What does cosmology tell us about physics beyond SM?

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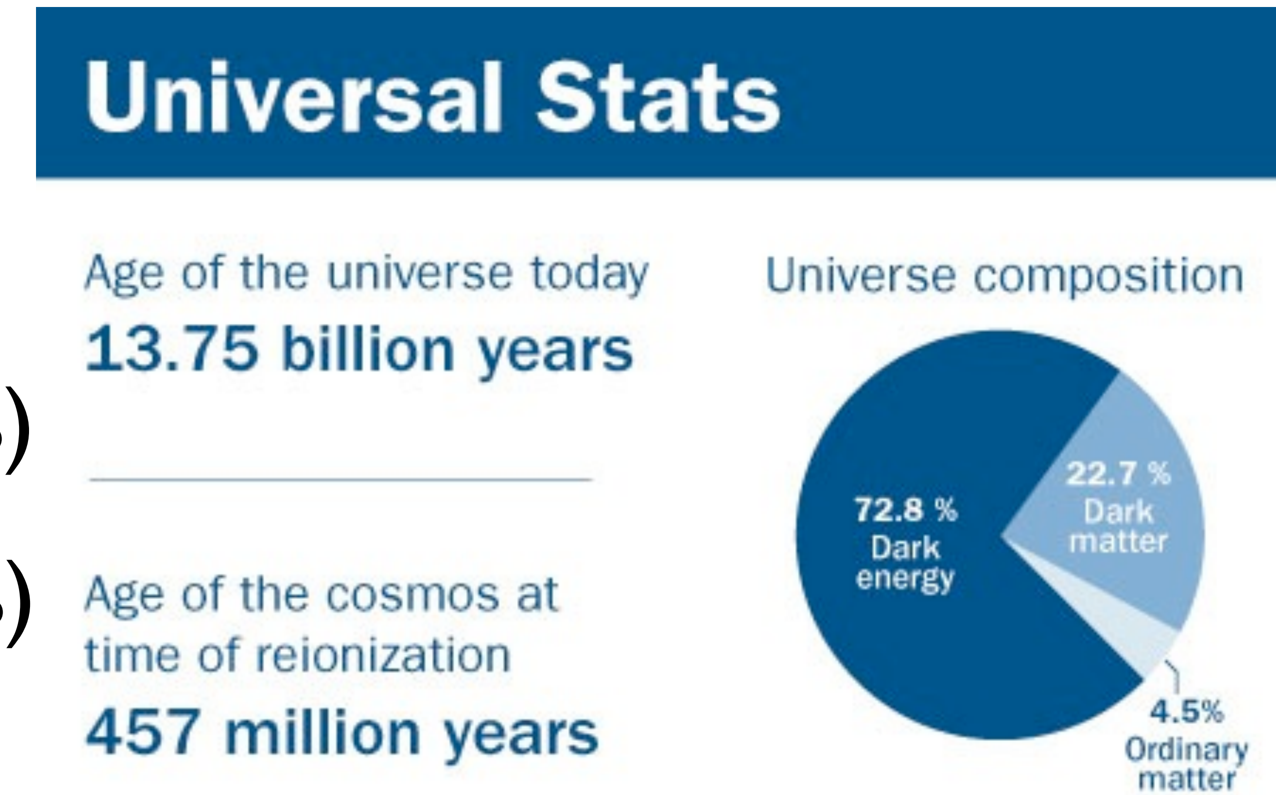
Do we even need physics beyond SM?

- Let us remind ourselves that the answer to this question is a definite **yes**, despite null results from LHC (Jinnouchi's talk) because:
    - We have dark matter,
    - We have dark energy, and
    - We (probably) have inflation,
- all of which require new physics.

“Standard Model” of Our Universe

- **Standard Model**
  - H&He = 4.56% (±0.16%)
  - Dark Matter = 27.2% (±1.6%)
  - Dark Energy = 72.8% (±1.6%)
  - H_0=70.4±1.4 km/s/Mpc
  - Age of the Universe = 13.75 billion years (±0.11 billion years)



“ScienceNews” article on the WMAP 7-year results

How does cosmology tell us about physics beyond SM?

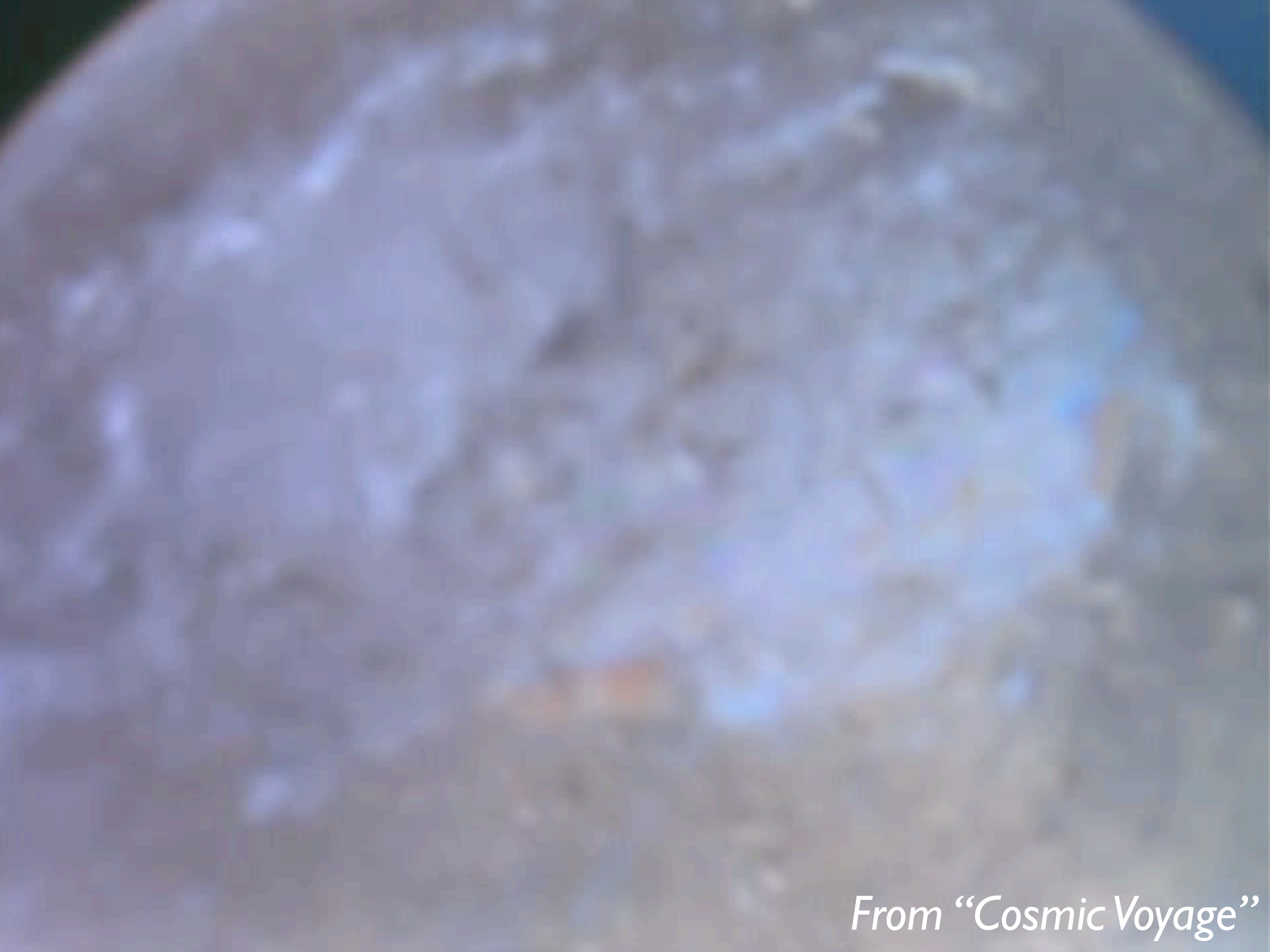
Let me focus on the
cosmic microwave background (CMB)

The Breakthrough

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

CMB

- Fossil light of the Big Bang!



From "Cosmic Voyage"

Night Sky in Optical (~0.5μm)

Night Sky in Microwave (~1mm)

courtesy University of Arizona

Night Sky in Microwave (~1mm)

$$T_{today}=2.725K$$

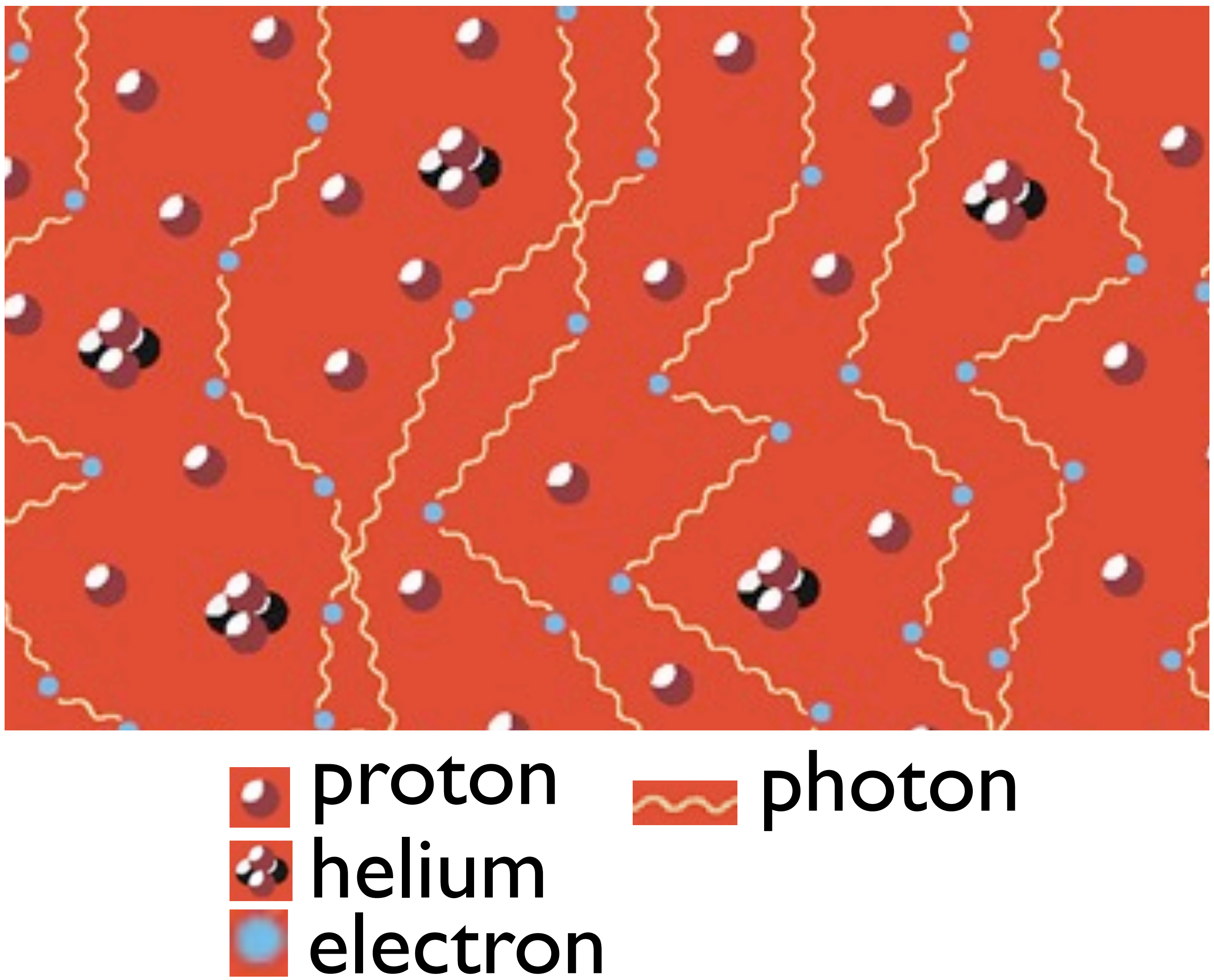
COBE Satellite, 1989-1993

courtesy University of Arizona

How was CMB created?

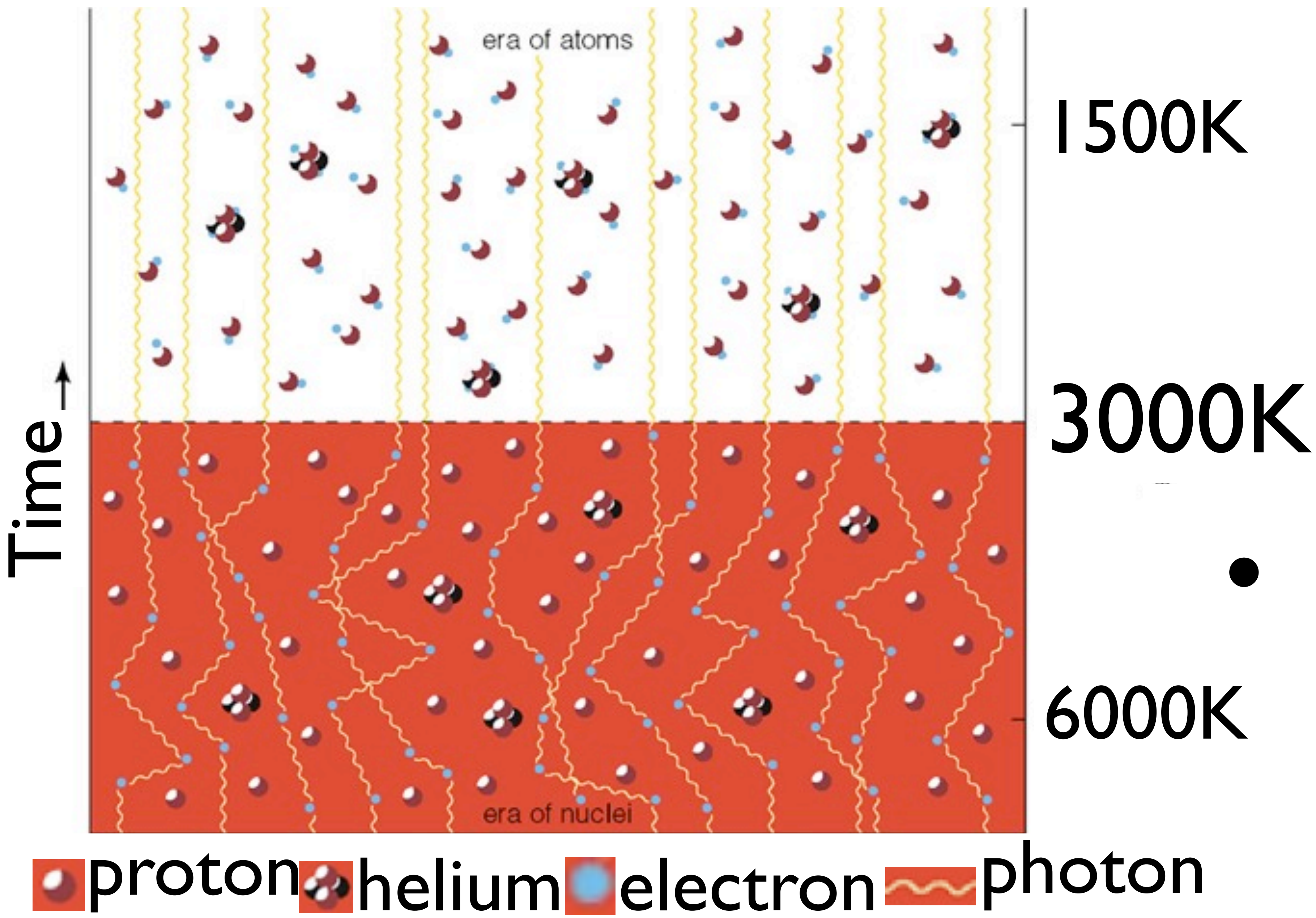
- When the Universe was hot, the Universe was a hot soup made of:
  - Protons, electrons, and helium nuclei
  - Photons and neutrinos
  - Dark matter

Universe as a hot soup



- Free electrons Thomson-scatter photons efficiently.
- Photons cannot go very far.

Recombination and Decoupling



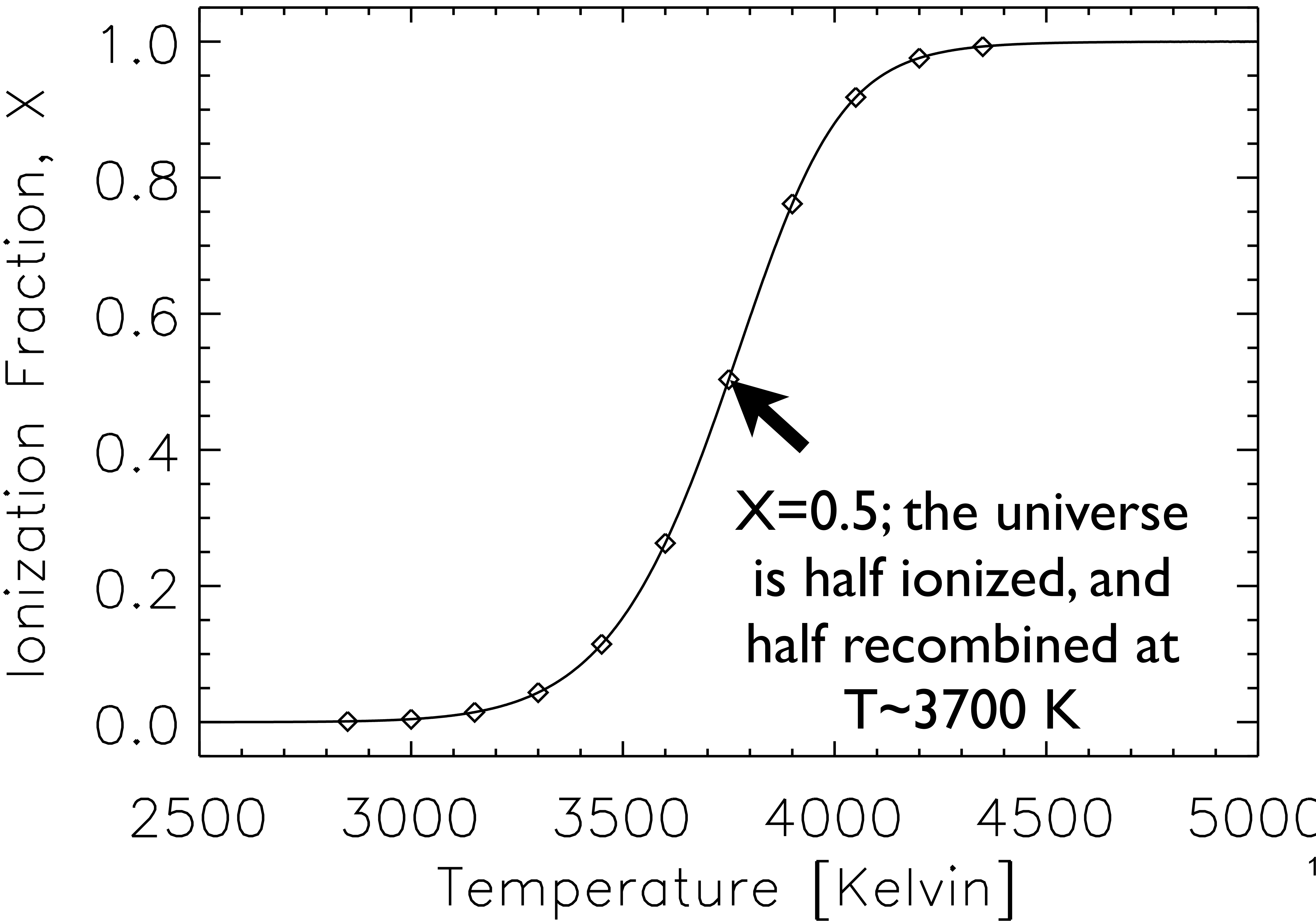
- [***recombination***] When the temperature falls below 3000 K, almost all electrons are captured by protons and helium nuclei.
- [***decoupling***] Photons are no longer scattered. I.e., photons and electrons are no longer coupled.

