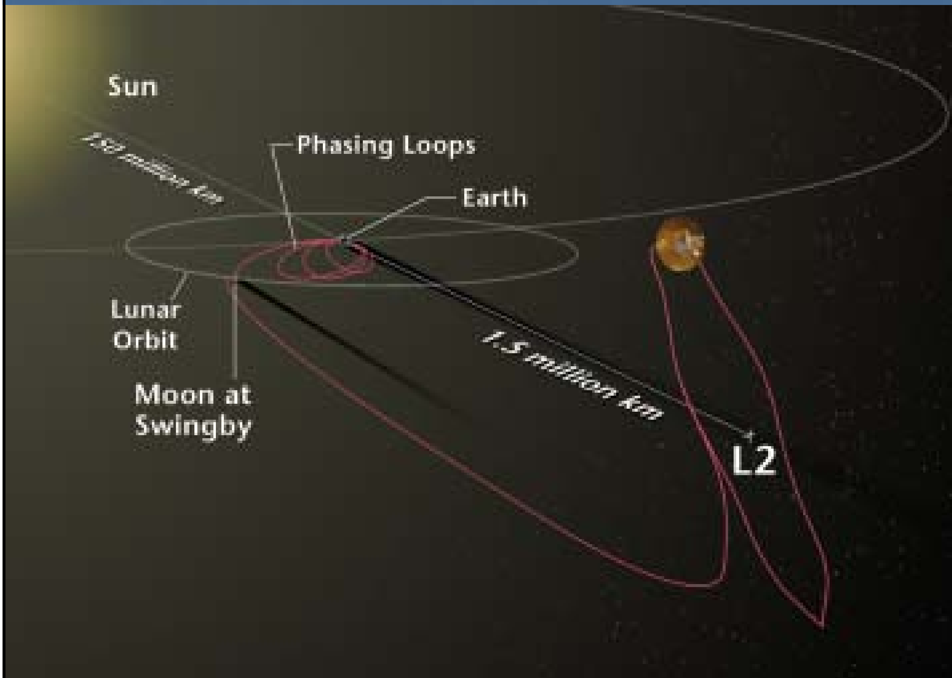
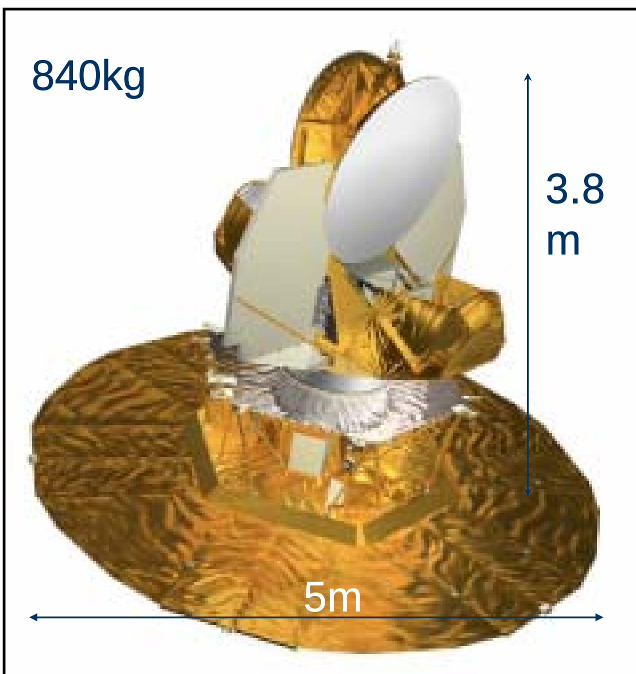
First Results of Wilkinson Microwave Anisotropy Probe：WMAP

