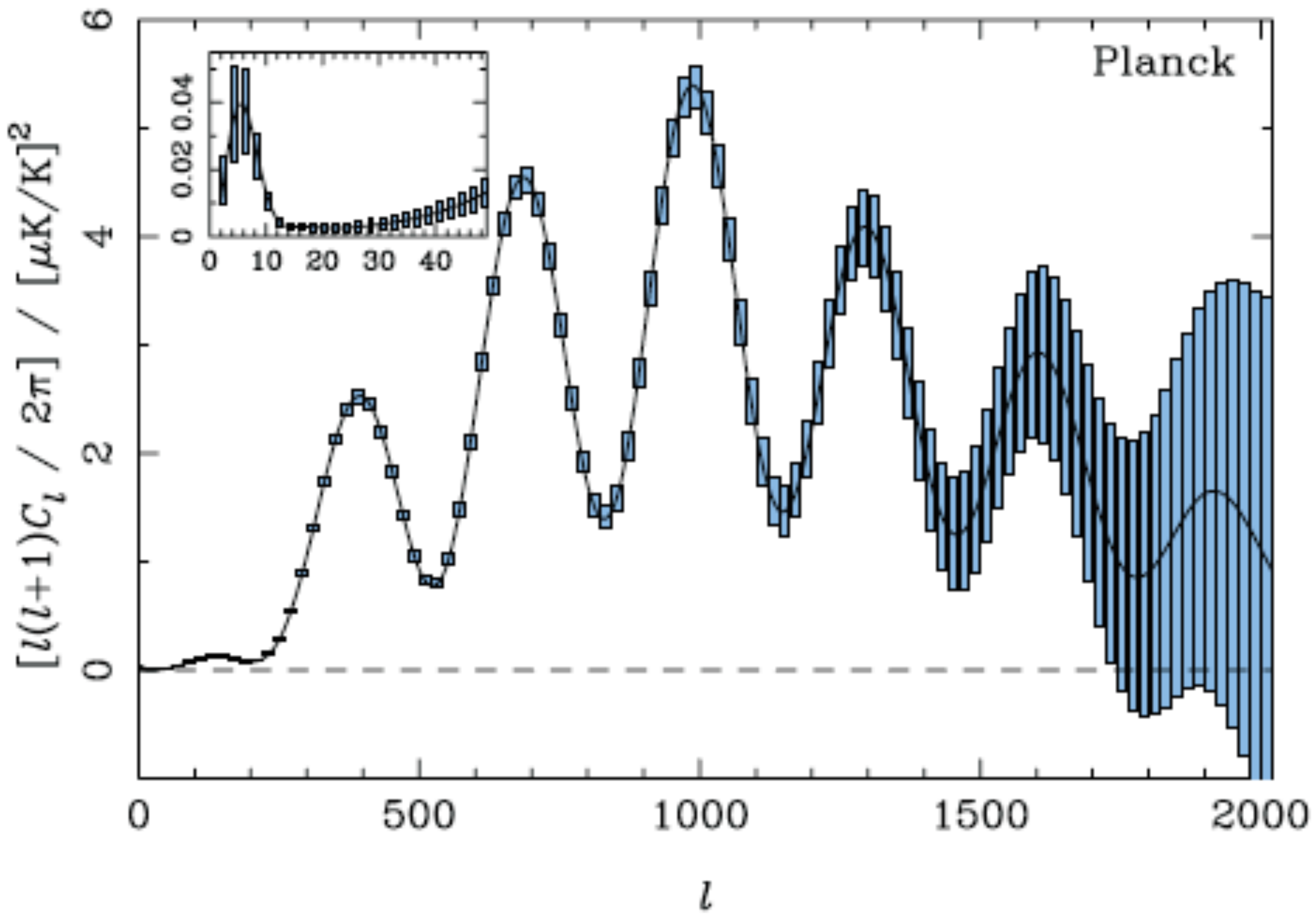
Planck: Expected $C_l^{\text{Temperature}}$

