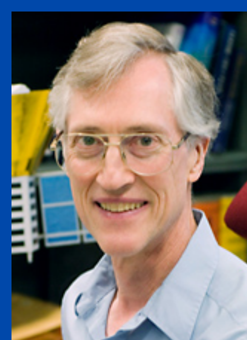
Cosmic Microwave Background

A New & Ultimate Tool for Cosmology and Particle Physics

杉山　直
名古屋大学
IPMU, Unviersity of Tokyo

Cosmic Microwave Background

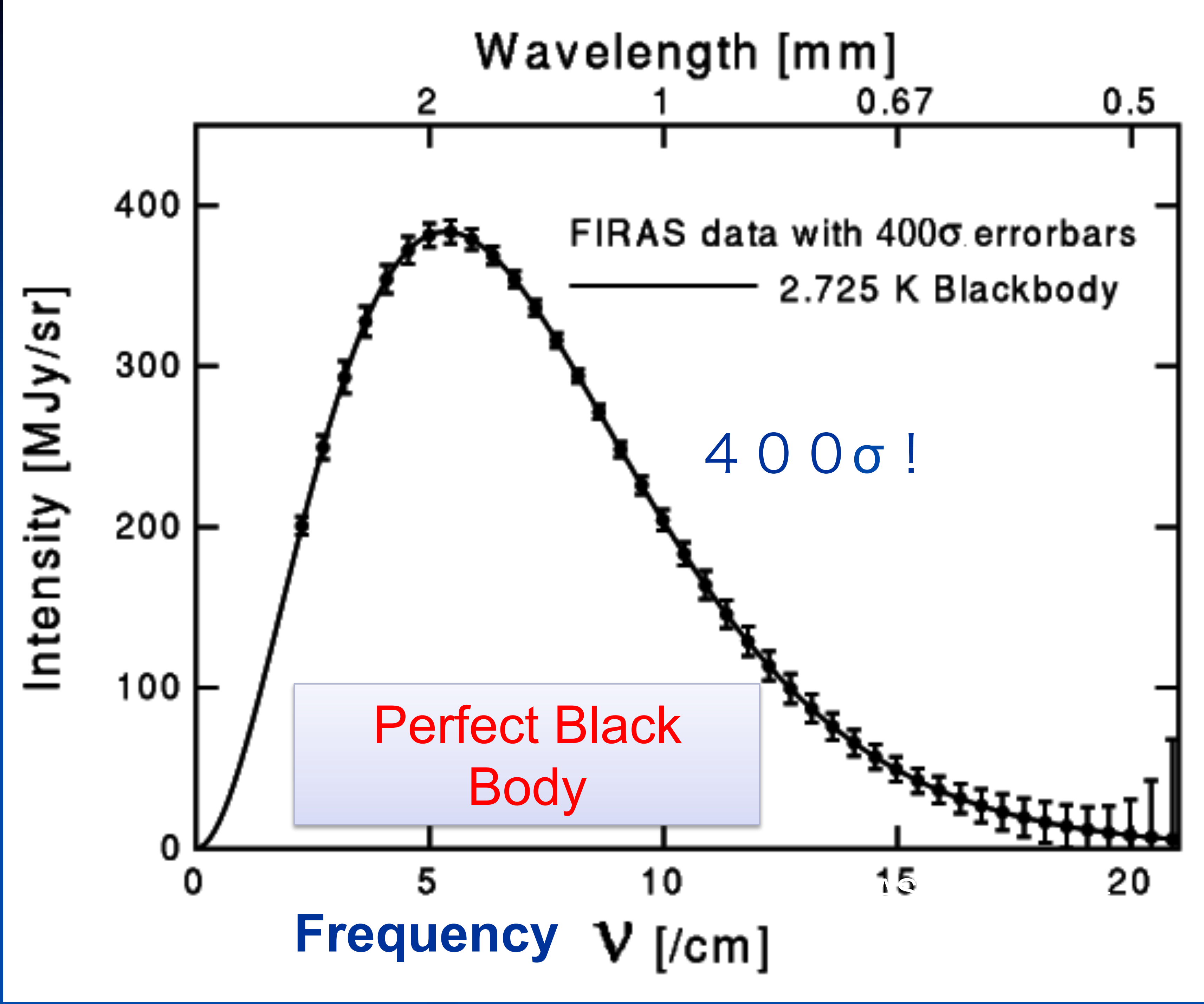
- Direct Evidence of Big Bang
  - Found in 1964 by Penzias & Wilson
  - Very Precise Black Body by COBE (J.Mather)



John Mather

Arno Allan Penzias

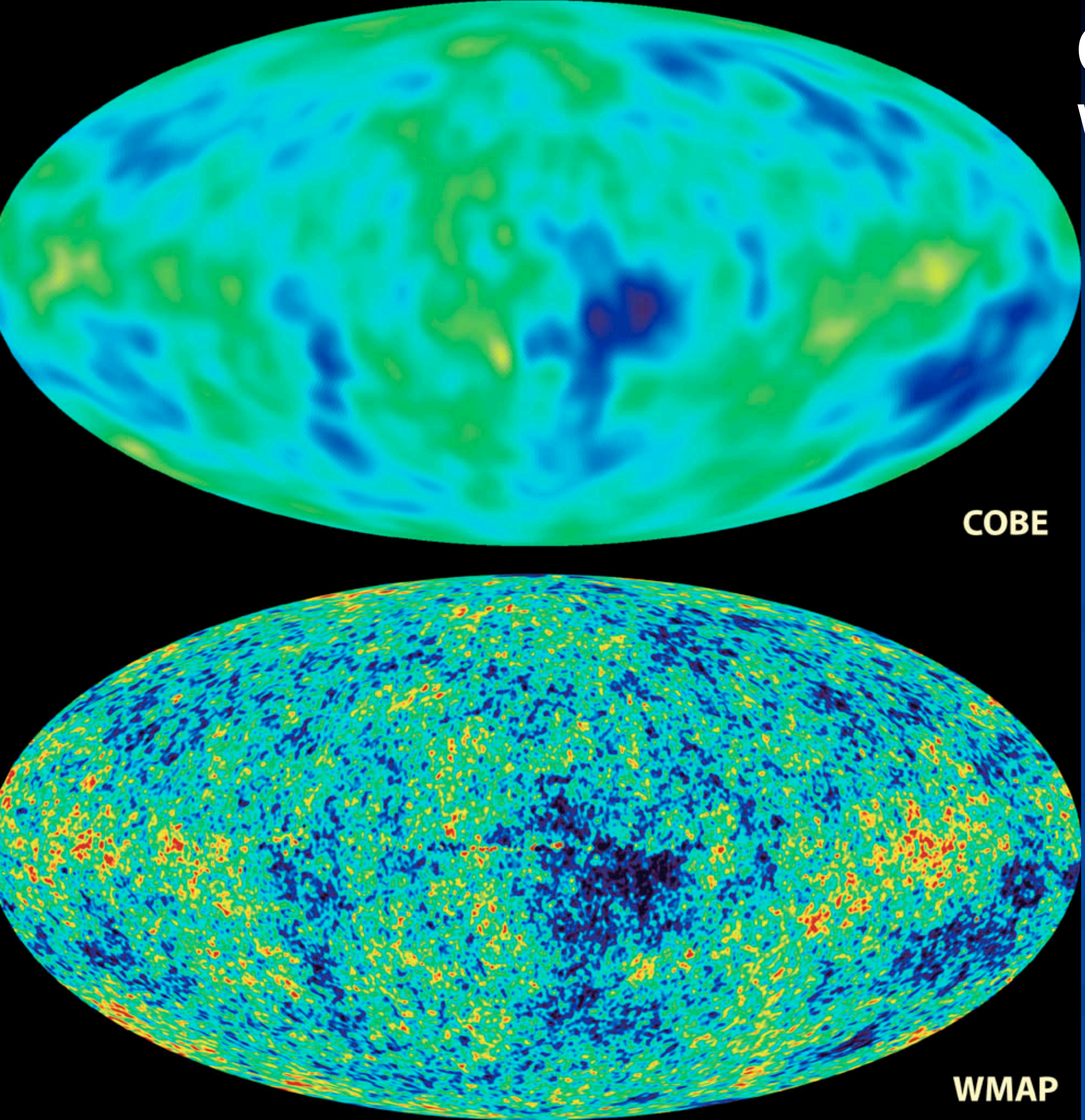
Robert Woodrow Wilson

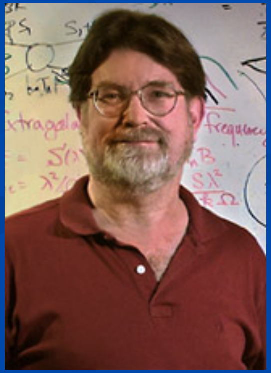

Wavelength [mm]
2
1
0.67
0.5
400
300
200
100
0
FIRAS data with 400σ errorbars
2.725 K Blackbody
4 0 0σ !
Perfect Black Body
Intensity [MJy/sr]
0
5
10
15
20
Frequency ν [/cm]

Temperature Fluctuations of Cosmic Microwave Background

- Found by COBE/DMR (G.Smoot), measured in detail by WMAP
- Structure at 380,000 yrs (z=1100)
  - Recombination epoch of Hydrogen atoms
- Missing Link between Inflation (10^{-36}s) and Present (13.7 Billion yrs)
- Ideal Probe of Cosmological Parameters
  - Typical Sizes of Fluctuation Patters are Theoretically Known as Functions of Various Cosmological Parameters

COBE & WMAP



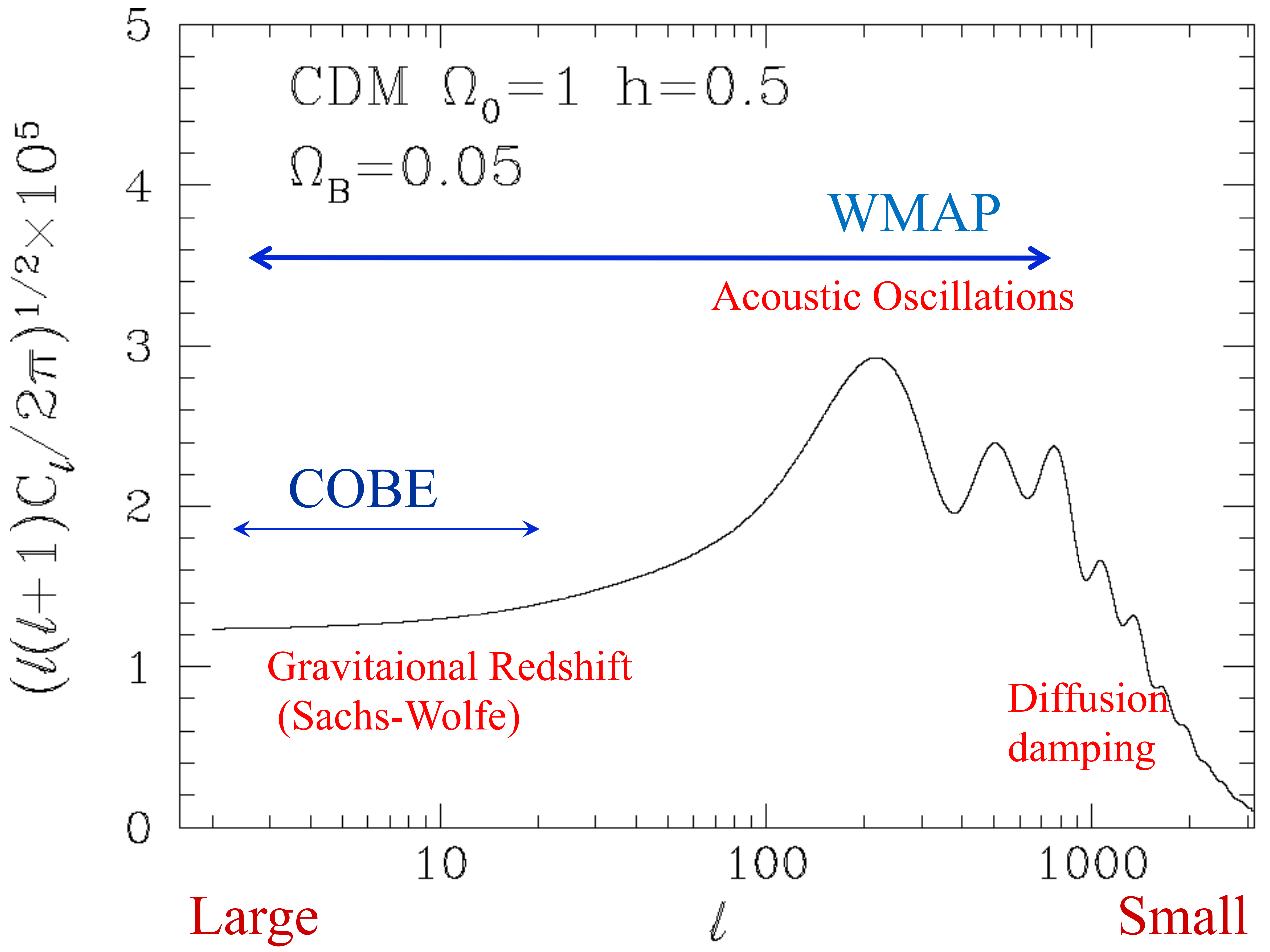


George Smoot

Physical Processes to Induce CMB Fluctuations

- Originated from Quantum Fluctuations at the Inflation Epoch
  - Almost Scale Free (Invariant Spectrum):
- Dominated by Gravitational Redshift (Sachs-Wolfe effect) on Large Scales
- Acoustic Oscillations Play an Important Role on Intermediate Scales
- Diffusion Damping works on Small Scales

Statistical Quantity: Angular Power Spectrum C_l



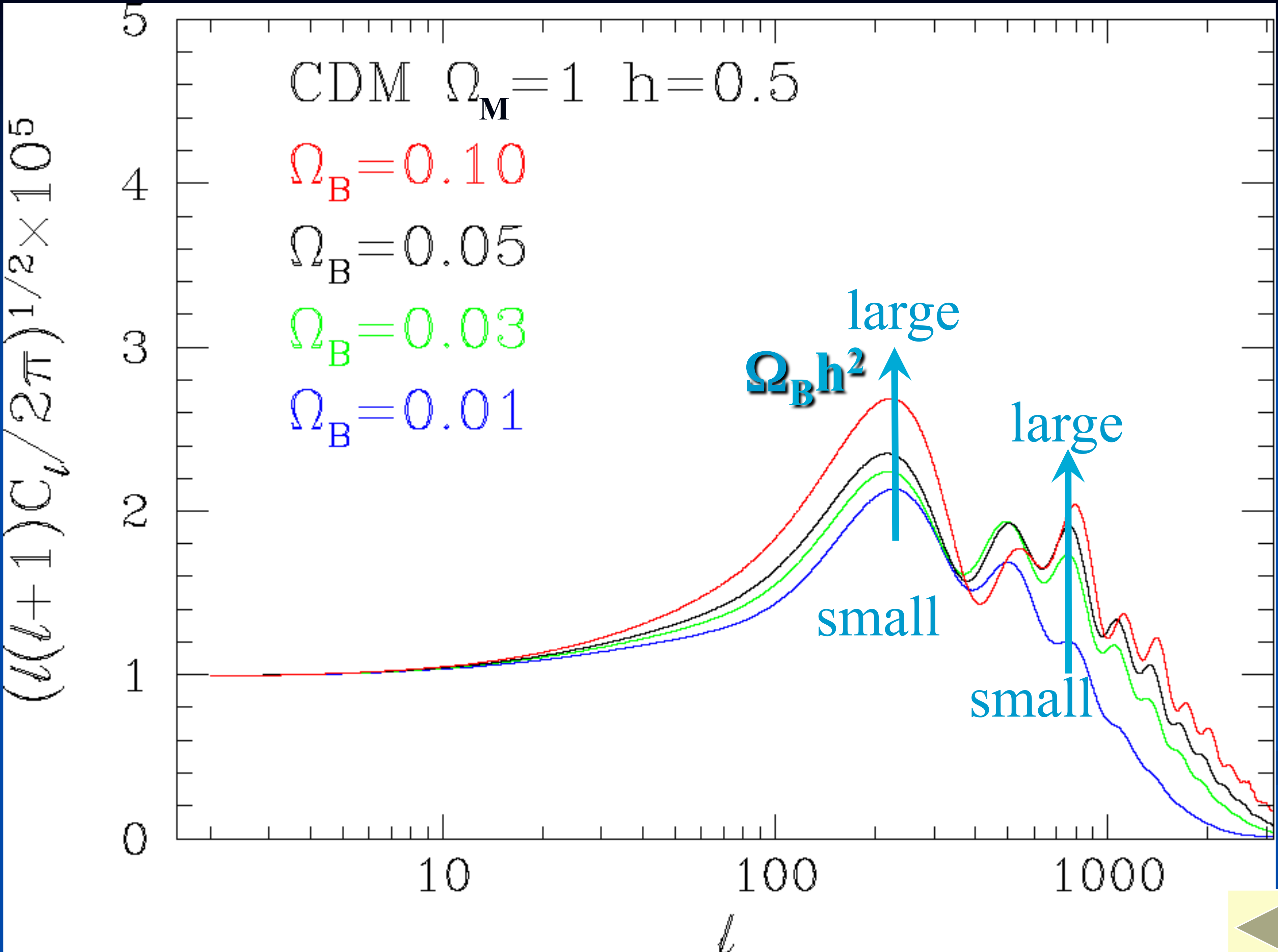
CDM Ω_0=1 h=0.5
Ω_B=0.05
WMAP
Acoustic Oscillations
COBE
Gravitaional Redshift
(Sachs-Wolfe)
Diffusion
damping
$(\ell(\ell+1)C_\ell/2\pi)^{1/2}\times10^5$
0
1
2
3
4
5
10
100
1000
ℓ
Large
Small

What control CMB Anisotropies

- Sound Velocity at Recombination
  - Baryon Density: $\Omega_B h^2$
- Horizon Size at Recombination
  - Matter Density: $\Omega_M h^2$
- Radiative Transfer between Recombination and Present
  - Space Curvature: Ω_K
- Initial Condition of Fluctuations
  - If Power law, its index n ($P(k) \propto k^n$)

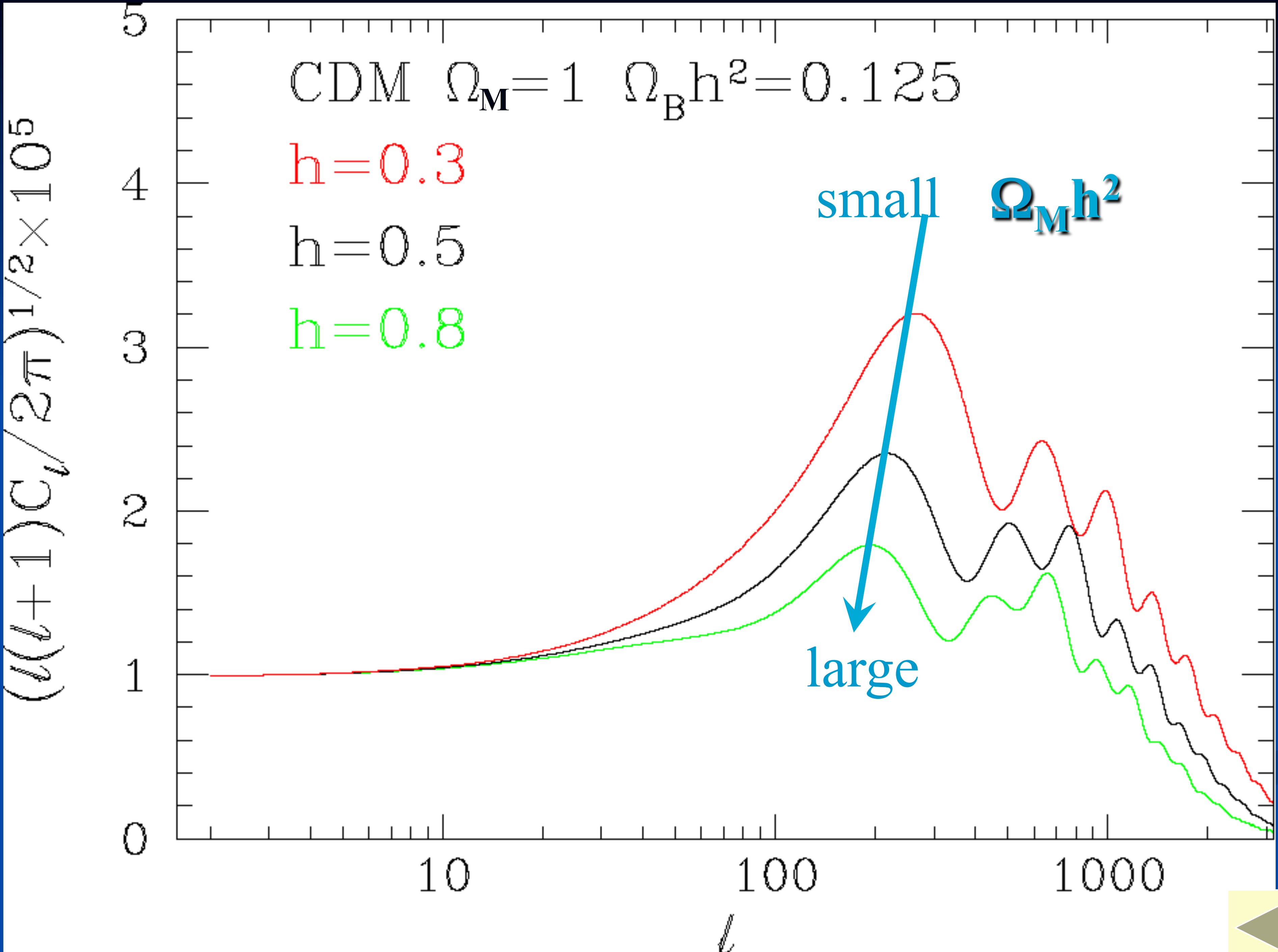
What control CMB Anisotropies

- Sound Velocity at Recombination
  - Baryon Density: $\Omega_B h^2$
- Horizon Size at Recombination
  - Matter Density: $\Omega_M h^2$
- Radiative Transfer between Recombination and Present
  - Space Curvature: Ω_K
- Initial Condition of Fluctuations
  - If Power law, its index n ($P(k) \propto k^n$)

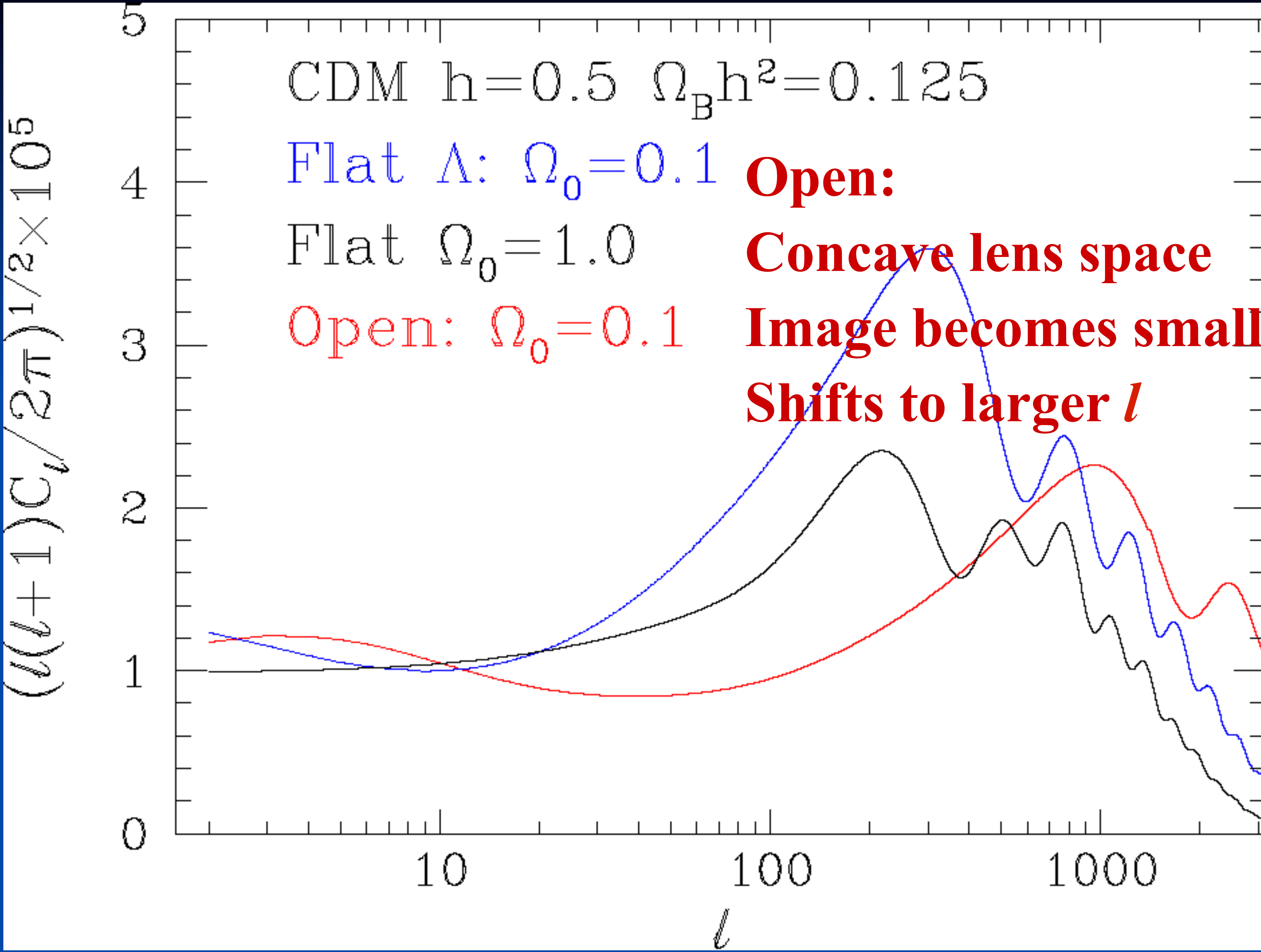

CDM Ω_M=1 h=0.5
Ω_B=0.10
Ω_B=0.05
Ω_B=0.03
Ω_B=0.01
large
Ω_Bh²
small
large
small
((ℓ(ℓ+1)C_ℓ/2π)^1/2×10^5
0
1
2
3
4
5
10
100
1000
ℓ

What control CMB Anisotropies

- Sound Velocity at Recombination
  - Baryon Density: $\Omega_B h^2$
- Horizon Size at Recombination
  - Matter Density: $\Omega_M h^2$
- Radiative Transfer between Recombination and Present
  - Space Curvature: Ω_K
- Initial Condition of Fluctuations
  - If Power law, its index n ($P(k) \propto k^n$)