Wilkinsonは昨年亡くなったチームの精神的リーダー

国立天文台
理論天文学研究系
杉山直

- 人工衛星、ラグランジュポイントＬ２、地球から１５０万キロ太陽とは逆側に。
- ＣＯＢＥ以後、最初のスペース、全天観測
- ＣＯＢＥの１０倍細かく分解し、１０倍感度のよい観測(l=900まで)
- 多波長で観測：5-bands, 23,33,41,61,94 GHz
- 宇宙マイクロ波背景放射の温度の分布を１００万分の１の精度で観測
- 偏光成分も詳細に測定
- 誕生からおよそ４０万年（３８万年）後の宇宙の様子


Sun
150 million km
Phasing Loops
Earth
Lunar Orbit
Moon at Swingby
1.5 million km
L2


840kg
3.8
m
5m

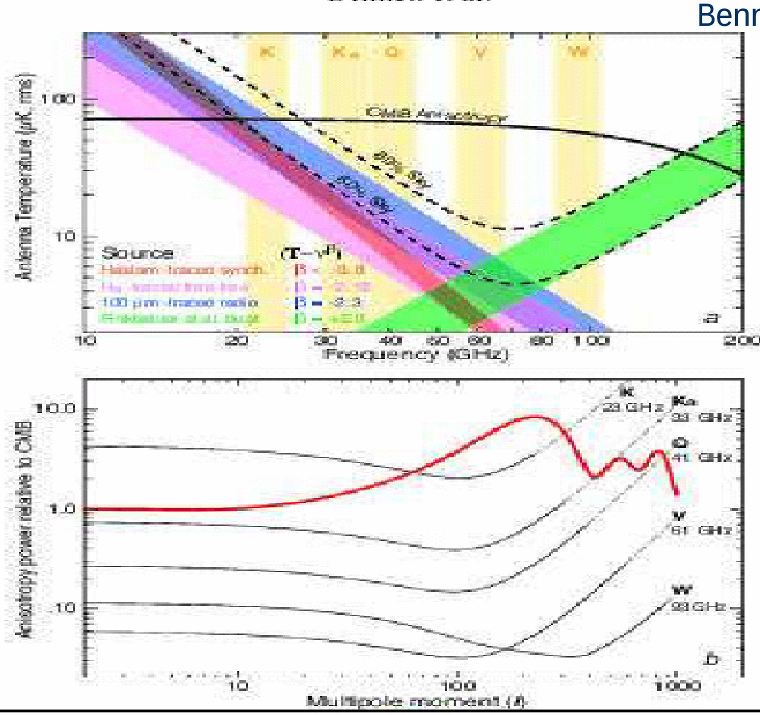
4年の観測計画

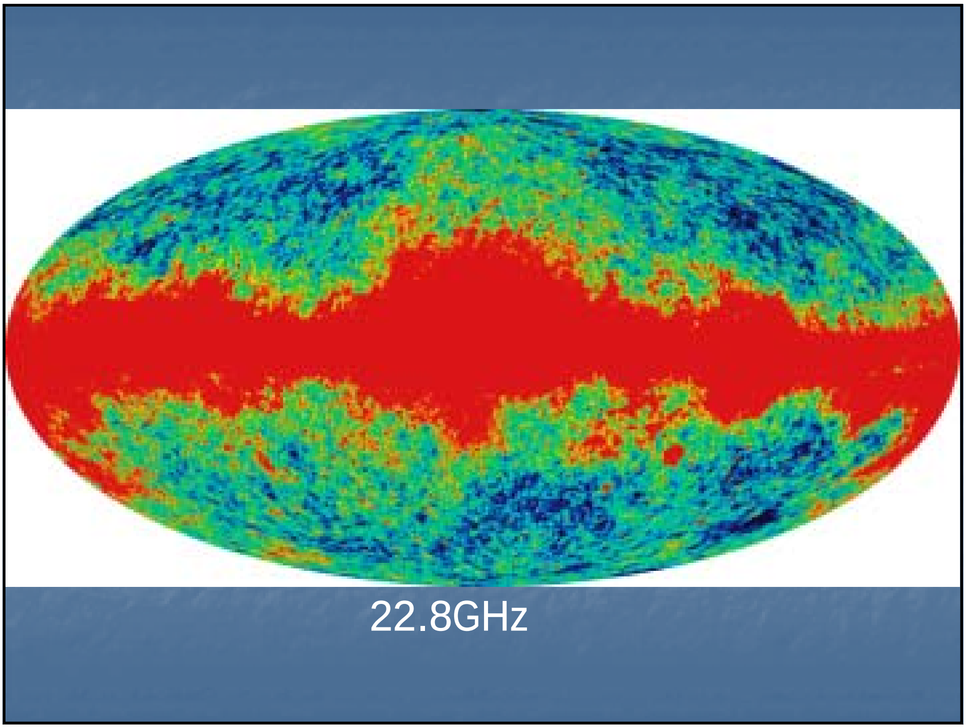
Table 1. Approximate Observational Properties by Band