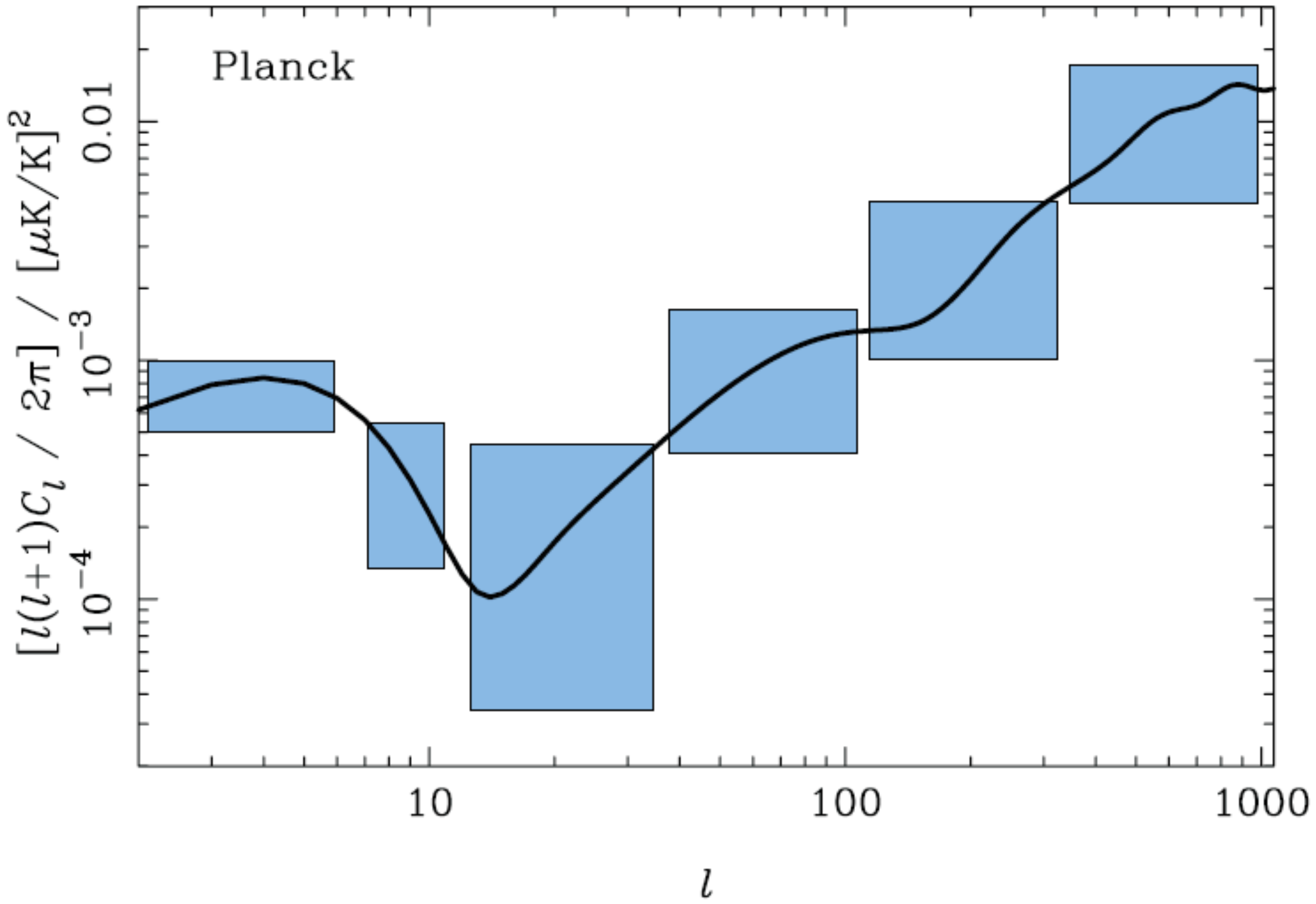


- WMAP: l~1000 => Planck: l~3000

Planck: Expected $C_l^{\text{Polarization}}$





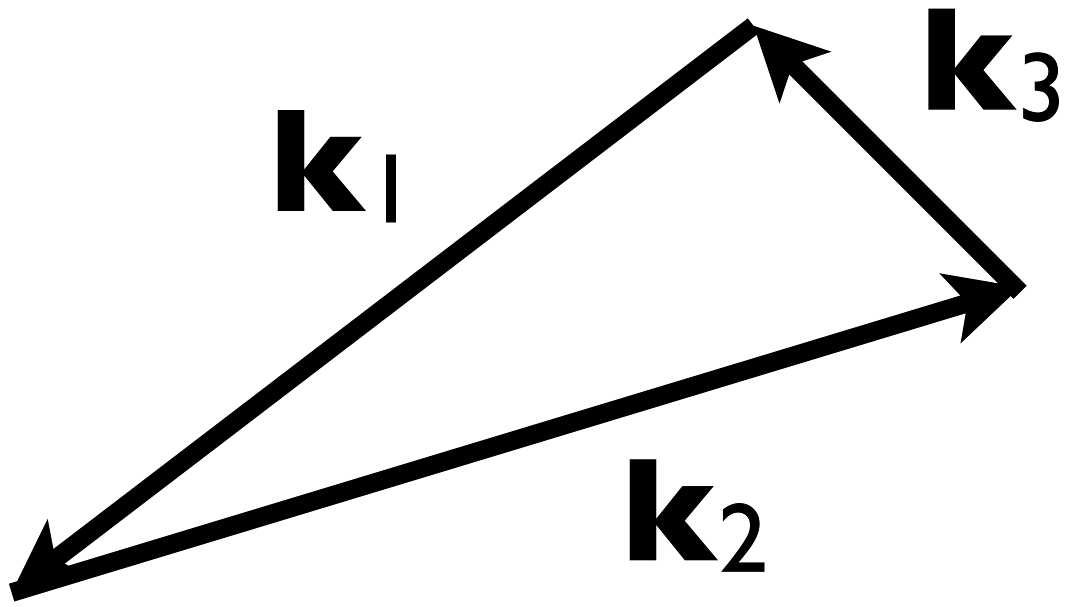


- (Above) E-modes
- (Left) B-modes (r=0.3)