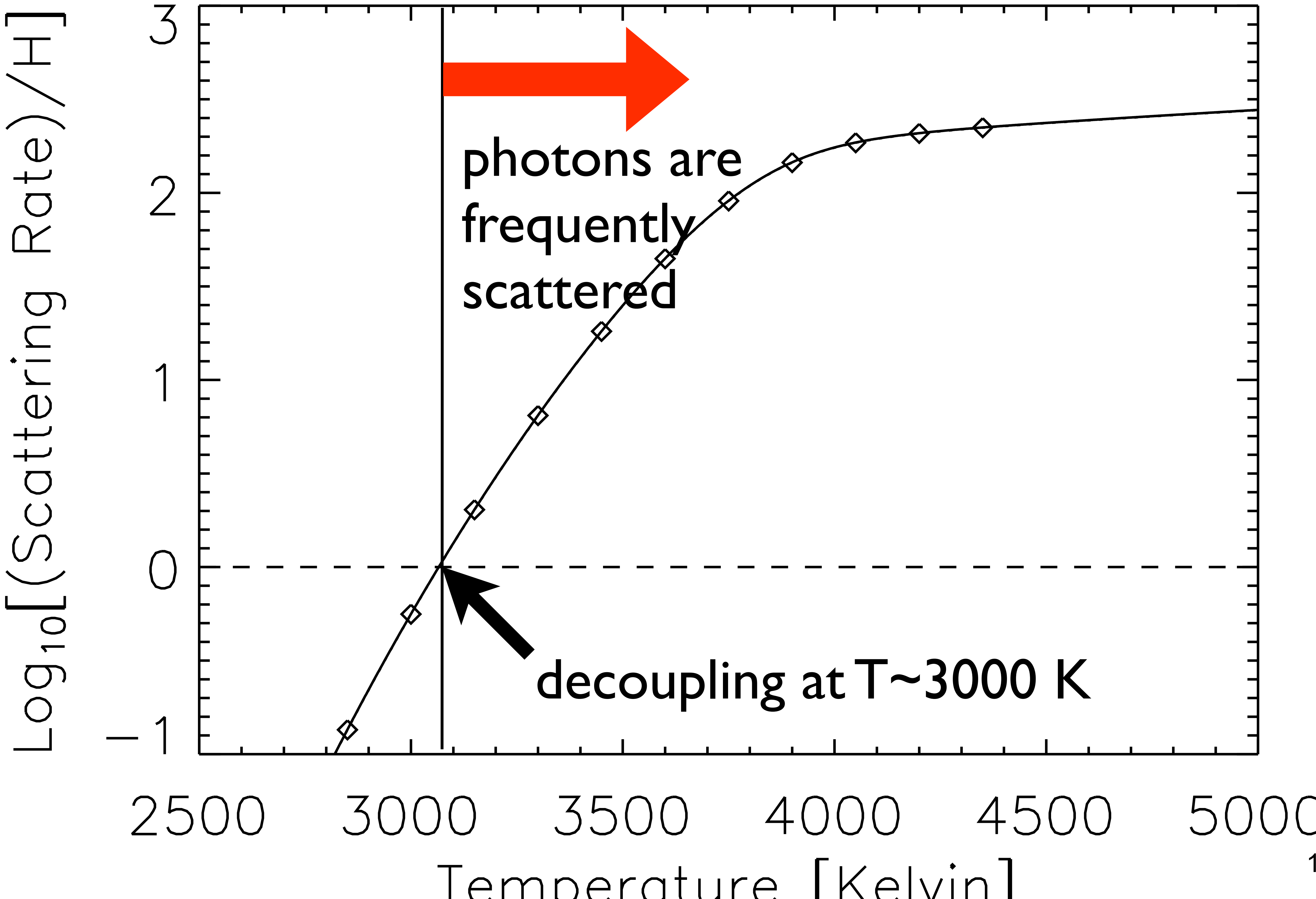
Ionization

H + photon –> p + e⁻

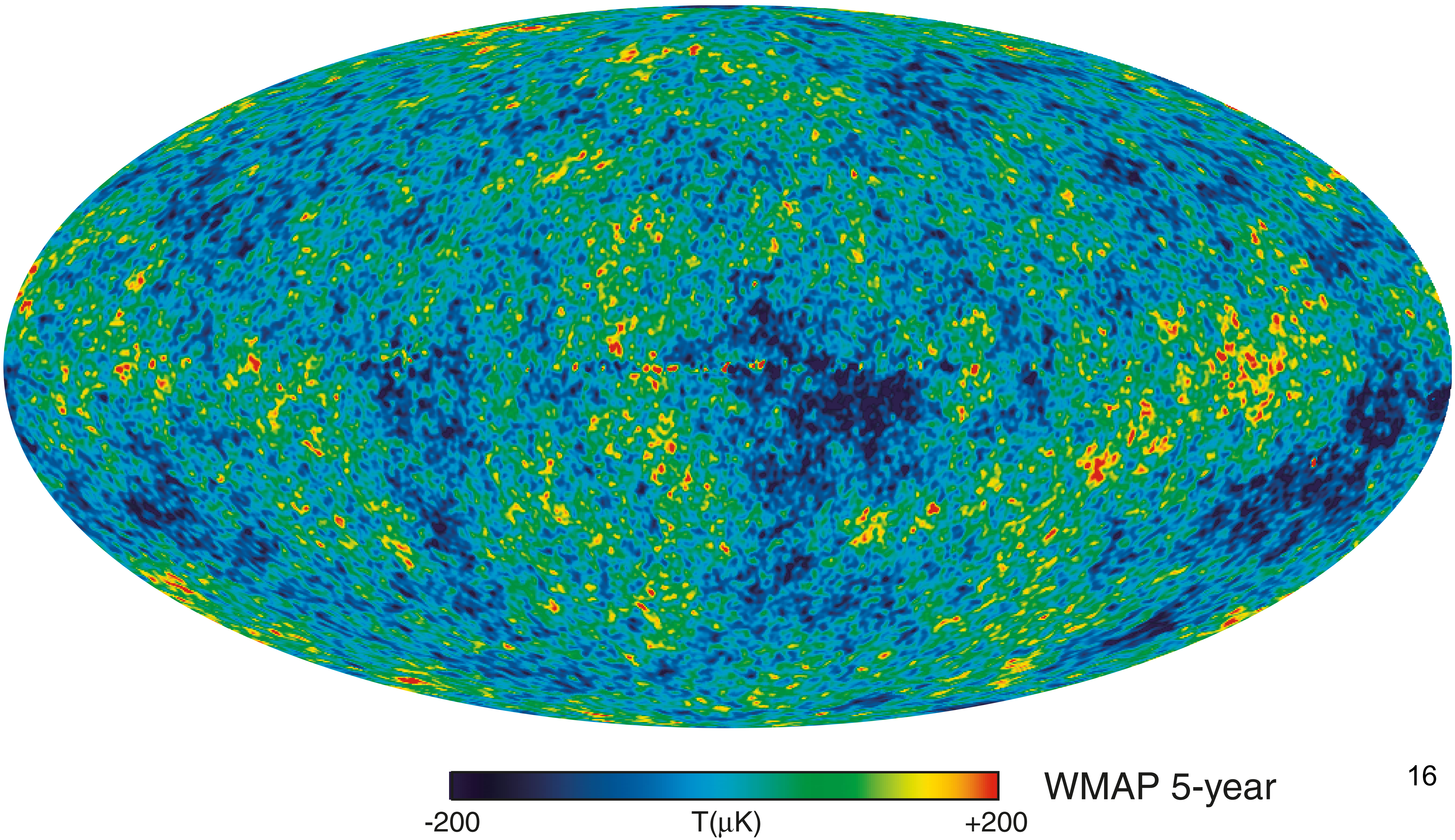
Recombination

p + e⁻ –> H + photon

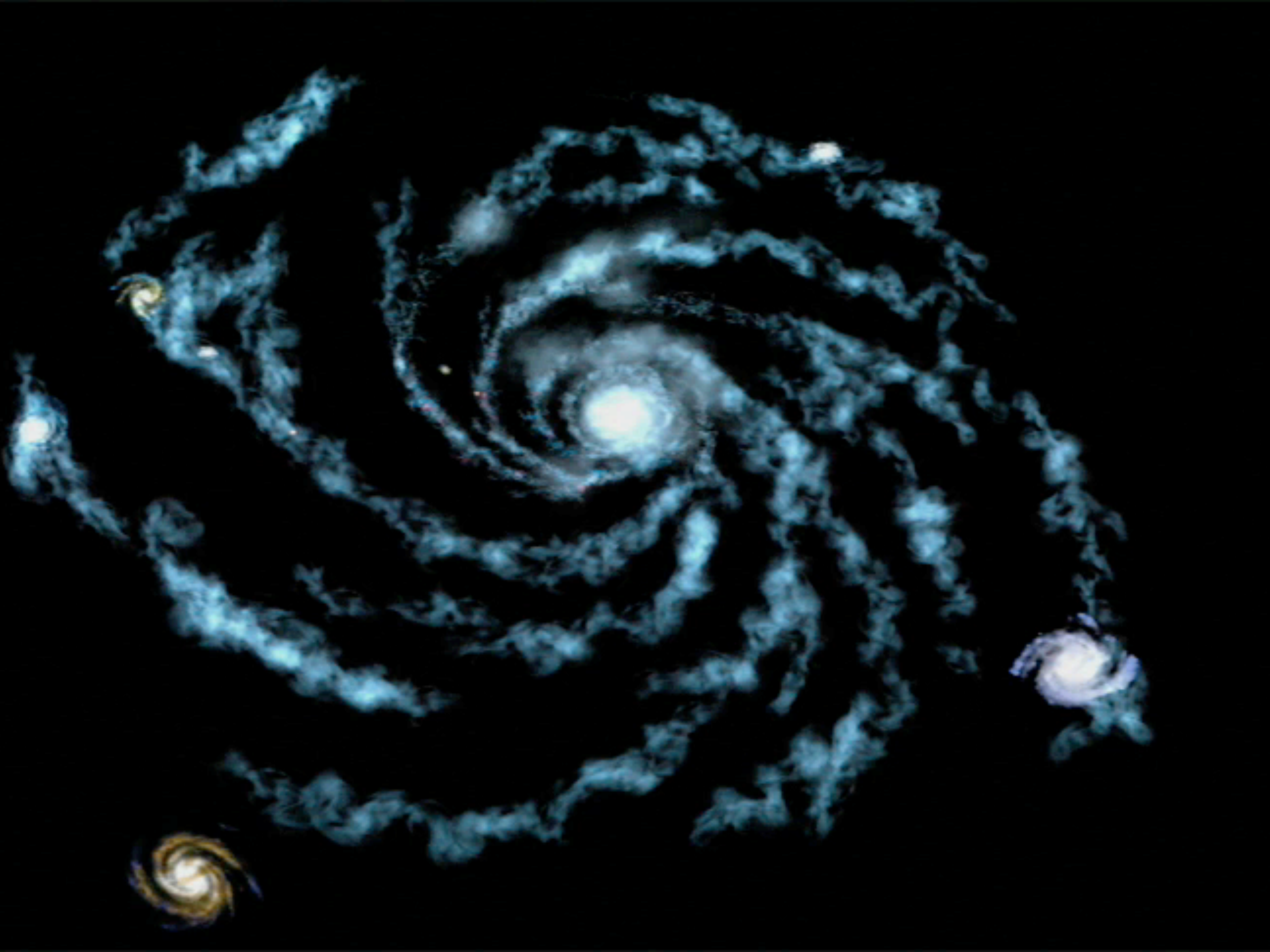



photons are frequently scattered
decoupling at T~3000 K
Log10[(Scattering Rate)/H]
Temperature [Kelvin]
3
2
1
0
−1
2500
3000
3500
4000
4500
5000

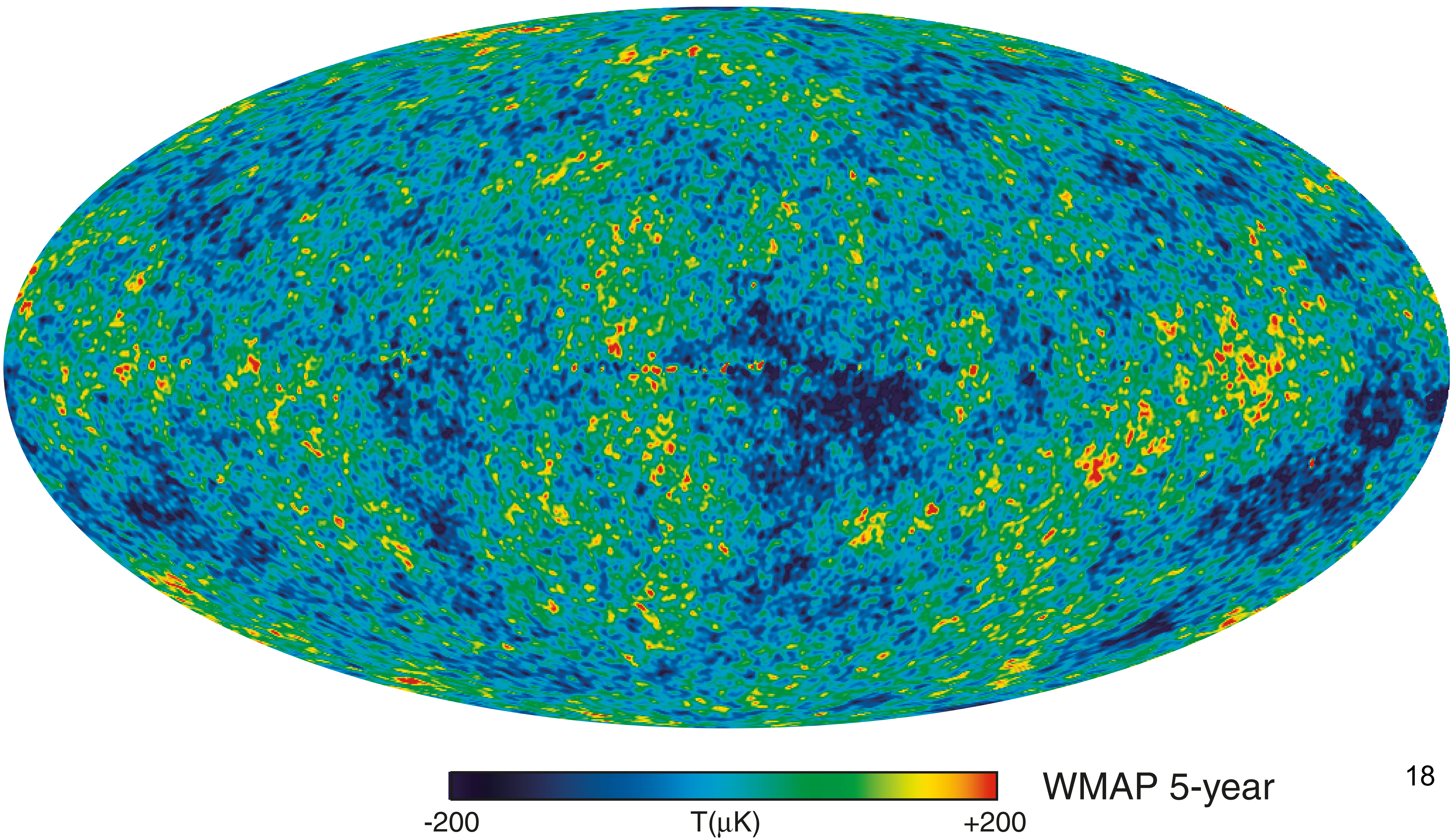
A direct image of the Universe when it was 3000 K.



WMAP 5-year



How were these ripples created?

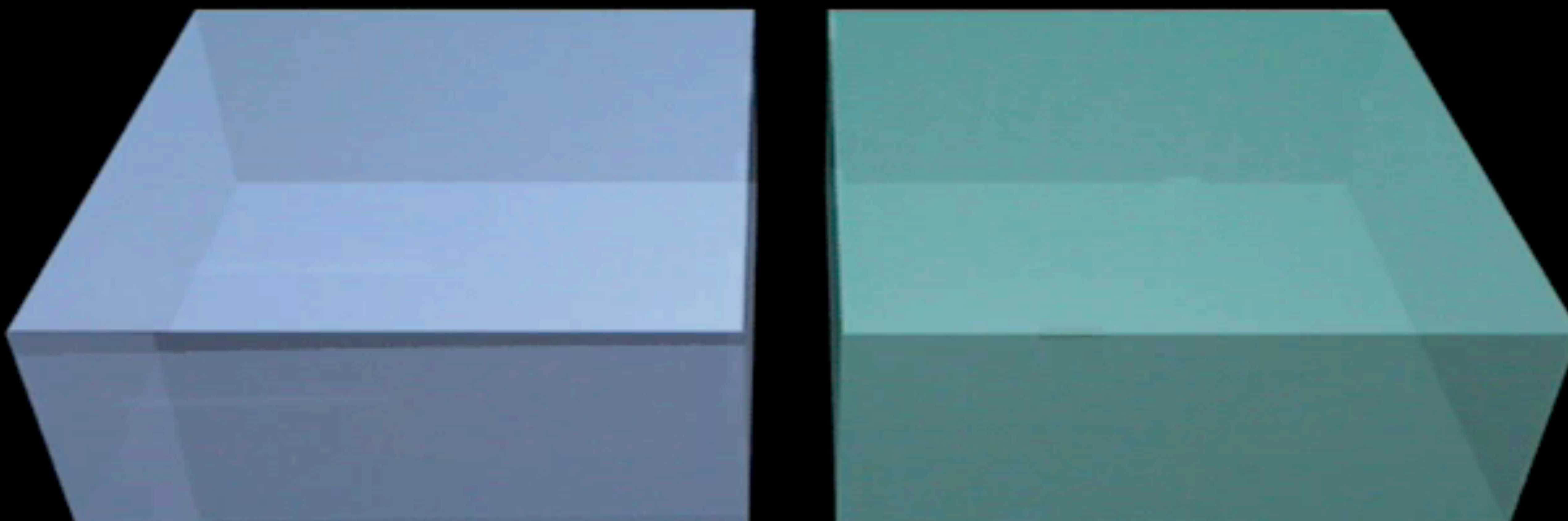


WMAP 5-year

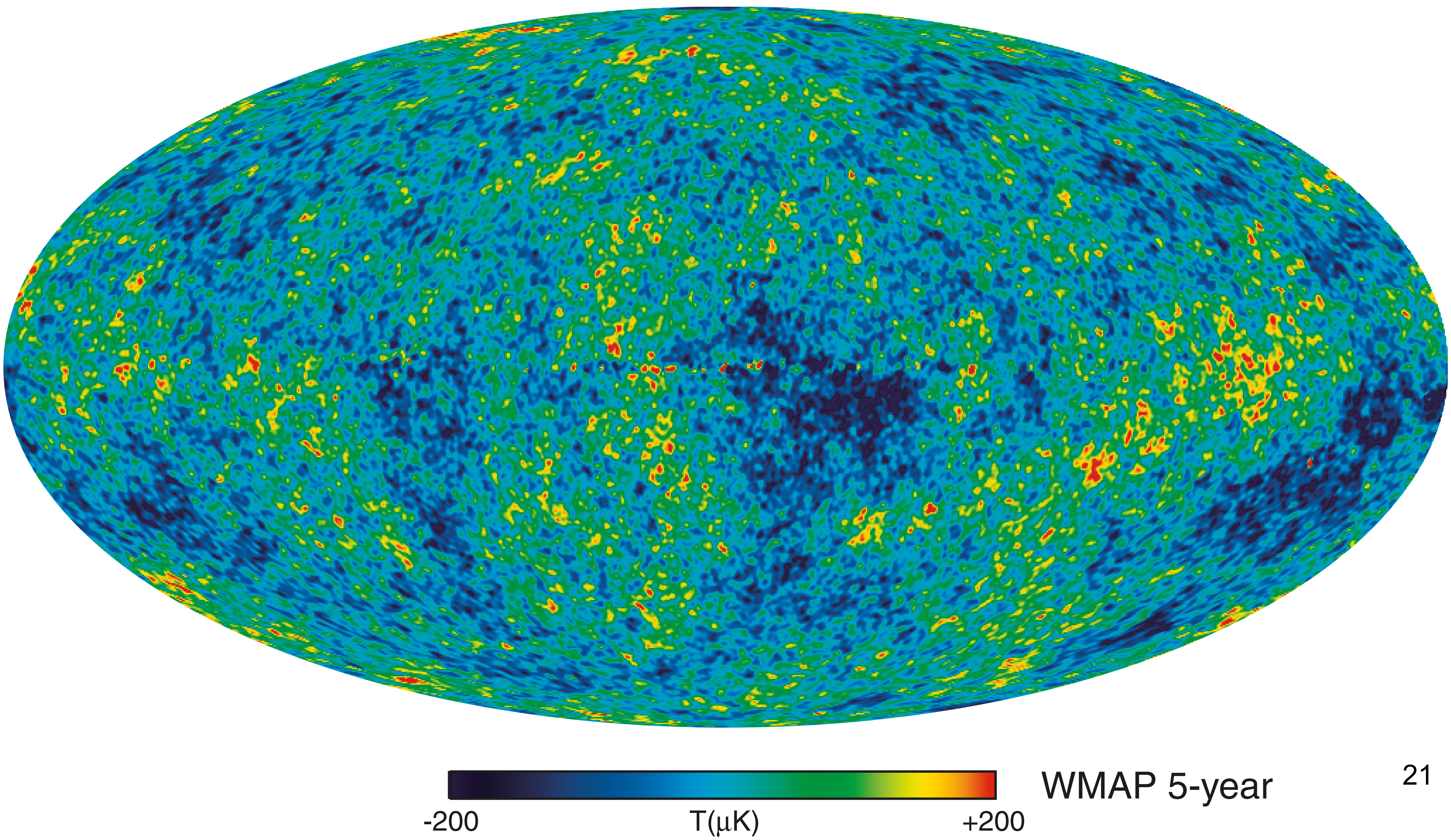
Have you dropped potatoes in a soup?