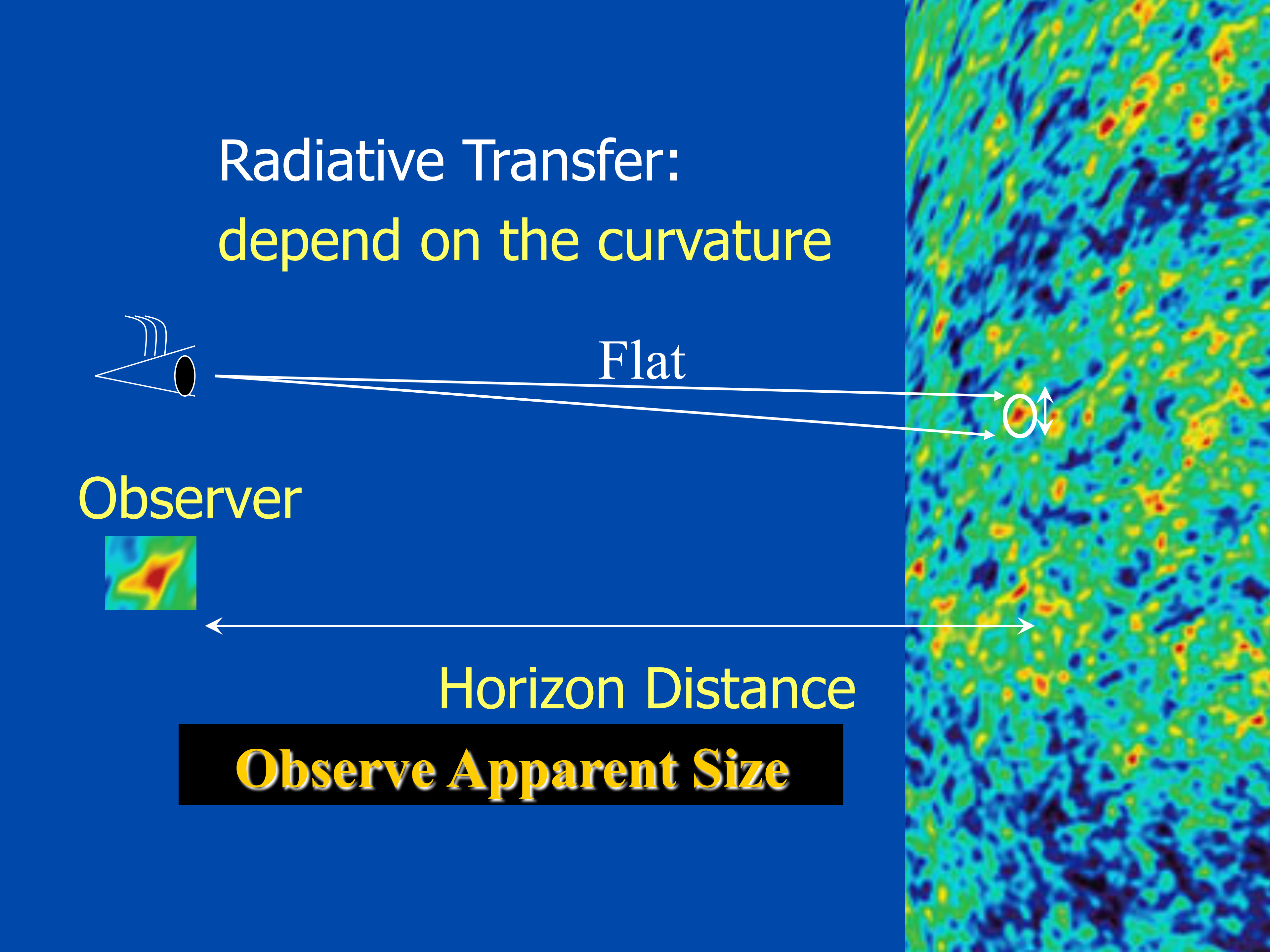
CDM $\Omega_M=1$ $\Omega_B h^2=0.125$
h=0.3
h=0.5
h=0.8
small
$\Omega_M h^2$
large
$(\ell(\ell+1)C_\ell/2\pi)^{1/2}\times10^5$
0
1
2
3
4
5
10
100
1000
ℓ



CDM h=0.5 $\Omega_B h^2$=0.125
Flat Λ: Ω_0=0.1
Flat Ω_0=1.0
Open: Ω_0=0.1
Open:
Concave lens space
Image becomes small
Shifts to larger *l*
$(\ell(\ell+1)C_\ell/2\pi)^{1/2}\times10^5$
ℓ
0
1
2
3
4
5
10
100
1000

What control CMB Anisotropies

- Sound Velocity at Recombination
  - Baryon Density: $\Omega_B h^2$
- Horizon Size at Recombination
  - Matter Density: $\Omega_M h^2$
- Radiative Transfer between Recombination and Present
  - Space Curvature: Ω_K
- Initial Condition of Fluctuations
  - If Power law, its index n ($P(k) \propto k^n$)



Radiative Transfer:
depend on the curvature
Flat
Observer
Horizon Distance
Observe Apparent Size

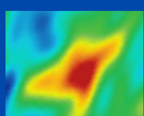
Space Curvature=Lens

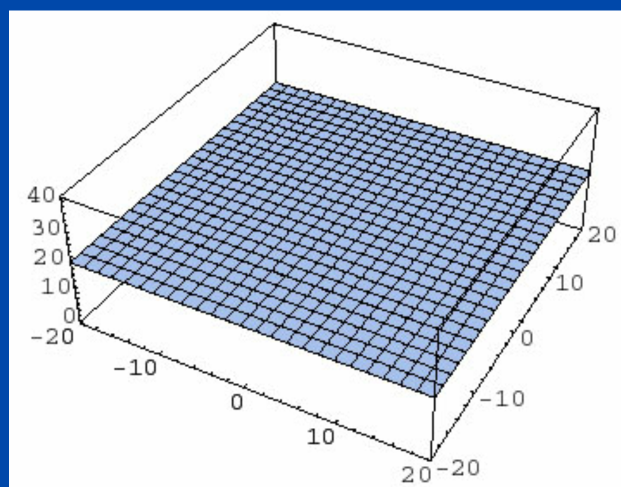
Radiative Transfer:

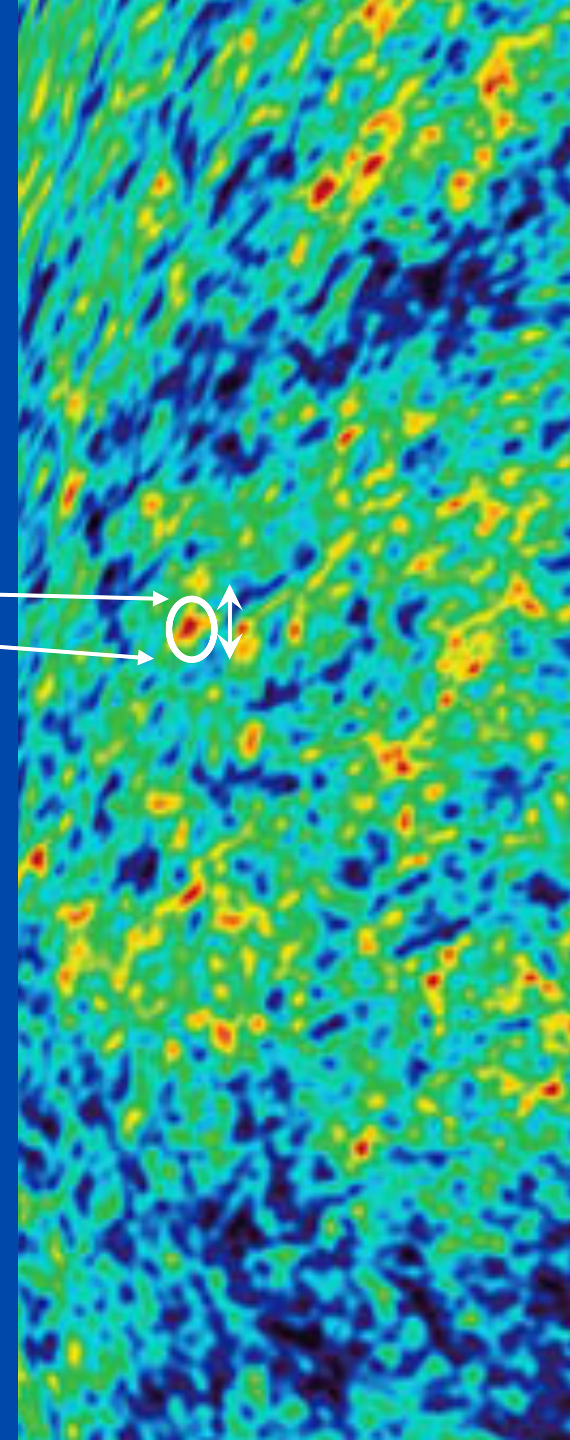
depend on the curvature

Flat, 0 Curvature

Observer





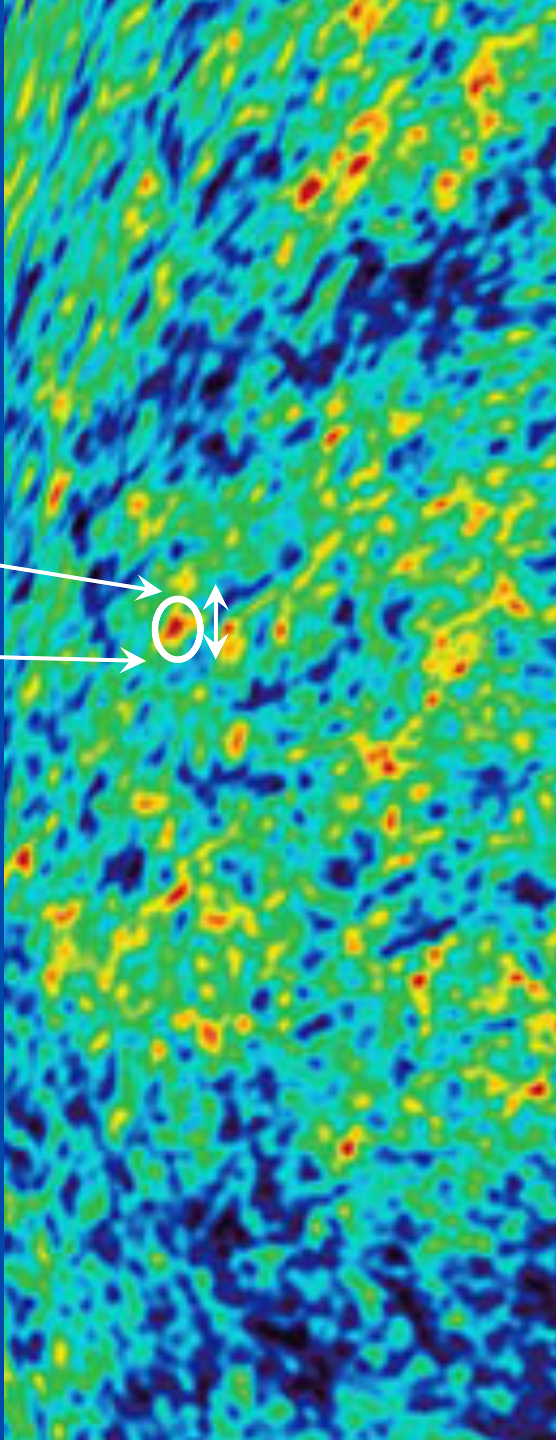


Space Curvature=Lens

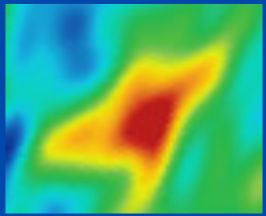
Radiative Transfer:

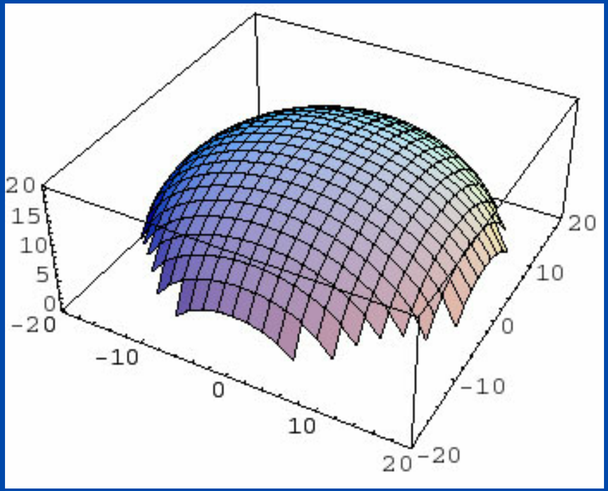
depend on the curvature

Positive Curvature



Observer





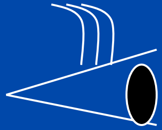
Magnify!

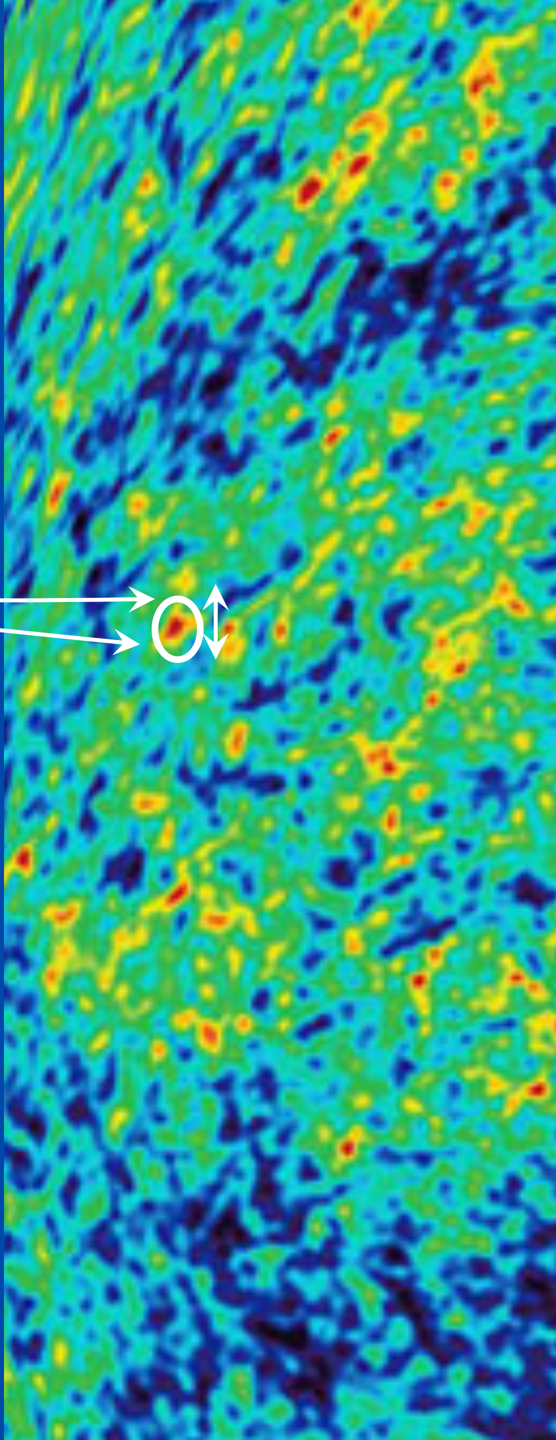
Space Curvature=Lens

Radiative Transfer:

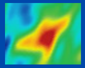
depend on the curvature

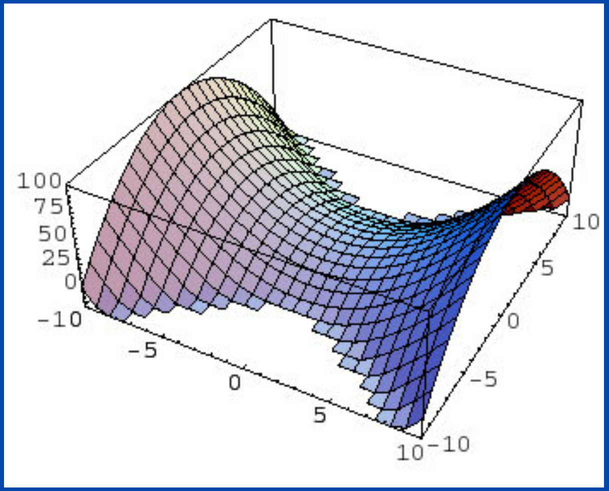
Negative Curvature



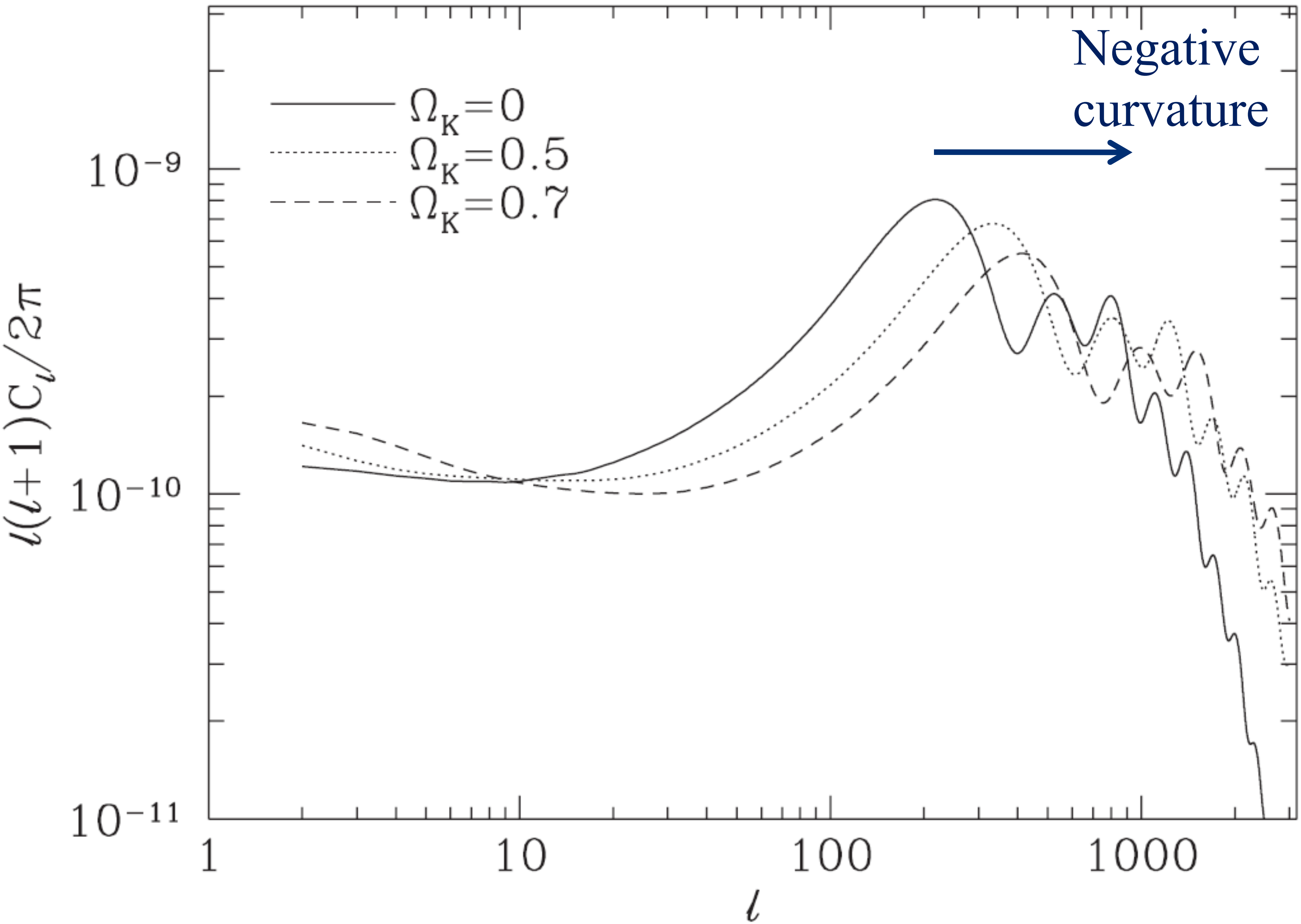


Observer

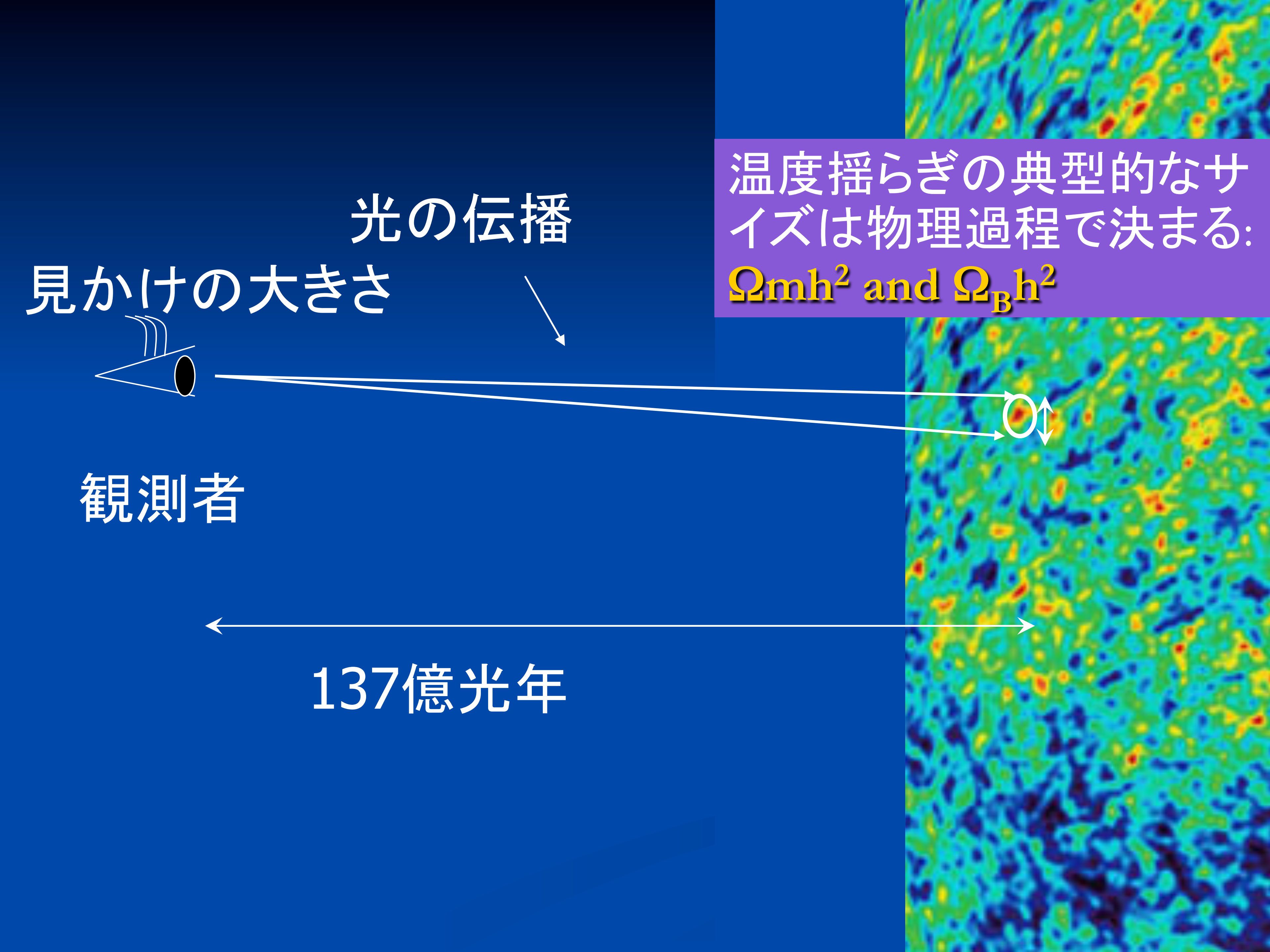


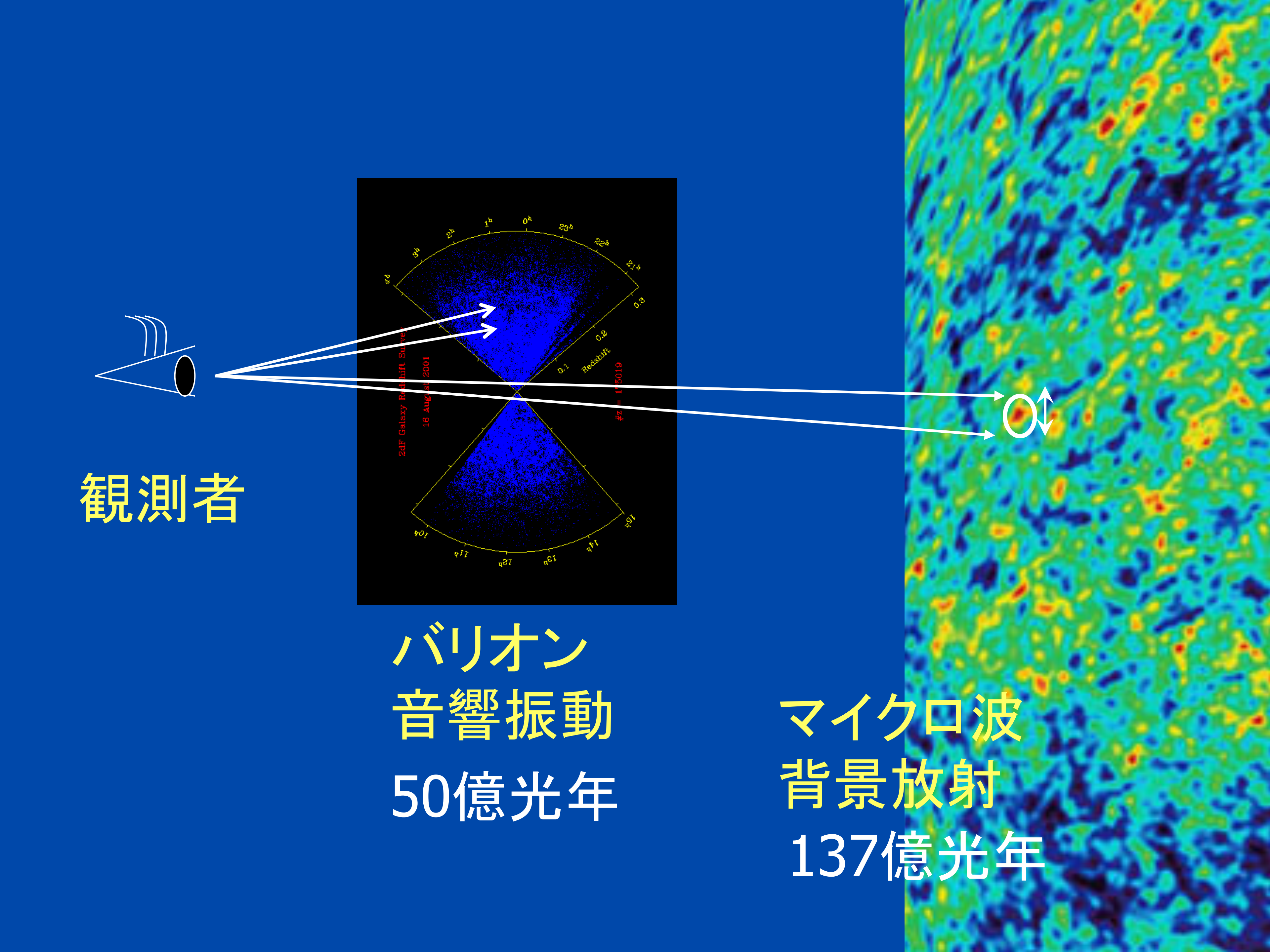


Shrink!