More to Learn:
Beyond 2-pt Function

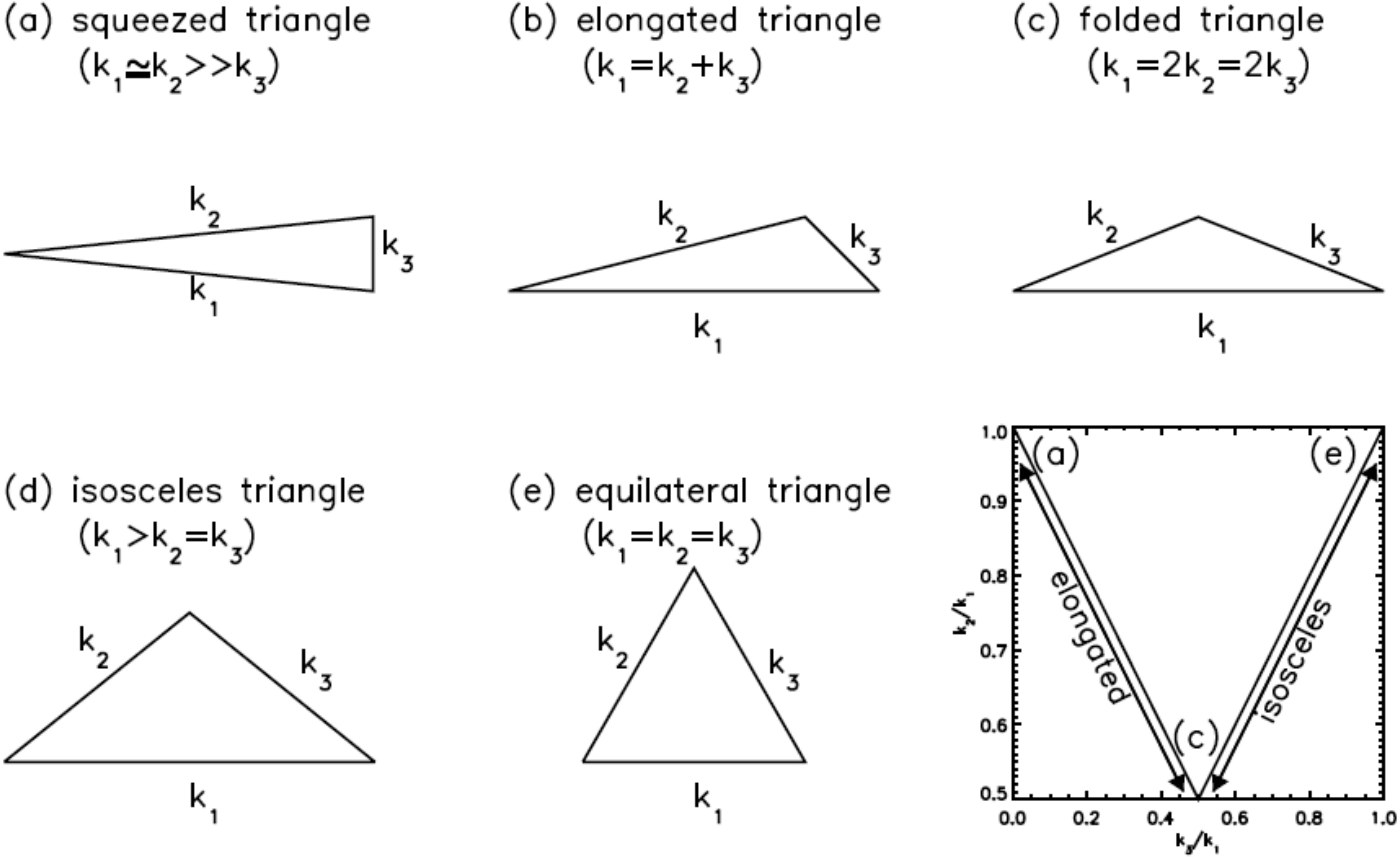
- So far, I have been talking only about what we learned from the 2-point correlation function, or the power spectrum.
- How about a 3-point function, or the *bispectrum*?
- There is potentially a lot more information out there!

Bispectrum



- Three-point function!
- $B_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$
  $= \langle\zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle = (\text{amplitude}) \times (2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)b(k_1,k_2,k_3)$

  model-dependent function


(a) squeezed triangle
$(k_1 \simeq k_2 >> k_3)$
(b) elongated triangle
$(k_1 = k_2 + k_3)$
(c) folded triangle
$(k_1 = 2k_2 = 2k_3)$
k_2
k_3
k_1
(d) isosceles triangle
$(k_1 > k_2 = k_3)$
(e) equilateral triangle
$(k_1 = k_2 = k_3)$
k_2/k_1
k_3/k_1
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.2
0.4
0.6
0.8
1.0
(a)
(e)
(c)
elongated
isosceles

Why Study Bispectrum?