- What would happen if you "perturb" the soup?

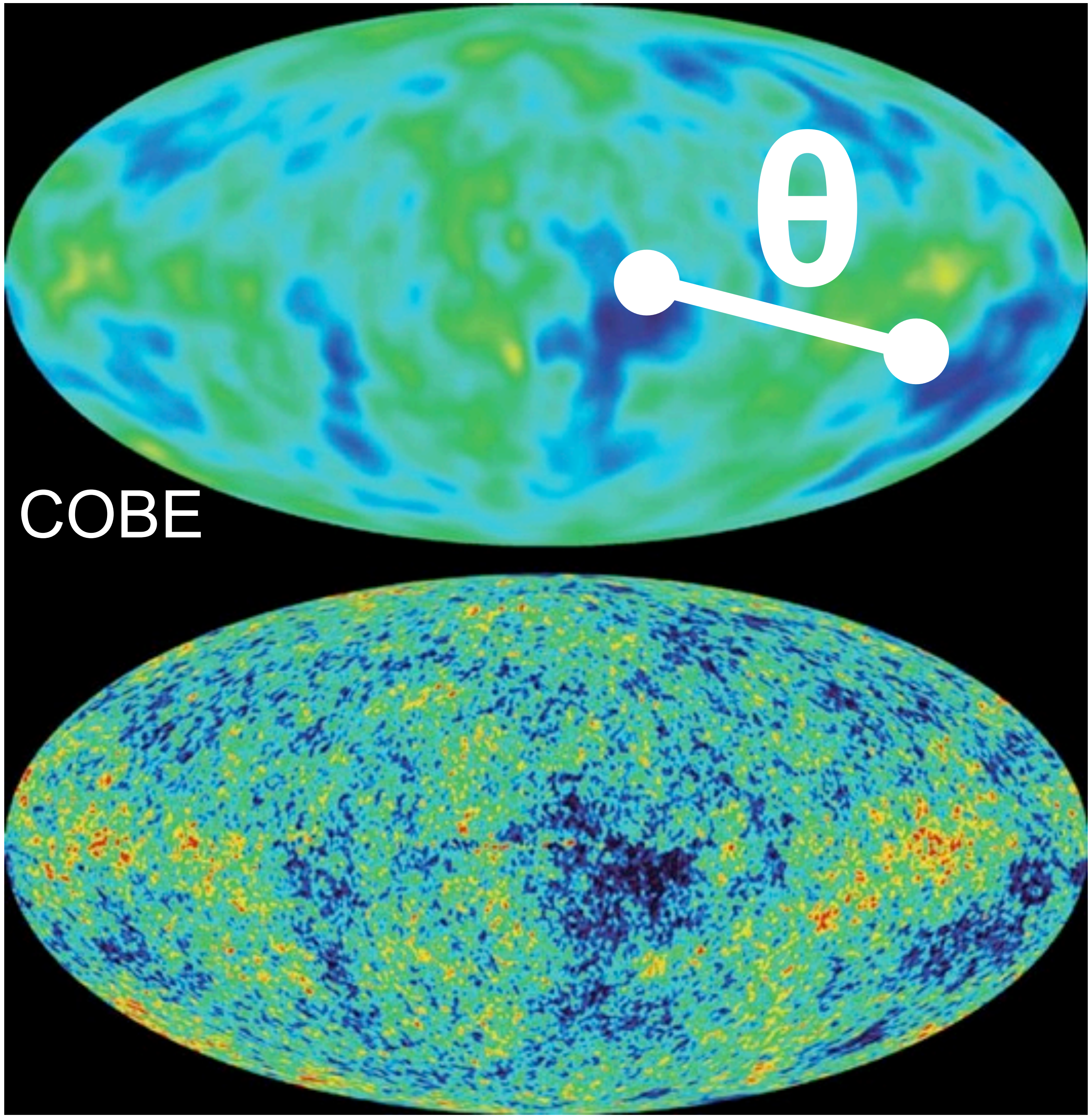
The Cosmic Sound Wave



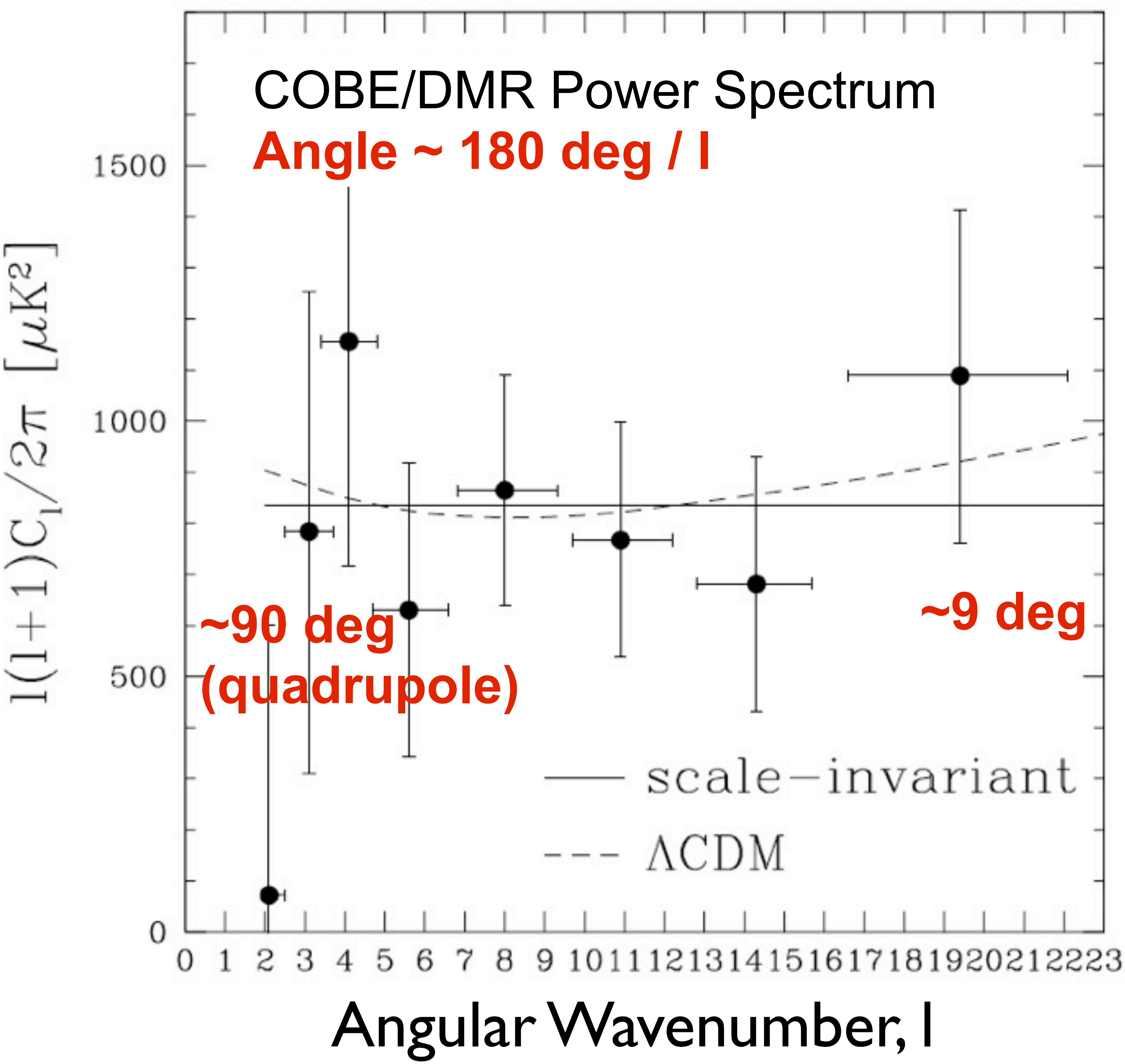
Can You See the Sound Wave?



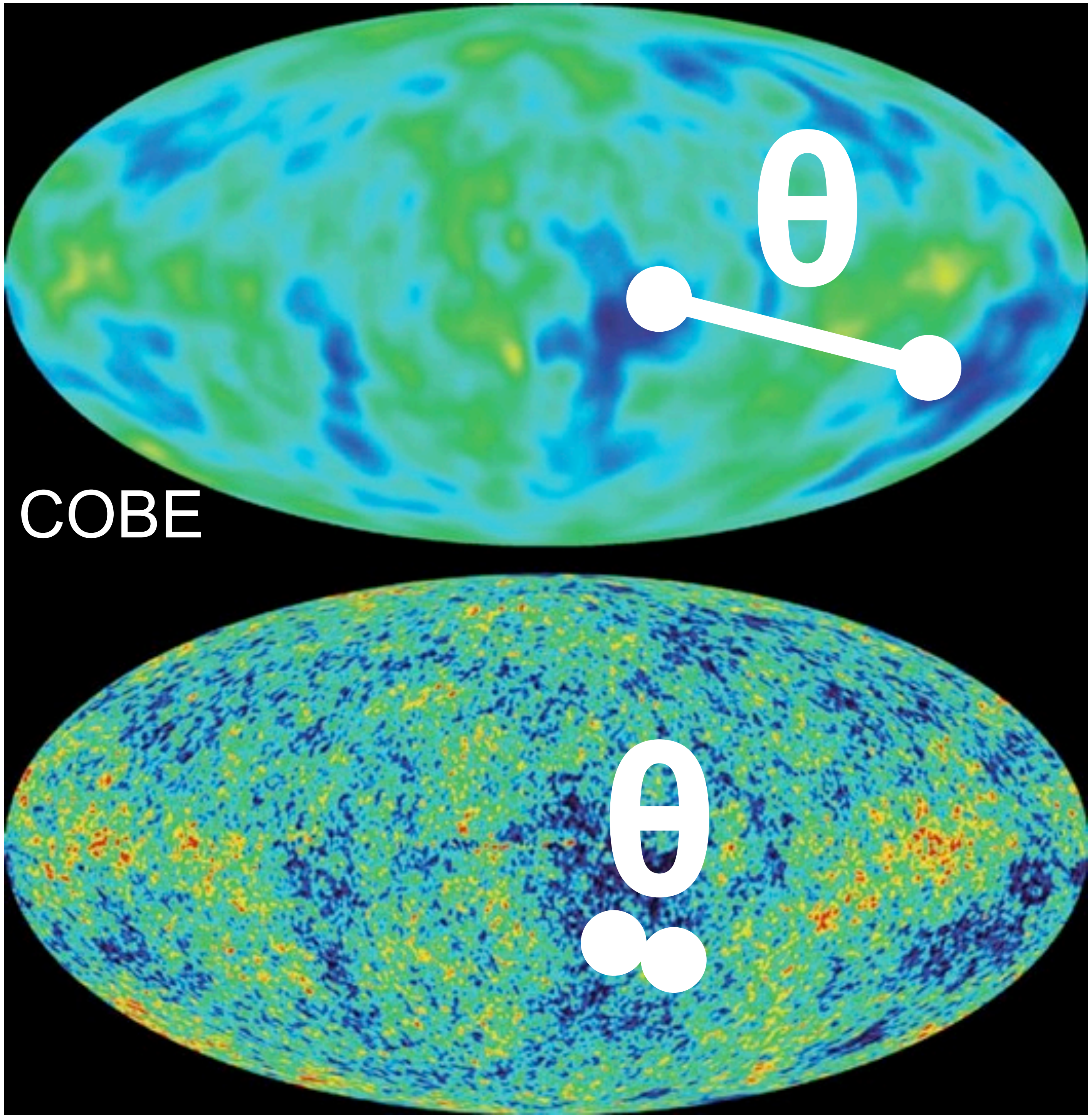
Analysis: 2-point Correlation



- $C(\theta)=(1/4\pi)\sum(2l+1)C_l P_l(\cos\theta)$
- 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~180 degrees / θ**

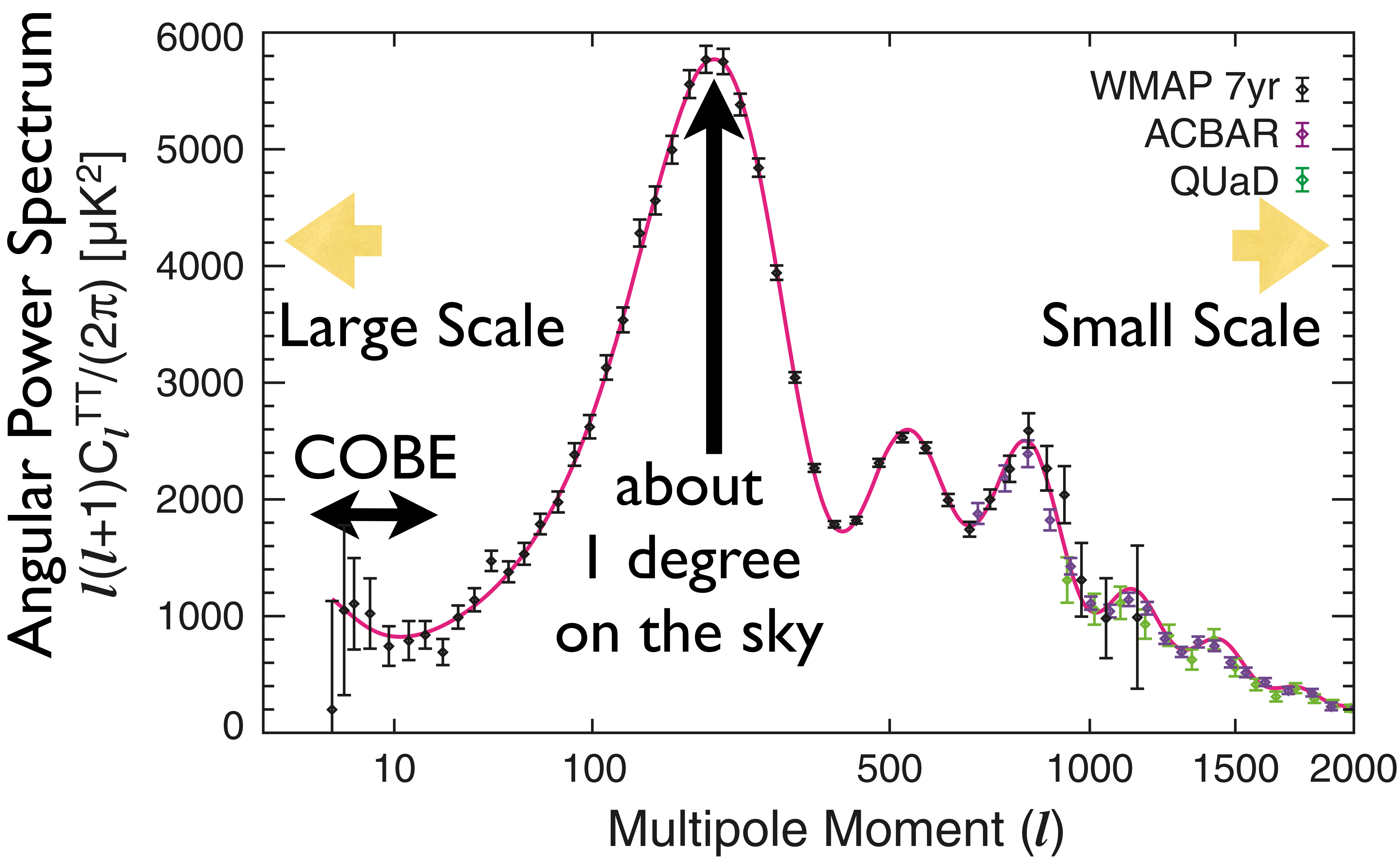

COBE/DMR Power Spectrum
Angle ~ 180 deg / l
~90 deg
(quadrupole)
~9 deg
scale−invariant
ΛCDM
l(l+1)C_l/2π [μK²]
1500
1000
500
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Angular Wavenumber, l

COBE To WMAP

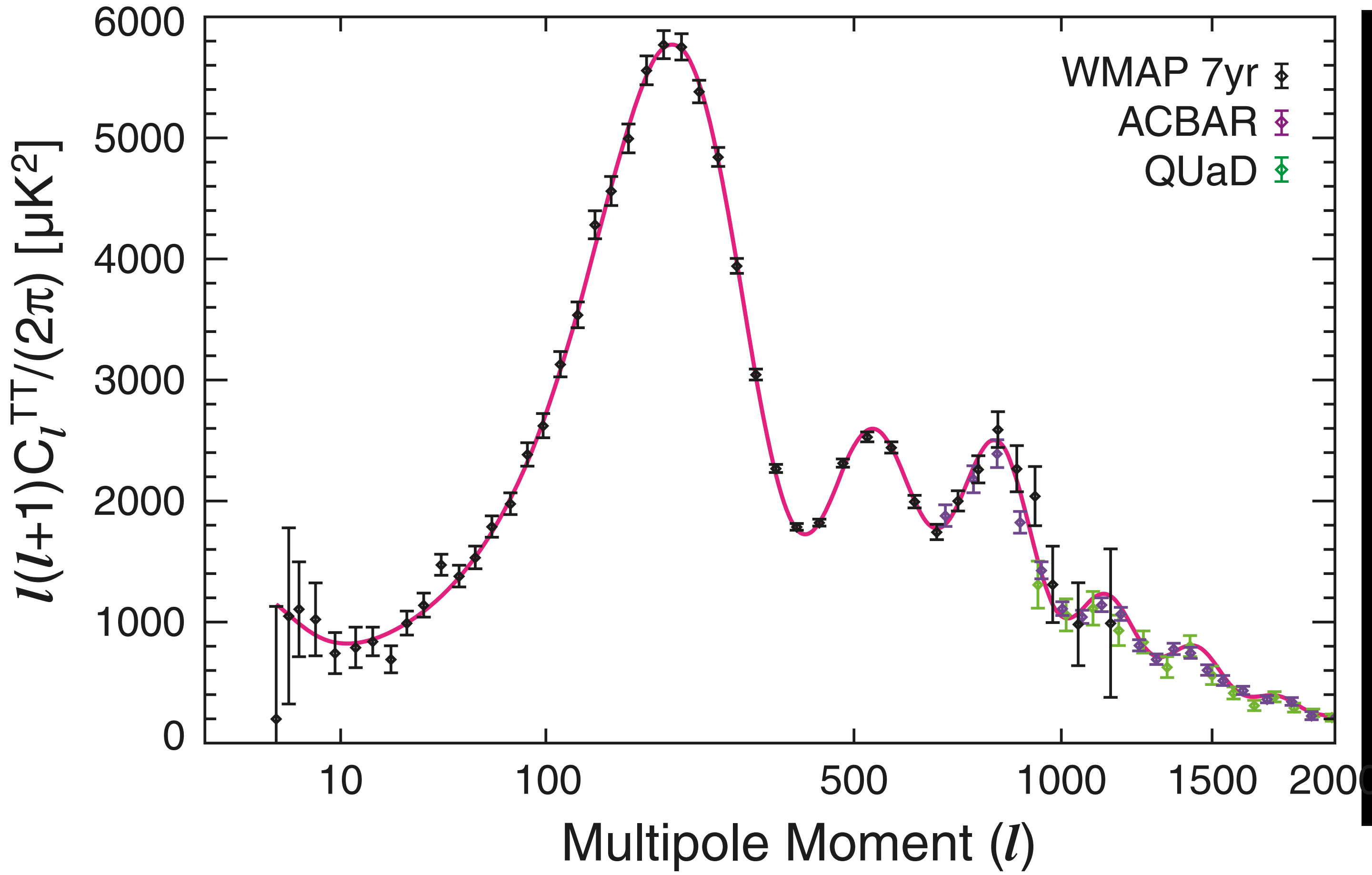


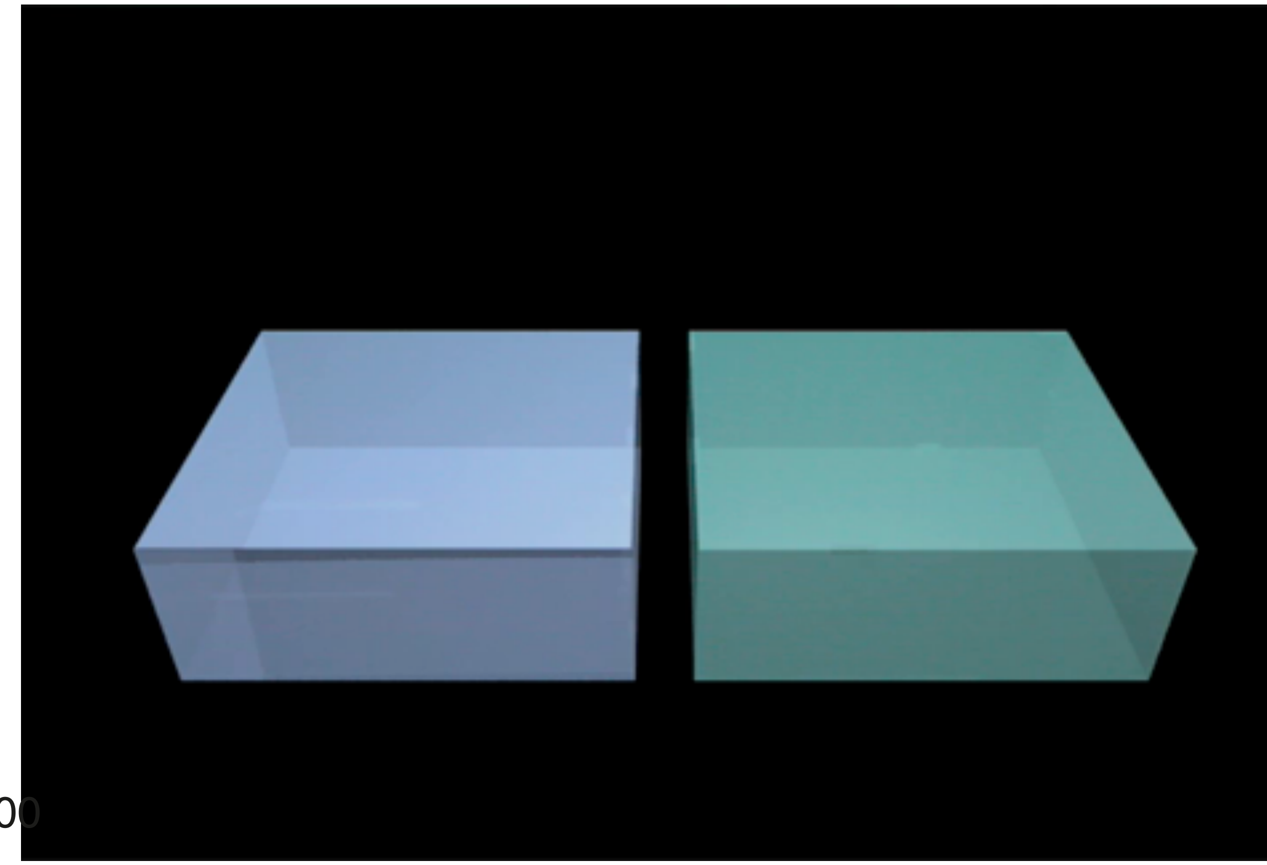
- COBE is unable to resolve the structures below ~7 degrees
- WMAP's resolving power is 35 times better than COBE.
- What did WMAP see?