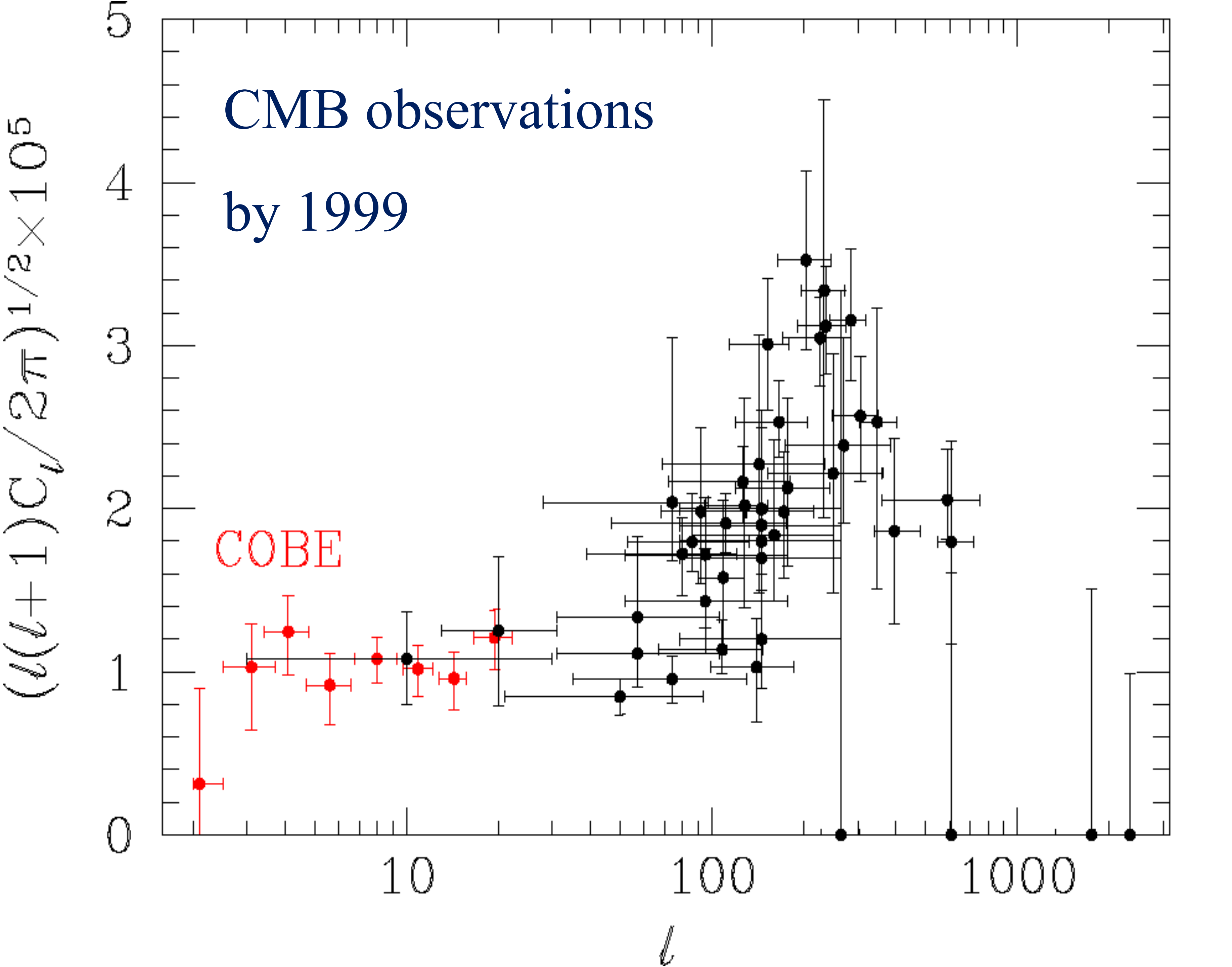
Negative
curvature
$\Omega_K = 0$
$\Omega_K = 0.5$
$\Omega_K = 0.7$
10^{-9}
10^{-10}
10^{-11}
1
10
100
1000
l
$l(l+1)C_l/2\pi$


温度揺らぎの典型的なサイズは物理過程で決まる:
Ωmh² and Ω_B h²
光の伝播
見かけの大きさ
観測者
137億光年

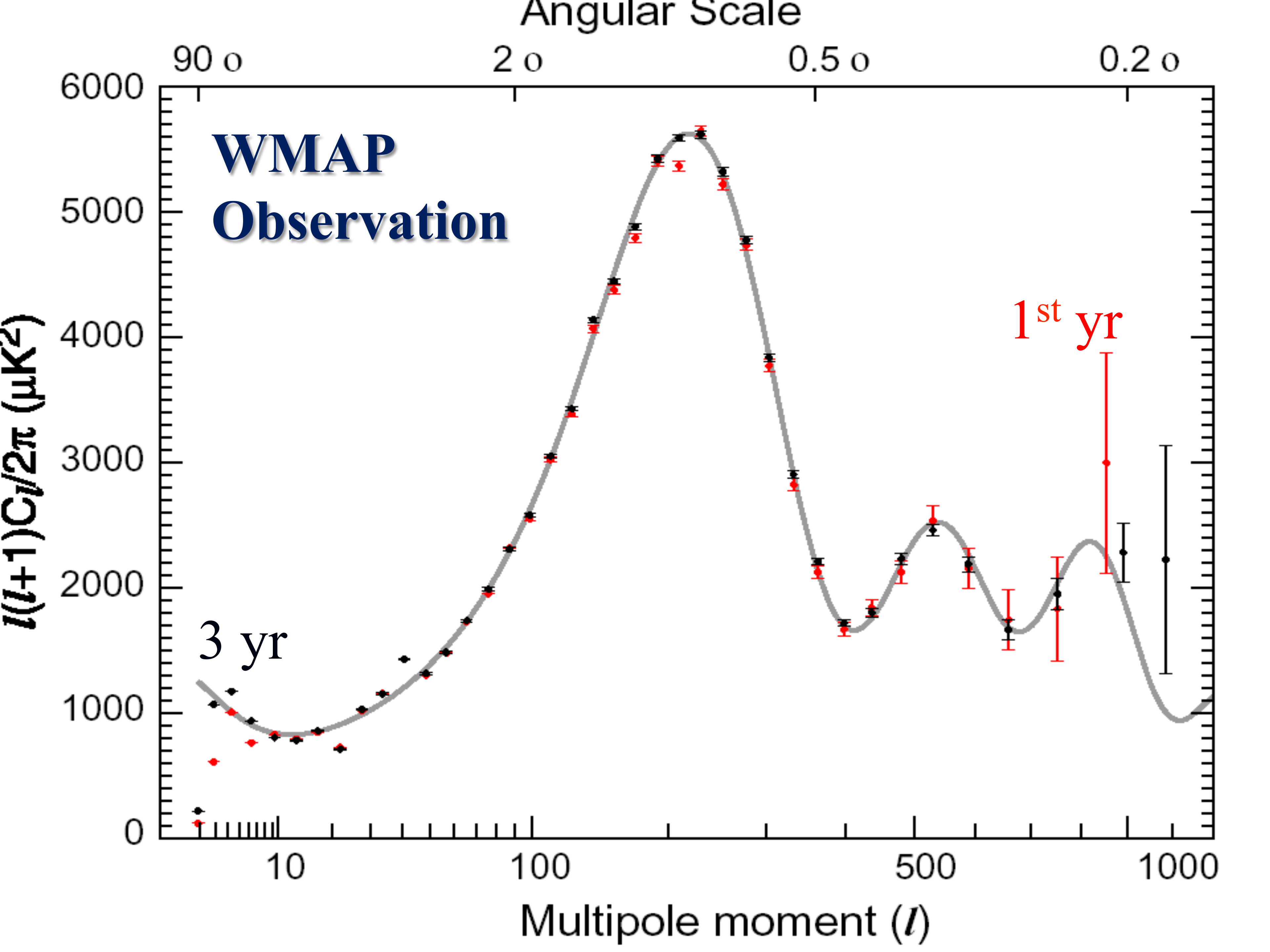

観測者
バリオン
音響振動
50億光年
マイクロ波
背景放射
137億光年

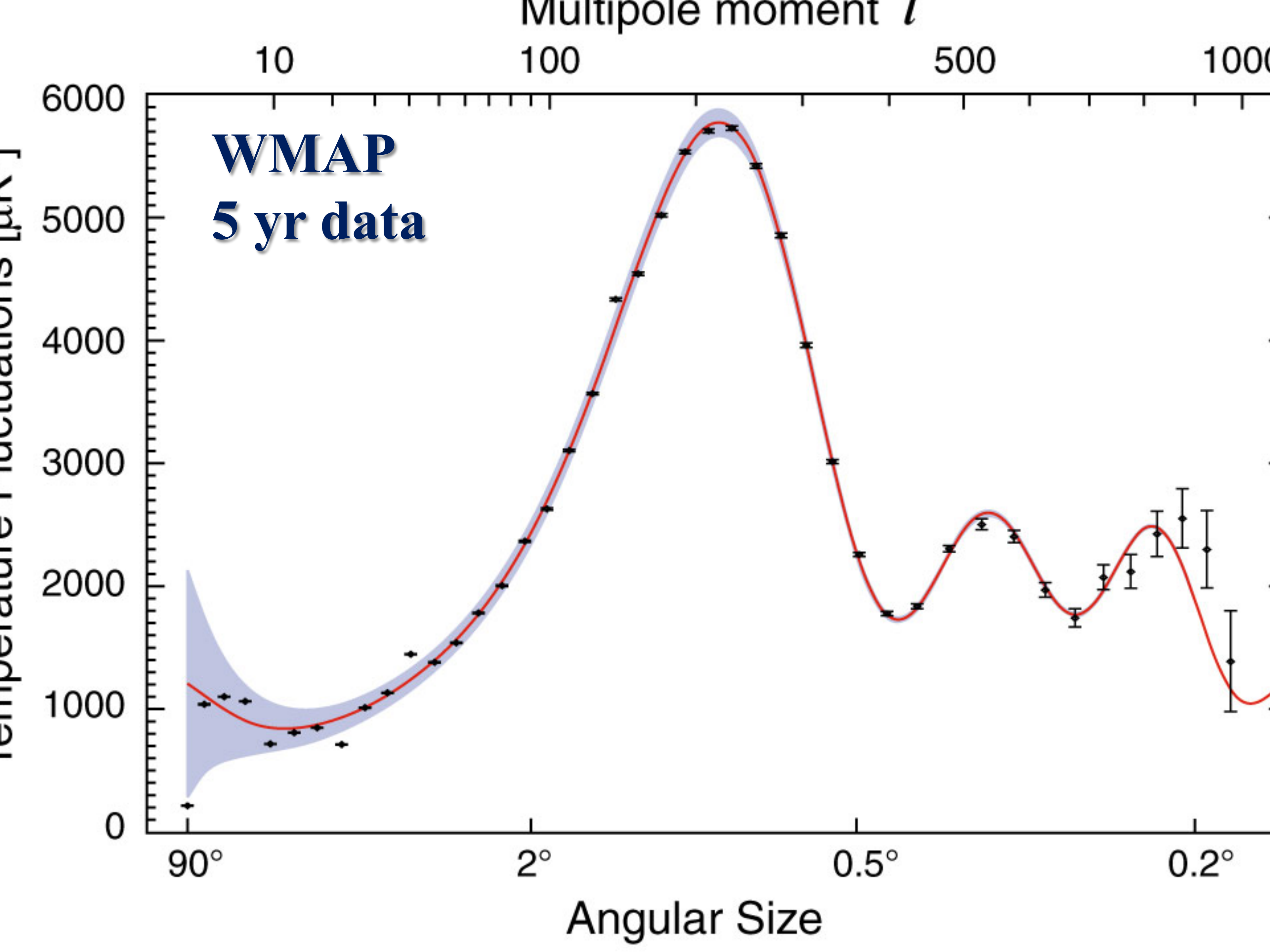
Observations

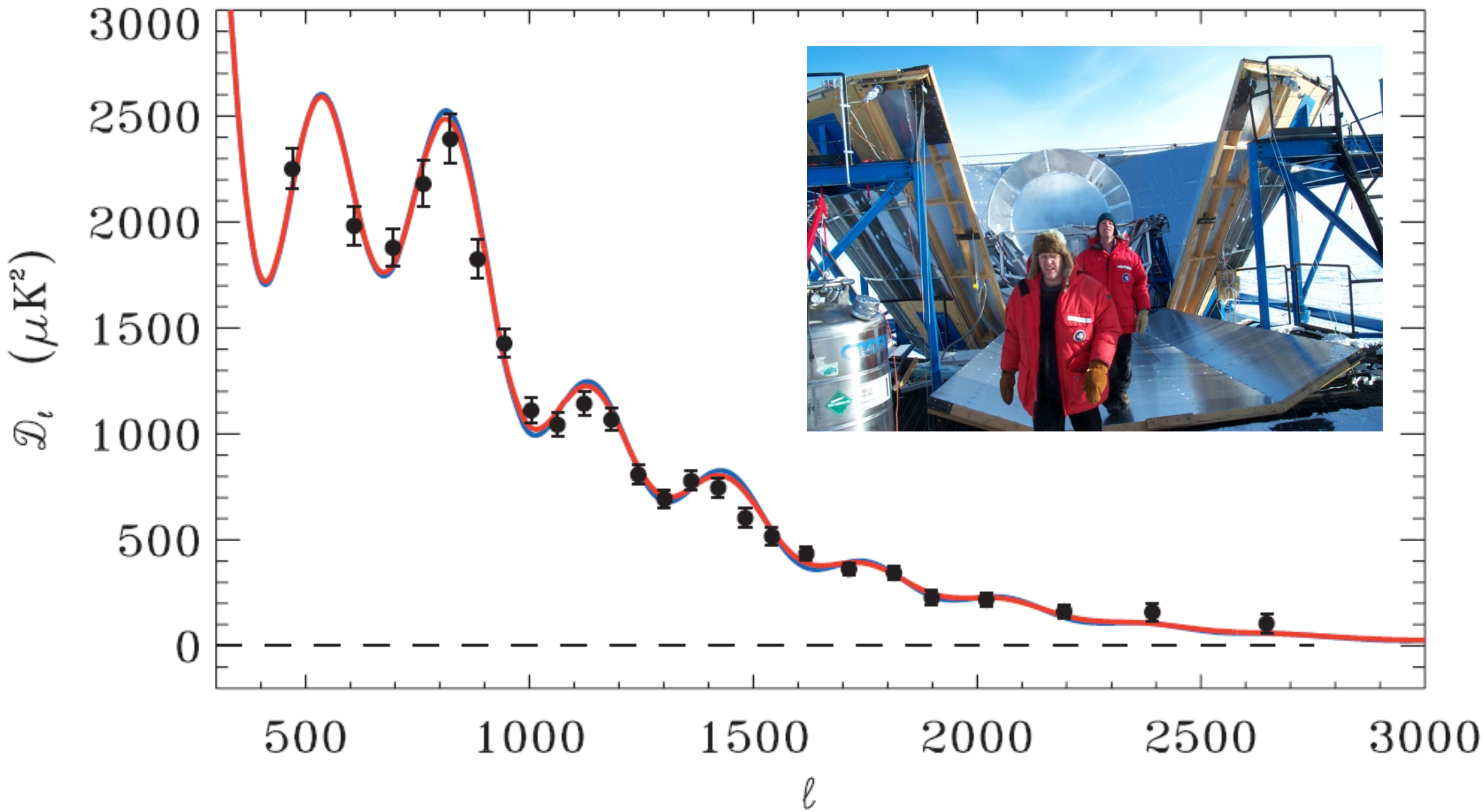
- COBE
  - Clearly see large scale (low *l*) tail
  - angular resolution was too bad to resolve peaks
- Balloon borne/Grand Base experiments
  - Boomerang, MAXMA, CBI, Saskatoon, Python, OVRO, etc
  - See some evidence of the first peak, even in Last Century!
- WMAP
  - Precise measurement of Acoustic Osccilations
  - See up to 3^{rd} Peaks
- ACBAR
  - See Silk damping tails



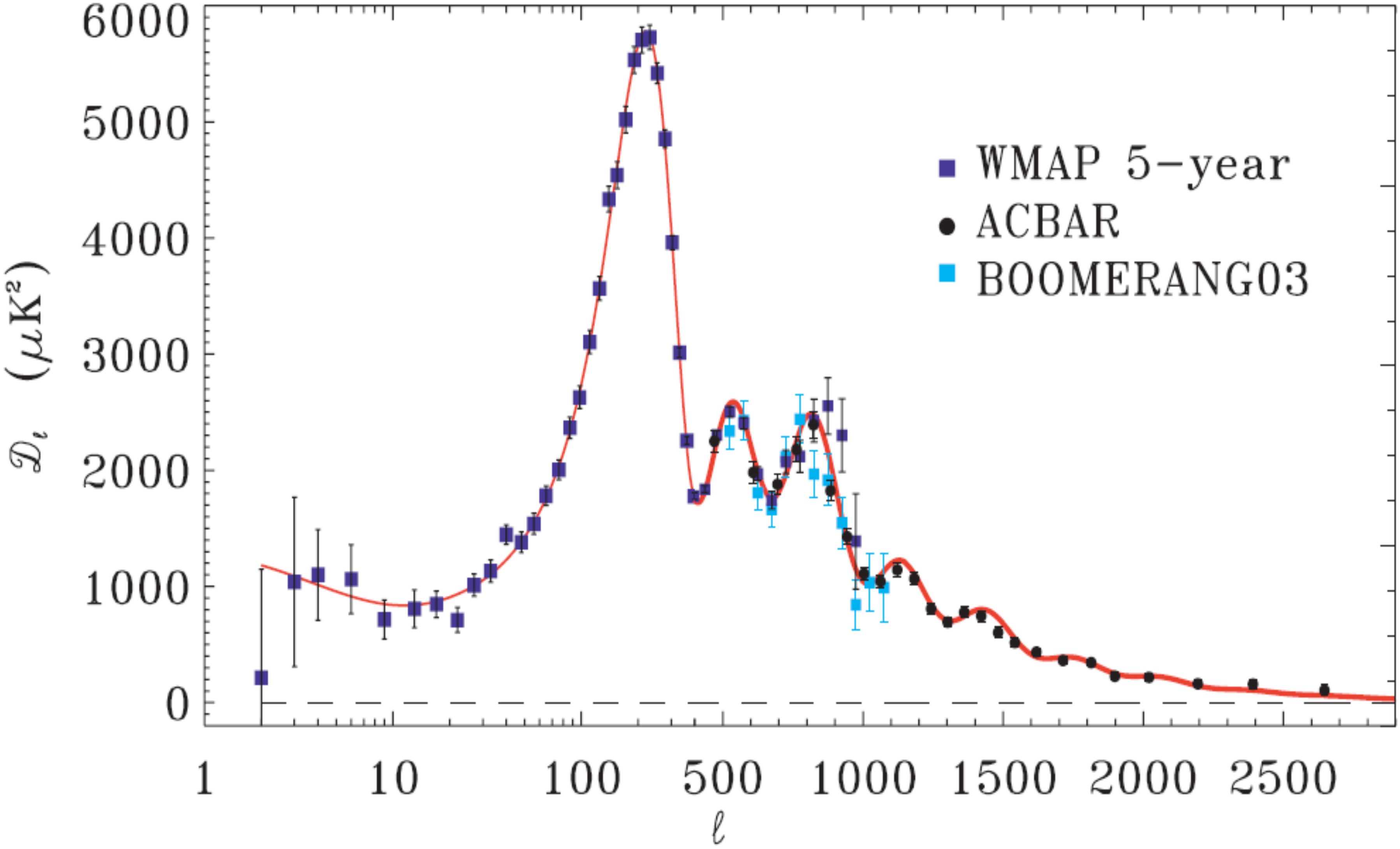
CMB observations
by 1999
COBE
$(\ell(\ell+1)C_\ell/2\pi)^{1/2}\times10^5$
0
1
2
3
4
5
10
100
1000
ℓ


Angular Scale
90 o
2 o
0.5 o
0.2 o
WMAP
Observation
1st yr
3 yr
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
l(l+1)Cl/2π (μK2)
Multipole moment (l)

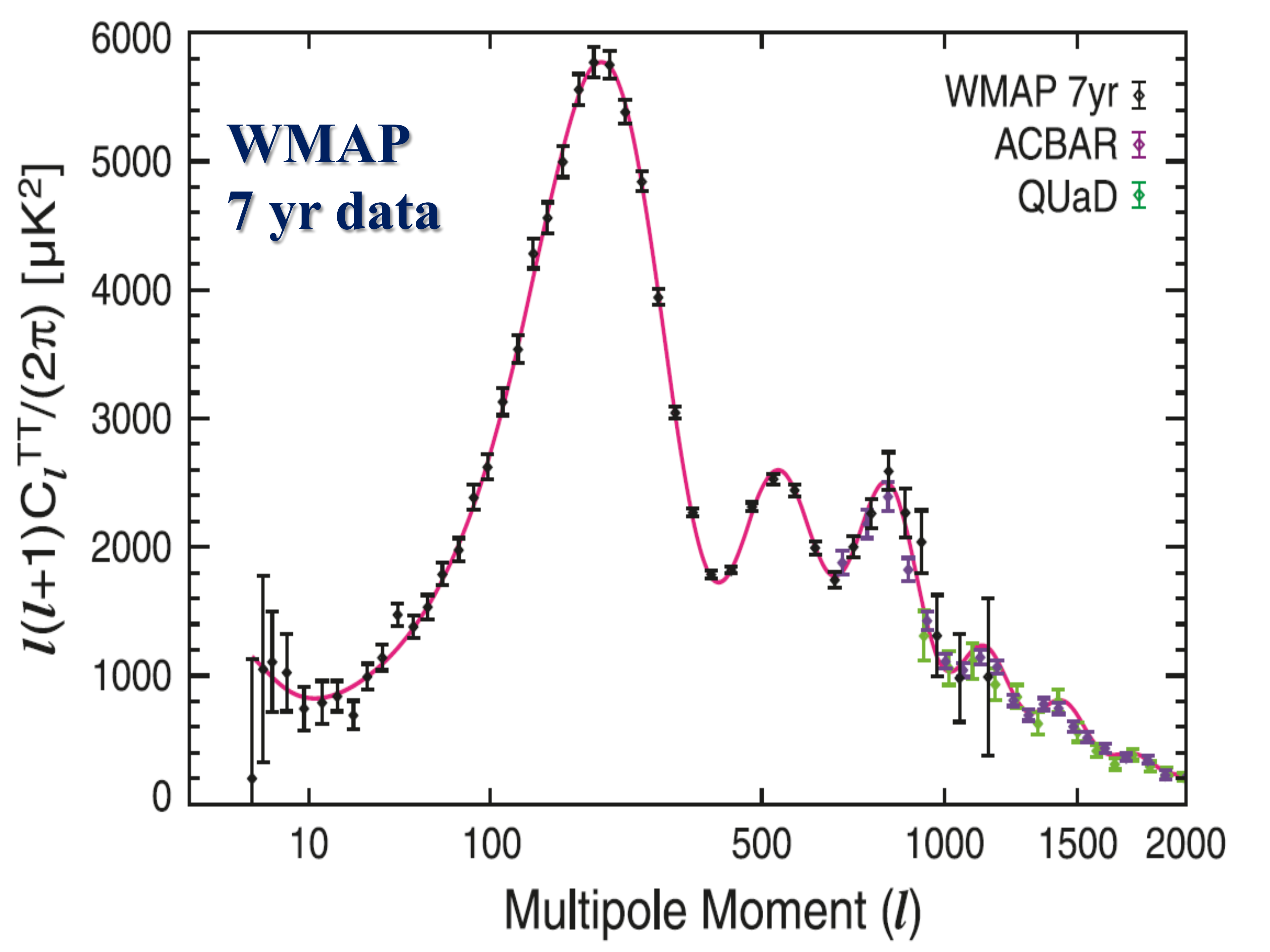

Multipole moment l
10
100
500
1000
6000
5000
4000
3000
2000
1000
0
WMAP
5 yr data
90°
2°
0.5°
0.2°
Angular Size

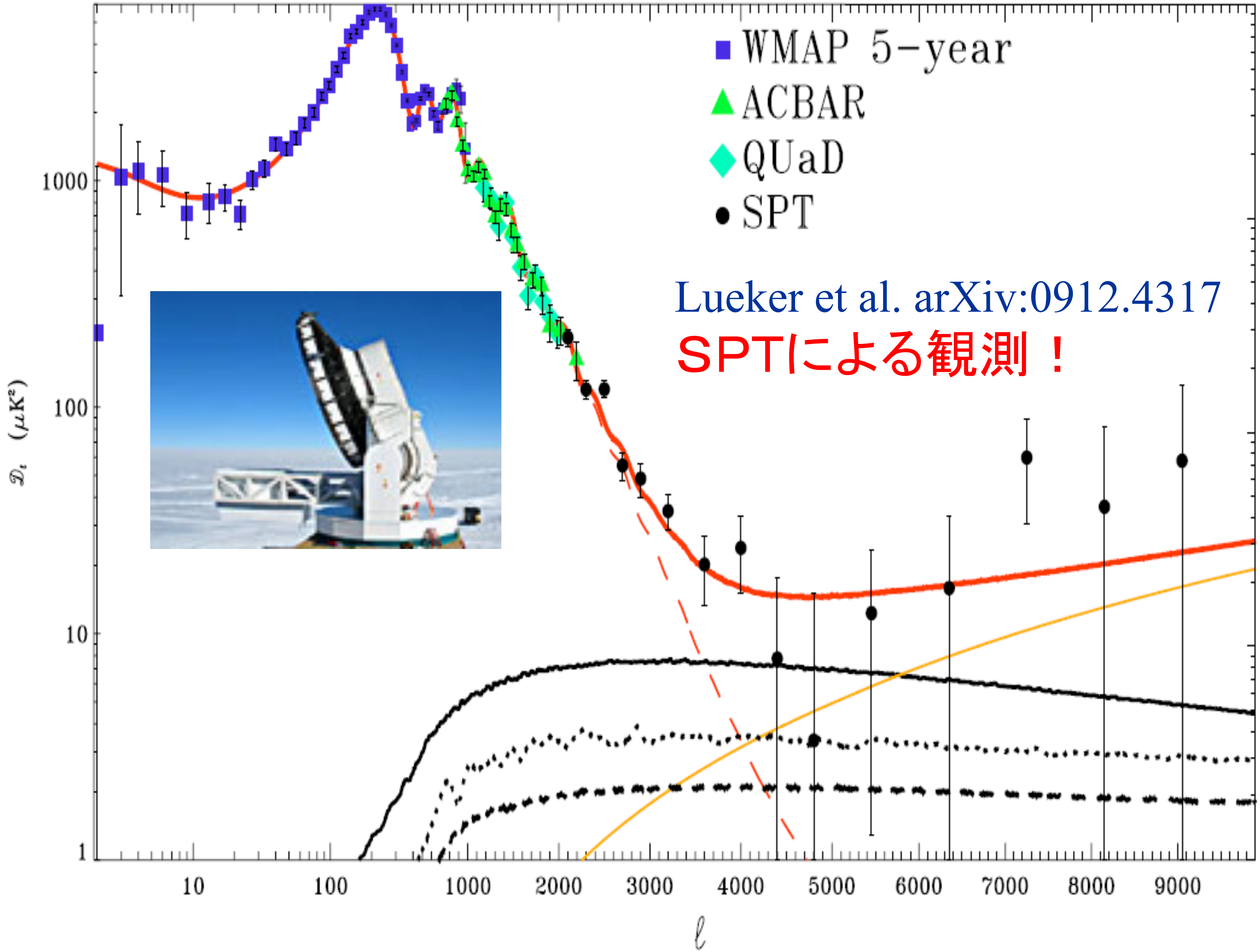


ACBAR: Reichardt et al. 2008



ACBAR: Reichardt et al. 2008


WMAP
7 yr data
WMAP 7yr
ACBAR
QUaD
$l(l+1)C_l^{TT}/(2\pi)$ [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
2000
Multipole Moment (l)