- It probes the interactions of fields - new piece of information that cannot be probed by the power spectrum
- But, above all, it provides us with a **critical test** of the simplest models of inflation: "***are primordial fluctuations Gaussian, or non-Gaussian?***"
- Bispectrum vanishes for Gaussian fluctuations.
- Detection of the bispectrum = detection of non-Gaussian fluctuations

Inflation Likes Gaussianity

- According to inflation (Mukhanov & Chibisov; Guth & Yi; Hawking; Starobinsky; Bardeen, Steinhardt & Turner), CMB anisotropy was created from **quantum fluctuations of a scalar field in Bunch-Davies vacuum** during inflation
- Successful inflation (with the expansion factor more than e^{60}) *demands* the scalar field be almost interaction-free
- The wave function of free fields in the ground state is a Gaussian!

B_ζ in the Squeezed Limit

- In the squeezed limit, the f_{NL} bispectrum becomes: $B_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) \approx (12/5)f_{NL} \times (2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3) \times P_\zeta(k_1)P_\zeta(k_3)$

Maldacena (2003); Seery & Lidsey (2005); Creminelli & Zaldarriaga (2004)

Single-field Theorem (Consistency Relation)

- For **ANY** single-field models*, the bispectrum in the squeezed limit is given by
  - $B_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) \approx (1-n_s) \times (2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3) \times P_\zeta(k_1)P_\zeta(k_3)$
  - Therefore, all single-field models predict $f_{NL}\approx(5/12)(1-n_s)$.
  - With the current limit $n_s=0.96$, f_{NL} is predicted to be 0.017.

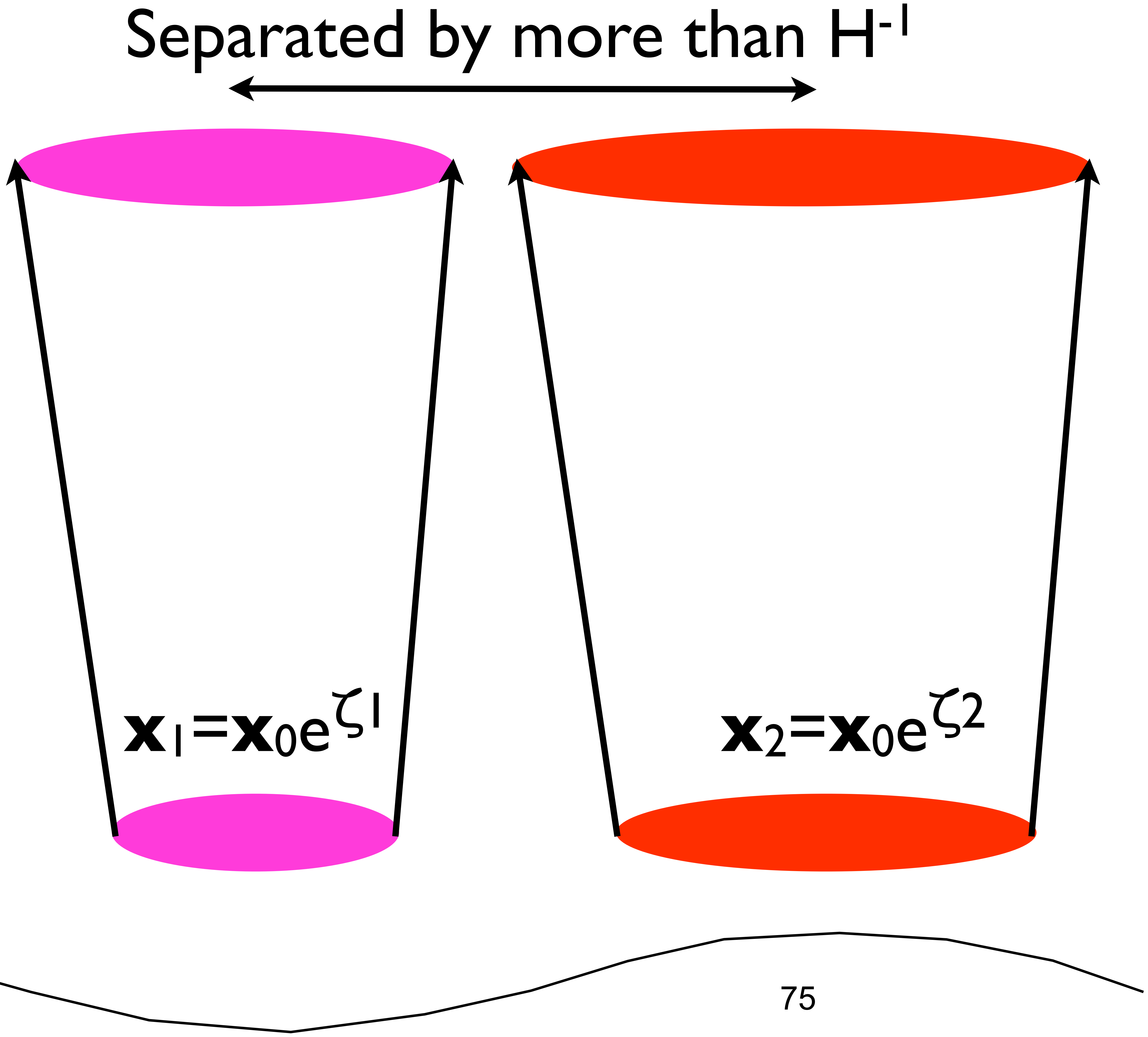
* for which the single field is solely responsible for driving inflation and generating observed fluctuations.