WMAP Power Spectrum



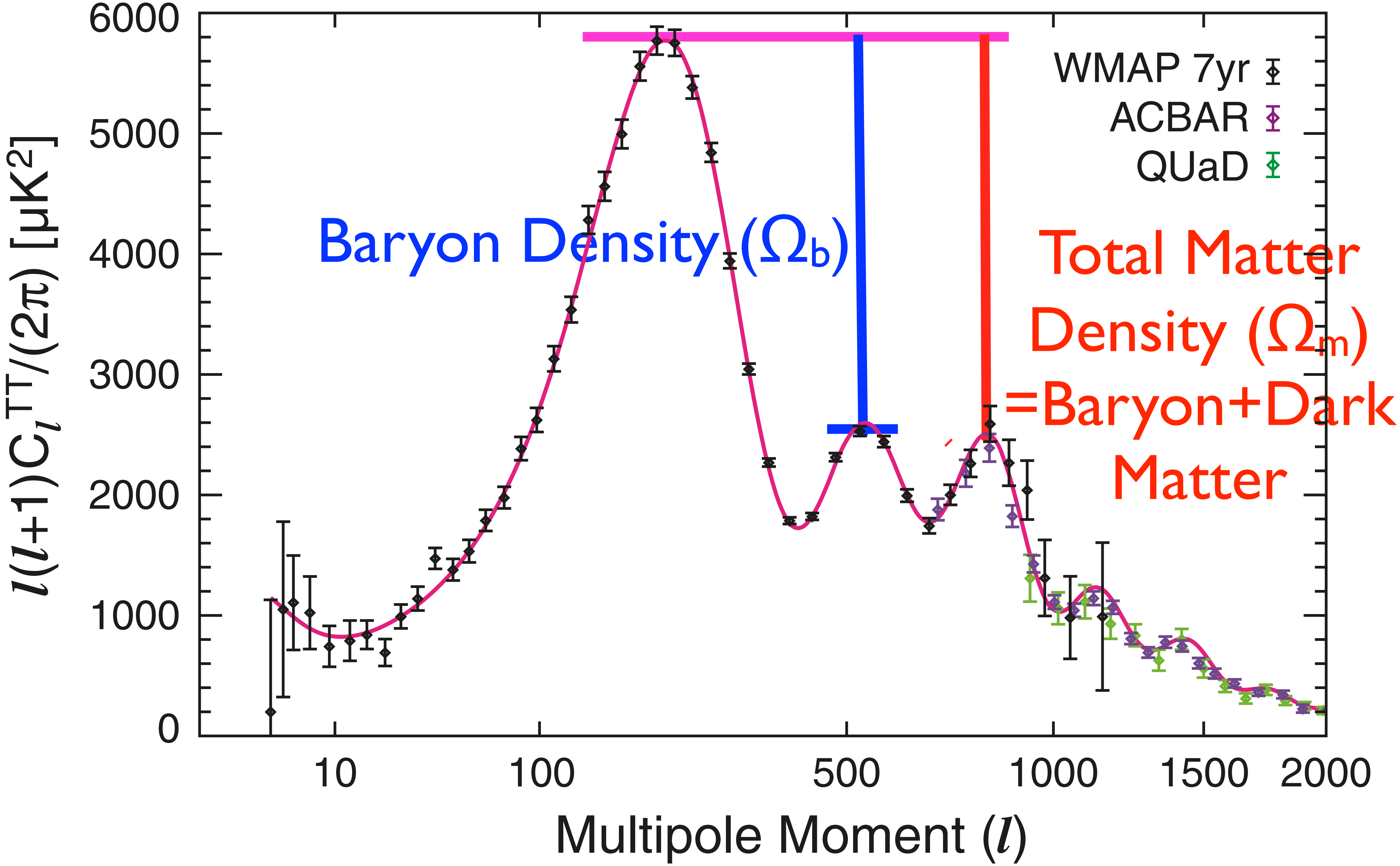
The Cosmic Sound Wave





- *"The Universe as a potato 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



By "baryon," I mean hydrogen and helium.

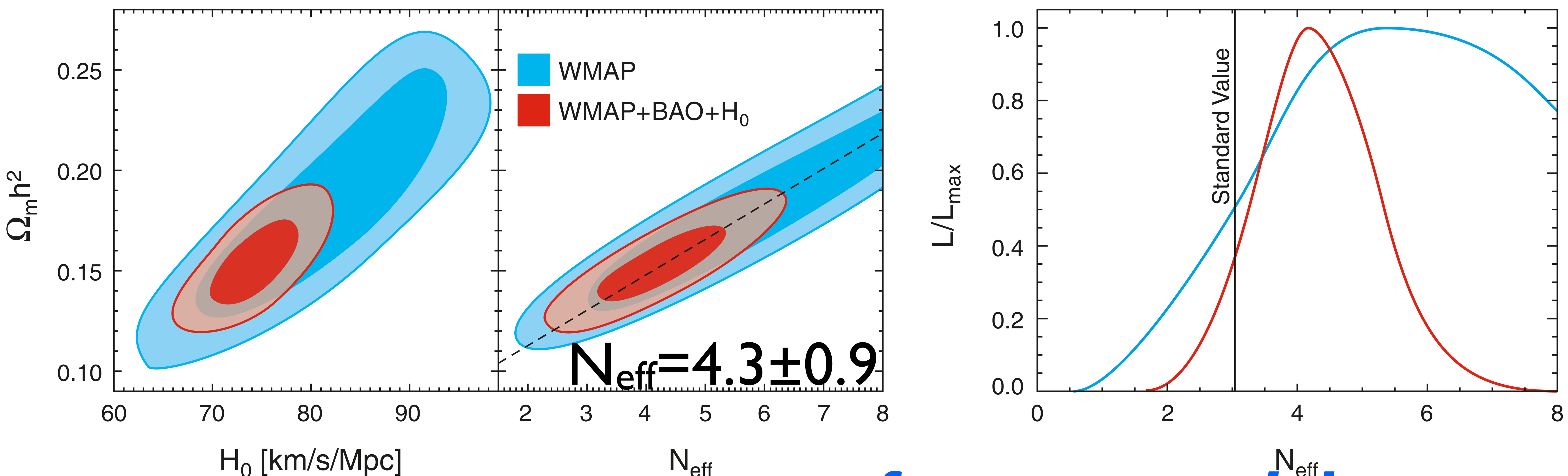
Fundamental Observables from WMAP

- 1st-to-2nd peak ratio: "baryon-to-photon ratio," ρ_B/ρ_γ
- 1st-to-3rd peak ratio: "matter-to-radiation ratio," ρ_M/ρ_R $(=1+z_{EQ})$
  - $\rho_M=\rho_B+\rho_{CDM}$
  - $\rho_R=\rho_\gamma+\rho_\nu$
- If we assume that we know ρ_ν, we can determine ρ_{CDM} from the 1st-to-3rd peak ratio; however, if we do not, we lose our ability to determine ρ_{CDM}!

3rd-peak "Spectroscopy"

- Total Matter = Baryons (H&He) + Dark Matter
- Total Radiation = Photons + Neutrinos (+new radiation)
  - Neutrino temperature = $(4/11)^{1/3}$ Photon temperature
- So, for a given assumed value of the number of neutrino species (or the number of new radiation species, i.e., zero), we can measure the dark matter density.
- Or, we can get the dark matter density from elsewhere, and determine the number of radiation species!

"3rd peak spectroscopy": Number of Relativistic Species

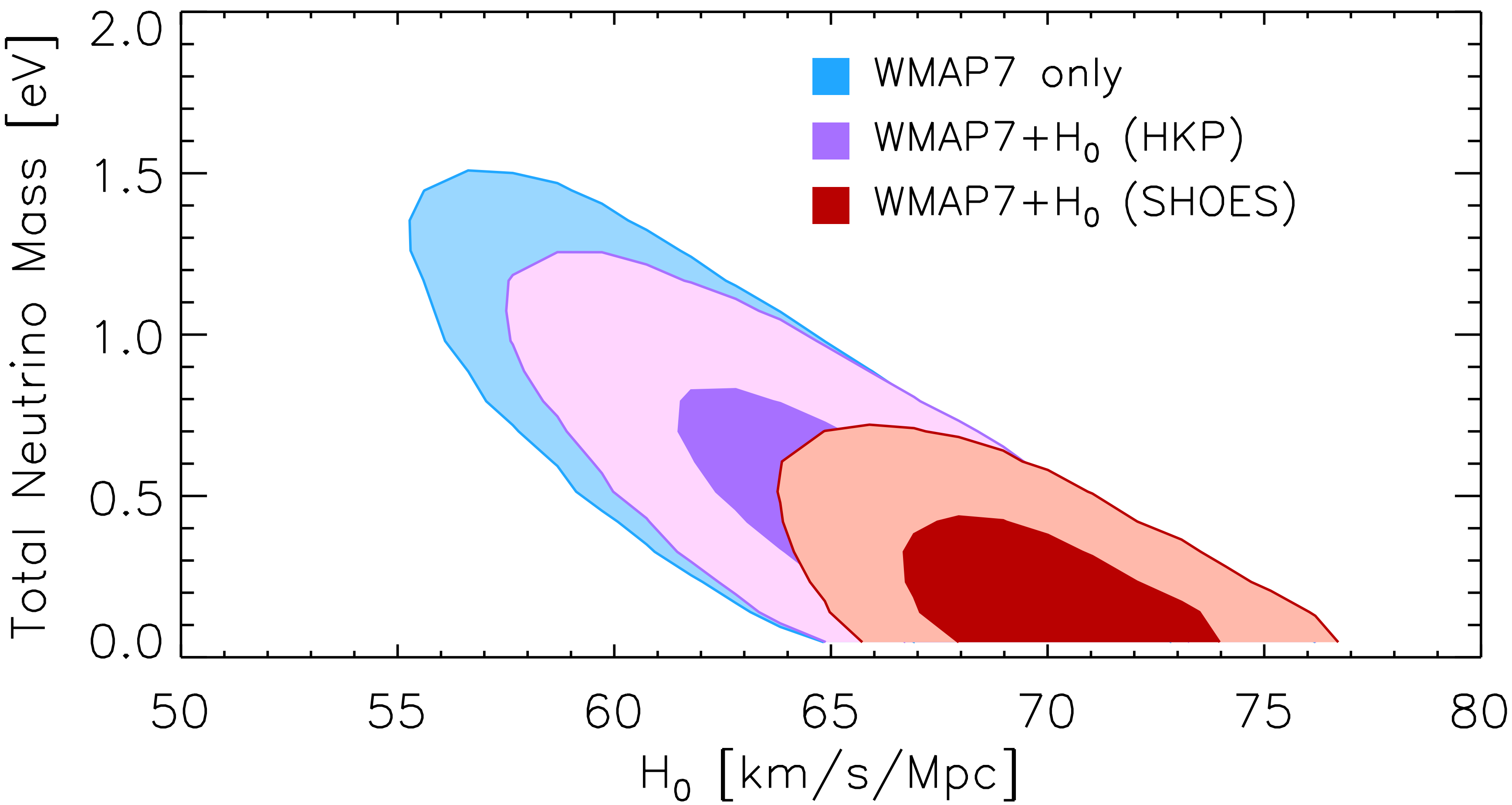


from external data

$$N_{\rm eff} = 3.04 + 7.44\left(\frac{\Omega_m h^2}{0.1308}\frac{3139}{1+z_{\rm eq}} - 1\right)$$

from 3rd peak

And, the mass of neutrinos



- WMAP data combined with the local measurement of the expansion rate (H_0), we get $\sum m_\nu < 0.6$ eV (95%CL)

$\sum m_\nu$ from CMB alone

- There is a simple limit by which one can constrain $\sum m_\nu$ using the primary CMB from z=1090 alone (ignoring gravitational lensing of CMB by the intervening mass distribution)
- When all of neutrinos were lighter than ~0.6 eV, they were still relativistic at the time of photon decoupling at z=1090 (photon temperature 3000K=0.26eV).
  - $\langle E_\nu \rangle = 3.15(4/11)^{1/3} T_{photon} = 0.58$ eV
- Neutrino masses didn't matter if they were relativistic!
- For degenerate neutrinos, $\sum m_\nu = 3.04 \times 0.58 = 1.8$ eV
  - **If $\sum m_\nu \ll 1.8$eV, CMB alone cannot see it**

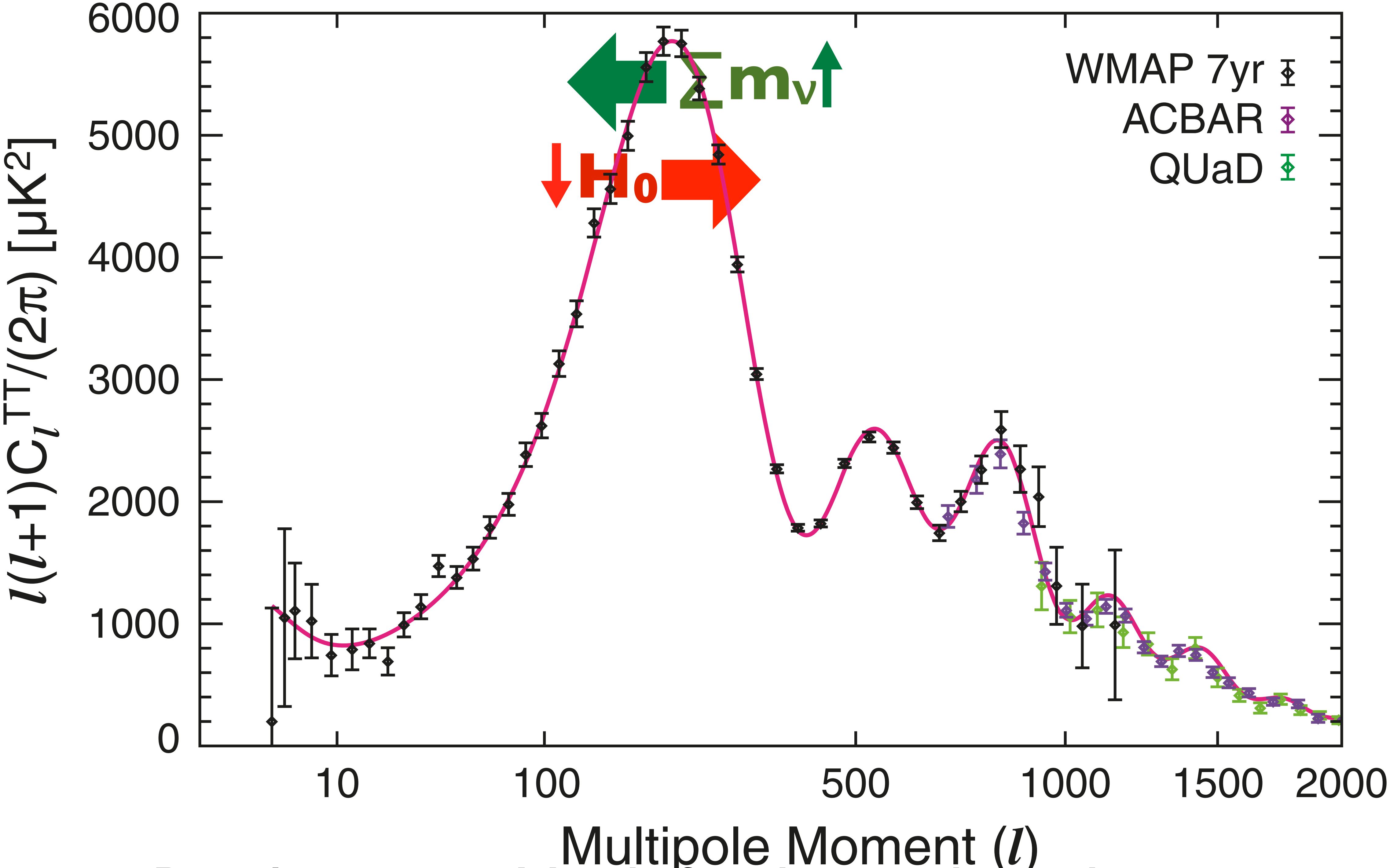
Neutrino Subtlety

- For $\sum m_\nu << 1.8$eV, neutrinos were relativistic at z=1090
- But, we know that $\sum m_\nu > 0.05$eV from neutrino oscillation experiments
    - This means that **neutrinos are definitely non-relativistic today!**
- So, today's value of Ω_M is the sum of baryons, CDM, and neutrinos: $\boldsymbol{\Omega_M h^2 = (\Omega_B + \Omega_{CDM}) h^2 + 0.0106(\sum m_\nu / 1\text{eV})}$

Matter-Radiation Equality

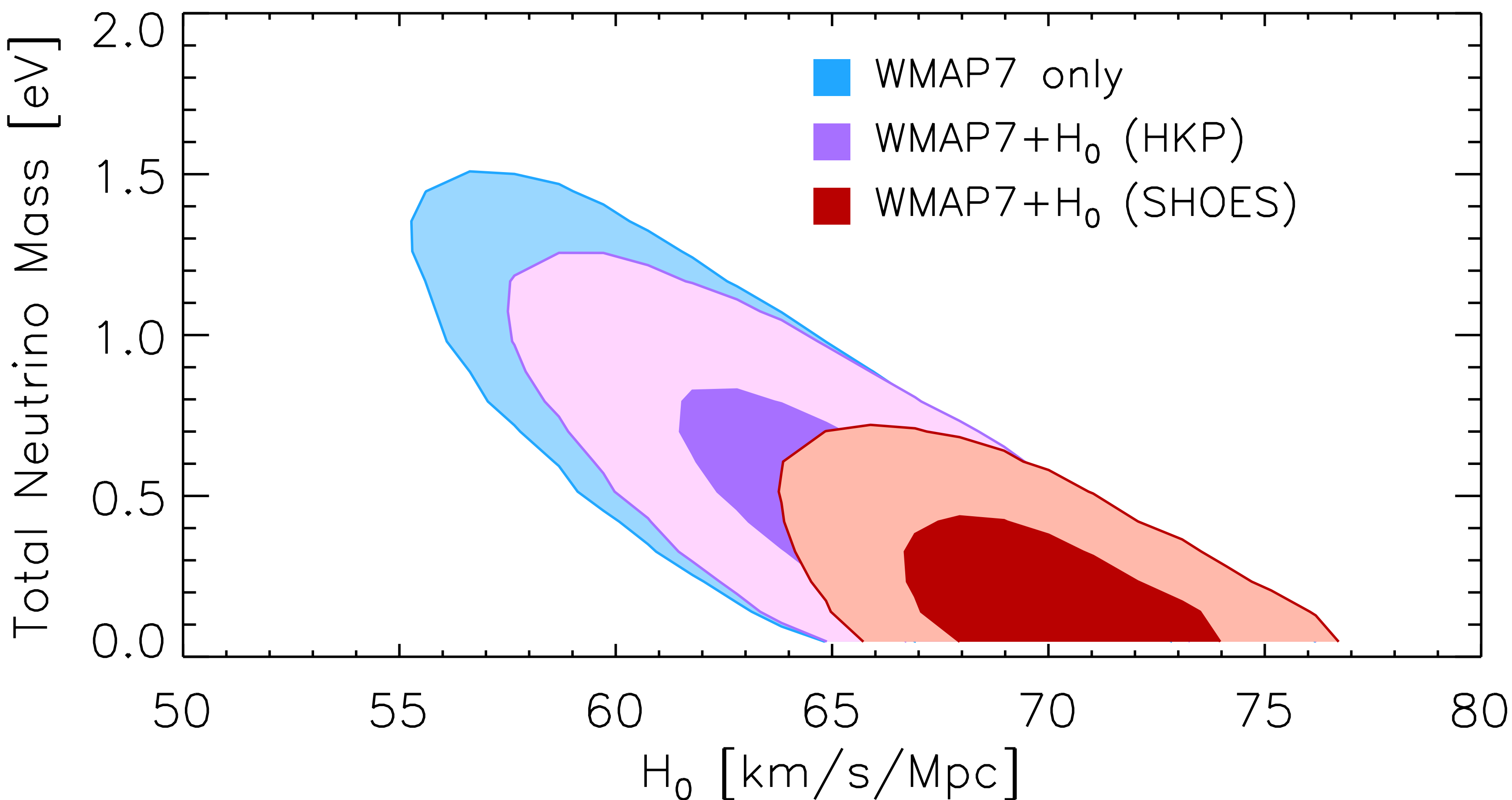
- However, since neutrinos were relativistic before z=1090, the matter-radiation equality is determined by:
  - $1+z_{EQ} = (\Omega_B+\Omega_{CDM}) / \Omega_R$
  - Now, recall $\Omega_M h^2 = (\Omega_B+\Omega_{CDM})h^2 + 0.0106(\sum m_\nu/1\,\mathrm{eV})$
  - For a given $\Omega_M h^2$ constrained by the other data, adding $\sum m_\nu$ makes $(\Omega_B+\Omega_{CDM})h^2$ smaller -> smaller z_{EQ} -> **Radiation Era lasts longer**
- **This effect shifts the first peak to a lower multipole**

$\sum m_\nu$: Shifting the Peak To Low-l



- But, lowering H_0 shifts the peak in the opposite direction. So...