WMAP 5-year
ACBAR
QUaD
SPT
Lueker et al. arXiv:0912.4317
SPTによる観測！
$\mathcal{D}_\ell$ (μK²)
1000
100
10
1
10
100
1000
2000
3000
4000
5000
6000
7000
8000
9000
ℓ

WMAP Temperature Power Spectrum

- Clear existence of large scale Plateau
- Clear existence of Acoustic Peaks
  - 3rd Peak has been clearly seen in 7 yr data

Consistent with

Inflation and Cold Dark Matter Paradigm

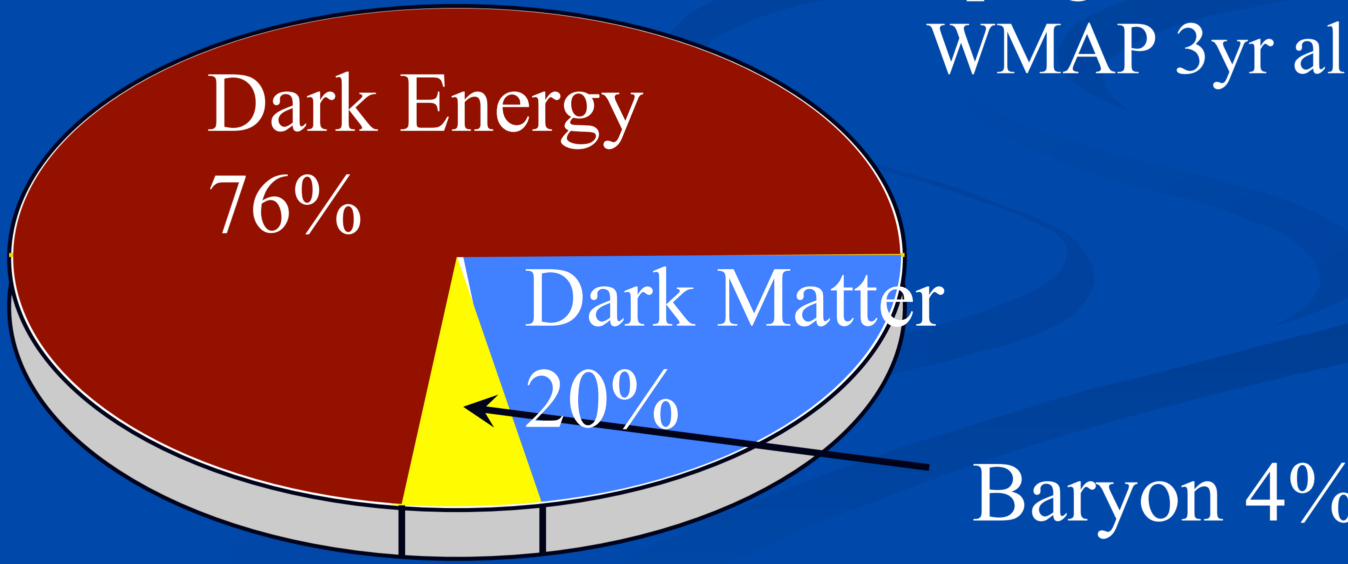
One Puzzle:

Unexpectedly low Quadrupole (l=2)

Measurements of Cosmological Parameters by WMAP 3yr

- $\Omega_B h^2 = 0.02229 \pm 0.00073$ (3% error!)
- $\Omega_M h^2 = 0.128 \pm 0.008$
- $\Omega_K = 0.014 \pm 0.017$ (with H=72±8km/s/Mpc)
- $n = 0.958 \pm 0.016$

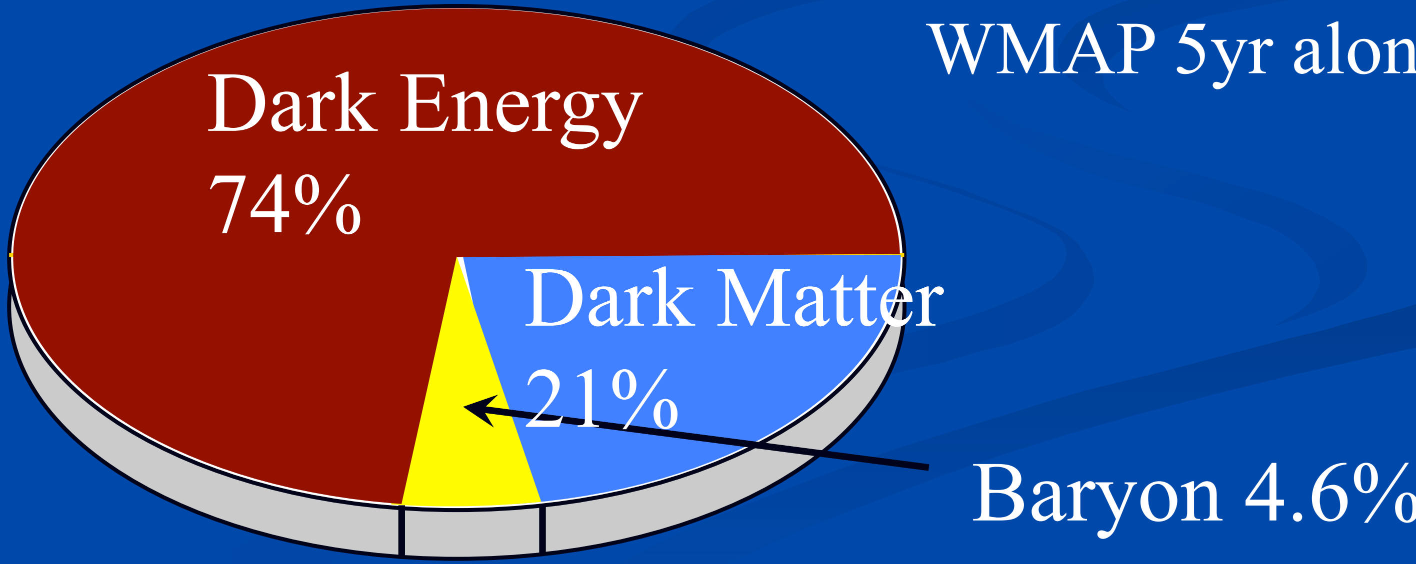
Spergel et al.
WMAP 3yr alone



Measurements of Cosmological Parameters by WMAP 5yr

- $\Omega_B h^2 = 0.02273 \pm 0.00062$
- $\Omega_M h^2 = 0.1326 \pm 0.0063$
- $\Omega_\Lambda = 0.742 \pm 0.030$ (with BAO+SN, 0.72)
- $n = 0.963 \pm 0.015$

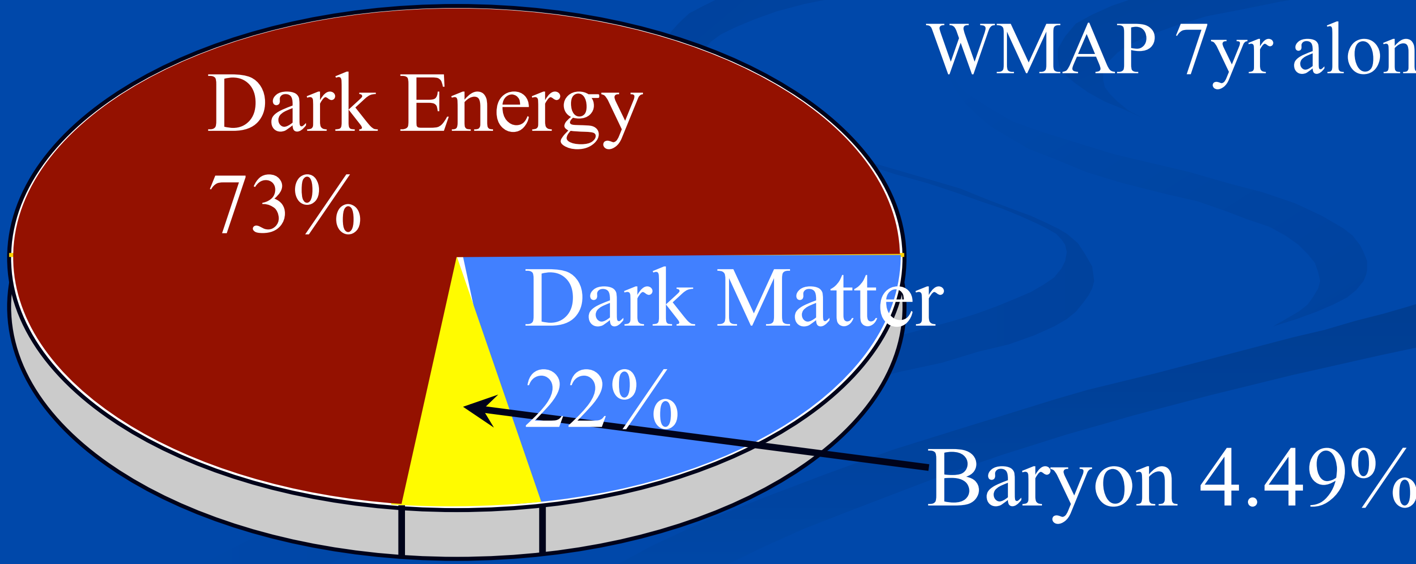
Komatsu et al.
WMAP 5yr alone



Measurements of Cosmological Parameters by WMAP 7yr

- $\Omega_B h^2 = 0.02258 \pm 0.00057$
- $\Omega_M h^2 = 0.1334 \pm 0.0056$
- $\Omega_\Lambda = 0.734 \pm 0.029$ (with BAO+Hubble, 0.728)
- $n = 0.963 \pm 0.014$

Komatsu et al.
WMAP 7yr alone



Finally Cosmologists Have the "Standard Model!"

- But…
  - 73% of total energy/density is unknown: Dark Energy
  - 22% of total energy/density is unknown: Dark Matter

Dark Energy is perhaps a final piece of the puzzle
for cosmology
equivalent to Higgs for particle physics

CMB

- Independently measure baryon density and matter density
  - Since: baryon density << matter density, existence of non-baryonic dark matter is inevitable!

Big Motivation of LHC=Big Bang Machine

- How about dark energy?
  - CMB directly measure dark energy?

Dark Energy

- How do we determine Ω_Λ=0.73?

Subtraction!: $\Omega_\Lambda = 1 - \Omega_M - \Omega_K$

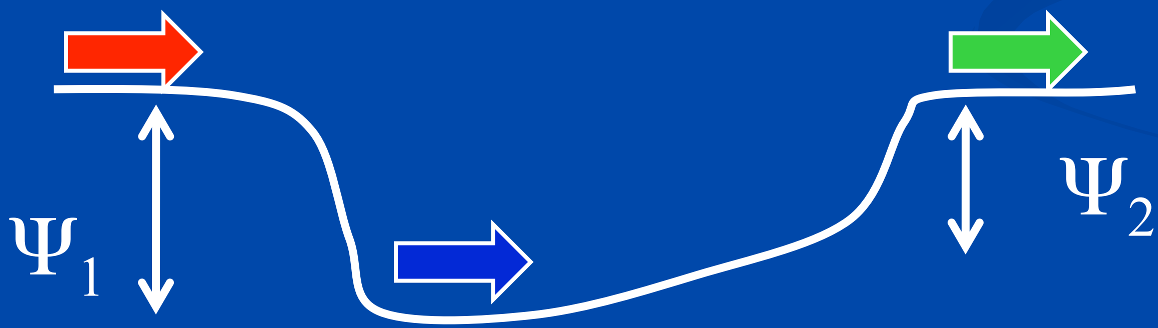
Q: Can CMB provide a direct probe of Dark Energy?

A: Yes. But not primary fluctuations, but secondary, which are produced after recombination

Dark Energy

- CMB can be a unique probe of dark energy
  - Temperature Fluctuations are generated by the growth (decay) of the Large Scale Structure (z~1)

Integrated Sachs-Wolfe Effect



Photon gets blue Shift due to decay

$E=|\Psi_1-\Psi_2|$

Gravitational Potential of Structure decays due to Dark Energy

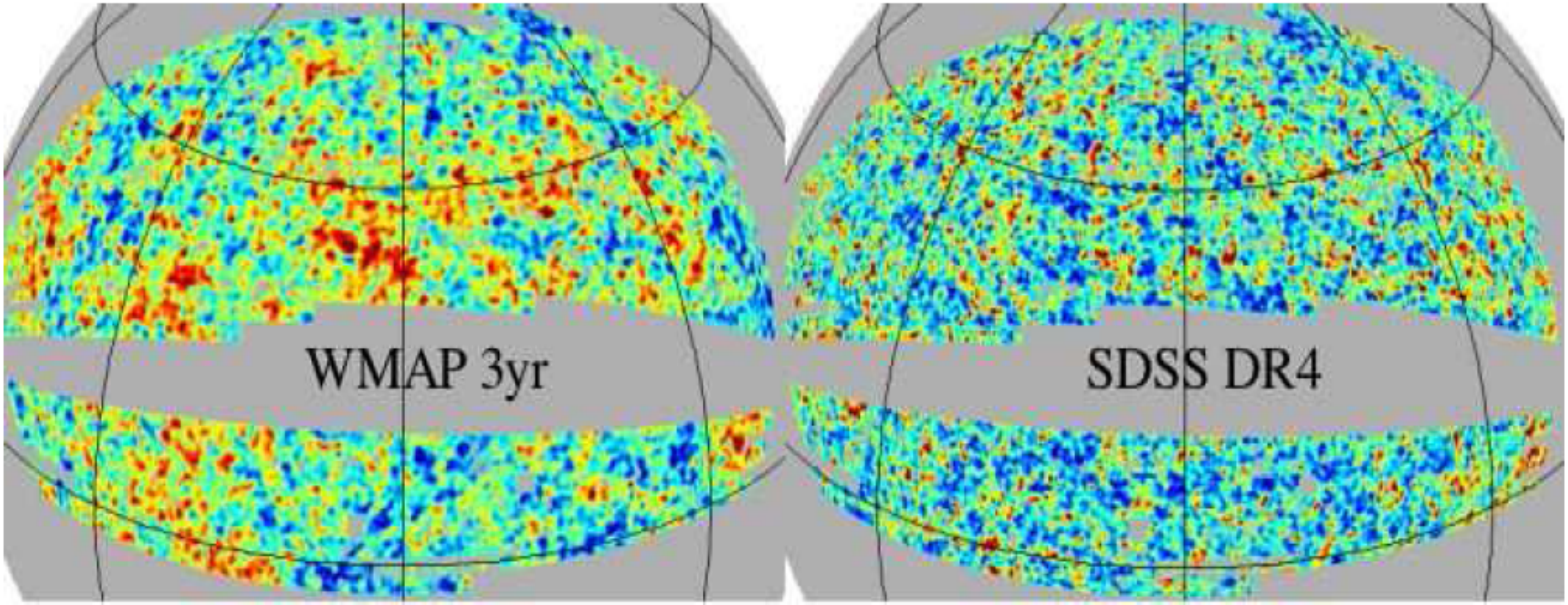
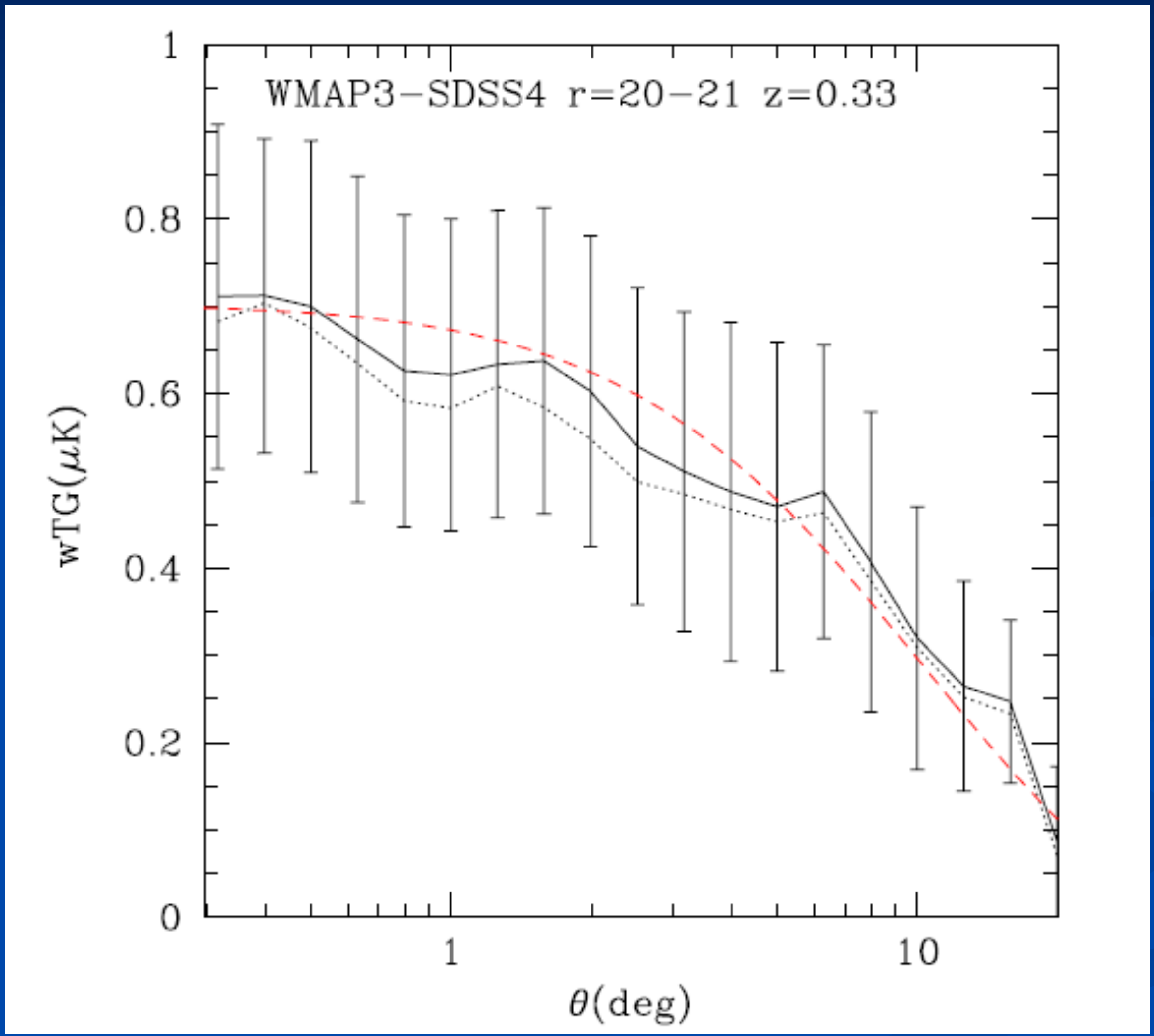


Figure 1. SDSS DR4 galaxy density (LRG) fluctuation maps (right panel) compared to WMAP (V-band 3yr) temperature map (left panel). Both maps are smoothed with a Gaussian beam of FWHM = 0.3 deg.

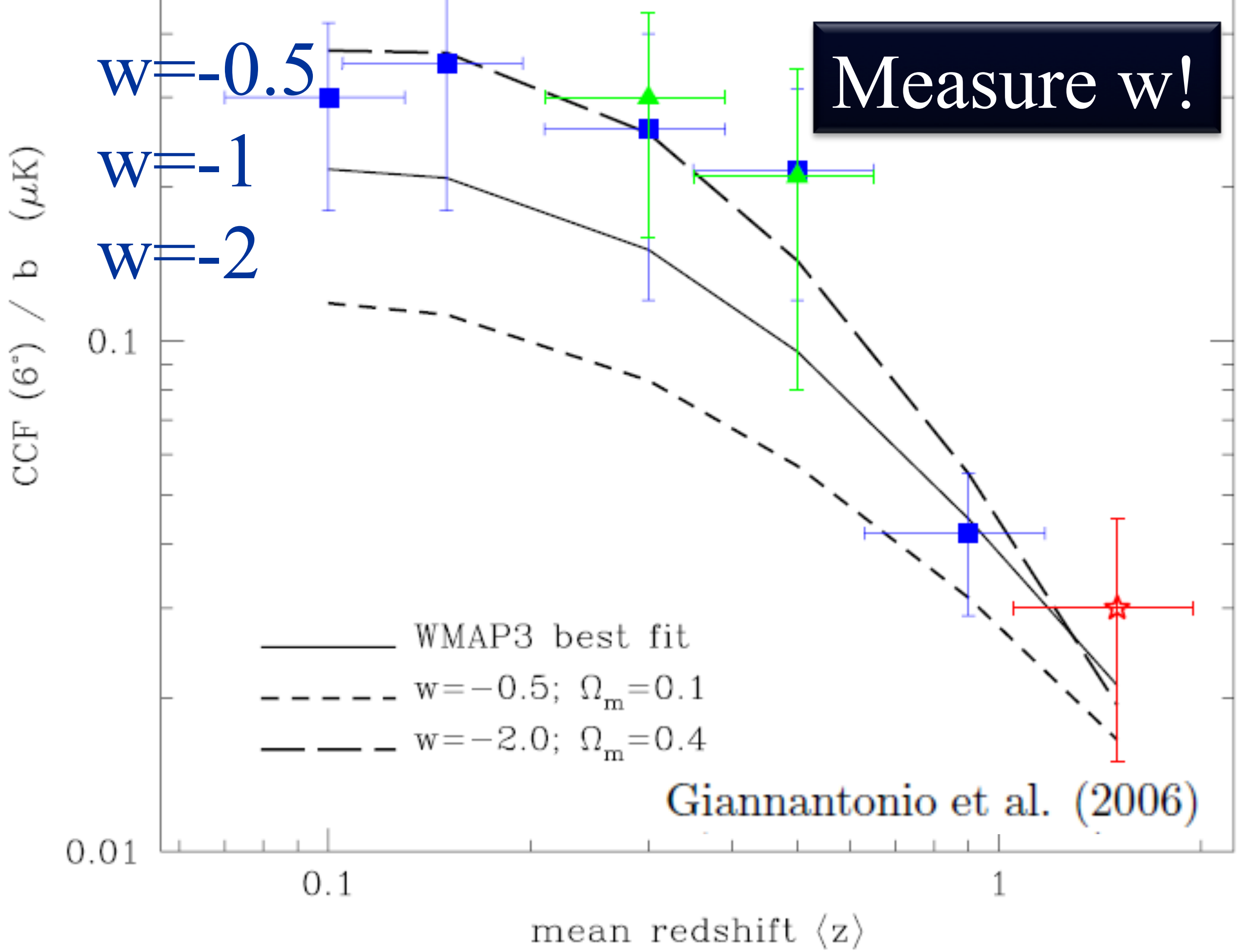
Cabre, A., et al., 2006, see astro-ph/0603690.

CMB (WMAP) and SDSS(LSS) can have cross-correlation **only** thorough the **ISW** effect

Cabre, A., et al., 2006, see astro-ph/0603690.



Various Samples of CMB-LSS Cross-Correlation as a function of redshift



Less Than 10min

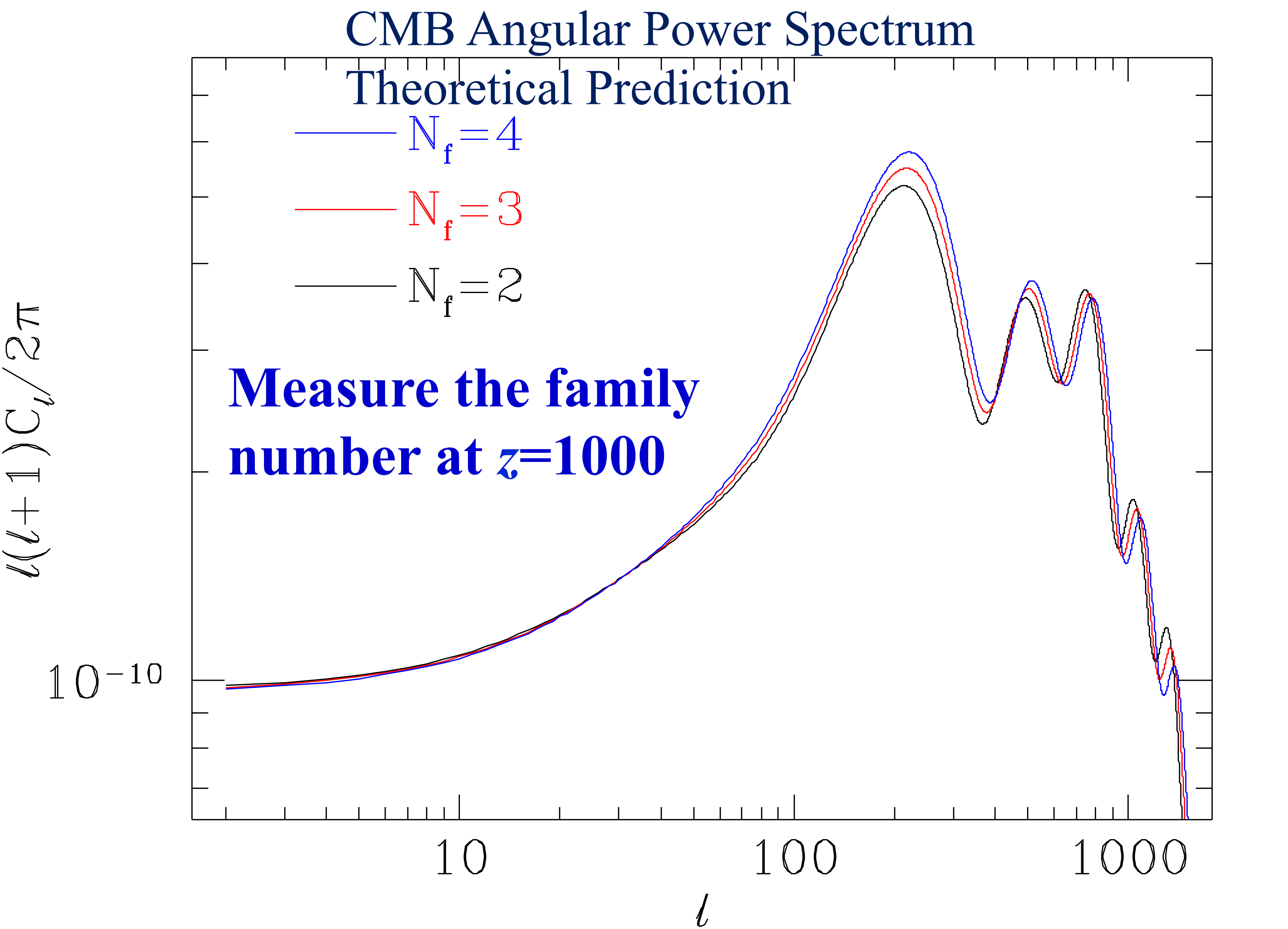
What else can we learn about fundamental physics from WMAP or future Experiments?