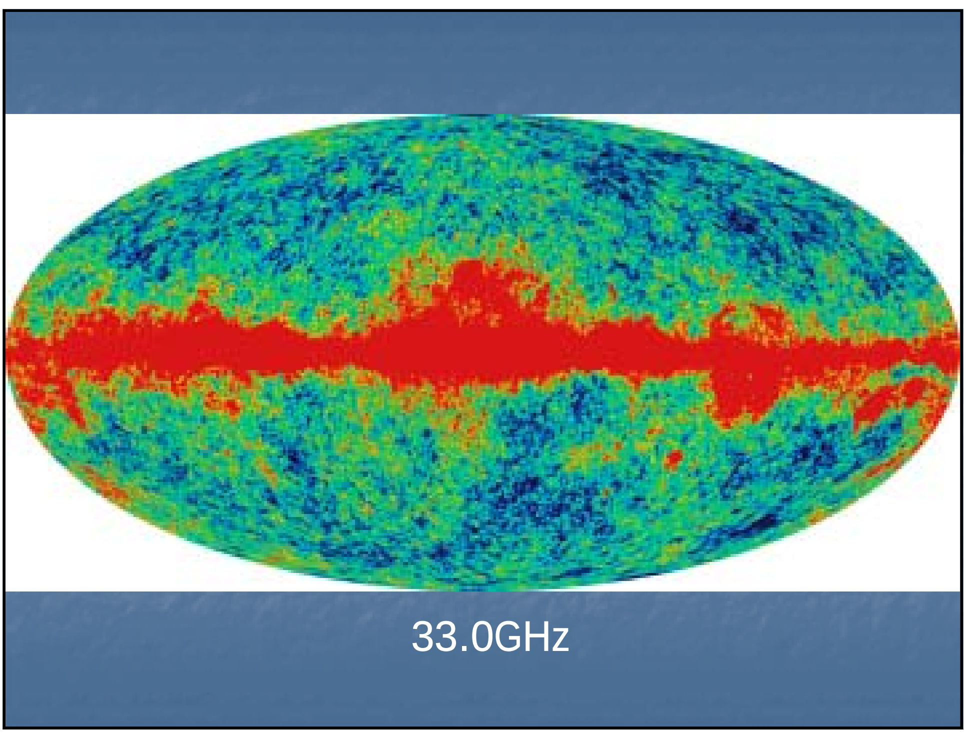
Item	K-Band	Ka-Band	Q-Band	V-Band	W-Band
Wavelength, λ (mm)	13	9.1	7.3	4.9	3.2
Frequency, ν (GHz)	22.8	33.0	40.7	60.8	93.5
Ant./therm. conversion factor, $\Delta T/\Delta T_A$	1.014	1.029	1.044	1.100	1.251
Noise, σ_0 (mK) $\sigma = \sigma_0 N_{obs}^{-1/2}$	1.424	1.449	2.211	3.112	6.498
Beam width θ(°FWHM)	0.82	0.62	0.49	0.33	0.21
No. of Differencing Assemblies	1	1	2	2	4
No. of Radiometers	2	2	4	4	8
No. of Channels	4	4	8	8	16