Understanding the Theorem

- First, the squeezed triangle correlates one very long-wavelength mode, k_L (=k_3), to two shorter wavelength modes, k_S (=$k_1 \approx k_2$):
    - $<\zeta_{\mathbf{k}1}\zeta_{\mathbf{k}2}\zeta_{\mathbf{k}3}> \approx <(\zeta_{\mathbf{k}S})^2\zeta_{\mathbf{k}L}>$
- Then, the question is: "why should $(\zeta_{\mathbf{k}S})^2$ ever care about $\zeta_{\mathbf{k}L}$?"
    - The theorem says, "it doesn't care, if $\zeta_{\mathbf{k}}$ is exactly scale invariant."

$\zeta_{\mathbf{k}L}$ rescales coordinates

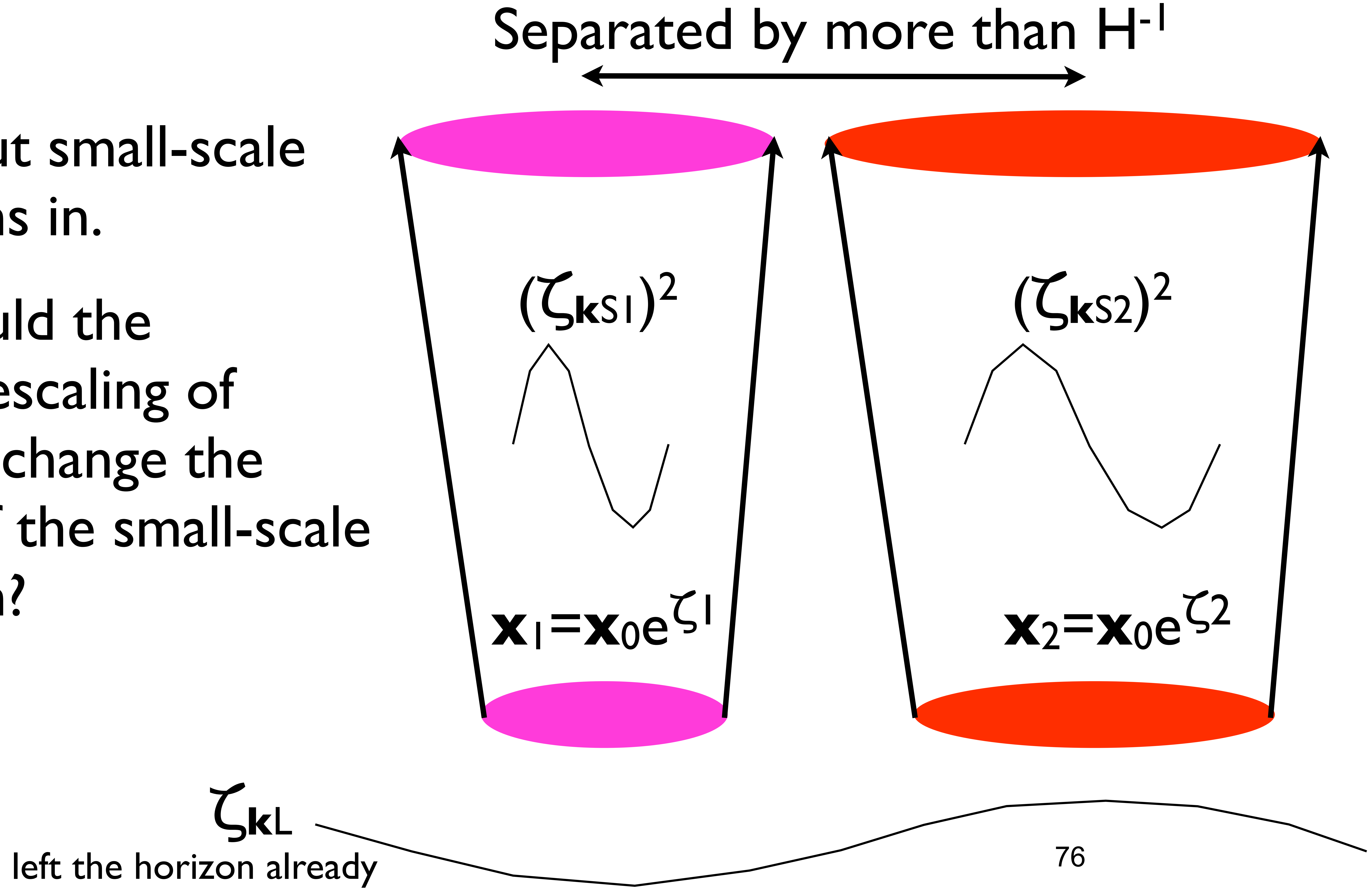
- The long-wavelength curvature perturbation rescales the spatial coordinates (or changes the expansion factor) within a given Hubble patch:
  - $ds^2 = -dt^2 + [a(t)]^2 e^{2\zeta} (d\mathbf{x})^2$