Shift of Peak Absorbed by H_0



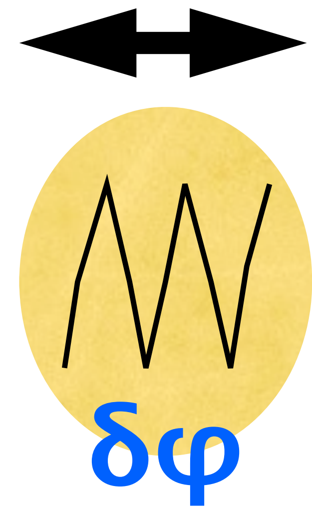
- Here is a catch:
  - **Shift of the first peak to a lower multipole can be canceled by lowering H_0!** $\sum m_\nu < 0.6$ eV (95%CL)

How Do We Test Inflation?

- How can we answer a simple question like this:
  - "*How were primordial fluctuations generated?*"

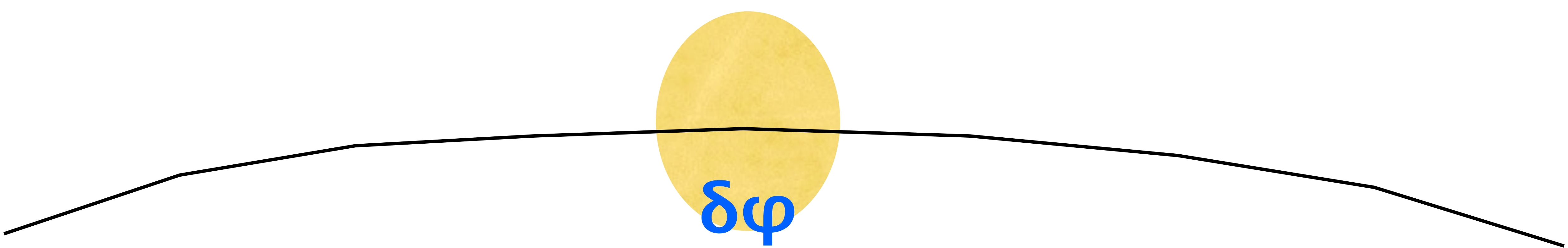
Stretching Micro to Macro

H^{-1} = Hubble Size



Quantum fluctuations on microscopic scales

INFLATION!

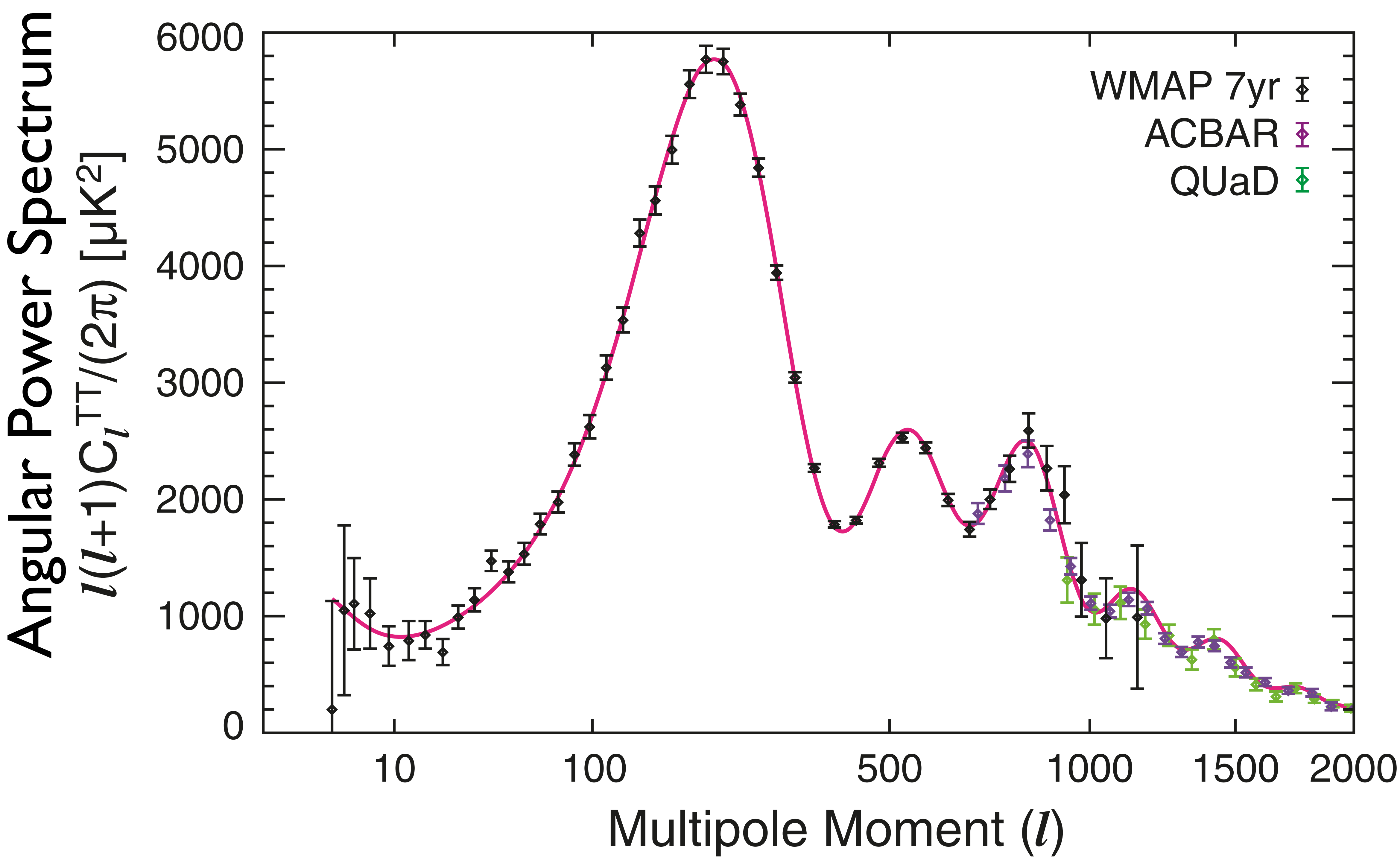


Quantum fluctuations cease to be quantum, and become observable

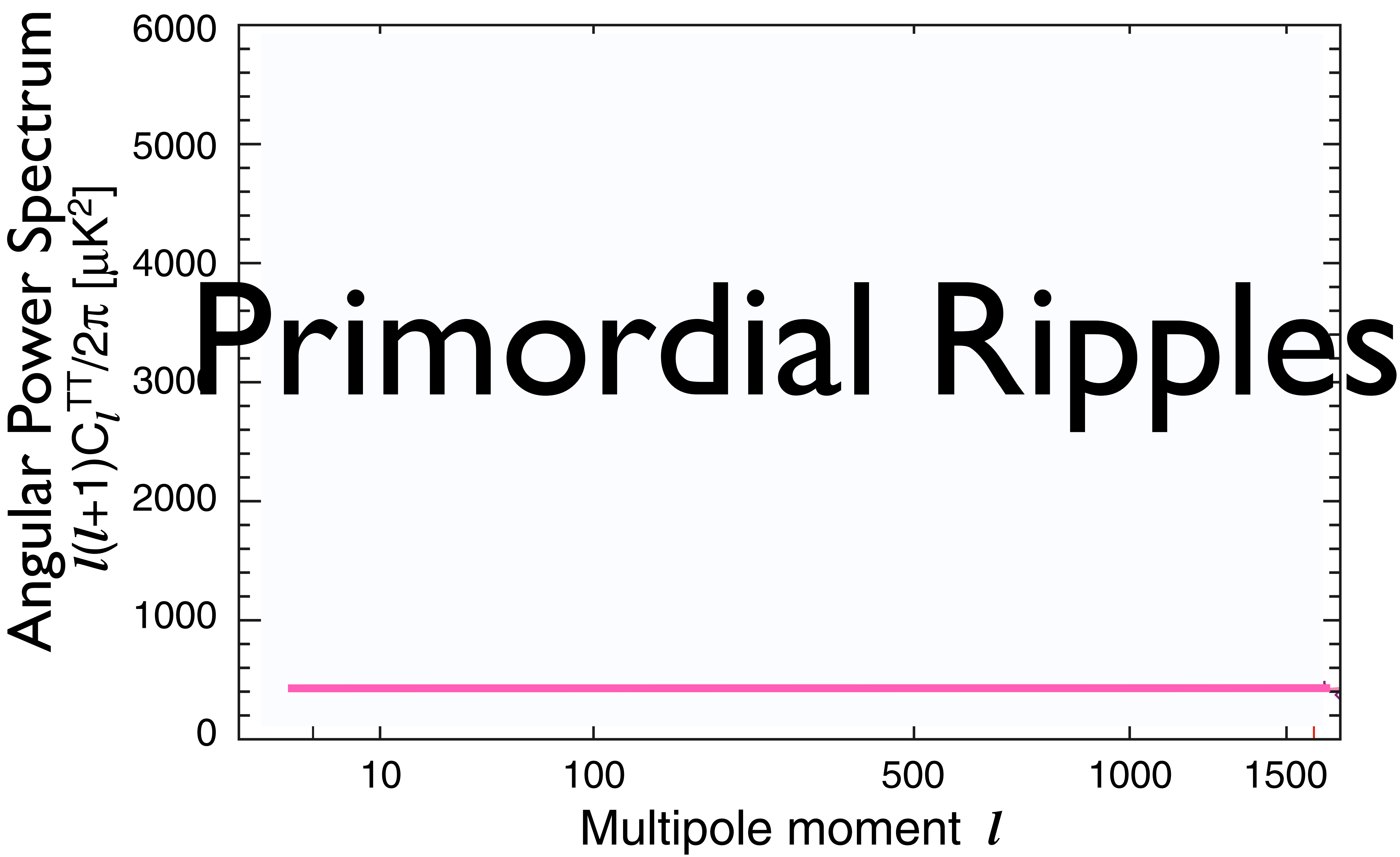
Power Spectrum

- A very successful explanation (Mukhanov & Chibisov; Guth & Pi; Hawking; Starobinsky; Bardeen, Steinhardt & Turner) is:
  - *Primordial fluctuations were generated by quantum fluctuations of the scalar field that drove inflation.*
  - The prediction: a nearly scale-invariant power spectrum in the curvature perturbation, $\zeta = -(Hdt/d\varphi)\delta\varphi$
    - **$P_\zeta(k) = \langle|\zeta_k|^2\rangle = A/k^{4-n_s} \sim A/k^3$**
    - where $n_s \sim 1$ and A is a normalization.

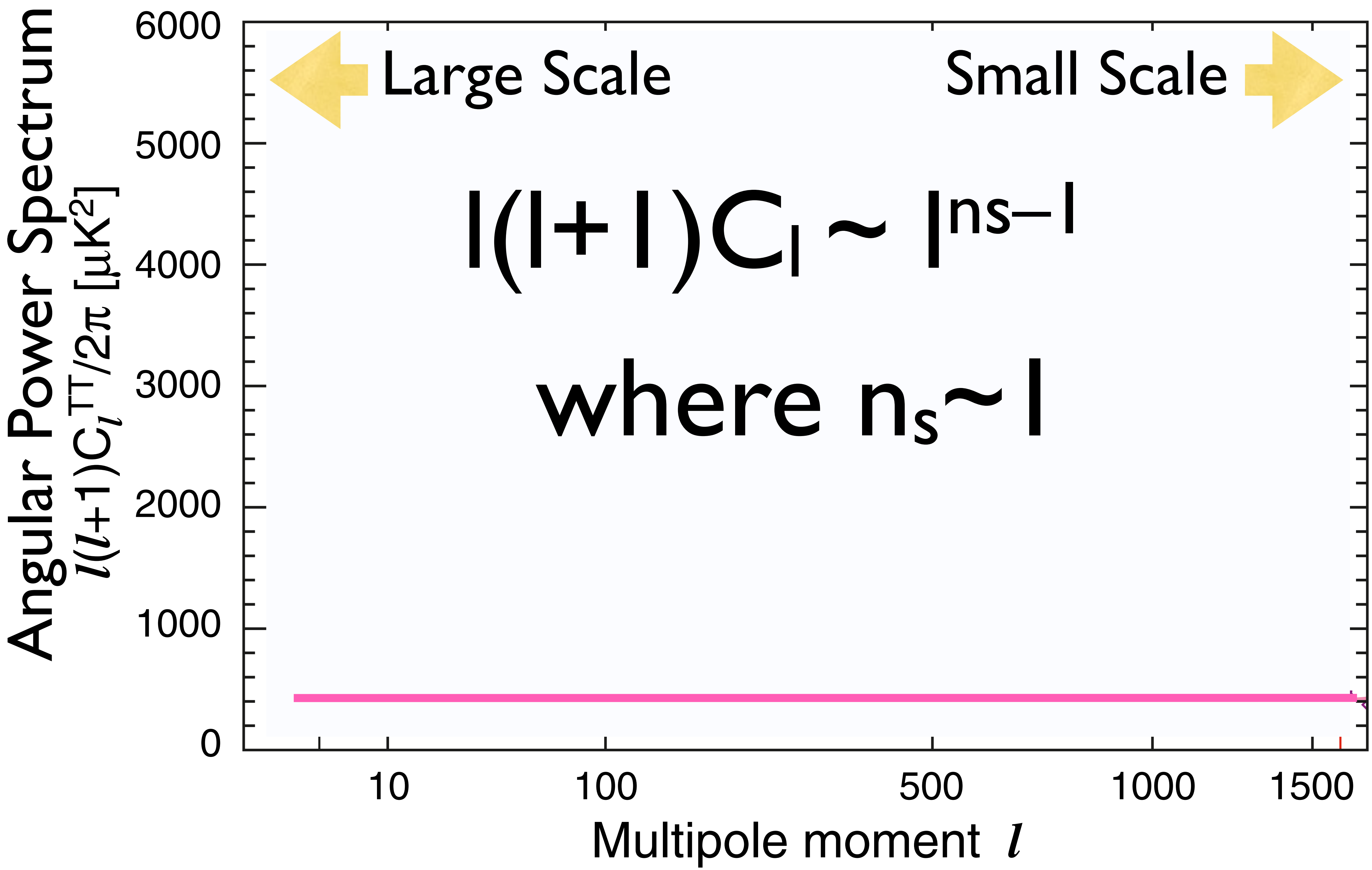
WMAP Power Spectrum



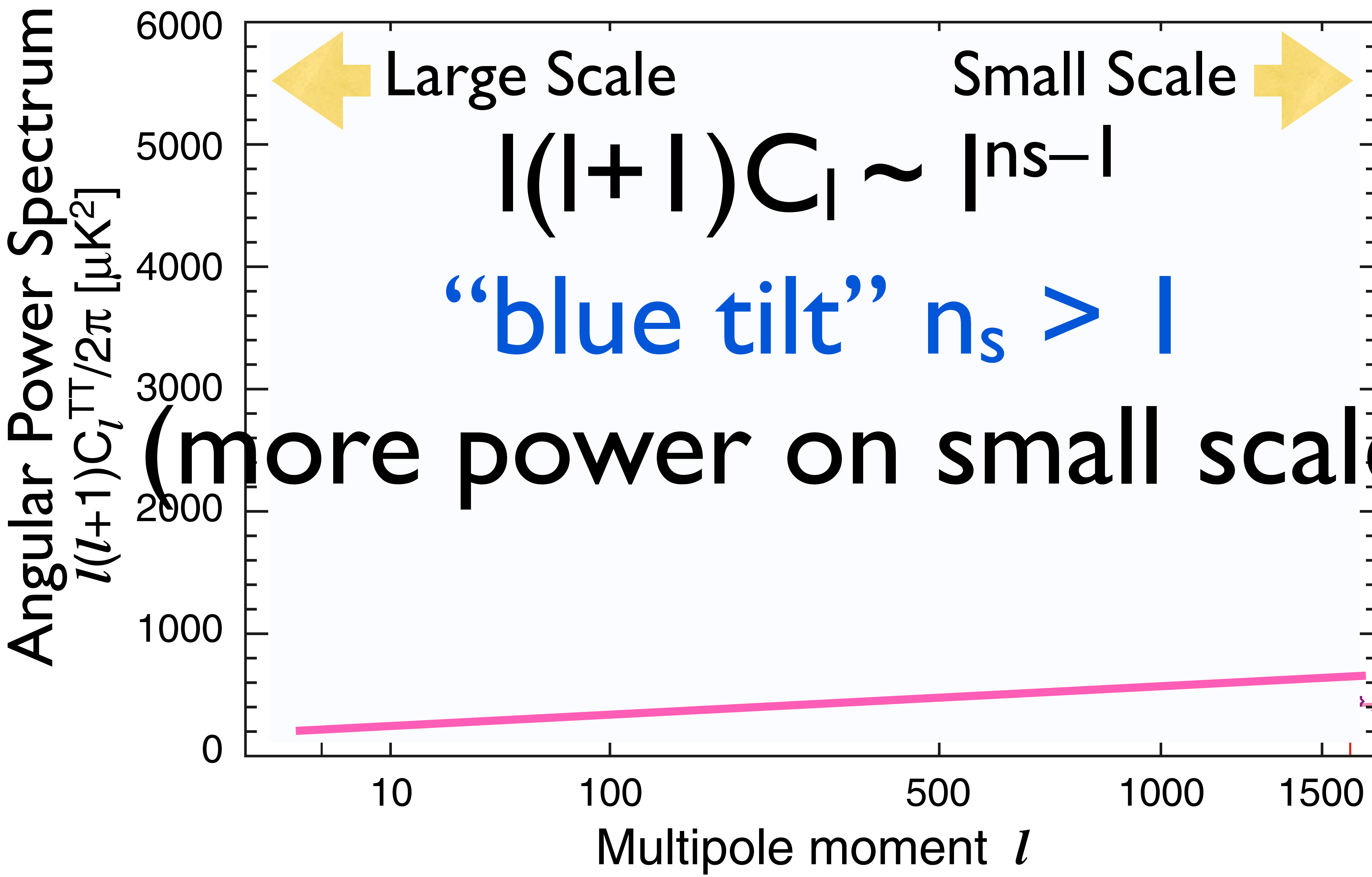
Getting rid of the Sound Waves



Inflation Predicts:



Inflation may do this

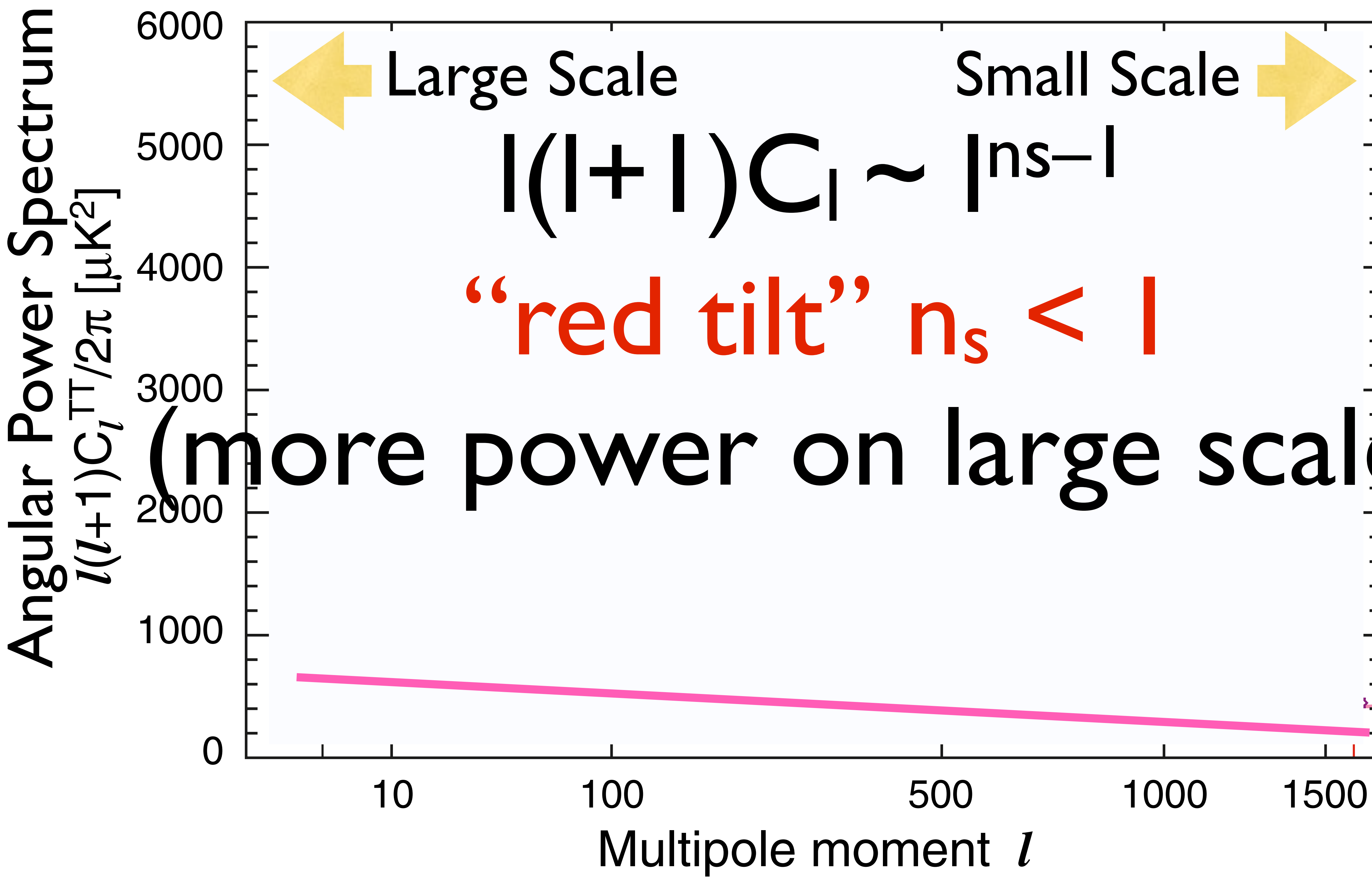


$l(l+1)C_l \sim l^{ns-1}$

"blue tilt" $n_s > 1$

(more power on small scales)

...or this

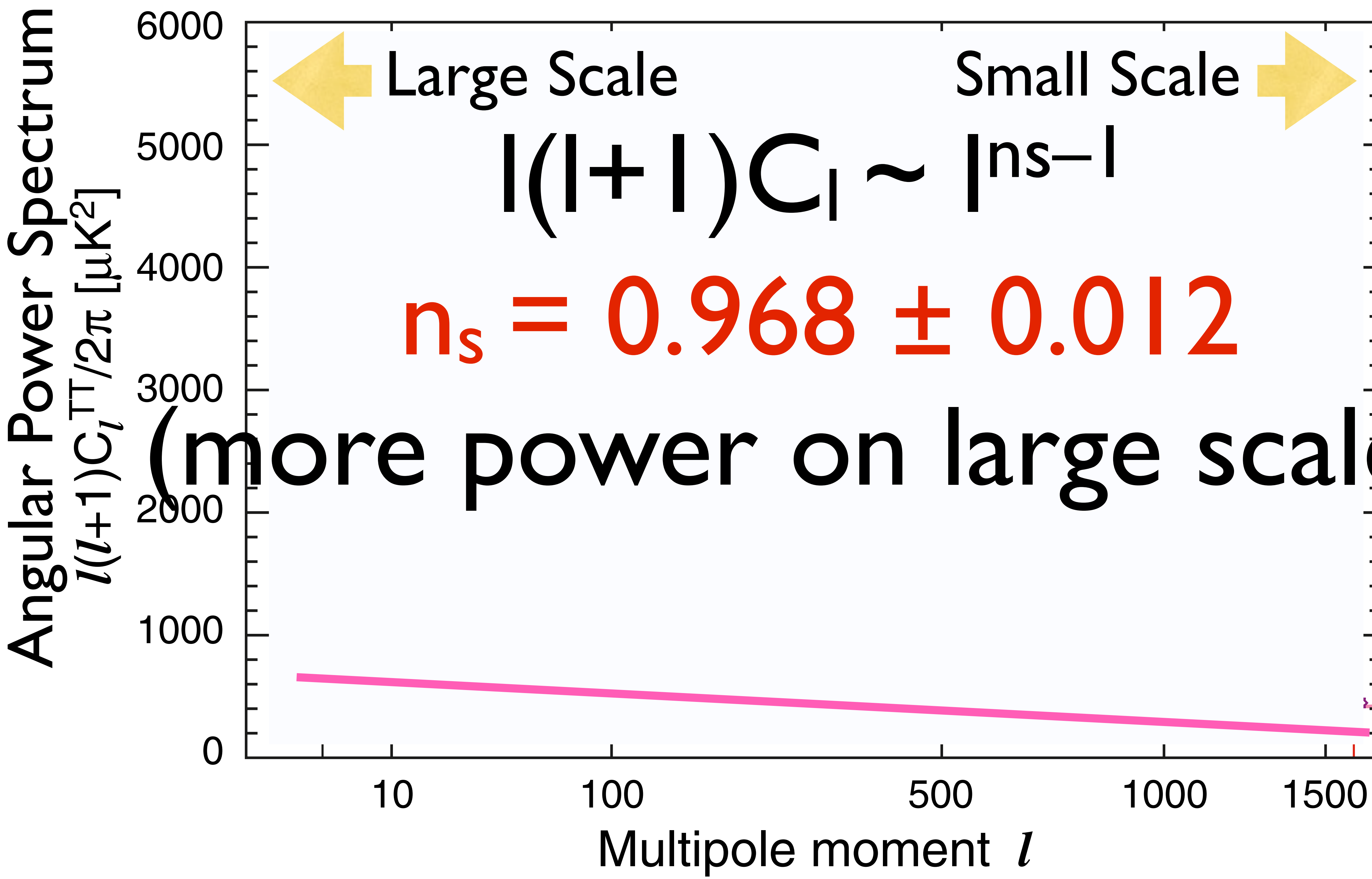


$l(l+1)C_l \sim l^{ns-1}$

"red tilt" $n_s < 1$

(more power on large scales)

WMAP 7-year Measurement (Komatsu et al. 2011)



$$l(l+1)C_l \sim l^{ns-1}$$

$$n_s = 0.968 \pm 0.012$$

(more power on large scales)

After 9 years of observations...

WMAP taught us:

- **All of the basic predictions of single-field and slow-roll inflation models are consistent with the data**
    - But, not all models are consistent (i.e., $\lambda\varphi^4$ is out unless you introduce a non-minimal coupling)

Testing Single-field by Adiabaticity

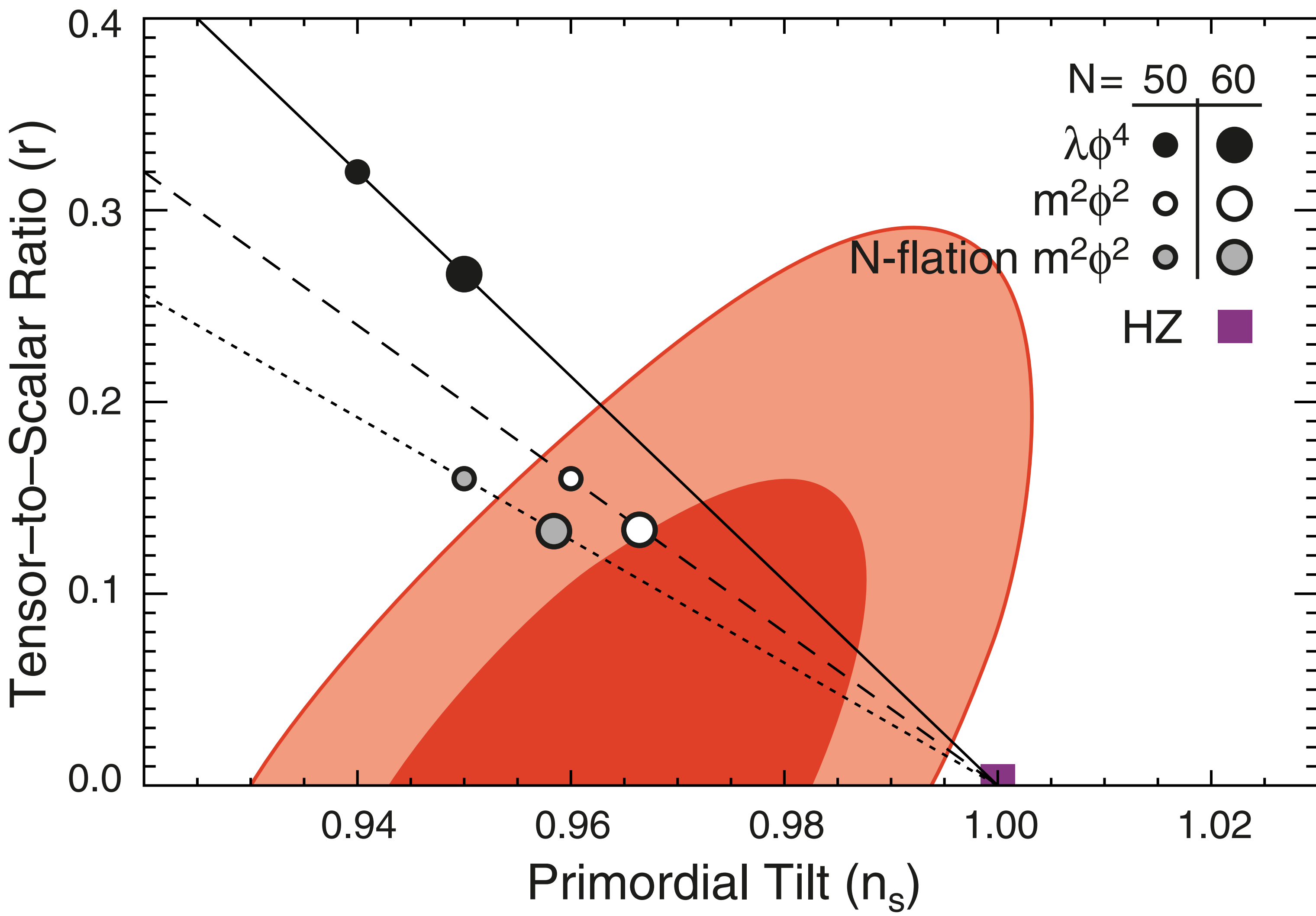
- Within the context of single-field inflation, all the matter and radiation originated from a single field, and thus there is a particular relation (adiabatic relation) between the perturbations in matter and photons:

$$\mathcal{S}_{c,\gamma} \equiv \frac{\delta\rho_c}{\rho_c} - \frac{3\delta\rho_\gamma}{4\rho_\gamma} = 0$$

The data are consistent with S=0:

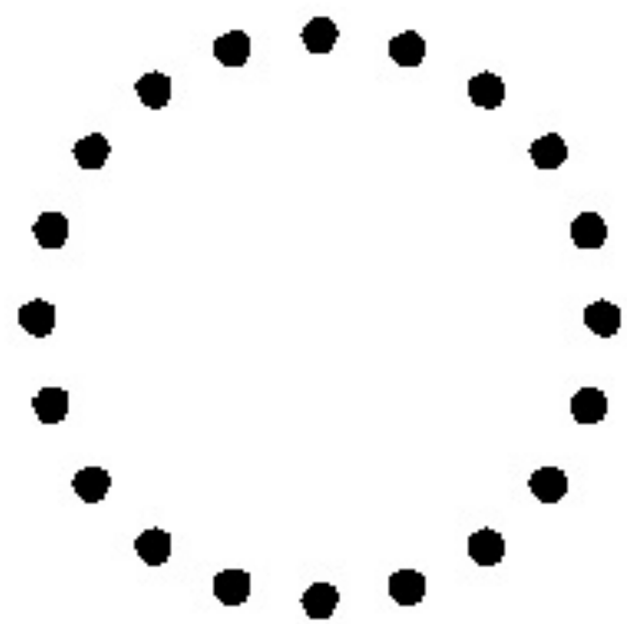
$$\frac{|\delta\rho_c/\rho_c - 3\delta\rho_\gamma/(4\rho_\gamma)|}{\frac{1}{2}[\delta\rho_c/\rho_c + 3\delta\rho_\gamma/(4\rho_\gamma)]} < 0.09 \quad (95\%\ \mathrm{CL})$$

Inflation looks good



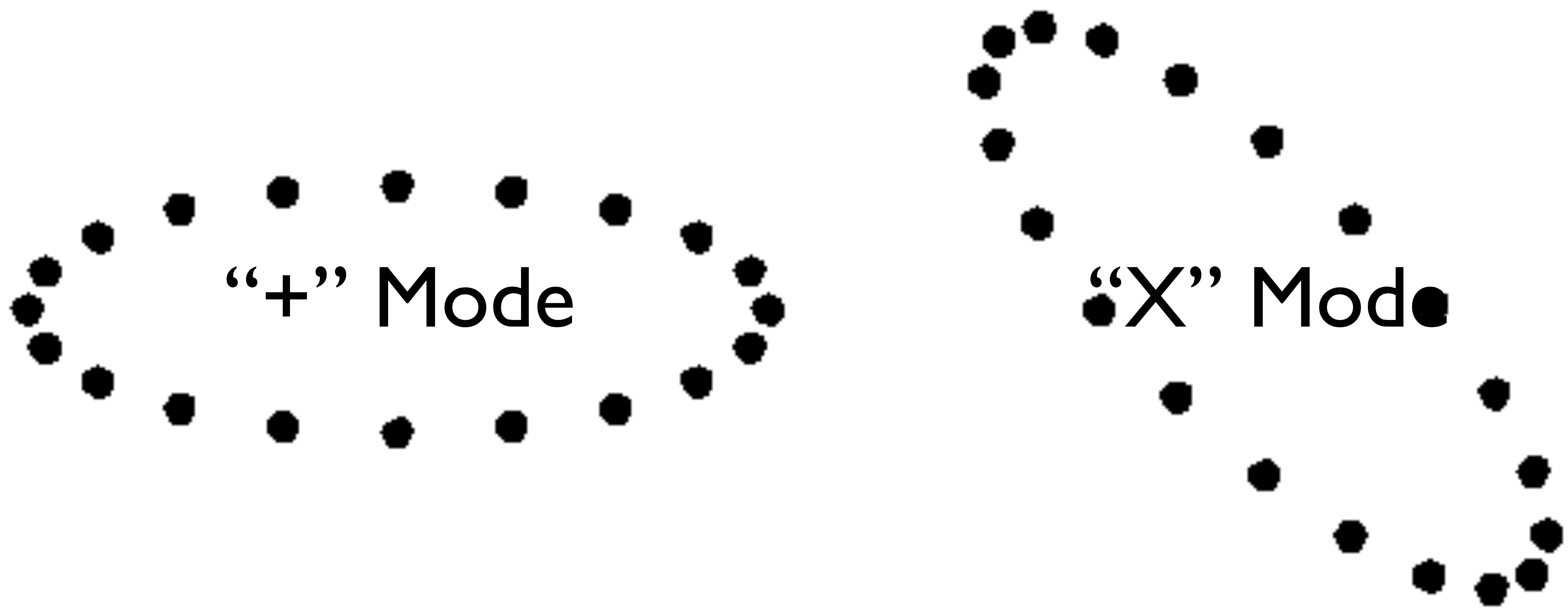
- Joint constraint on the primordial tilt, n_s, and the tensor-to-scalar ratio, r.
- **r < 0.24** (95%CL; WMAP7+BAO+H_0)

Gravitational waves are coming toward you... What do you do?



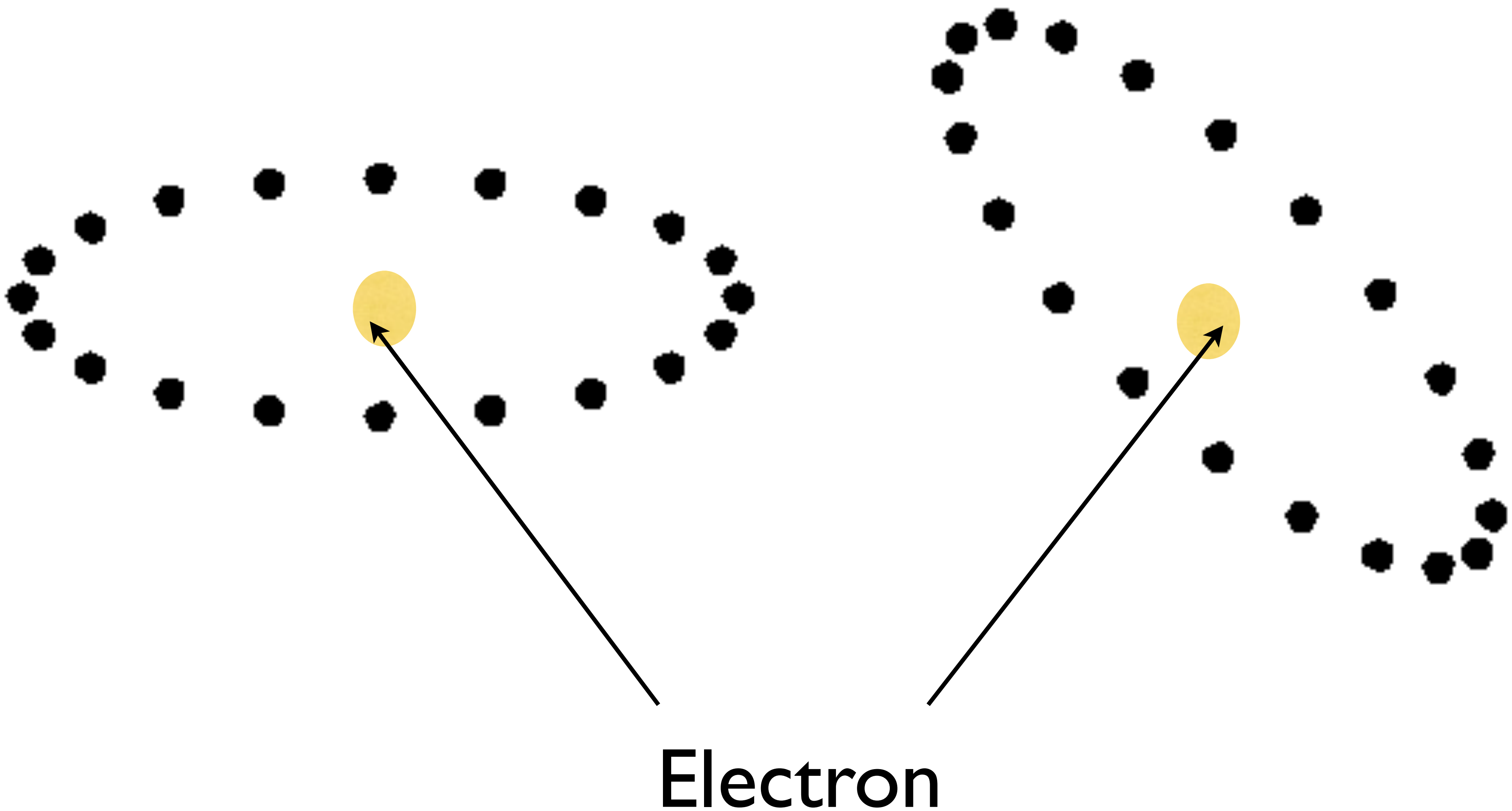
- Gravitational waves stretch space, causing particles to move.