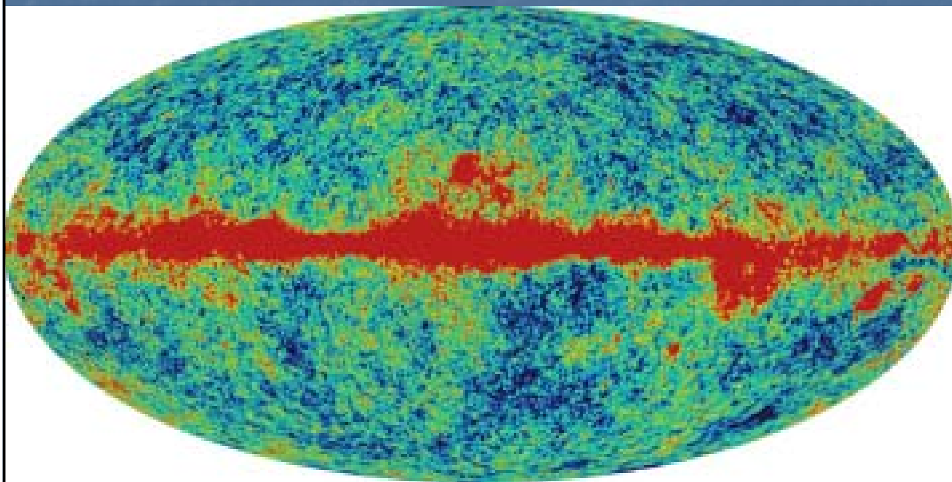
Beam Width: COBE, 7 degree (FWHM)

Bennet et al.