$\zeta_{\mathbf{k}L}$
left the horizon already

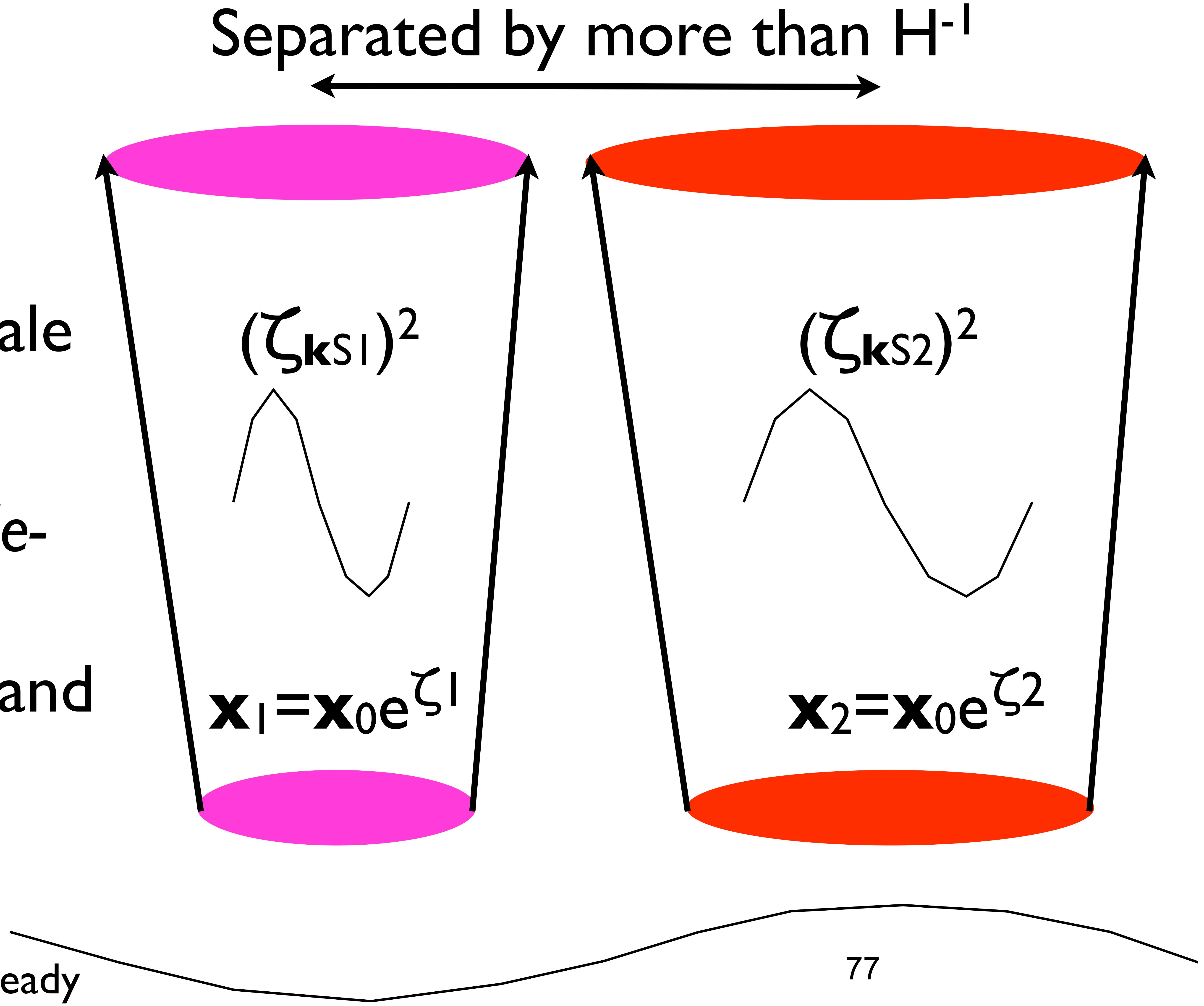
$\zeta_{\mathbf{k}L}$ rescales coordinates

- Now, let's put small-scale perturbations in.
- Q. How would the conformal rescaling of coordinates change the amplitude of the small-scale perturbation?



$\zeta_{\mathbf{k}L}$ rescales coordinates

- Q. How would the conformal rescaling of coordinates change the amplitude of the small-scale perturbation?
- A. No change, *if $\zeta_{\mathbf{k}}$ is scale-invariant*. In this case, no correlation between $\zeta_{\mathbf{k}L}$ and $(\zeta_{\mathbf{k}S})^2$ would arise.