- Properties of Neutrinos
  - Numbers of Neutrinos
  - Masses of Neutrinos
- Fundamental Physical Constants
  - Fine Structure Constant
  - Gravitational Constant

Constraints on Neutrino Properties

Neutrino Numbers N_{eff} and mass m_ν

- Change N_{eff} or m_ν modifies the peak heights and locations of CMB spectrum.



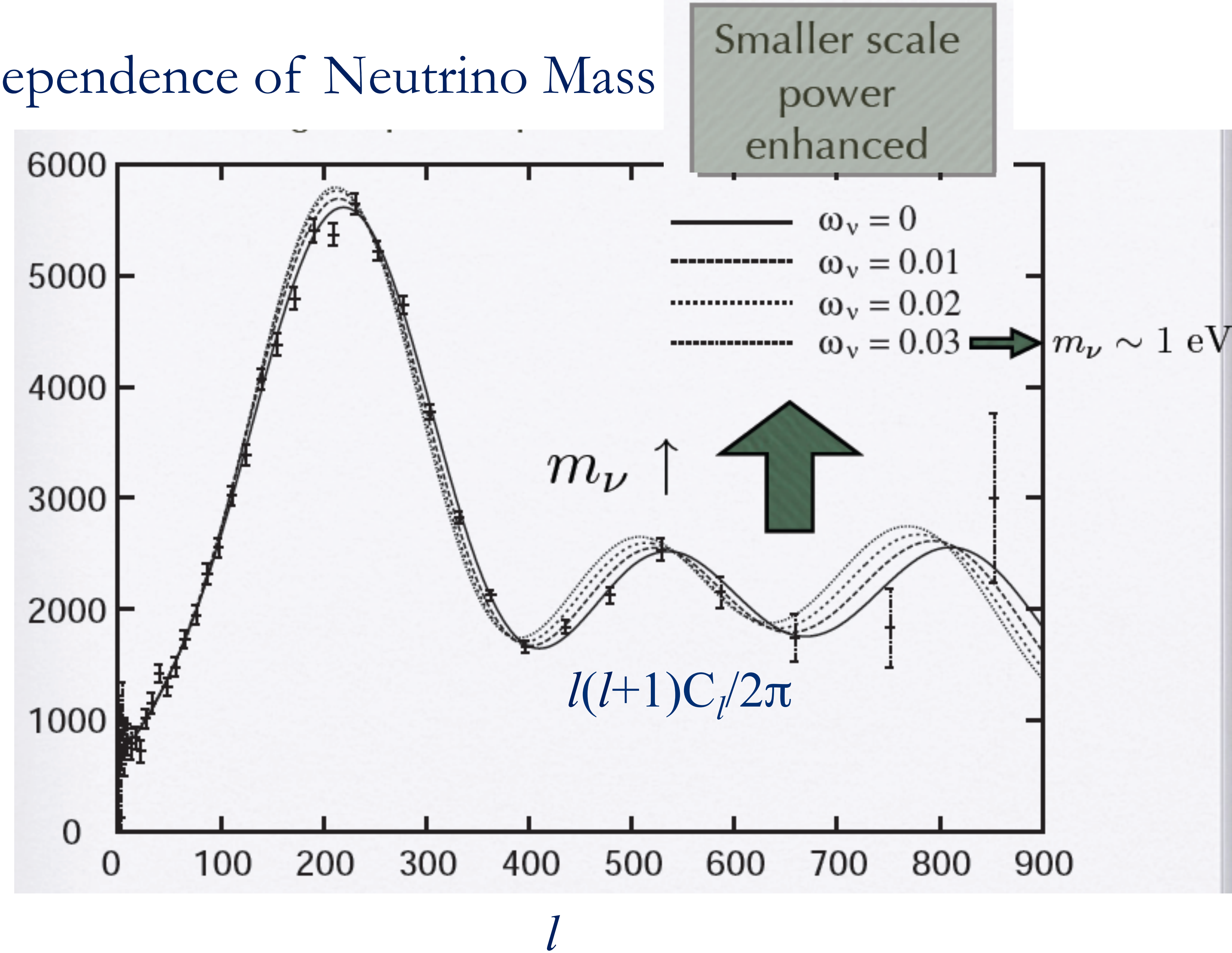
CMB Angular Power Spectrum
Theoretical Prediction
$N_f=4$
$N_f=3$
$N_f=2$
Measure the family number at z=1000
$\ell(\ell+1)C_\ell/2\pi$
10^{-10}
10
100
1000
ℓ

Unfortunately, difficult to set constraints on N_{eff} by CMB alone: Need to combine with other data

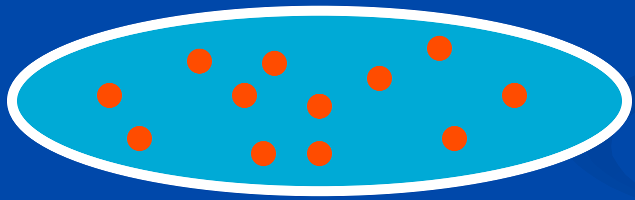
Bound on N_{eff}	Data used	
$1.8 \leq N_{eff} \leq 3.7$	CMB,BBN	P. Serpico *et al.*, ***(2004)***
$1.3 \leq N_{eff} \leq 6.1$	CMB, BBN(D)	A. Cuoco *et al.*, ***(2004)***
$1.6 \leq N_{eff} \leq 3.6$	BBN(D+Y_p)	
$1.4 \leq N_{eff} \leq 6.8$	CMB, LSS, HST	P. Crotty *et al.*, ***(2003)***
$1.9(2.3) \leq N_{eff} \leq 7.0(3.0)$	CMB, LSS, (+BBN)	S. Hannestad, ***(2003)***
$1.7 \leq N_{eff} \leq 3.0$	CMB, BBN	V. Barger *et al.*, ***(2003)***
$N_{eff} \leq 4.6$	CMB, BBN	R. Cyburt *et al.* ***(2005)***
$1.90 \leq N_{eff} \leq 6.62$	CMB, LSS, HST	E. Pierpaoli ***(2003)***

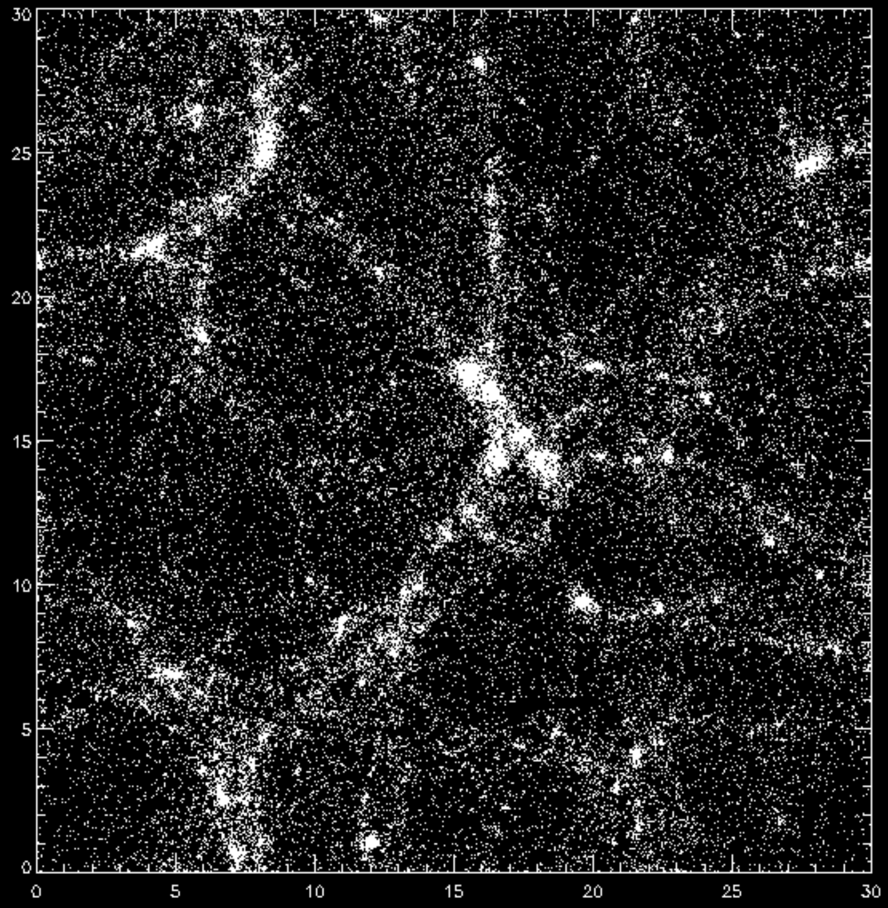
BBN: Big Bang Nucleothynthesis
LSS: Large Scale Structure
HST: Hubble constant from Hubble Space Telescope

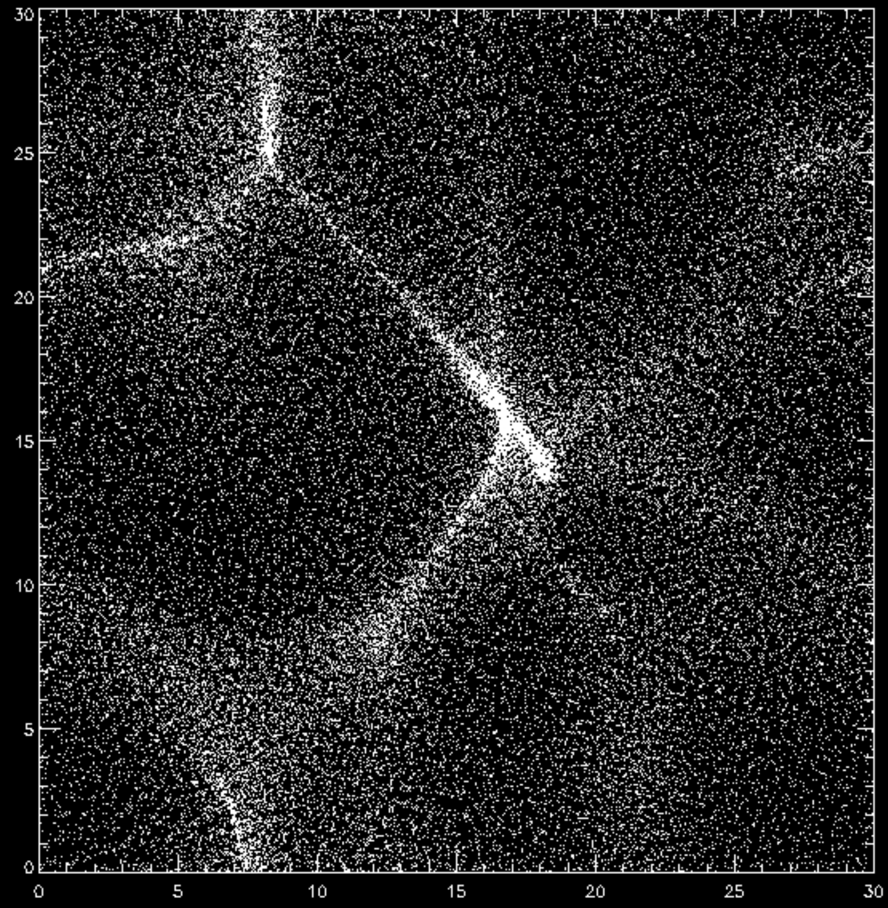
Dependence of Neutrino Mass



For Neutrino Mass, CMB with Large Scale Structure Data provide stringent limit since Neutrino Components prevent galaxy scale structure to be formed due to their kinetic energy



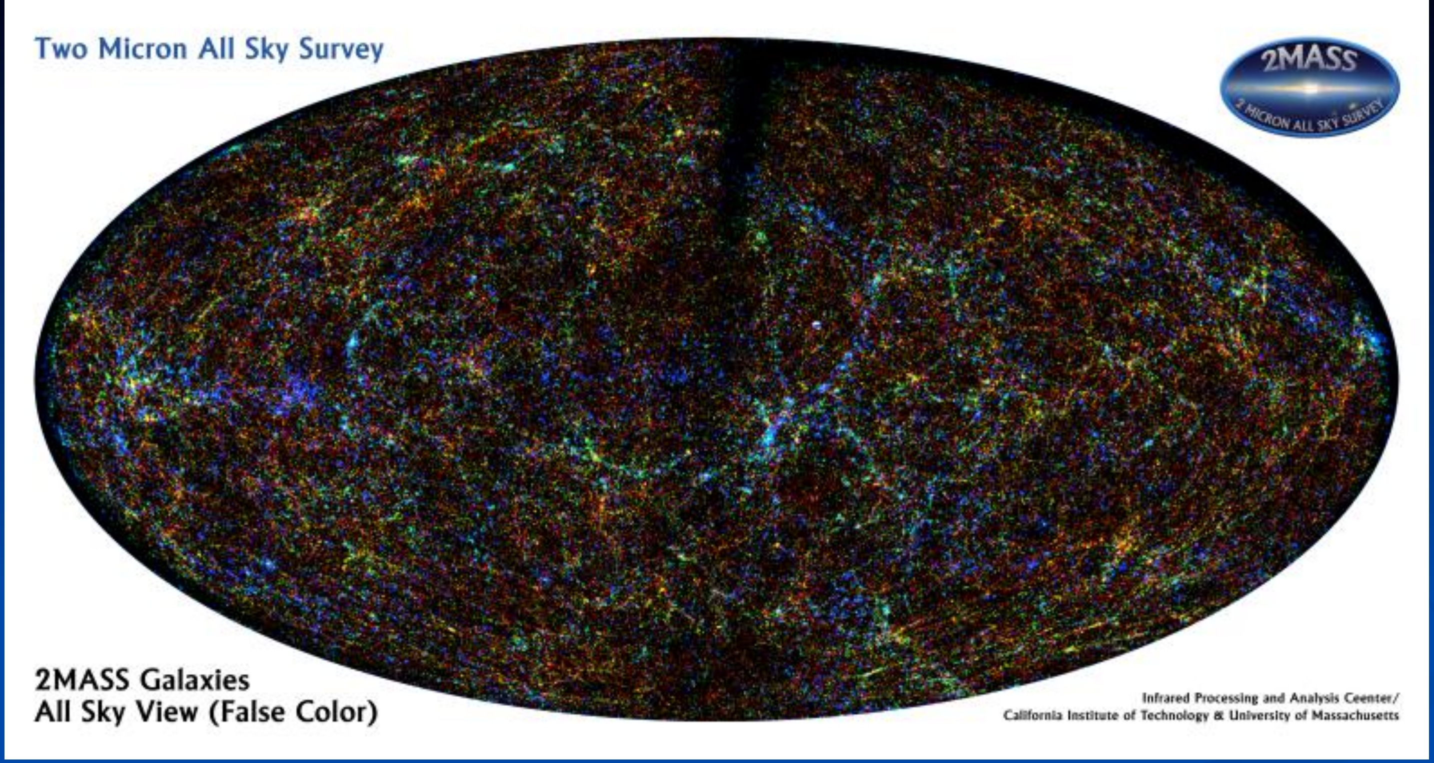


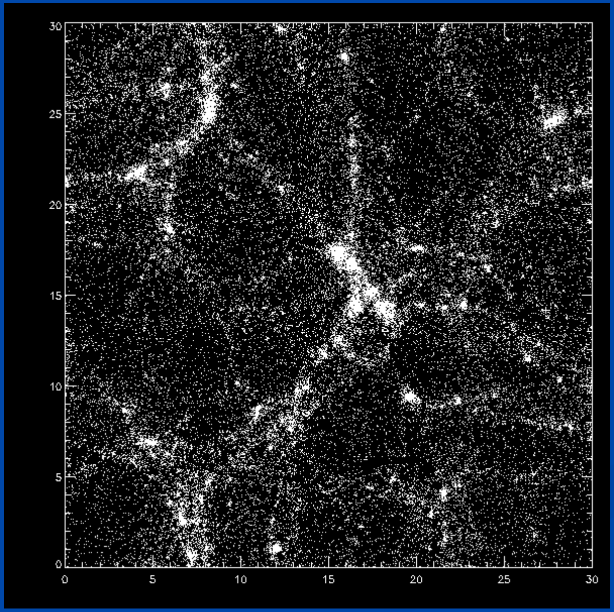


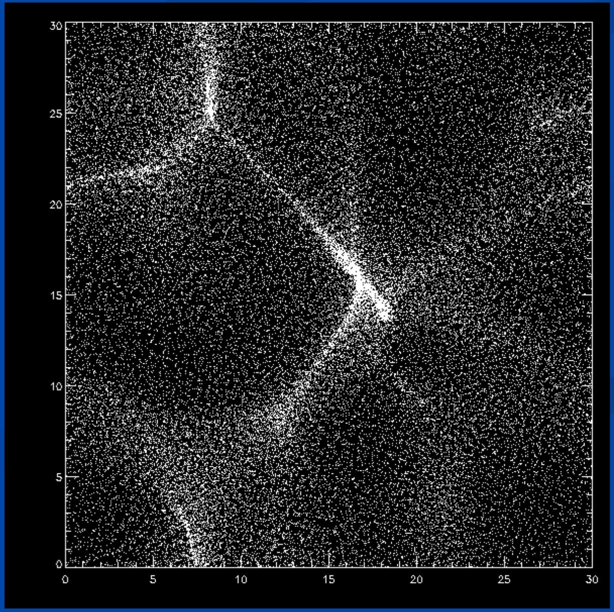
Cold Dark Matter

Neutrino as Dark Matter
(Hot Dark Matter)

Numerical Simulation


Two Micron All Sky Survey
2MASS
2 MICRON ALL SKY SURVEY
2MASS Galaxies
All Sky View (False Color)
Infrared Processing and Analysis Ceenter/
California Institute of Technology & University of Massachusetts


0
5
10
15
20
25
30


0
5
10
15
20
25
30

Constraints on m_ν and N_{eff}

WMAP 3yr Data paper by Spergel et al.

Data Set	$\sum m_\nu$ (95% limit for $N_\nu = 3.04$)	N_ν
WMAP	1.8 eV (95% CL)	–
WMAP + SDSS	1.3 eV (95% CL)	$7.1^{+4.1}_{-3.5}$
WMAP + 2dFGRS	0.88 eV (95% CL)	2.7 ± 1.4
CMB + LSS +SN	0.66 eV (95% CL)	3.3 ± 1.7

WMAP 5yr Data paper by Komatsu et al.

WMAP 5-year	*WMAP*+BAO+SN
$\sum m_\nu < 1.3$ eV^t $N_{\rm eff} > 2.3^v$	$\sum m_\nu < 0.67$ eV^u $N_{\rm eff} = 4.4 \pm 1.5^w$ (68%)

WMAP 7yr Data paper by Komatsu et al.

Name	Case	*WMAP* 7-year	*WMAP*+BAO+SN[a]	*WMAP*+BAO+H_0
Neutrino Mass[f]	$w = -1$	$\sum m_\nu < 1.3$ eV[c]	$\sum m_\nu < 0.71$ eV	$\sum m_\nu < 0.58$ eV[g]
	$w \neq -1$	$\sum m_\nu < 1.4$ eV[c]	$\sum m_\nu < 0.91$ eV	$\sum m_\nu < 1.3$ eV[h]
Relativistic Species	$w = -1$	$N_{eff} > 2.7$[c]	N/A	$4.34^{+0.86}_{-0.88}$ (68% CL)[i]

Constraints on Fundamental Physical Constants

<u>Fine Structure Constant α</u>

- There are debates whether one has seen variation of α in QSO absorption lines
- Time variation of α affects on recombination process and scattering between CMB photons and electrons
- WMAP 3yr data set:

  $-0.039<\Delta\alpha/\alpha<0.010$ (by P.Stefanescu 2007)

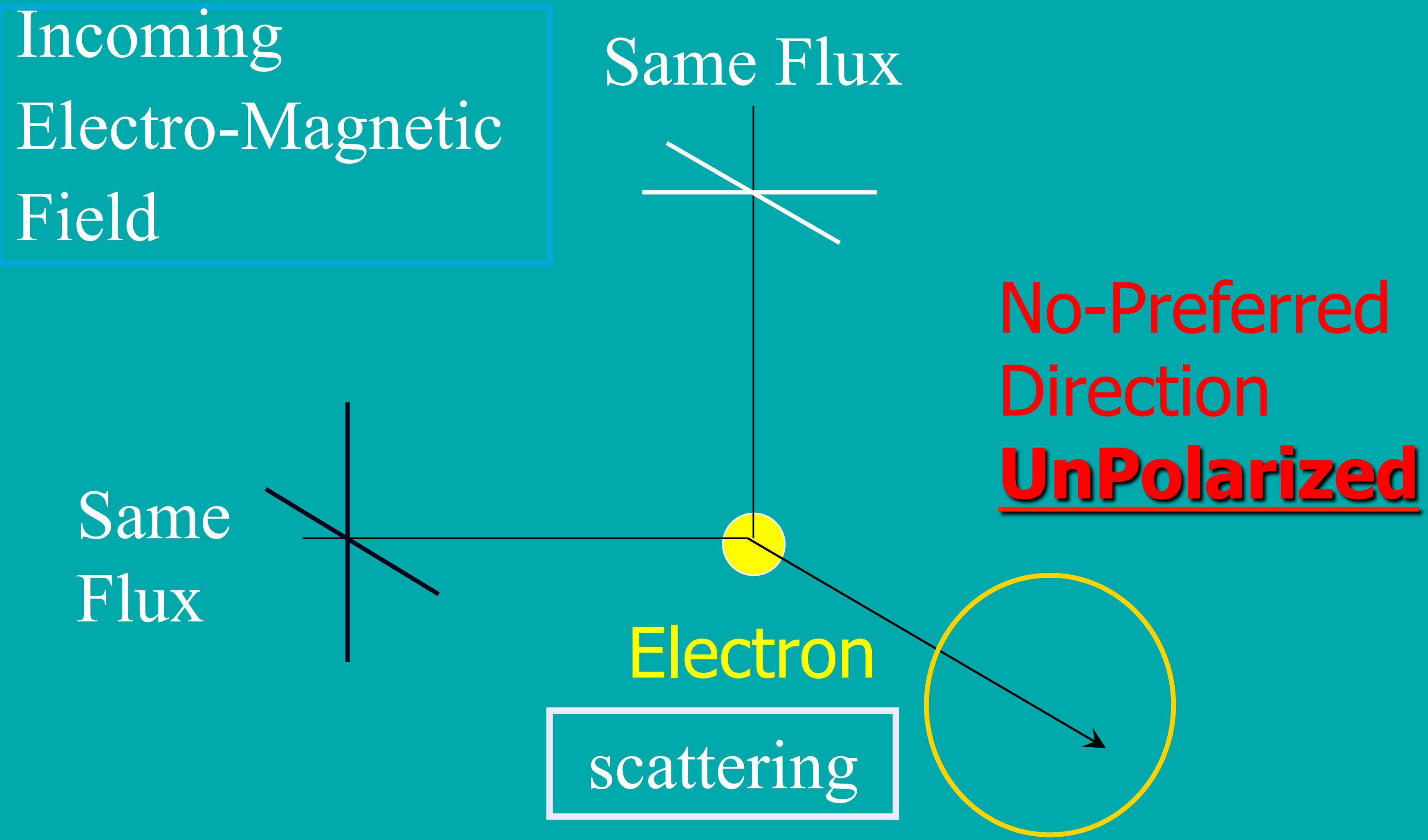
Gravitational Constant *G*

- *G* can couple with Scalar Field (c.f. Super String motivated theory)
- Alternative Gravity theory: Brans-Dicke / Scalar-Tensor Thoery
  - $G \propto 1/\phi$ (scalar filed)
  - ***G*** may be smaller in the early epoch
- WMAP data set constrain: $|\Delta G/G|<0.05$ (2σ) (Nagata, Chiba, N.S.)