Two Polarization States of GW

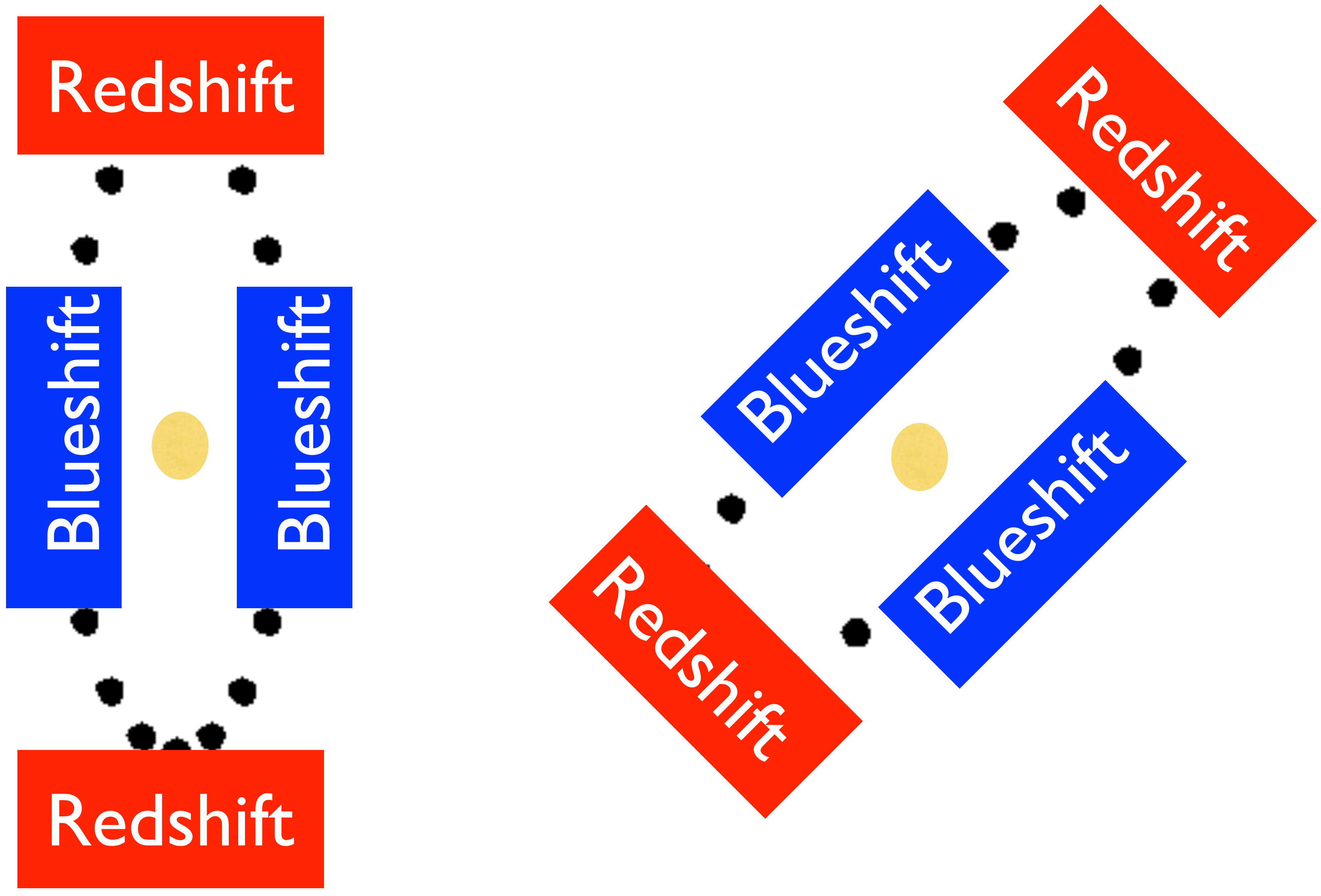


- This is great - this will automatically generate quadrupolar temperature anisotropy around electrons!

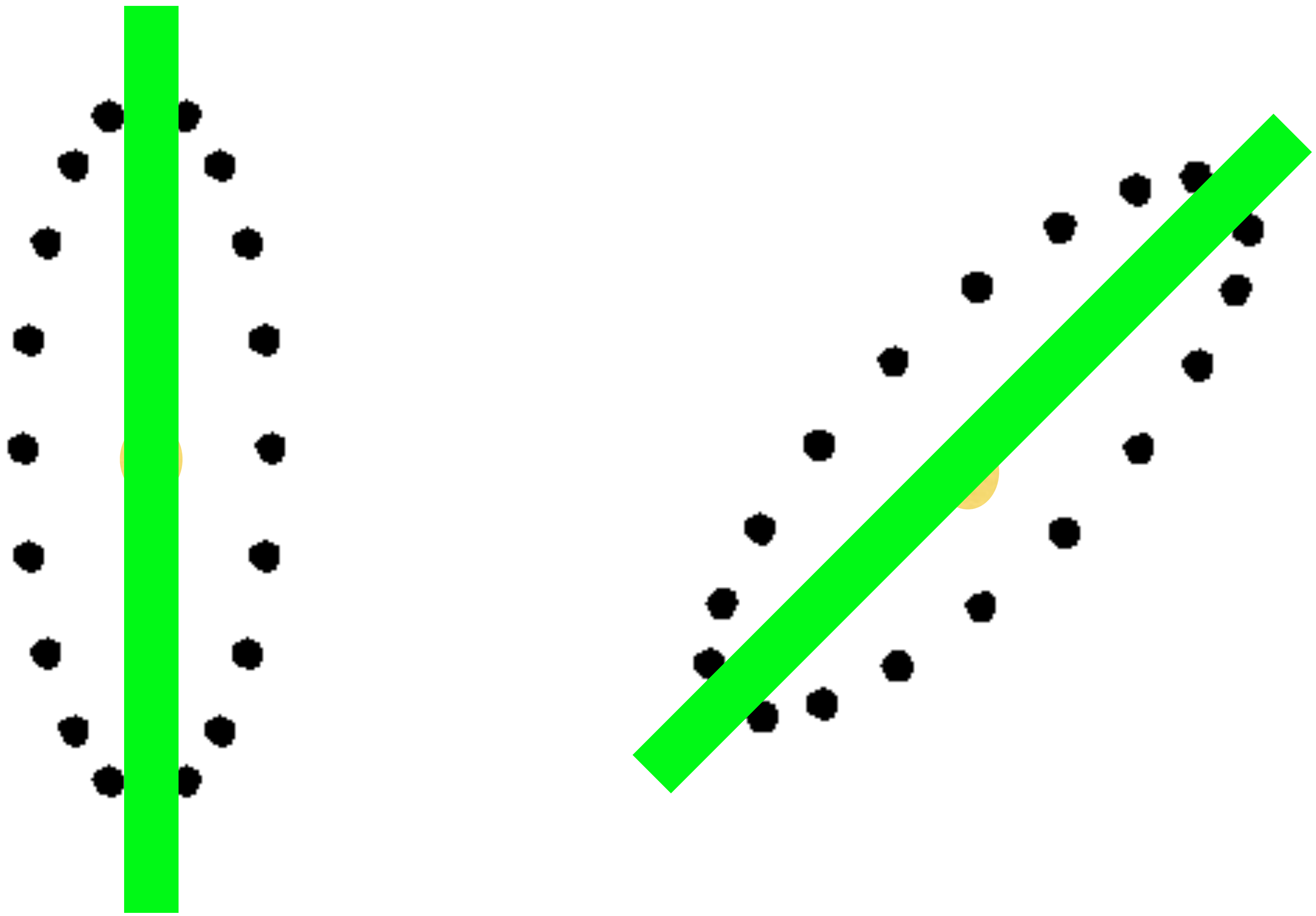
From GW to CMB Polarization



From GW to CMB Polarization



From GW to CMB Polarization



“Tensor-to-scalar Ratio,” r

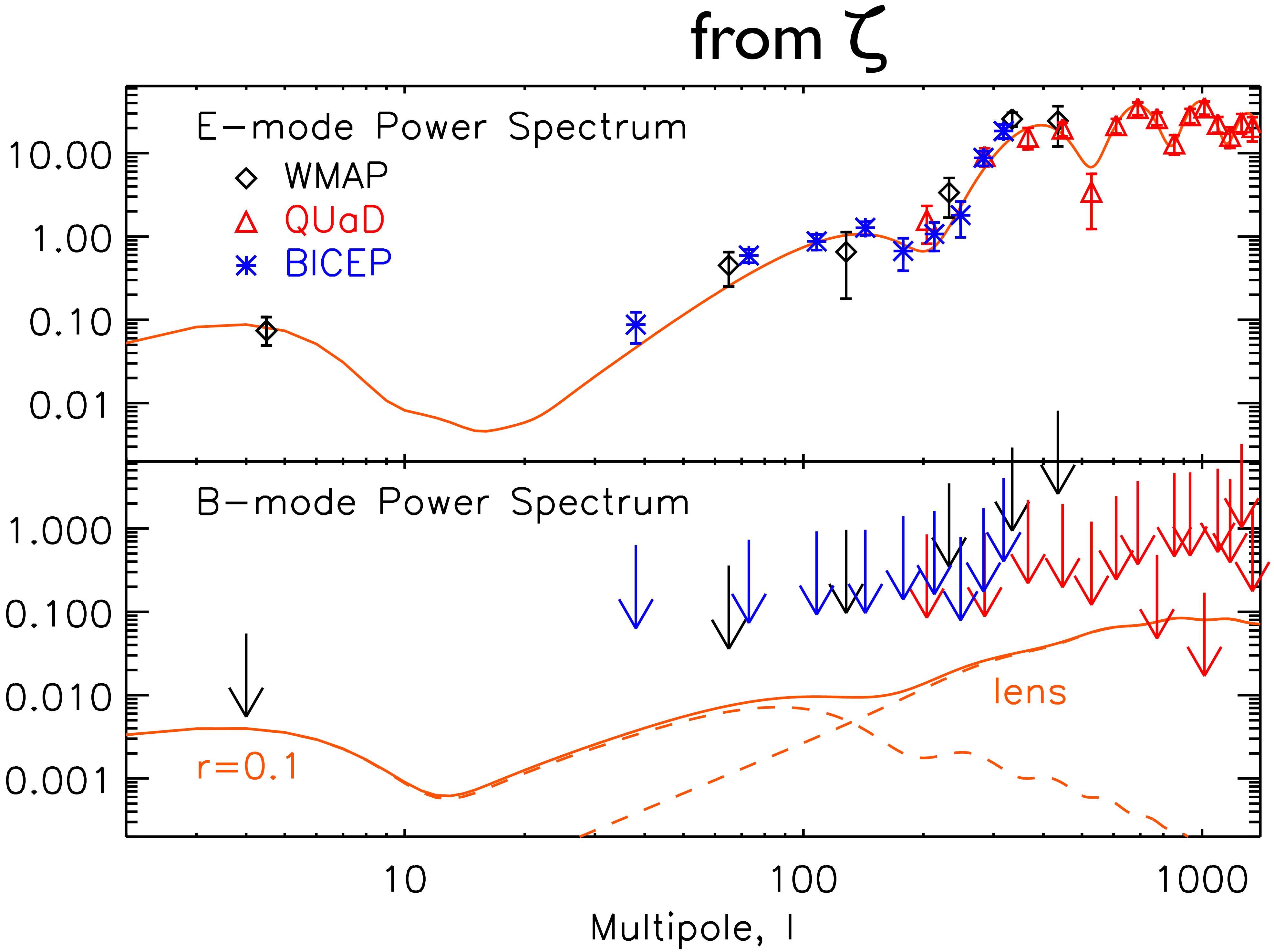
$$r \equiv \frac{2\langle |h_{\mathbf{k}}^{+}|^2 + |h_{\mathbf{k}}^{\times}|^2 \rangle}{\langle |\zeta_{\mathbf{k}}|^2 \rangle}$$

In terms of the slow-roll parameter:

$$r = 16\varepsilon$$

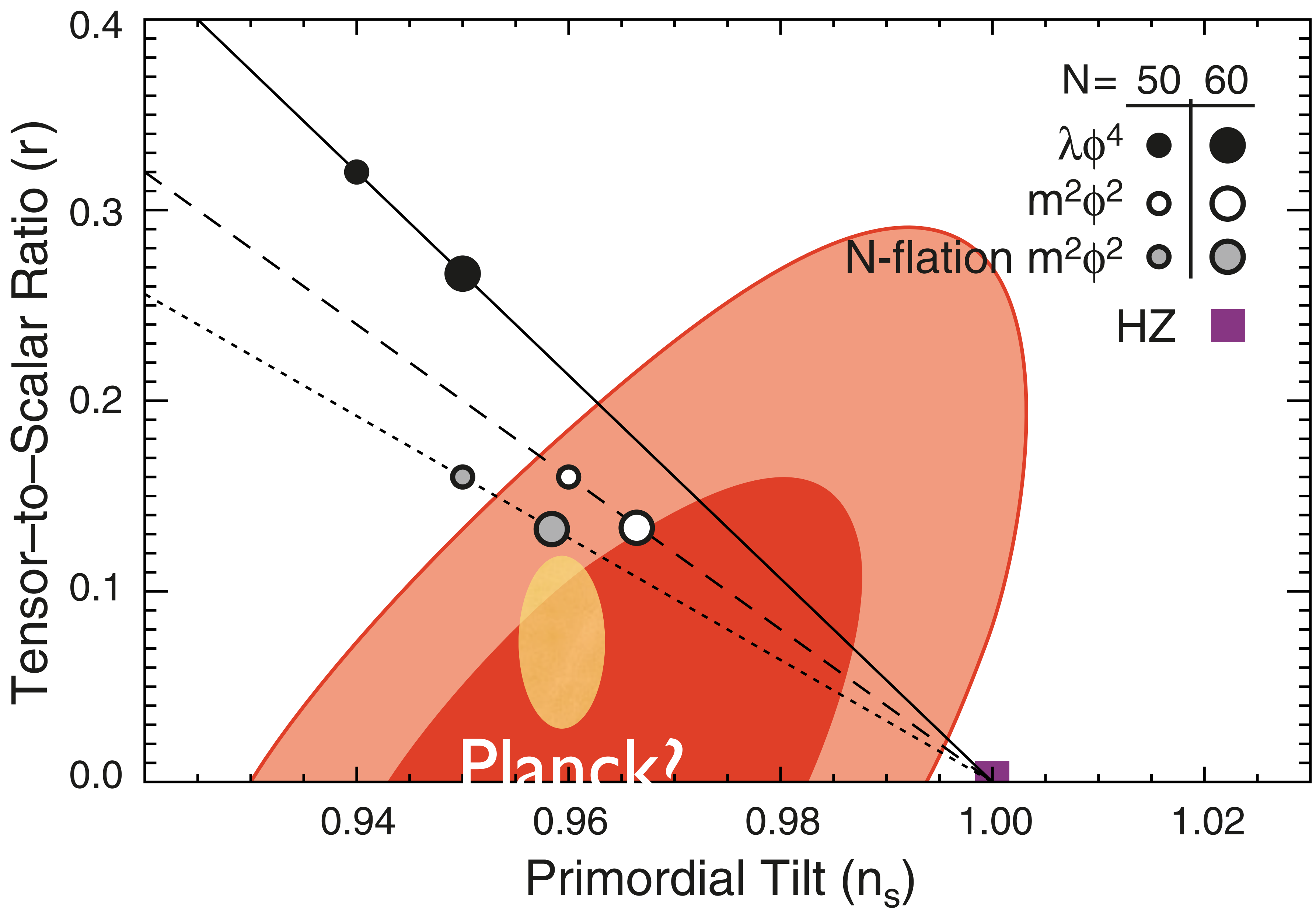
where $\varepsilon = -(dH/dt)/H^2 = 4\pi G(d\varphi/dt)^2/H^2$
$\approx (16\pi G)^{-1}(dV/d\varphi)^2/V^2$

Polarization Power Spectrum



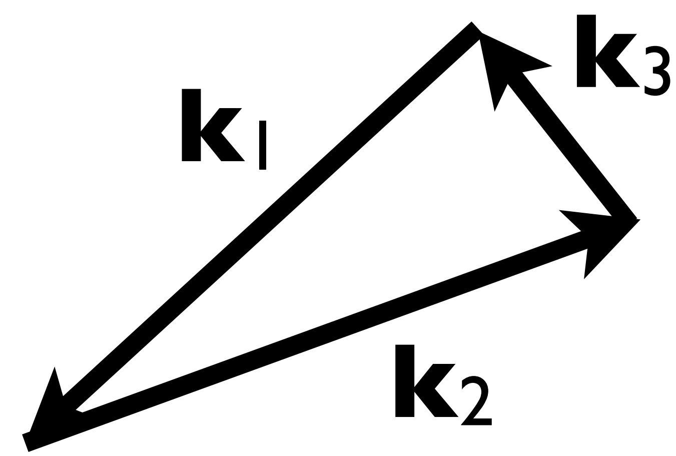
- No detection of polarization from gravitational waves (B-mode polarization) yet.

Planck might find gravitational waves (if r~0.1)

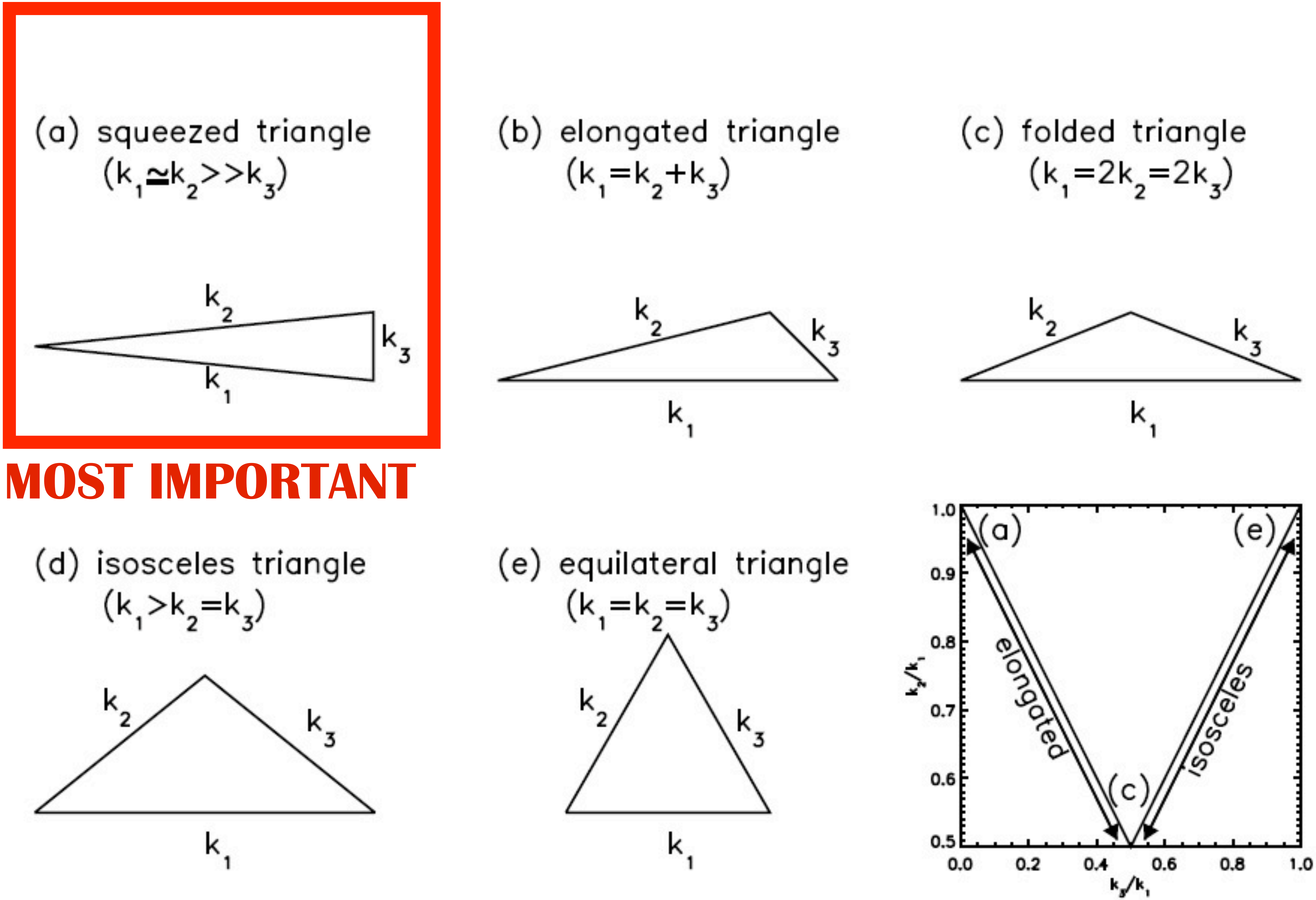


If found, this would give us a pretty convincing proof that inflation did indeed happen.