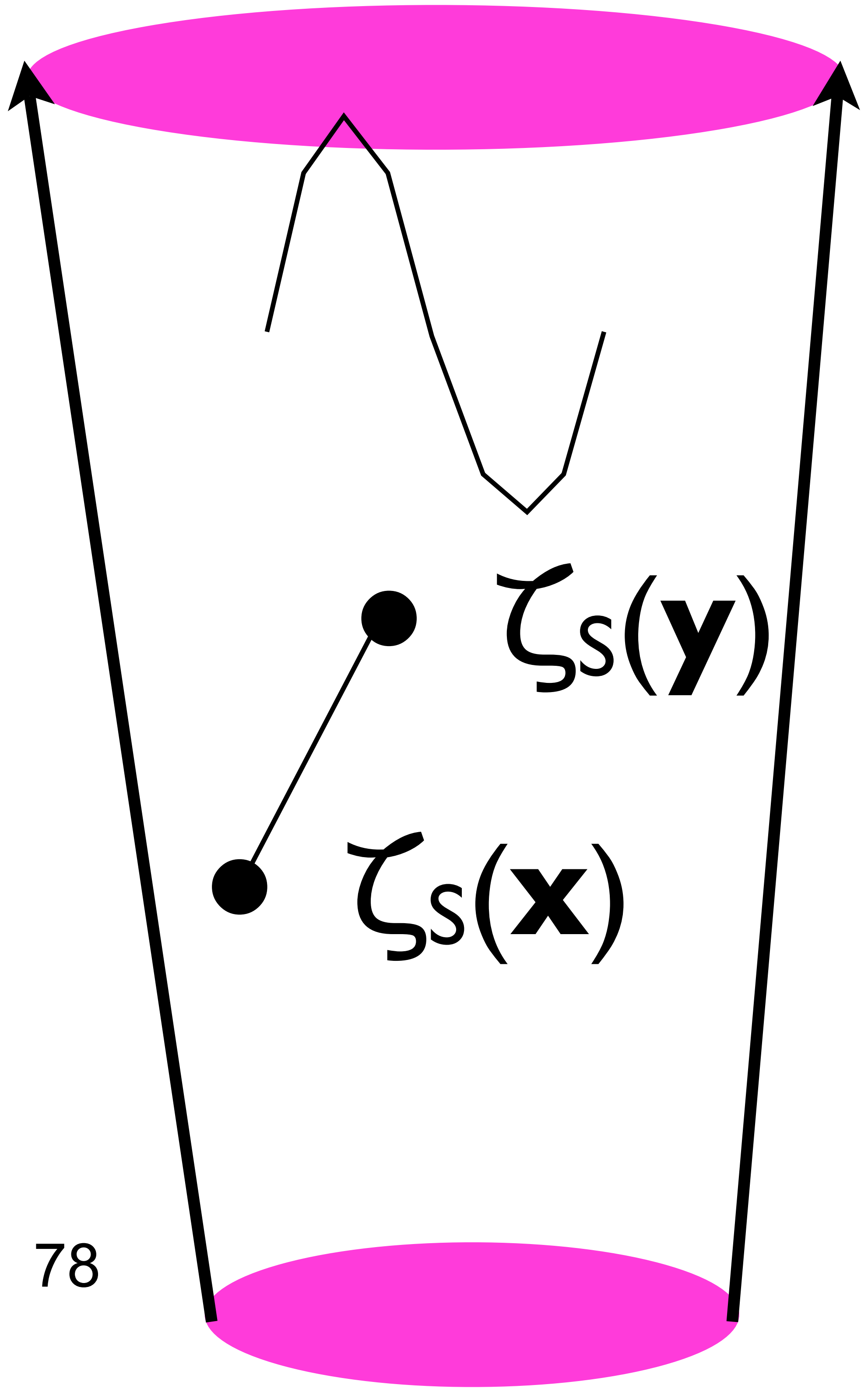


Creminelli & Zaldarriaga (2004); Cheung et al. (2008)

Real-space Proof

- The 2-point correlation function of short-wavelength modes, $\xi = \langle \zeta_S(\mathbf{x})\zeta_S(\mathbf{y}) \rangle$, within a given Hubble patch can be written in terms of its vacuum expectation value (in the absence of ζ_L), ξ_0, as:
  - $\xi_{\zeta_L} \approx \xi_0(|\mathbf{x}-\mathbf{y}|) + \zeta_L\,[d\xi_0(|\mathbf{x}-\mathbf{y}|)/d\zeta_L]$
  - $\xi_{\zeta_L} \approx \xi_0(|\mathbf{x}-\mathbf{y}|) + \zeta_L\,[d\xi_0(|\mathbf{x}-\mathbf{y}|)/d\ln|\mathbf{x}-\mathbf{y}|]$
  - $\xi_{\zeta_L} \approx \xi_0(|\mathbf{x}-\mathbf{y}|) + \zeta_L\,(1-n_s)\xi_0(|\mathbf{x}-\mathbf{y}|)$

$$\text{3-pt func.} = \langle (\zeta_S)^2 \zeta_L \rangle = \langle \xi_{\zeta_L} \zeta_L \rangle$$
$$= (1-n_s)\xi_0(|\mathbf{x}-\mathbf{y}|)\langle \zeta_L^2 \rangle$$



Therefore...

- A convincing detection of $f_{NL} > 1$ would rule out ***all*** of the single-field inflation models, <u>regardless of:</u>
  - the form of potential
  - the form of kinetic term (or sound speed)
  - the initial vacuum state
- A convincing detection of f_{NL} would be a breakthrough.