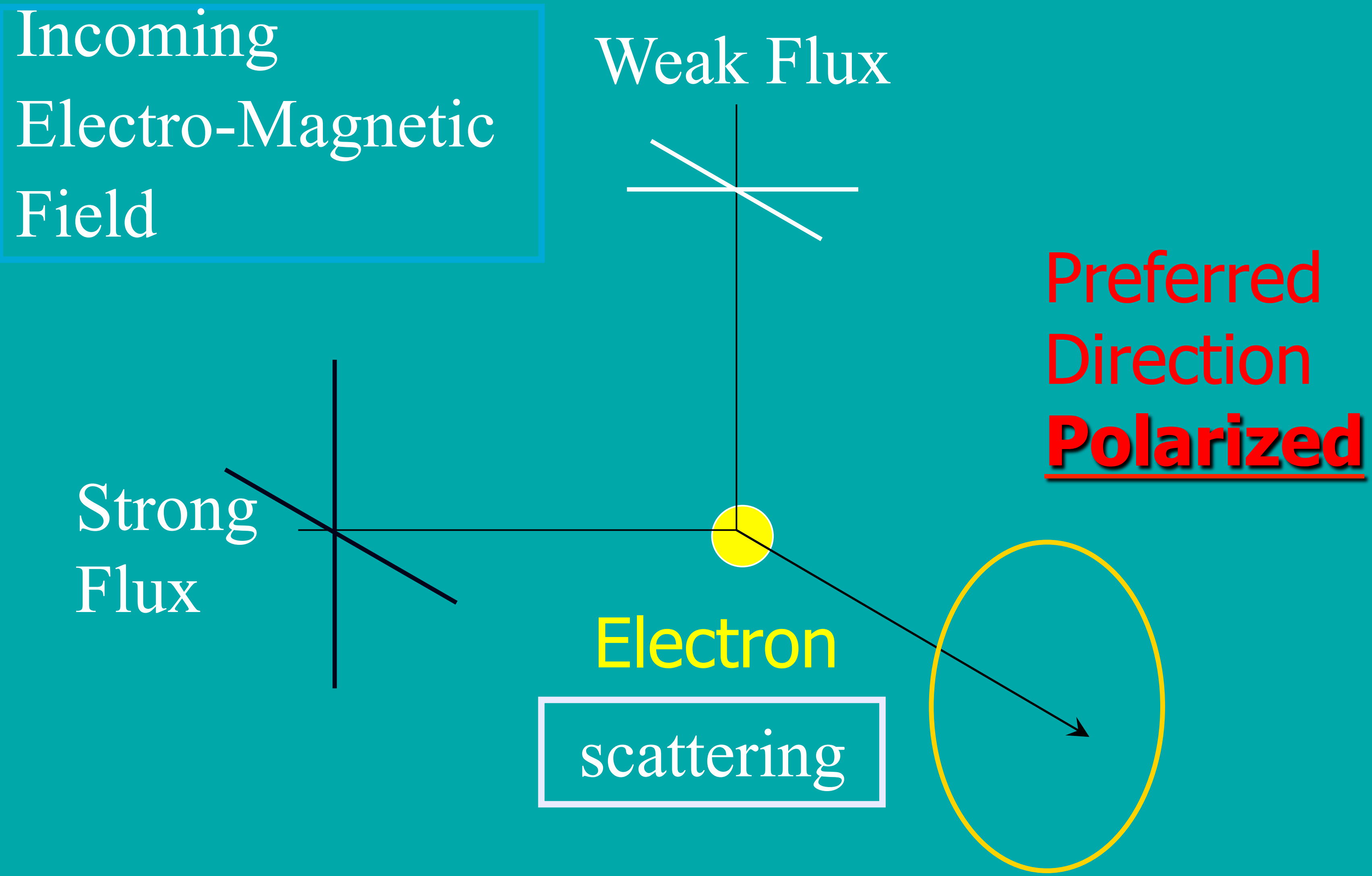
Polarization

Scattering off electrons & CMB quadrupole anisotropies

produce linear polarization



Homogeneously Distributed Photons



Photon Distributions with the Quadrupole Pattern

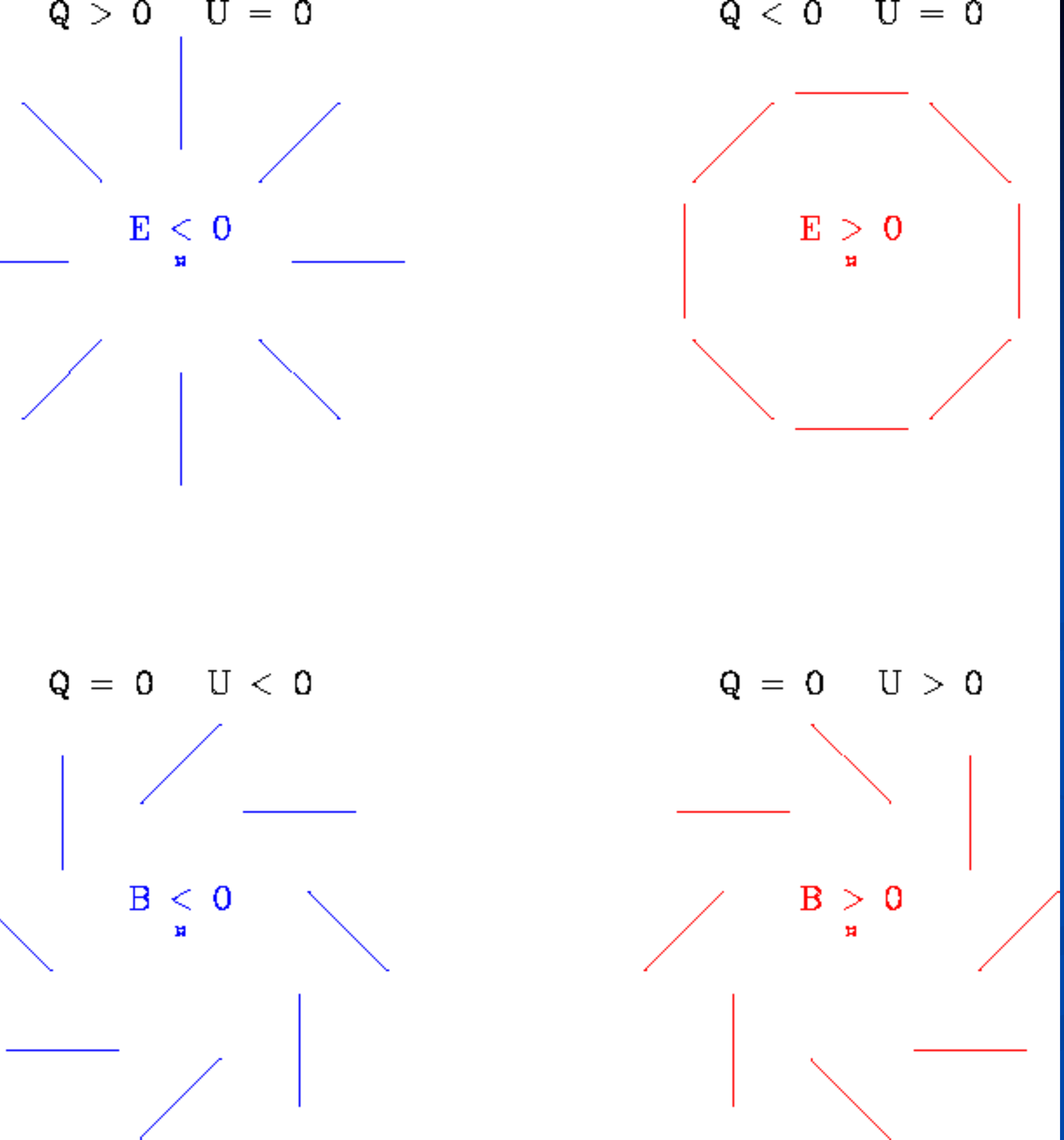
Why is Polarization Important?

- Provide information of last scattering of photons
  - Reionization of the Universe due to First Stars
- Better estimation for Cosmological Parameters
- **Sensitive to Gravity Wave (Tensor Mode Fluctuations)**

Two Independent Modes

- E-mode (Electronic), Divergence
  - Density Fluctuations associated to Structure formation induce only this mode
- B-mode (Magnetic), Rotation
  - Vector (rotational) Fluctuations: decaying mode
  - Tensor (Gravitational Wave) Fluctuations

B-mode polarization is a unique probe of Gravitational Wave generated during Inflation
c.f. No way to separate two modes in Temperature Fluctuations

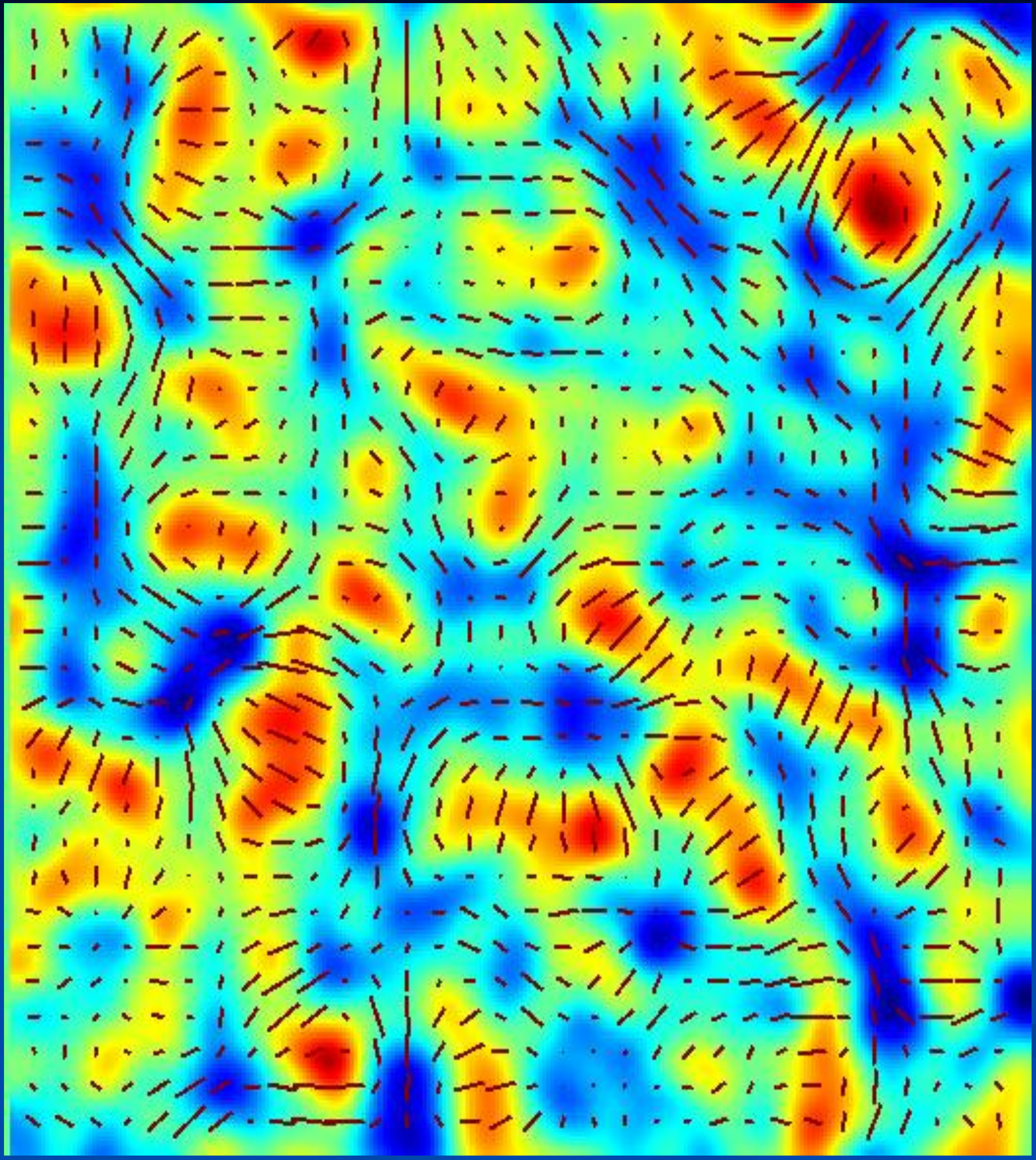


E-mode

2 independent parity modes

B-mode

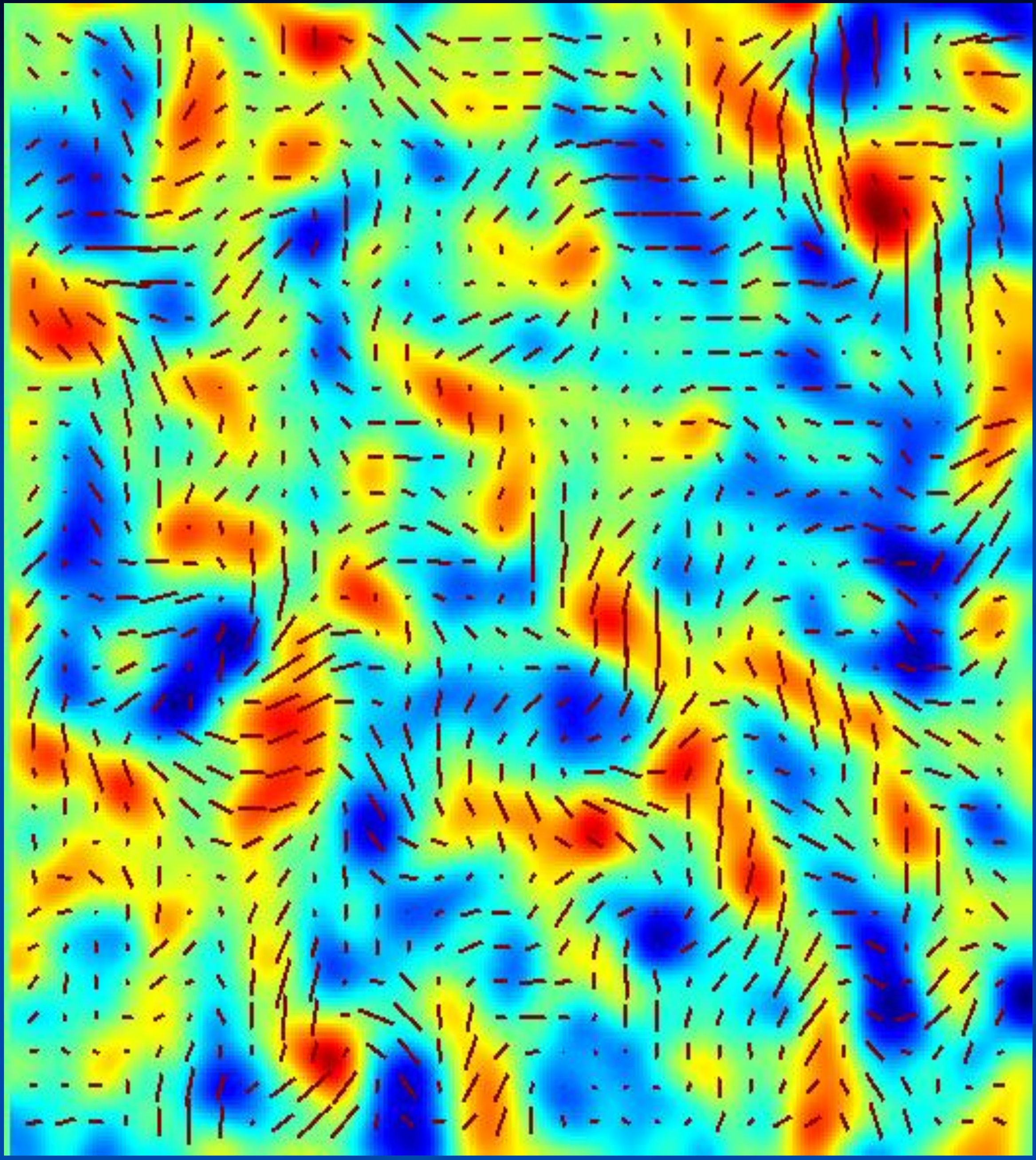
Seljak



E-mode

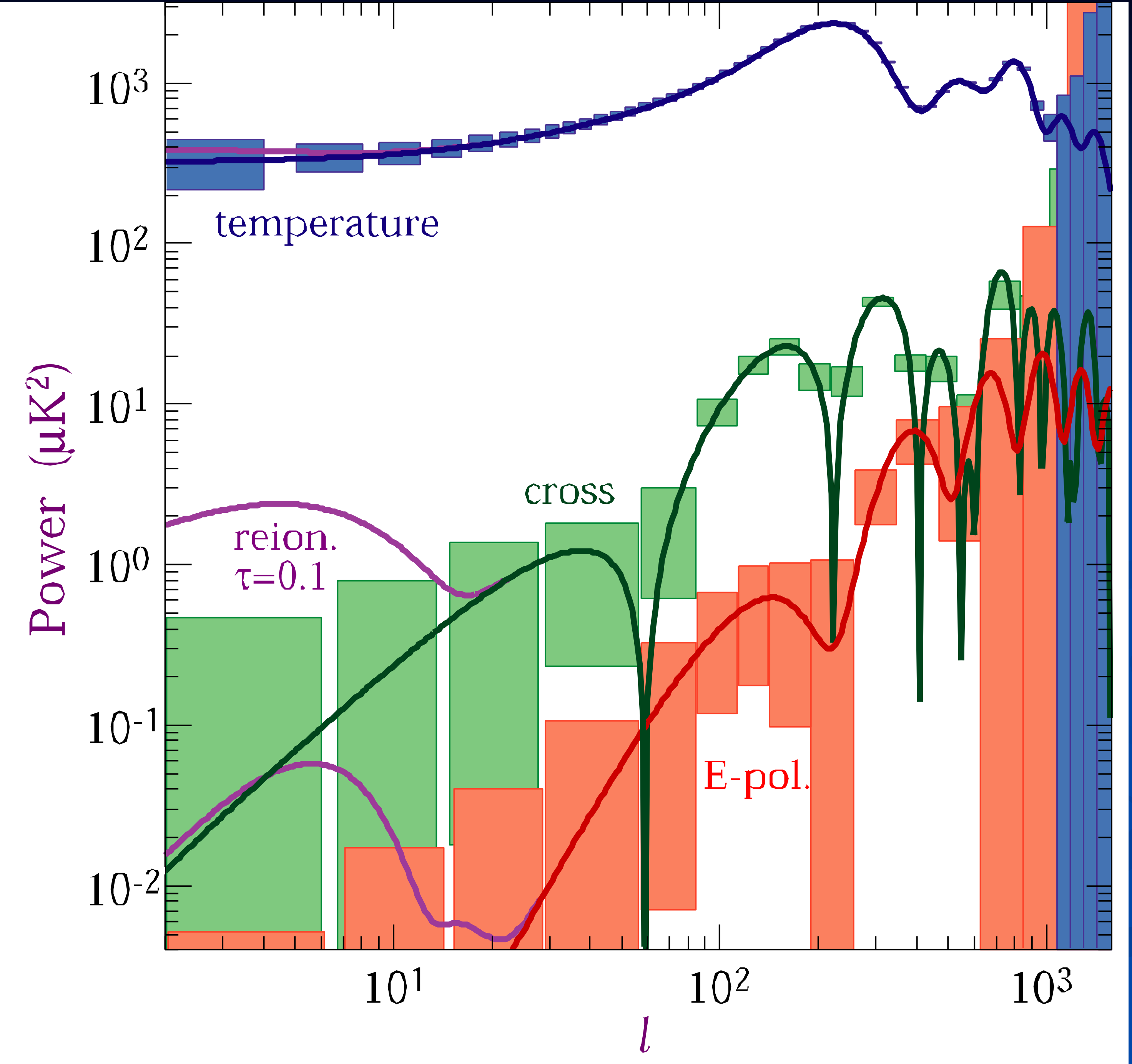
Seljak

Scalar Perturbations only produce E-mode

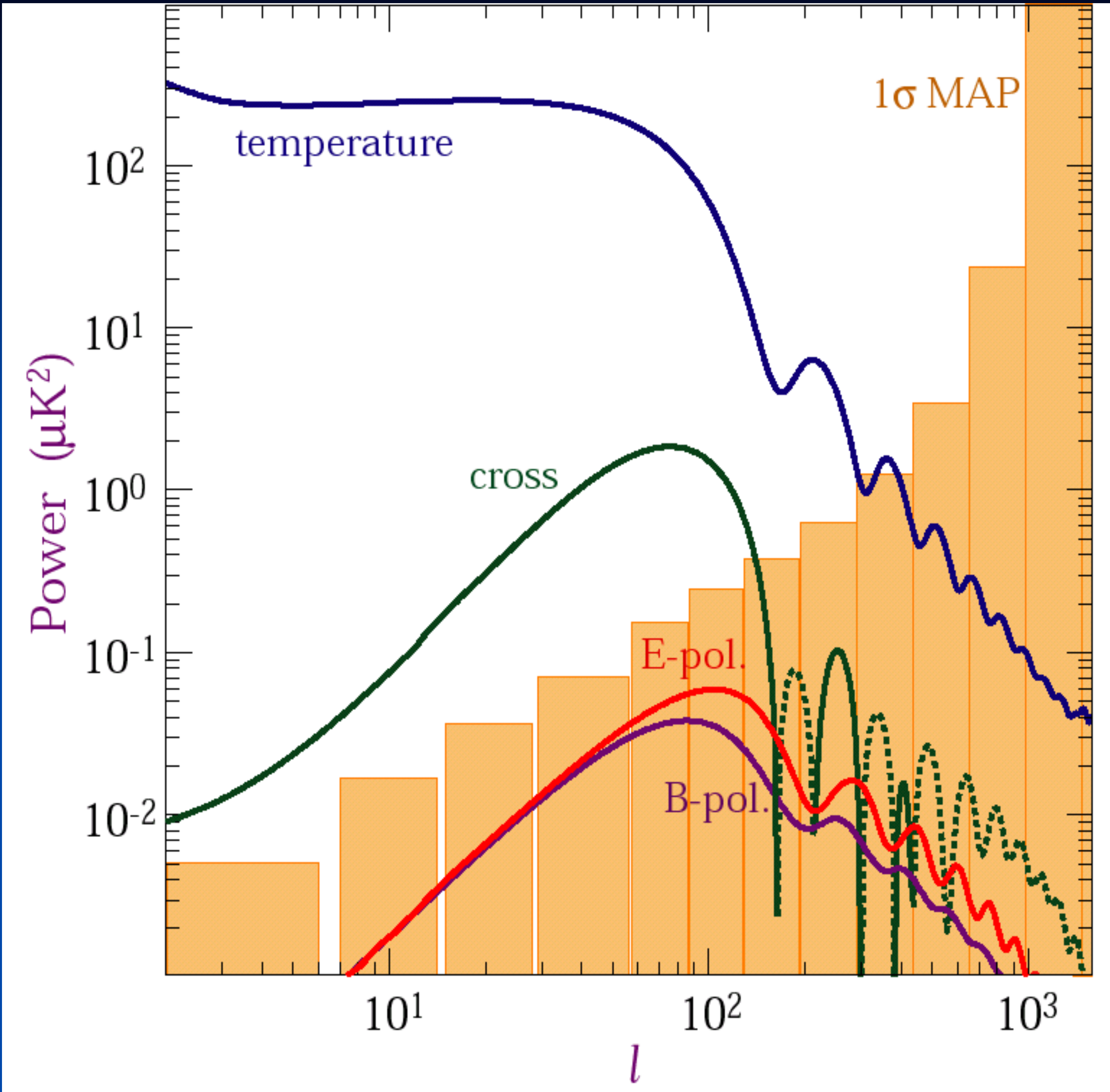


B-mode

Tensor perturbations produce both E- and B- modes



Scalar Component



Tensor Component

Hu & White

We can Prove Inflation from B-mode Polarization

- Consistency Relation

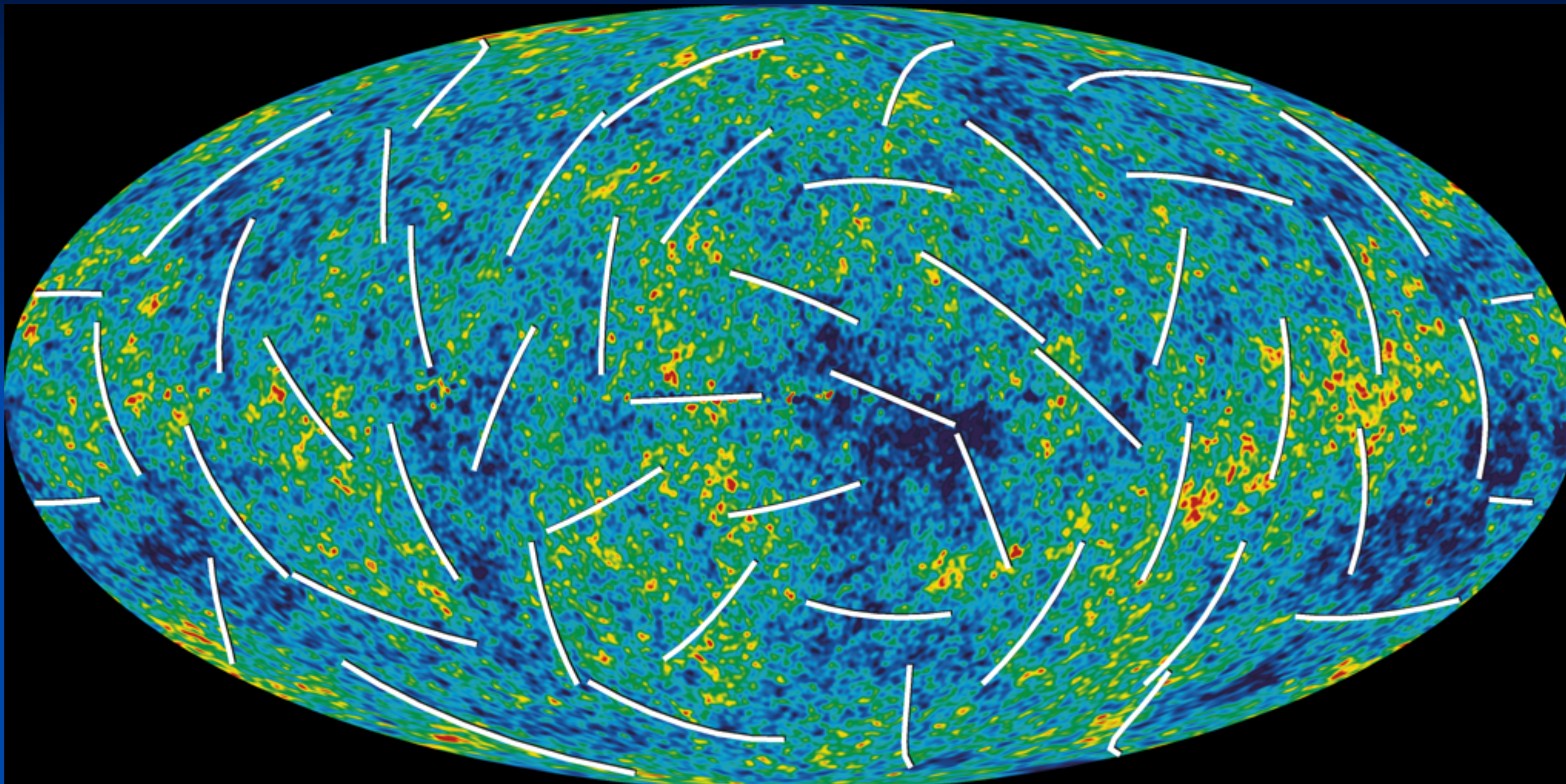
$$n_T = -2A_T / A_S$$

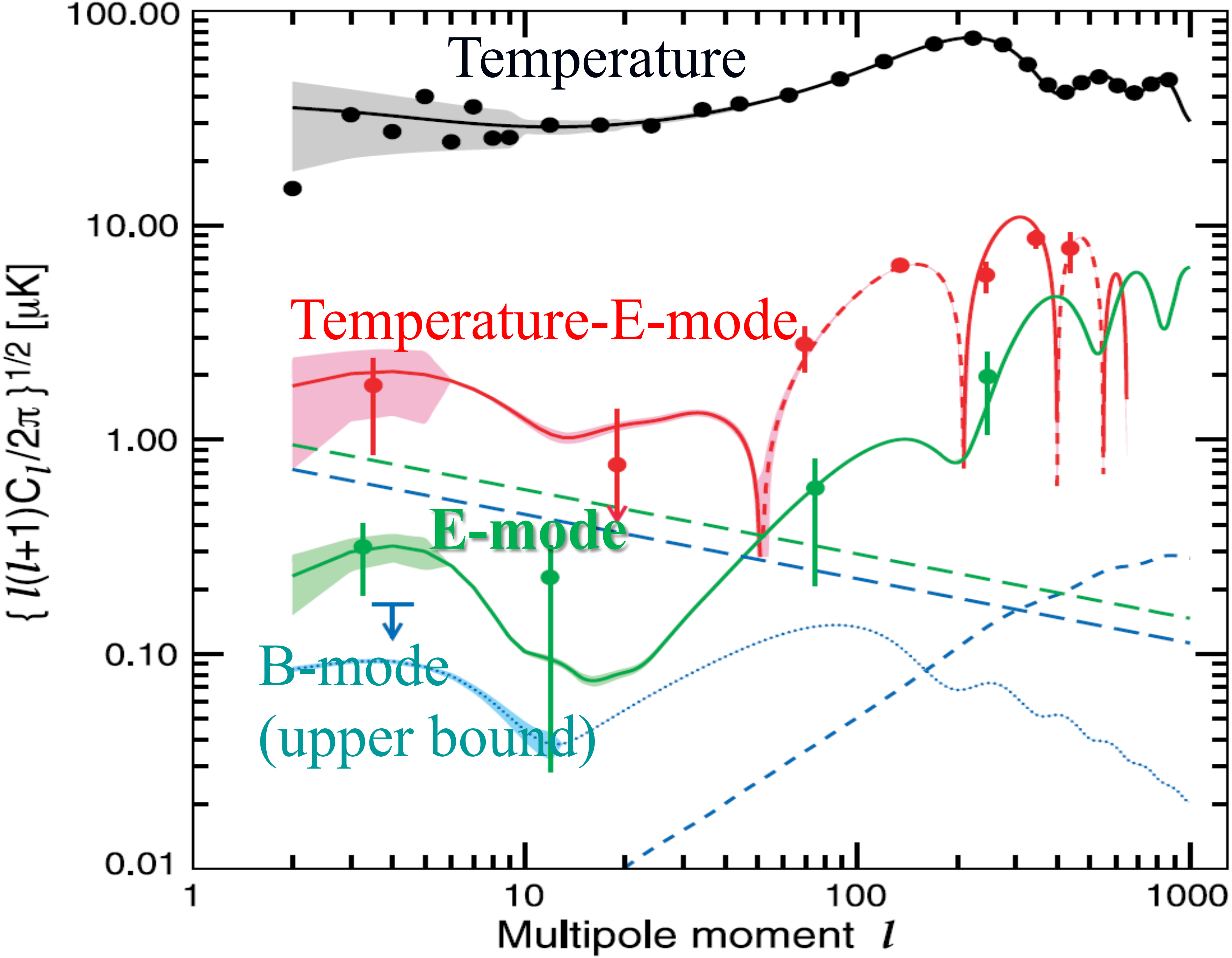
  - n_T: Tensor Power Law Index
  - A_T: Tensor Amplitude
  - A_S: Scalar Amplitude
- If we can find B-mode, we can measure tensor spectrum (n_T & A_T), and test consistency relation