Bispectrum



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


(a) squeezed triangle
($k_1 \simeq k_2 >> k_3$)
k_2
k_3
k_1
MOST IMPORTANT
(b) elongated triangle
($k_1 = k_2 + k_3$)
k_2
k_3
k_1
(c) folded triangle
($k_1 = 2k_2 = 2k_3$)
k_2
k_3
k_1
(d) isosceles triangle
($k_1 > k_2 = k_3$)
k_2
k_3
k_1
(e) equilateral triangle
($k_1 = k_2 = k_3$)
k_2
k_3
k_1
(a)
(e)
(c)
elongated
isosceles
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

Ruling-out Inflation (3-point Function)

- Inflation models predict that primordial fluctuations are very close to Gaussian.
  - In fact, ALL SINGLE-FIELD models predict the squeezed-limit 3-point function to have the amplitude of $f_{NL}=0.02$.
  - Detection of $f_{NL}>1$ would rule out ALL single-field models!

Ruling-out Inflation (3-point Function)

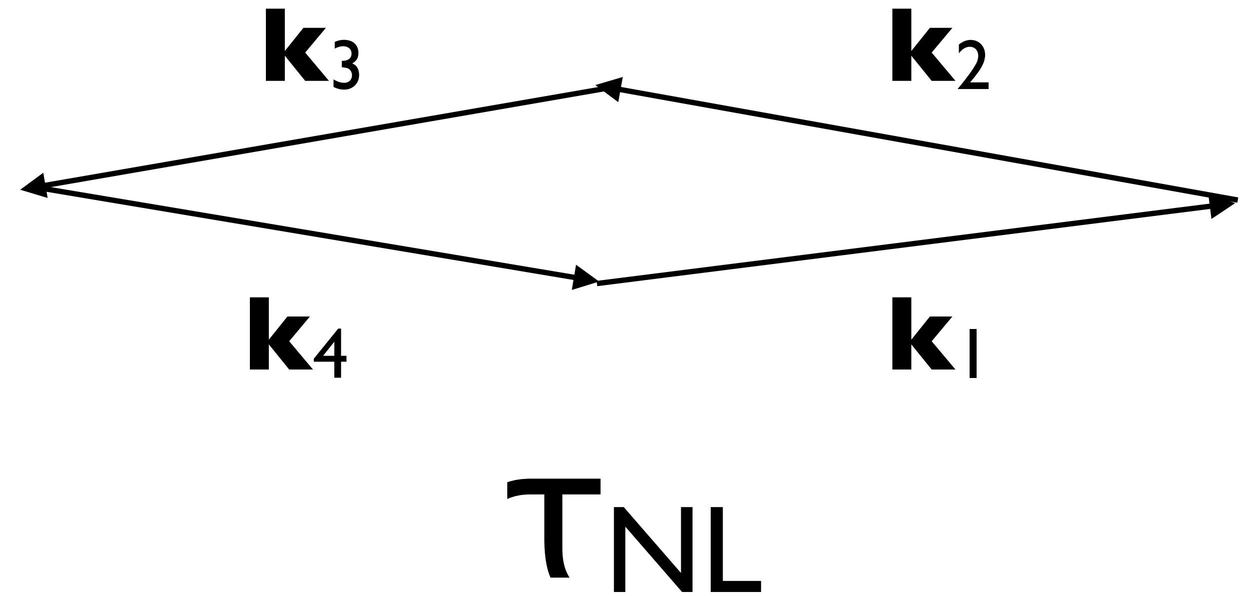
- No detection of this form of 3-point function of primordial curvature perturbations. The 95% CL limit is:
  - $-10 < f_{NL} < 74$
  - 68%CL: $f_{NL} = 32 \pm 21$
  - The WMAP data are consistent with the prediction of **simple single-field inflation** models: $1-n_s \approx r \approx f_{NL}$
- Planck will cut the error bar by a factor of four!

OK, for fun, let us suppose that single-field models are ruled out by Planck. Now what?

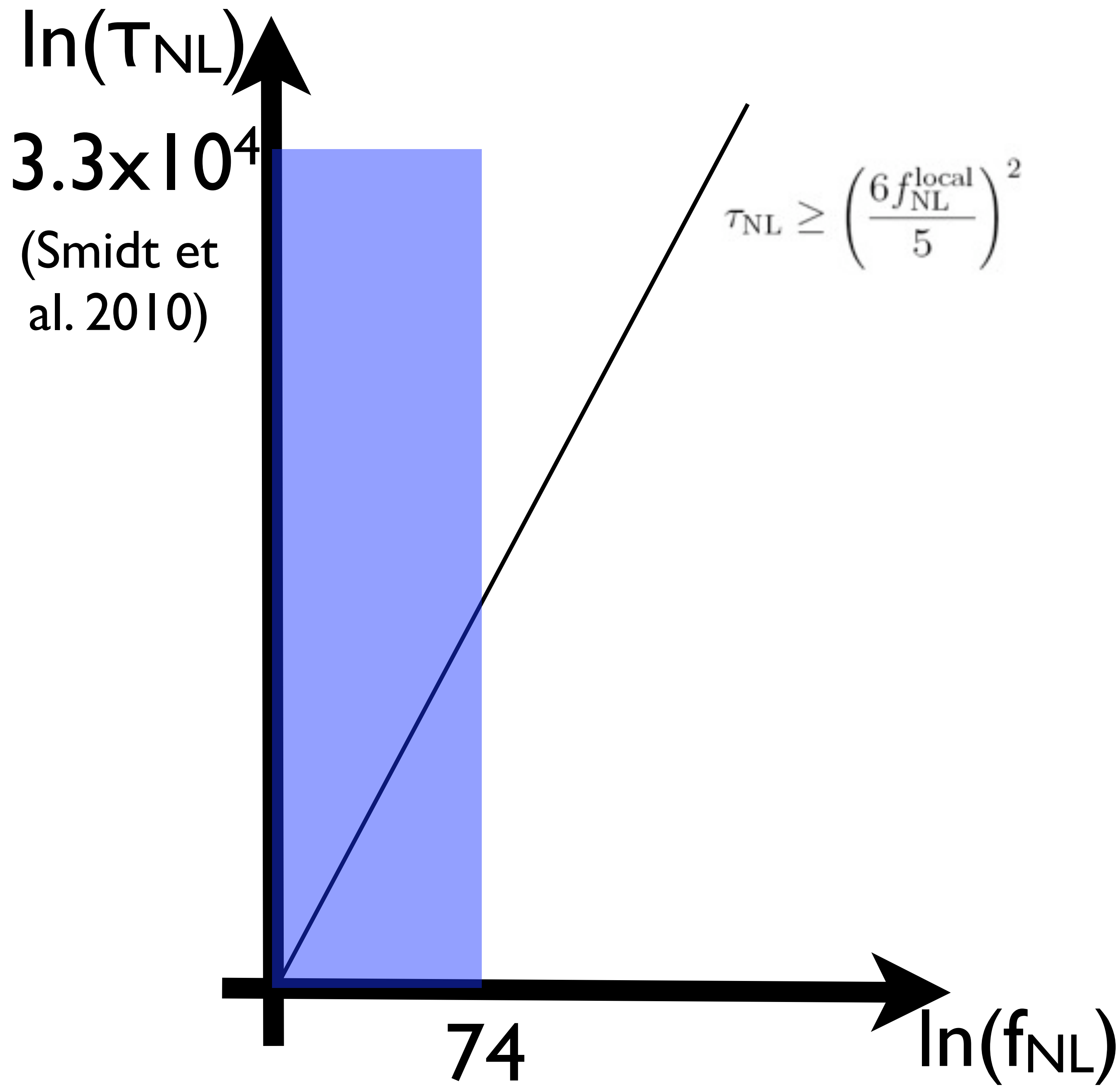
- We just don't want to be thrown into multi-field landscape without any clues...
- What else can we use?
  - Four-point function!

Trispectrum

- $T_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4)=(2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3+\mathbf{k}_4)$ $+\tau_{NL}[P_\zeta(k_1)P_\zeta(k_2)(P_\zeta(|\mathbf{k}_1+\mathbf{k}_3|)+P_\zeta(|\mathbf{k}_1+\mathbf{k}_4|))$ $+\text{cyc.}]$

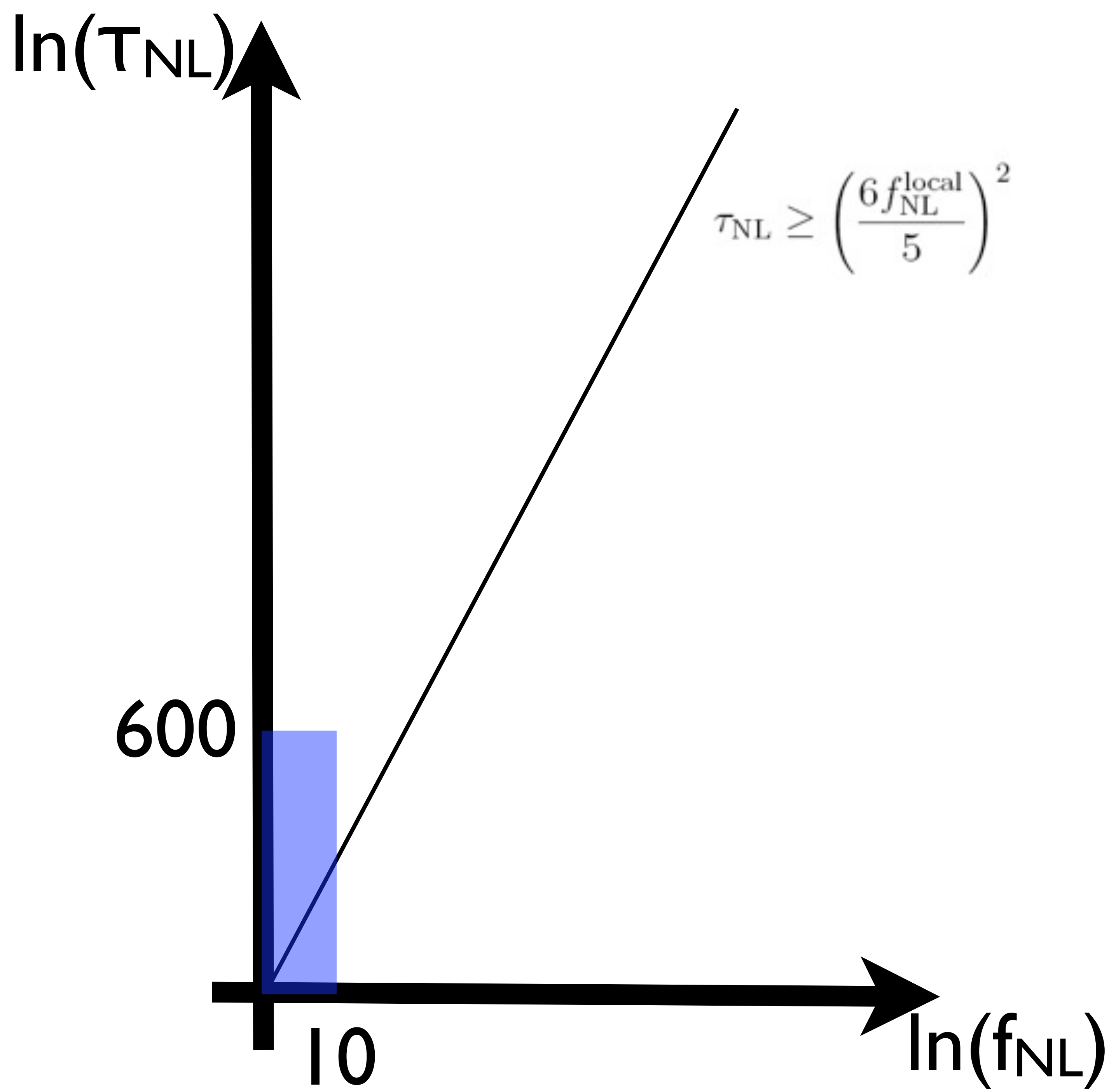


Testing Inflation Paradigm



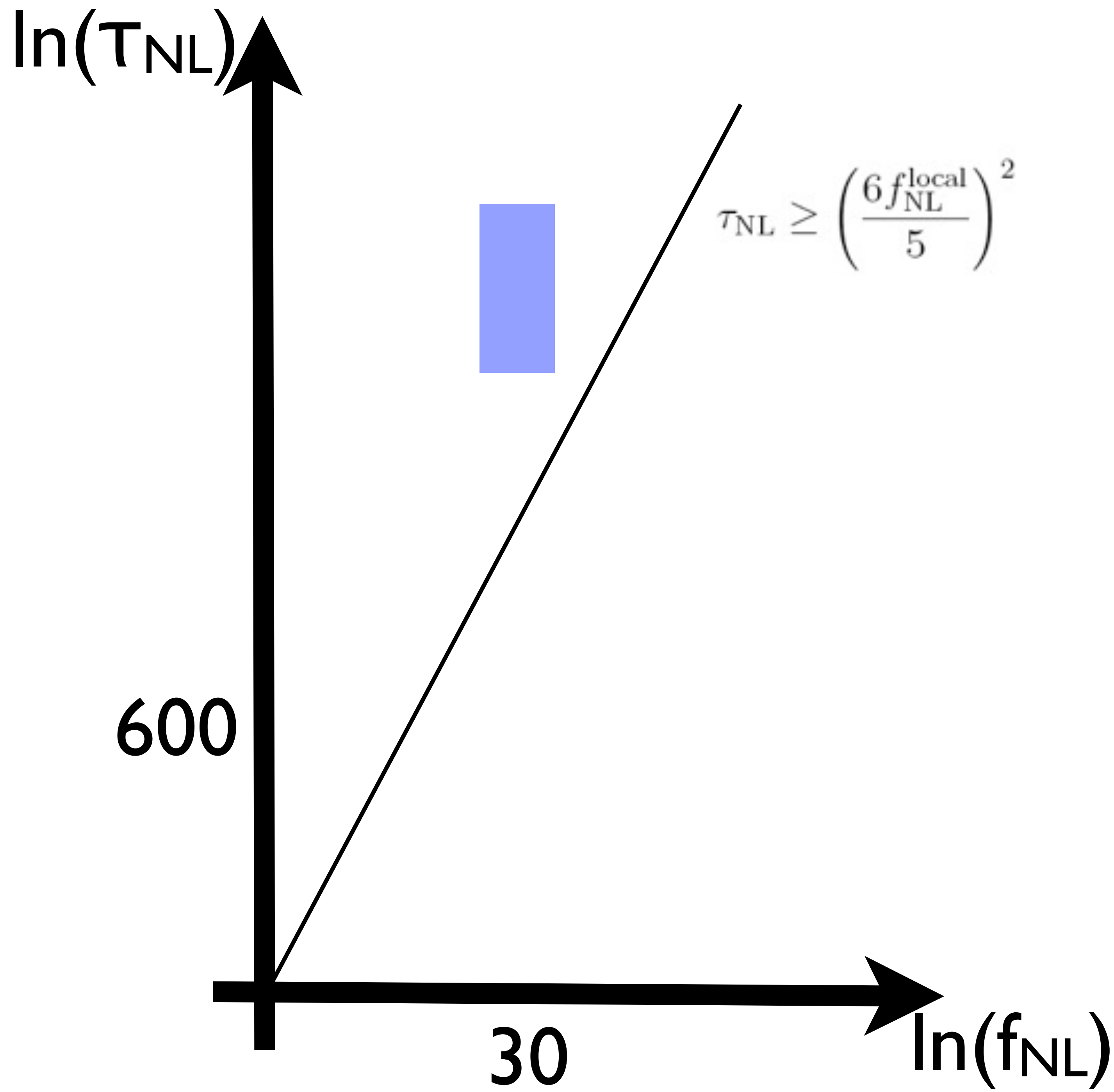
- The current limits from WMAP 7-year are consistent with single-field or multi-field models.
- So, let's play around with the future.

Case A: Single-field Happiness



- No detection of anything after Planck. Single-field survived the test.

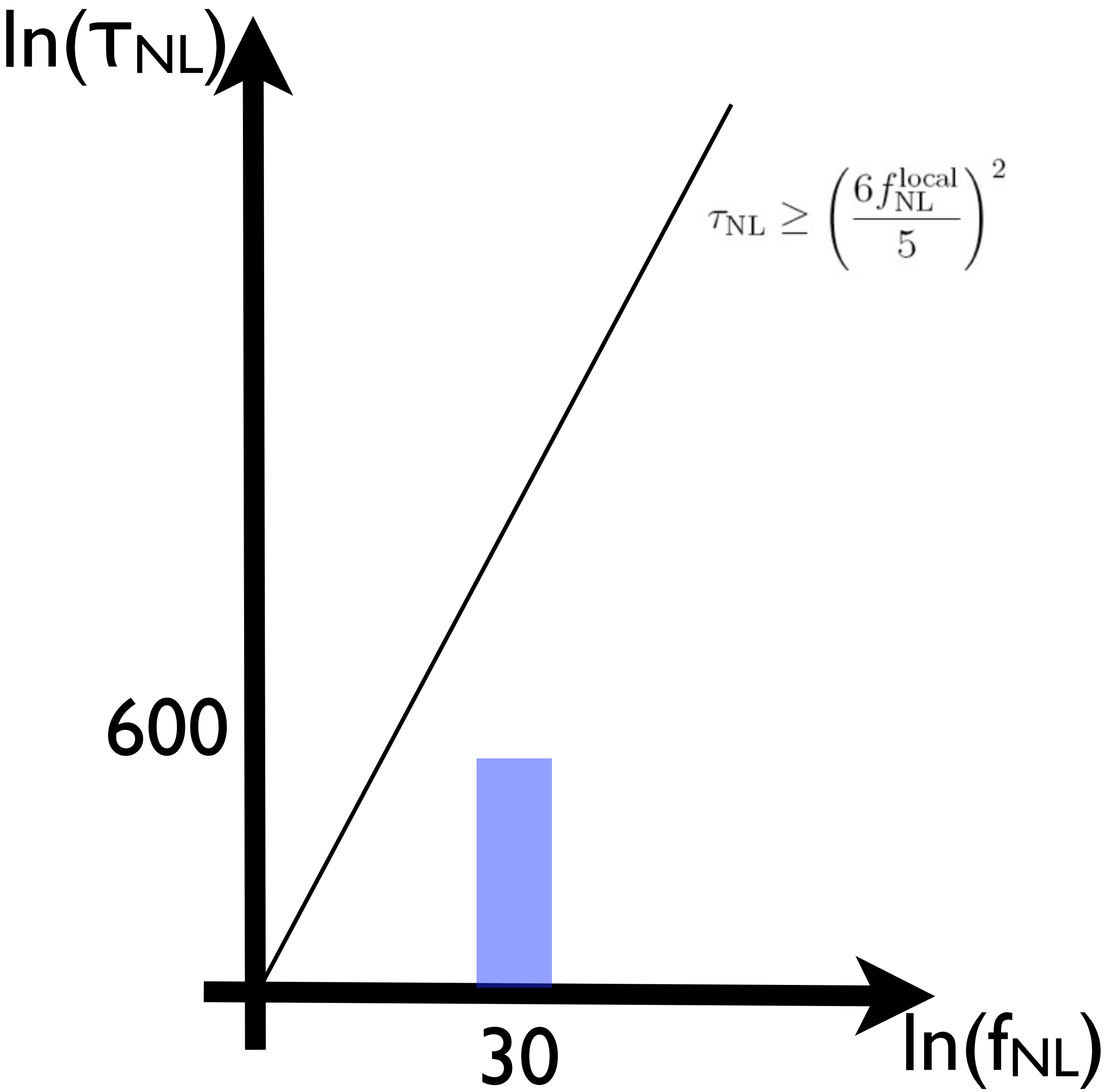
Case B: Multi-field Happiness



- f_{NL} is detected. Single-field is dead.
- But, τ_{NL} is also detected, in accordance with the multi-field inflation relation

$$\tau_{NL} \geq \left(\frac{6 f_{NL}^{local}}{5}\right)^2$$

Case C: Madness



- f_{NL} is detected. Single-field is dead.
- But, τ_{NL} is **not** detected, inconsistent with

$$\tau_{NL} \geq \left(\frac{6 f_{NL}^{local}}{5}\right)^2$$

- BOTH the single-field and multi-field are gone.

What should you expect in the future?

- Please keep your eyes on:
  - **Year 2013**
    - N_{eff}: is it 4? If it is 4, Planck will measure $N_{eff}=4.0\pm0.2$
    - f_{NL}: is it 30? If it is 30, Planck will measure $f_{NL}=30\pm5$. We should then do the 4-point function test.
  - **Year 2014**
  - r: is it as large as 0.1? If it is 0.1, Planck will measure $r=0.1\pm0.05$.