Large Non-Gaussianity from Single-field Inflation

- $S=(1/2)\int d^4x\ \sqrt{-g}\ [R-(\partial_\mu\varphi)^2-2V(\varphi)]$
- 2nd-order (which gives P_ζ)
  - $S_2=\int d^4x\ \varepsilon\ [a^3(\partial_t\zeta)^2-a(\partial_i\zeta)^2]$
- 3rd-order (which gives B_ζ)
  - $S_3=\int d^4x\ \boldsymbol{\varepsilon^2}\ [\ldots a^3(\partial_t\zeta)^2\zeta+\ldots a(\partial_i\zeta)^2\zeta+\ldots a^3(\partial_t\zeta)^3]+O(\varepsilon^3)$

Cubic-order interactions are suppressed by an additional factor of ε.
(Maldacena 2003)

Large Non-Gaussianity from Single-field Inflation

- $S=(1/2)\int d^4x\,\sqrt{-g}\,\{R-2P[(\partial_\mu\varphi)^2,\varphi]\}$ [general kinetic term]
- 2nd-order
  - $S_2=\int d^4x\,\varepsilon\,[a^3(\partial_t\zeta)^2/c_s^2-a(\partial_i\zeta)^2]$

"Speed of sound"
$c_s^2=P_{,X}/(P_{,X}+2XP_{,XX})$

- 3rd-order
  - $S_3=\int d^4x\,\boldsymbol{\varepsilon^2}\,[\ldots a^3(\partial_t\zeta)^2\zeta/\boldsymbol{c_s^2}+\ldots a(\partial_i\zeta)^2\zeta+\ldots a^3(\partial_t\zeta)^3/\boldsymbol{c_s^2}]+O(\varepsilon^3)$

Some interactions are enhanced for $c_s^2<1$.

(Seery & Lidsey 2005; Chen et al. 2007)

Large Non-Gaussianity from Single-field Inflation

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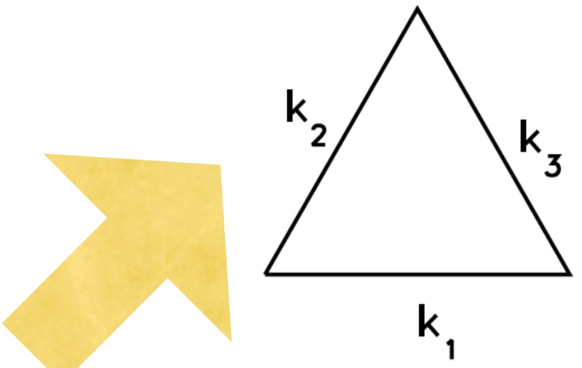
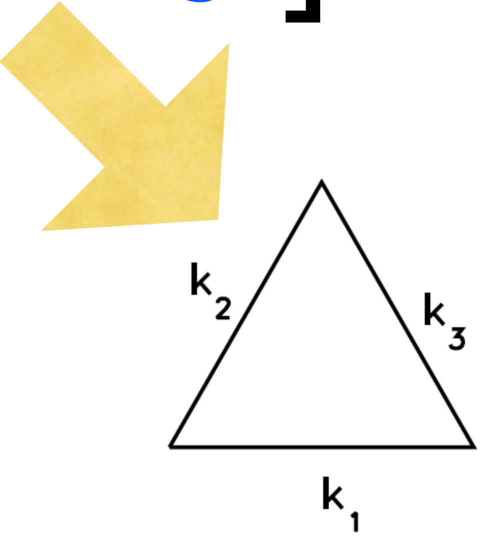
- 2nd-order
  - $S_2=\int d^4x\, \varepsilon\, [a^3(\partial_t\zeta)^2/c_s^2-a(\partial_i\zeta)^2]$

“Speed of sound”
$c_s^2=P_{,X}/(P_{,X}+2XP_{,XX})$

- 3rd-order



  - $S_3=\int d^4x\, \boldsymbol{\varepsilon^2}\, [\ldots a^3(\partial_t\zeta)^2\zeta/\boldsymbol{c_s^2}+\ldots a(\partial_i\zeta)^2\zeta+\ldots a^3(\partial_t\zeta)^3/\boldsymbol{c_s^2}]+O(\varepsilon^3)$



Some interactions are enhanced for $c_s^2<1$.

(Seery & Lidsey 2005; Chen et al. 2007)

Weak 2-σ “Hint”?

- So, currently we have something like f_{NL}~40±20 from the WMAP 5-year data, and 30±15 from WMAP5+LSS.
- Without a doubt, we need more data...
  - WMAP7 is coming up (early next year)
  - WMAP9 in ~2011–2012
- And...

Planck!

- Planck’s expected 68%CL errorbar is ~5.
  - Therefore, if f_{NL}~40, we would see it at 8σ. If ~30, 6σ. Either way, IF (big if) f_{NL}~30–40, we will see it unambiguously with Planck, which is expected to deliver the first-year results in $\geq$2012.