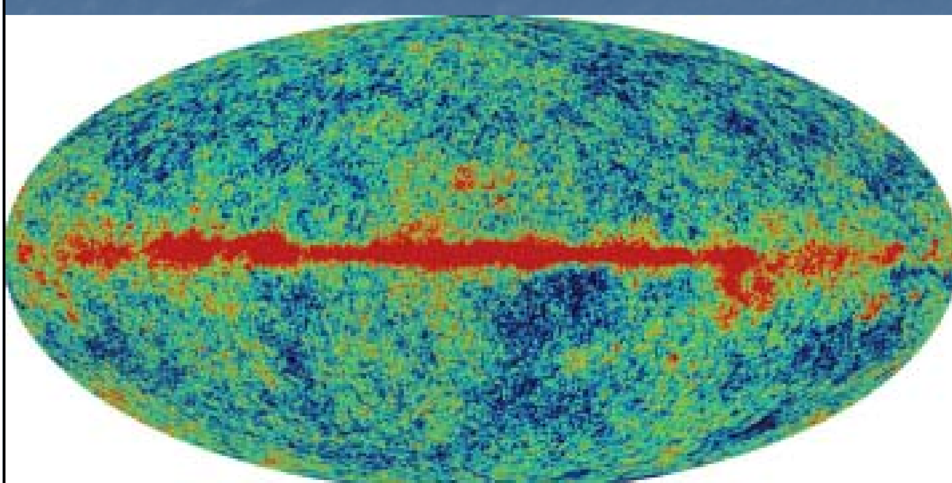



22.8GHz

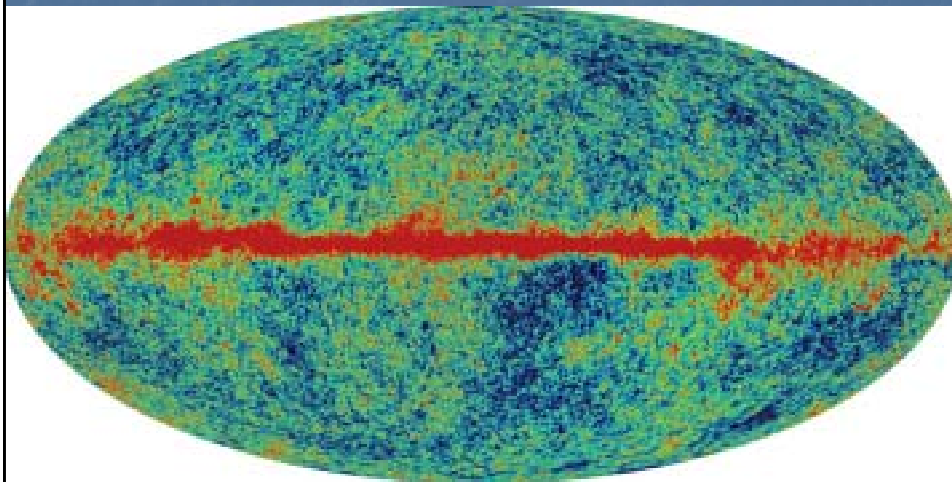

33.0GHz



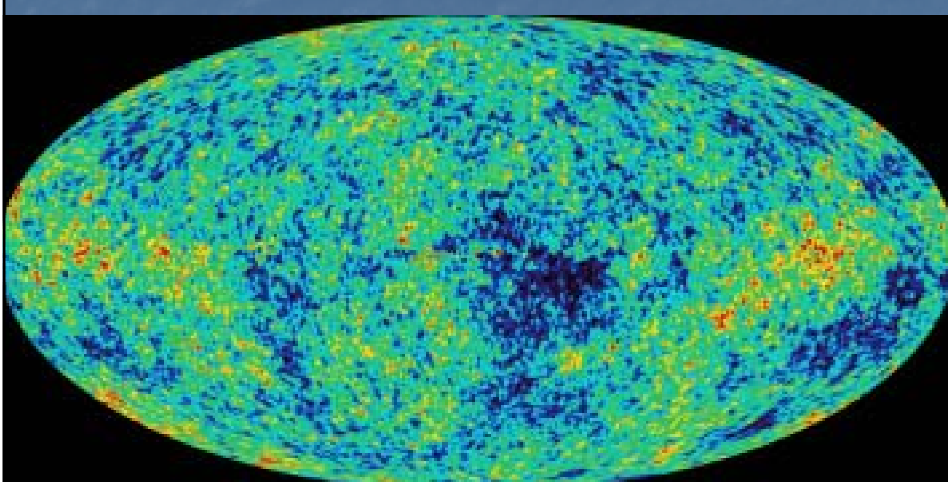
40.7GHz



60.8GHz

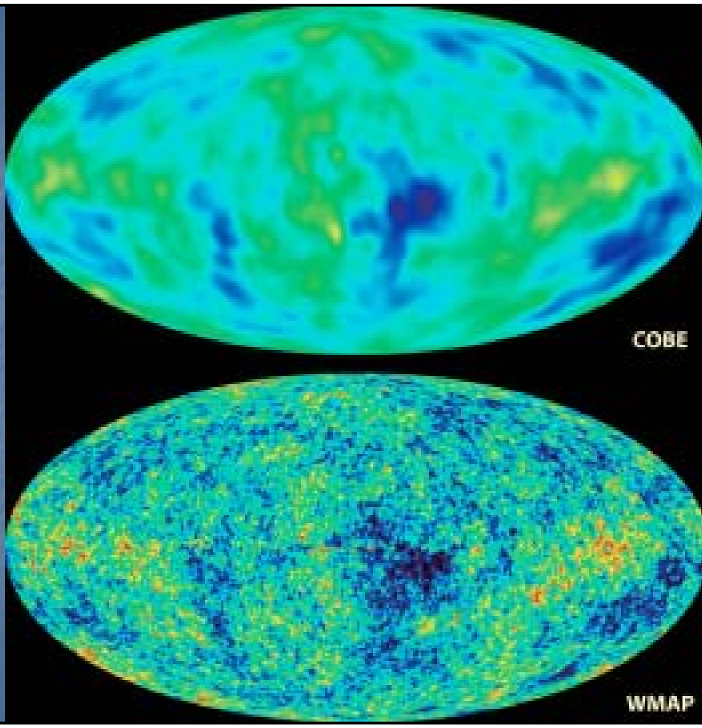