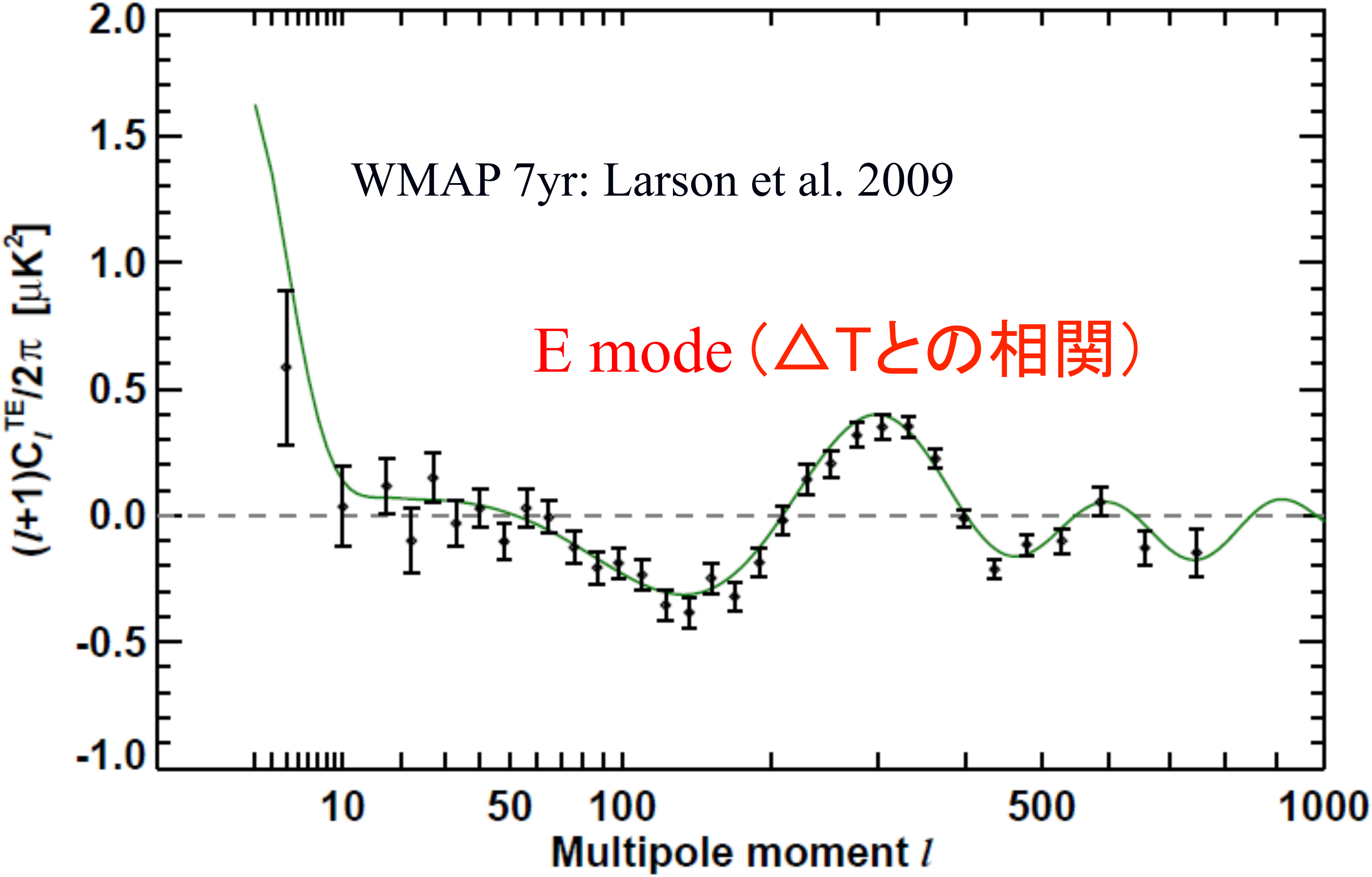
Observations

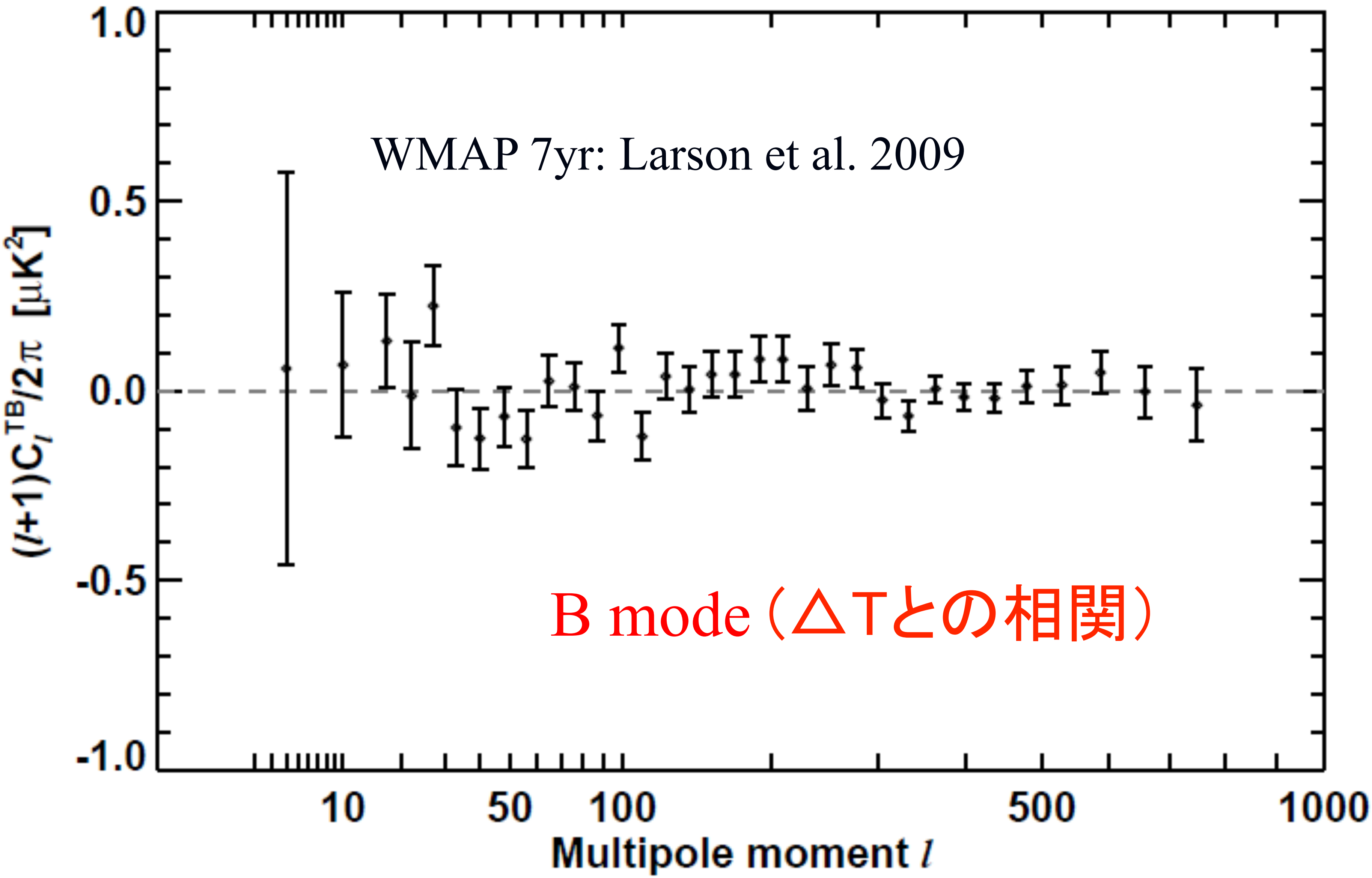
Very difficult to detect
•Typically amplitude of polarization is factor 10 smaller than temperature fluctuations
•Foreground from the Galaxy

- First Detection of E-mode Polarization was from DESI experiments (J.Carlstrom's group)
- Boomerang Experiment (Balloon at Antarctica)
- WMAP made clear detection of E-mode polarization in the all sky map (3yr data)

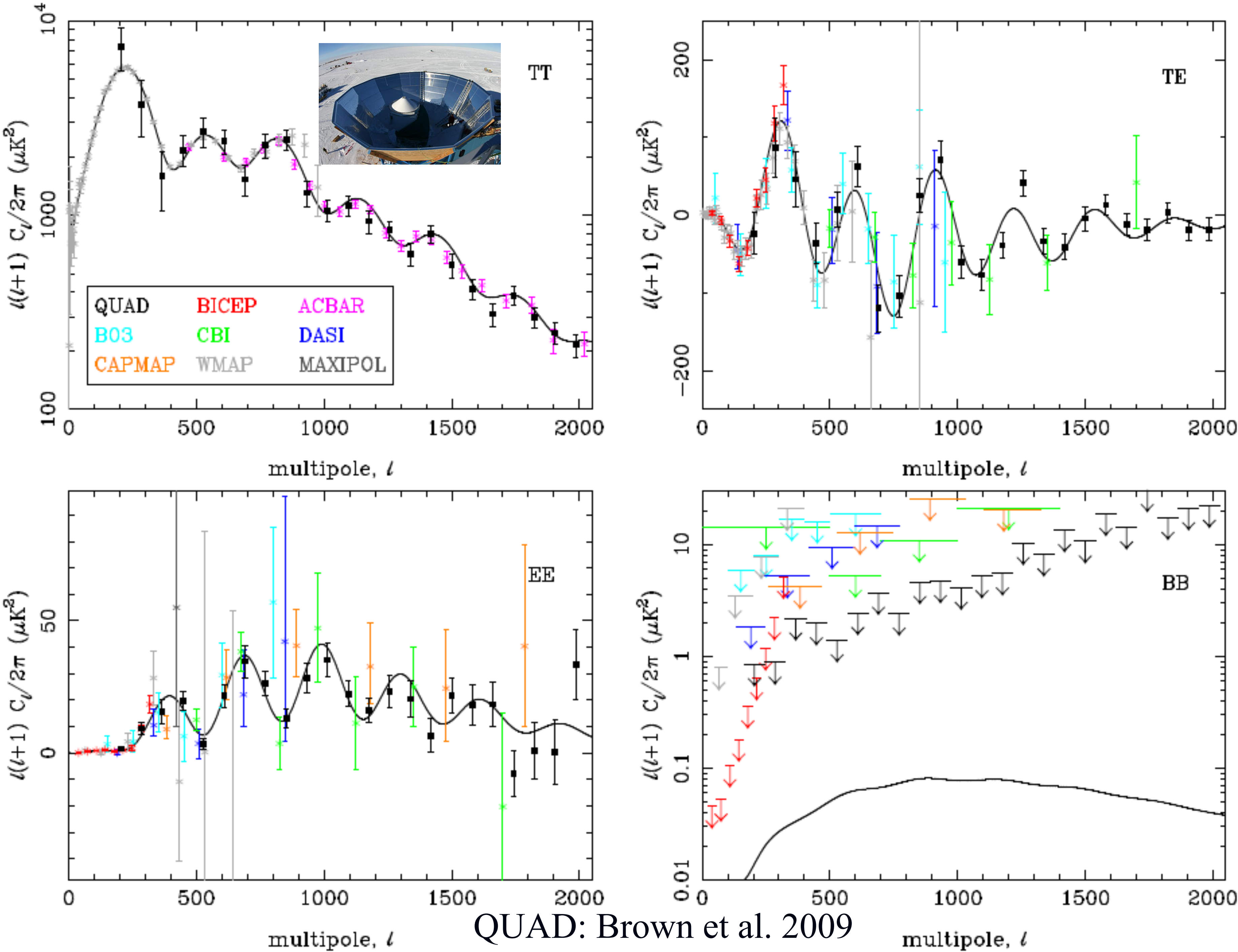



Temperature
Temperature-E-mode
E-mode
B-mode
(upper bound)
100.00
10.00
1.00
0.10
0.01
1
10
100
1000
Multipole moment l
$\{ l(l+1)C_l/2\pi \}^{1/2}$ [μK]

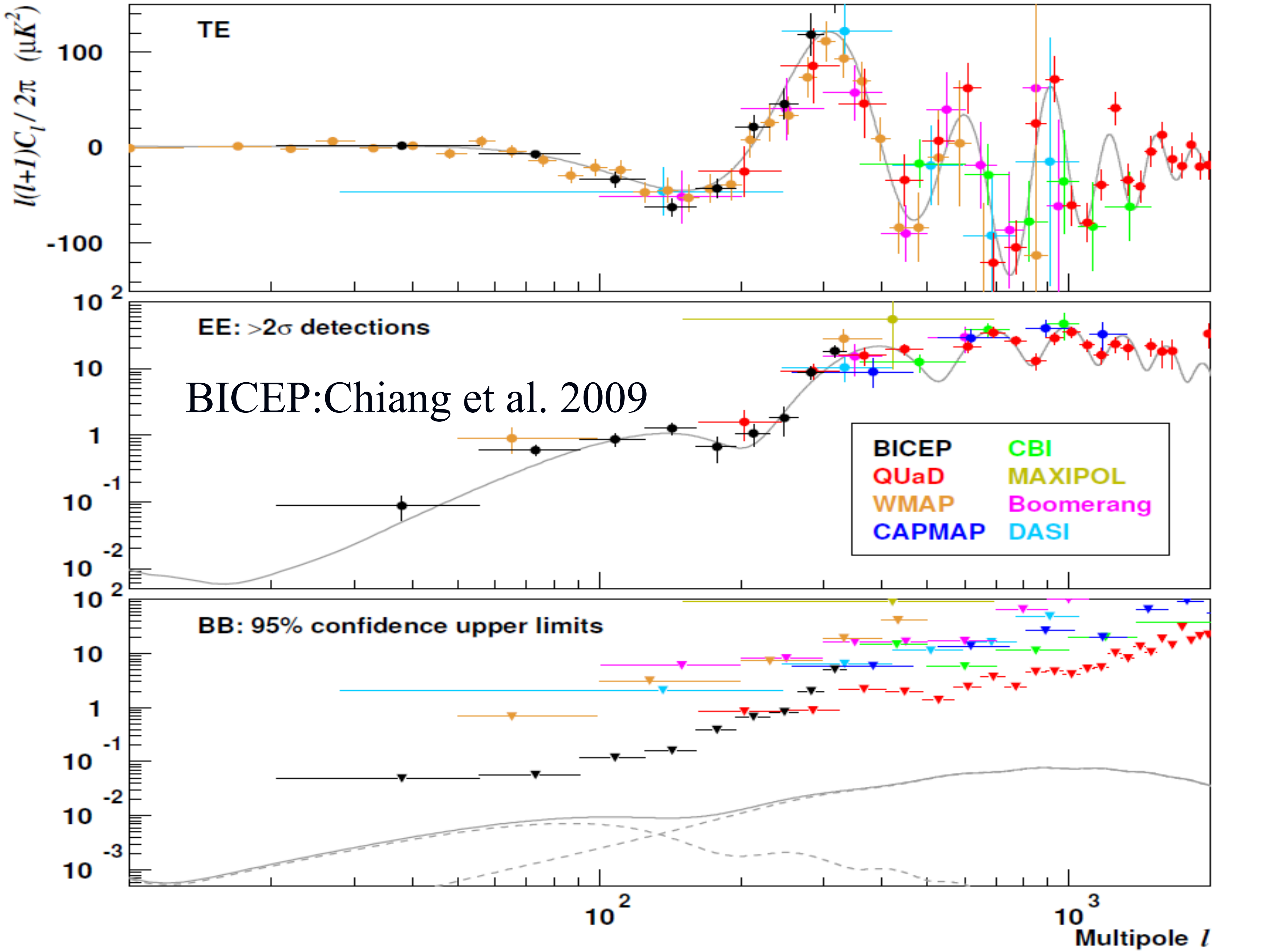

WMAP 7yr: Larson et al. 2009
E mode（△Tとの相関）
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
(l+1)C_l^TE/2π [μK²]
10
50
100
500
1000
Multipole moment l



1.0
0.5
0.0
-0.5
-1.0
(l+1)C_l^TB/2π [μK²]
WMAP 7yr: Larson et al. 2009
B mode（△Tとの相関）
10
50
100
500
1000
Multipole moment l



QUAD: Brown et al. 2009


TE
EE: >2σ detections
BB: 95% confidence upper limits
$l(l+1)C_l / 2\pi$ (μK^2)
100
0
-100
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^2
10^3
Multipole l
BICEP
QUaD
WMAP
CAPMAP
CBI
MAXIPOL
Boomerang
DASI
BICEP:Chiang et al. 2009

Polarization for WMAP is
Temperature Fluctuations for COBE
anyway, detect (E-mode)!

But only upper bound for B-mode Polarization

Now a big race in which who is going to detect B-mode first time is open!

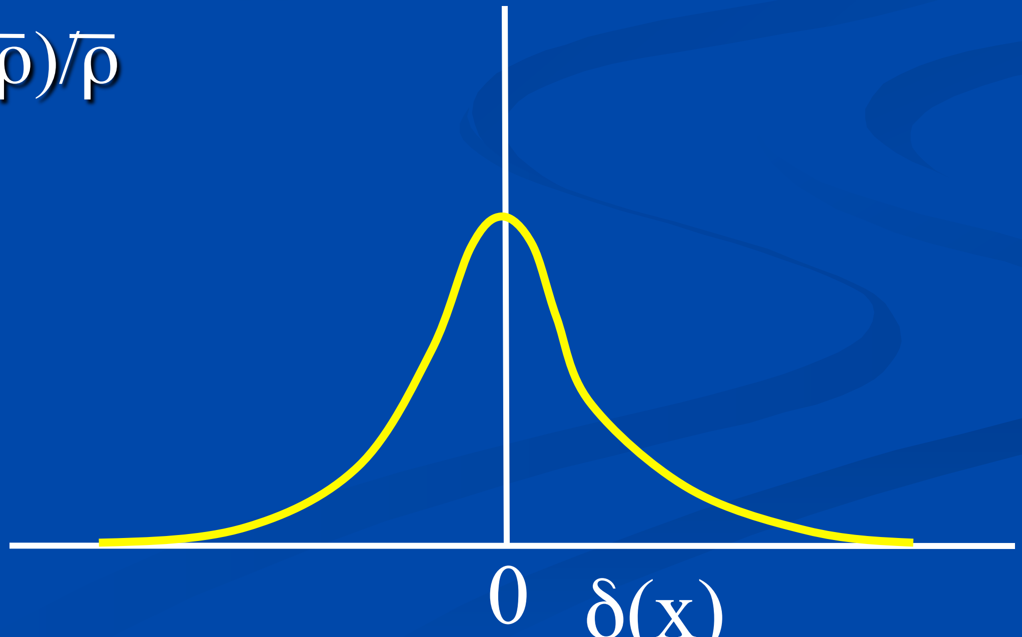
In Japan, Masashi Hazumi's group joins the race

- Join QUIET group
- Eventually launch a small satellite
- They just got a big grant! ~$10million

Recent Hot Topics: Non-Gaussianity

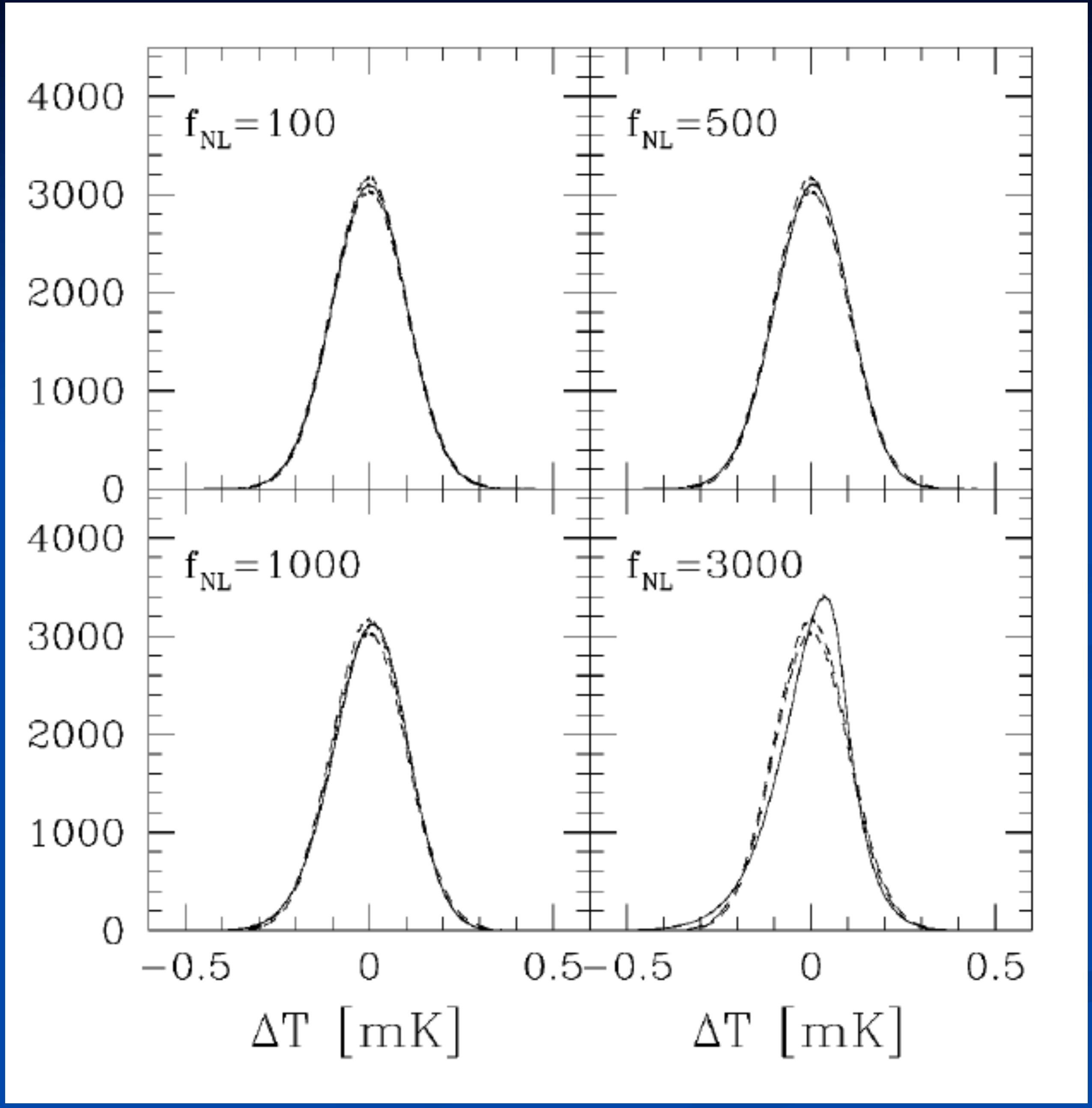
- Fluctuations generated during the inflation epoch
  - Quantum Origin
  - Gaussian as a first approximation

$\delta(x) \equiv (\rho(x) - \bar{\rho})/\bar{\rho}$



Non Gaussianity from Second Order Perturbations of the inflationary induced fluctuations

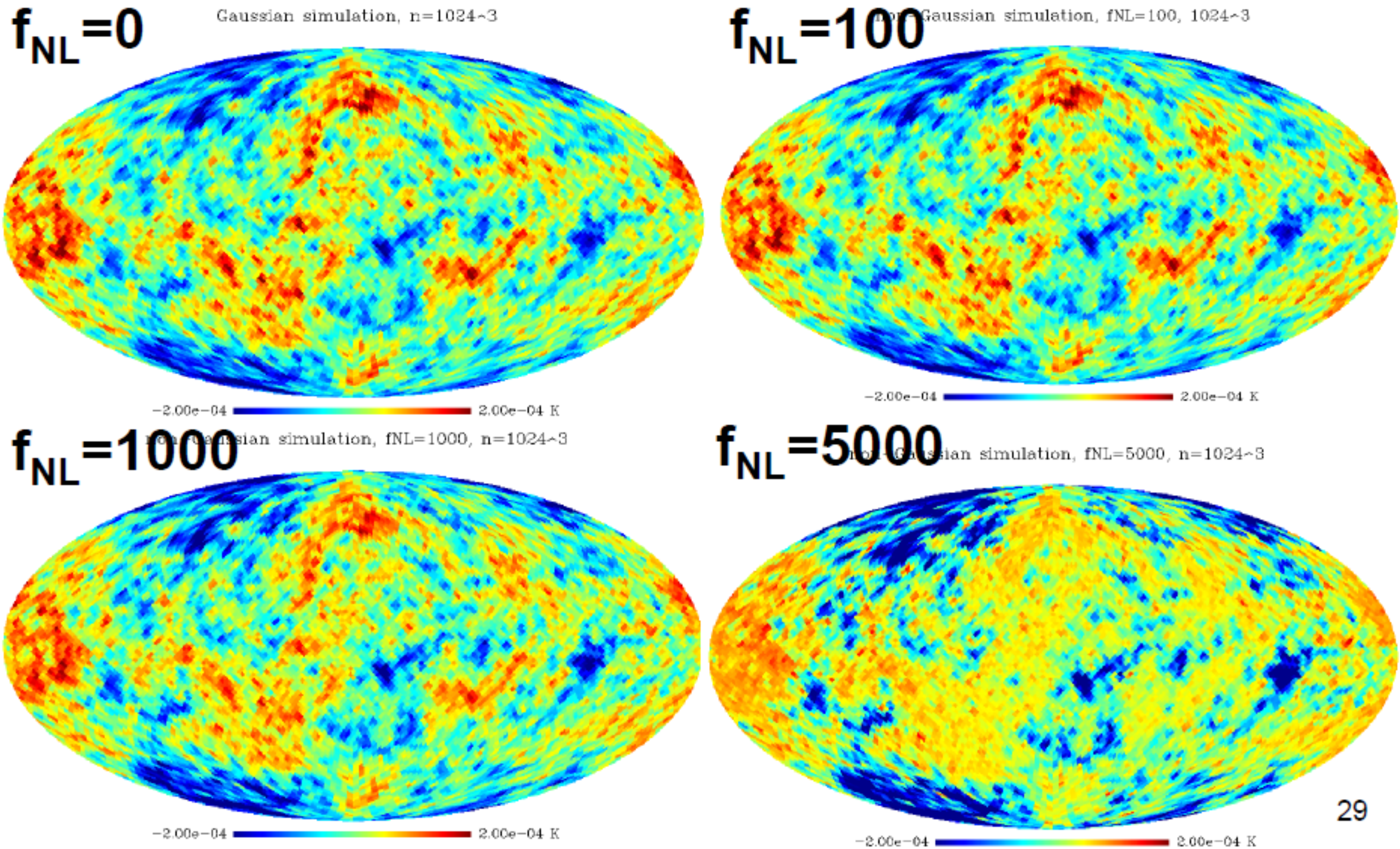
- $\Phi = \Phi_{Linear} + f_{NL}(\Phi_{Linear})^2$
  $\Phi_{Linear} = O(10^{-5})$, non-Gaussianity is tiny!
  Amplitude f_{NL} depends on inflation model
  [quadratic potential provides $f_{NL} = O(10^{-2})$]



4000
3000
2000
1000
0
$f_{NL}=100$
$f_{NL}=500$
$f_{NL}=1000$
$f_{NL}=3000$
−0.5
0
0.5
ΔT [mK]

Positive f_{NL} = More Cold Spots

Simulated temperature maps from $\Phi(x) = \Phi_G(x) + f_{NL}\Phi_G^2(x)$



Very Tiny Effect:
Fancy analysis (Bispectrum etc) starts to reveal non-Gaussianity?

First "Detection" in WMAP CMB map

$+27 < f_{NL}$(local) $< +147$ (95% CL; **lmax=750**)
(Yadav & Wandelt, arXiv:0712.1148)

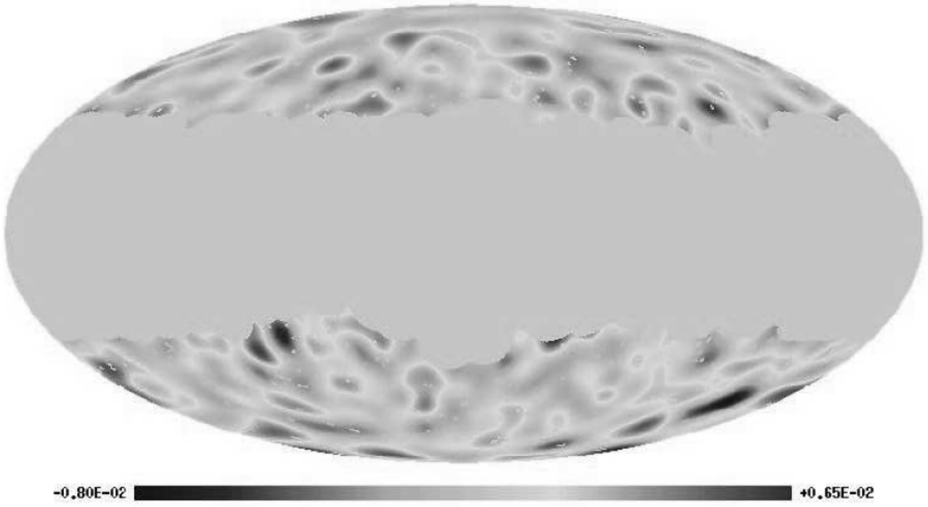
$-9 < f_{NL}^{\text{local}} < 111$ (95% CL) WMAP 5 yr.

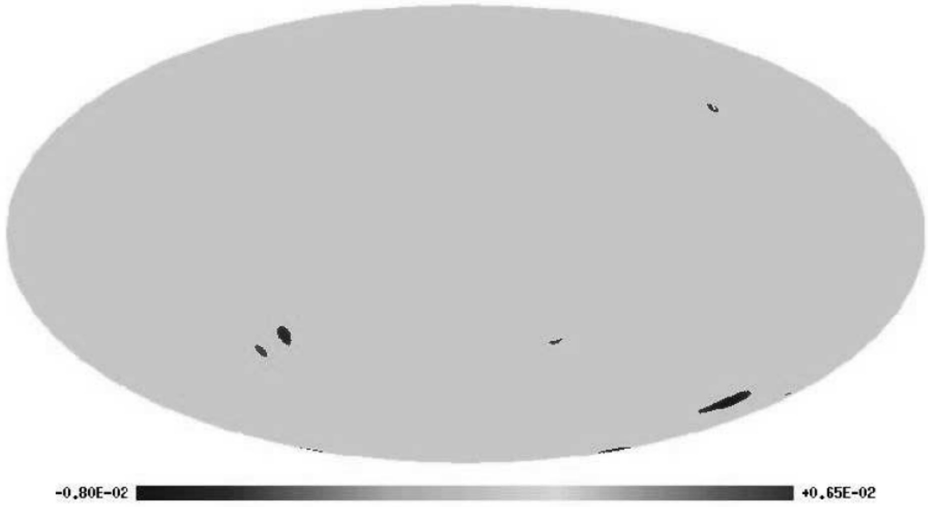
WMAP 7 yr.

Local	$-10 < f_{NL}^{\text{local}} < 74$[k]
Equilateral	$-214 < f_{NL}^{\text{equil}} < 266$
Orthogonal	$-410 < f_{NL}^{\text{orthog}} < 6$

Cold Spot

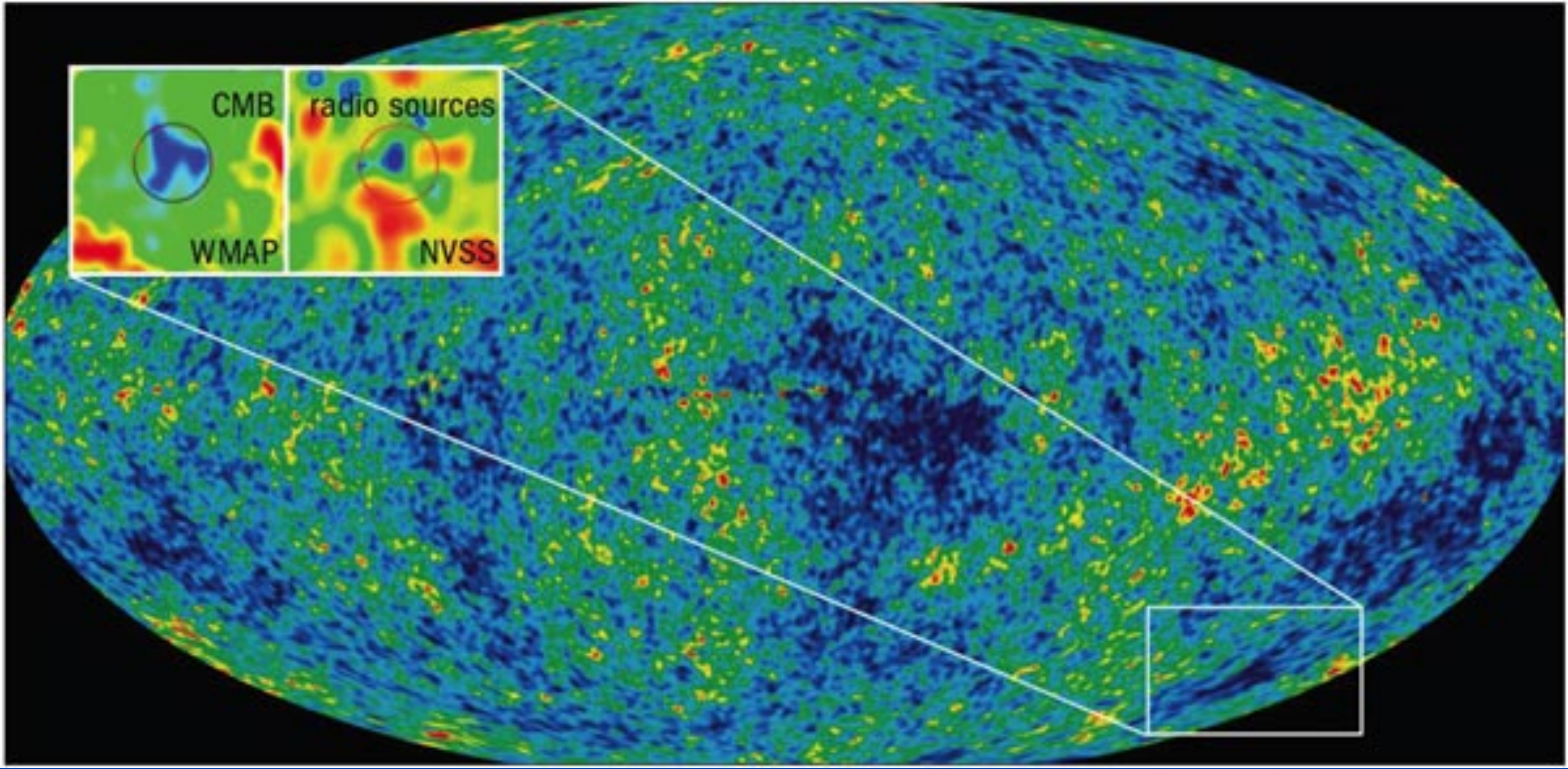
- Using Wavelet analysis for skewness and kurtosis, Santander people found cold spots





Kurtosis Coefficient

Only 3-sigma away

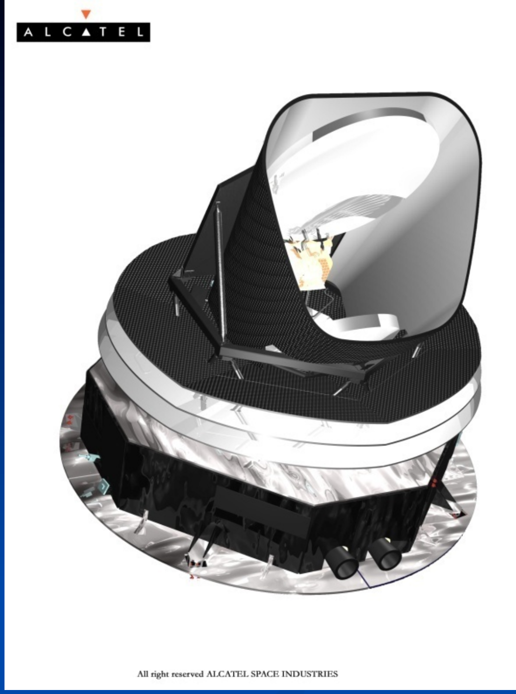


This cold spot might be induced by a Super-Void due to ISW since Rudnick et al. claimed to find a dip in NVSS radio galaxy number counts in the Cold Spot.

Super Void: One Billion light yr size

Typical Void: *10 Million light yr size

Ongoing, Forthcoming Experiments



- PLANCK will show first results:
  - More Frequency Coverage
  - Better Angular Resolution
- Other Experiments
  - *Ongoing Ground-based:*
    - CAPMAP, CBI, DASI, KuPID, Polatron
  - *Upcoming Ground-based:*
    - AMiBA, BICEP, PolarBear, QUEST, CLOVER
  - *Balloon:*
    - Archeops, BOOMERanG, MAXIPOL
  - *Space:*
    - Inflation Probe

PLANCK vs WMAP

WMAP Frequency

WMAP Frequency Bands					
Microwave Band	K	Ka	Q	V	W
Frequency (GHz)	22	30	40	60	90
Wavelength (mm)	13.6	10.0	7.5	5.0	3.3

WMAP Angular Resolution

Frequency	22 GHz	30 GHz	40 GHz	60 GHz	90 GHz
FWHM, degrees	0.93	0.68	0.53	0.35	<0.23

Summary of Planck Instrument Characteristics

Instrument Characteristic	LFI			HFI					
Detector Technology	HEMT arrays			Bolometer arrays					
Center Frequency [GHz]	30	44	70	100	143	217	353	545	857
Bandwidth ($\Delta\nu/\nu$)	0.2	0.2	0.2	0.33	0.33	0.33	0.33	0.33	0.33
Angular Resolution (arcmin)	33	24	14	10	7.1	5.0	5.0	5.0	5.0
$\Delta T/T$ per pixel (Stokes I)[a]	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
$\Delta T/T$ per pixel (Stokes Q &U)[a]	2.8	3.9	6.7	4.0	4.2	9.8	29.8	...	...

[a] Goal (in μK/K) for 14 months integration, 1σ, for square pixels whose sides are given in the row "Angular Resolution".

More Frequencies and better angular resolution

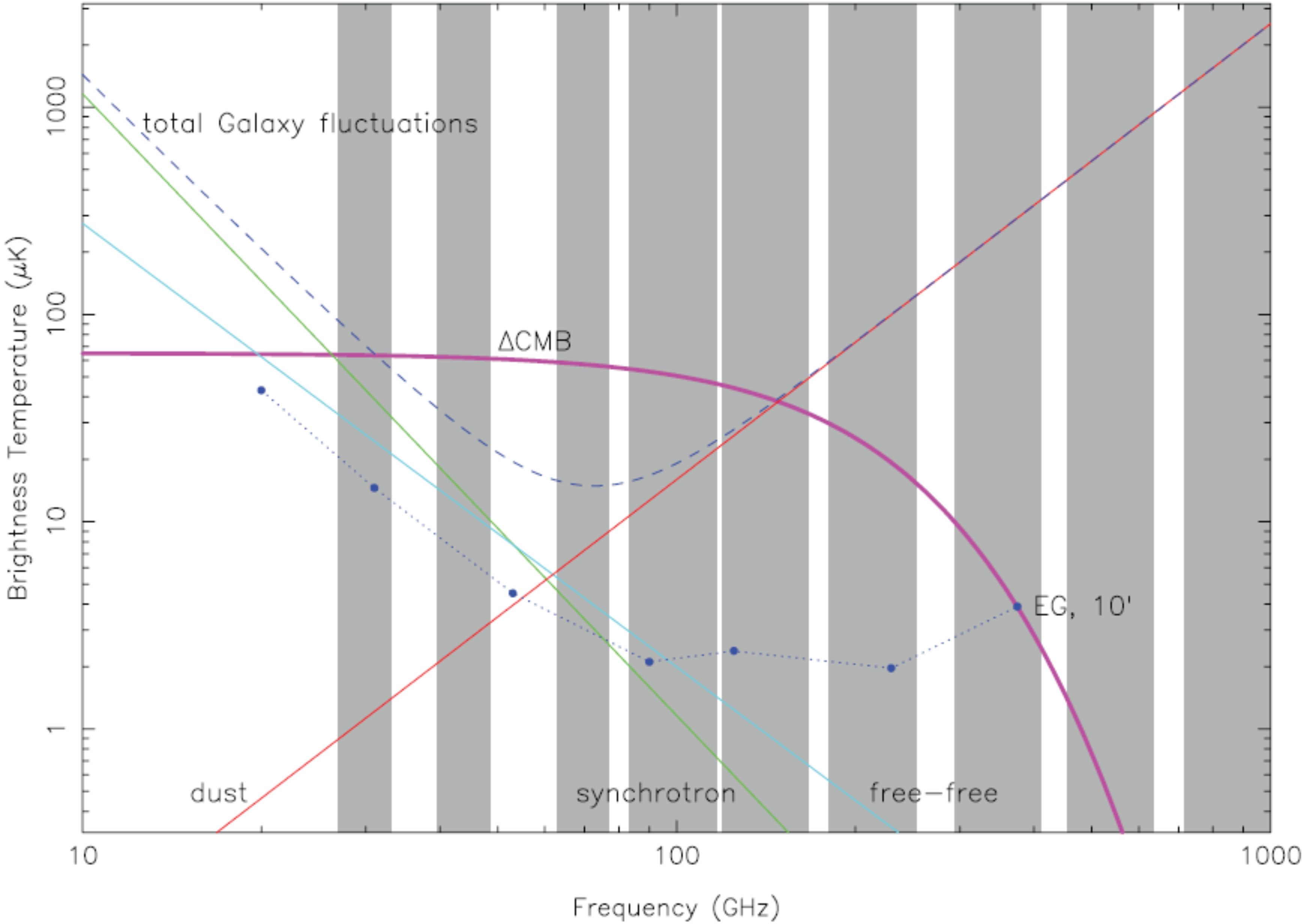
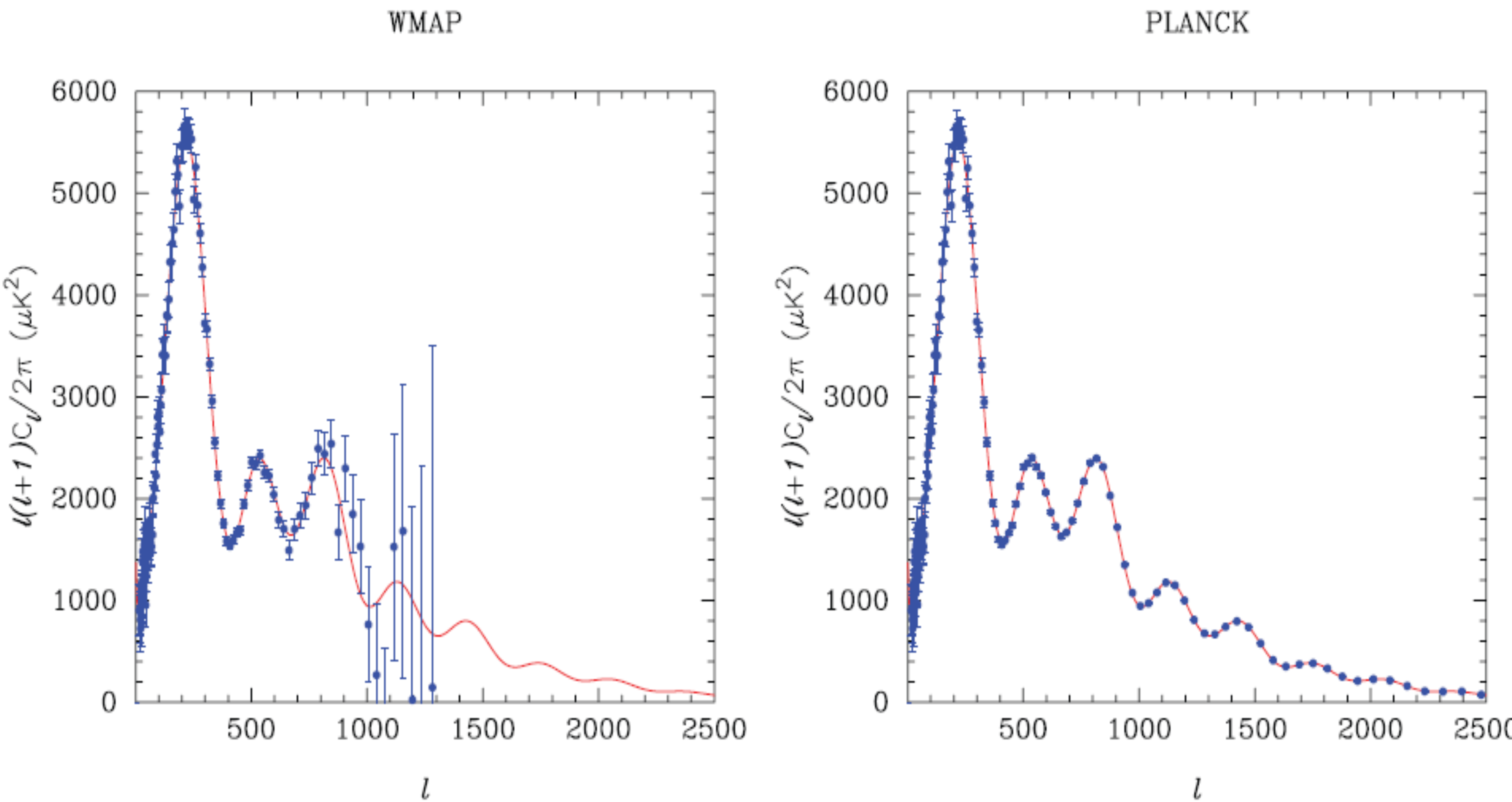
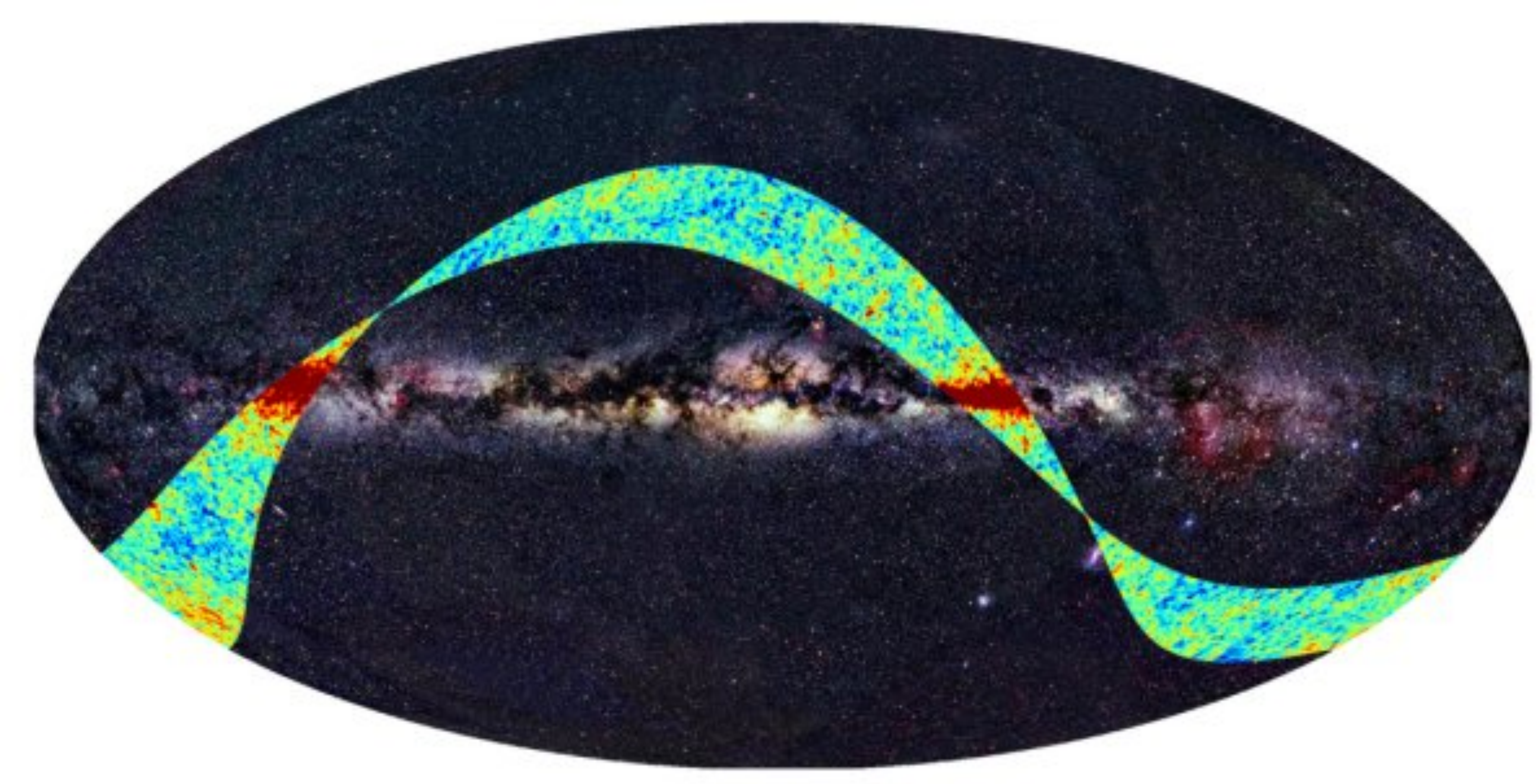


FIG 1.3.— Spectrum of the CMB, and the frequency coverage of the *Planck* channels. Also indicated are the spectra of other sources of fluctuations in the microwave sky. Dust, synchrotron, and free-free temperature fluctuation (i.e., unpolarized) levels correspond to the *WMAP* Kp2 levels (85% of the sky; Bennett et al. 2003). The CMB and Galactic fluctuation levels depend on angular scale, and are shown for ~1°. On small angular scales, extragalactic


WMAP
PLANCK
6000
5000
4000
3000
2000
1000
0
500
1000
1500
2000
2500
l
$l(l+1)C_l/2\pi$ (μK^2)

What We expect from PLANCK

- More Frequency Coverage
  - Better Estimation of Foreground Emission (Dust, Synchrotron etc)
  - Sensitivity to the SZ Effect
- Better Angular Resolution
  - Go beyond the third peak, and even reach Silk Damping: Much Better Estimation of Cosmological Parameters, and sensitivity to the secondary effect.
- Polarization
  - Gravitational Wave: Probe Inflation
  - Reionization: First Star Formation



Planck is coming!

Current Status of PLANCK

- Everything goes well!

Latest News

27 August: today at 14:49 CET is the official end of the First Light Survey and the start of the first all-sky survey ! This marks the start of routine operations for Planck. If everything goes well, this phase will be uninterrupted for at least 15 months. In fact, it is likely that later this week, the results of the preliminary data analysis of the First Light Survey will show that it can also be incorporated into the first survey, implying that it has actually started two weeks ago.

21 August: one week into the First Light Survey, operations are progressing as planned. The satellite, payload and the ground segment infrastucture are all stable. There is therefore good confidence that the routine phase of the mission will start during the pass of 27 August.

13 August: Following the last planned activities, including the spin-up/spin-down (which was executed very smoothly), the First Light Survey officially started today and will last two weeks. It will end on 27 August, at which time the first All-Sky Survey will begin.

Where will we be in 5 Years?

- PLANCK + ACTPol
  - Amplitude of structure to 0.5%
  - Acoustic scale to 0.02%
  - Matter Density to 1%
  - CMB Lensing
    - Measure power spectrum at z~2 (search for early dark energy)