93.5GHz



MAP

COBEとの比較



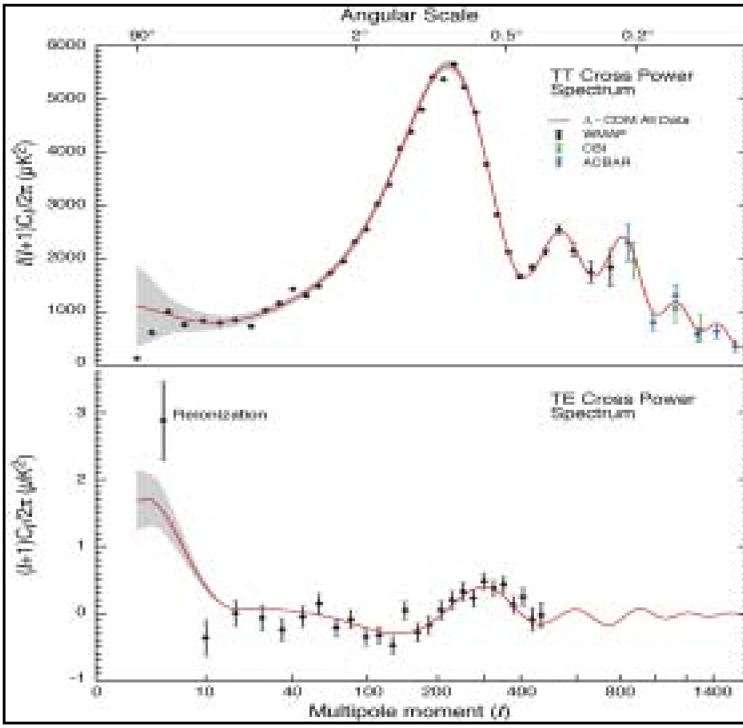
結果

- COBEとは完璧にconsistent (low quadrupole)
- Power Spectrum
- polarization

Visit

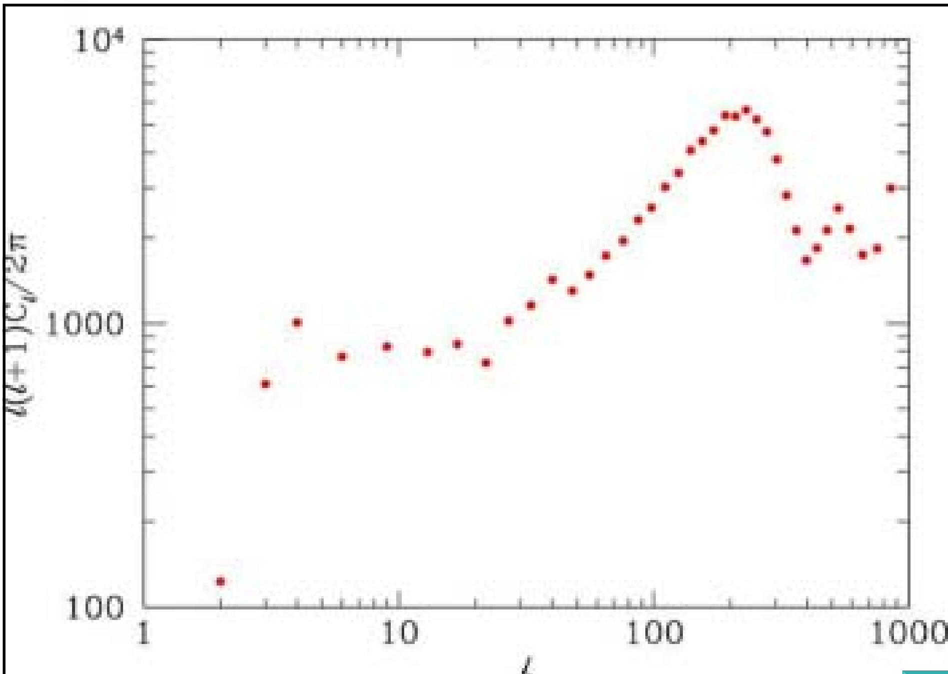
http://lambda.gsfc.nasa.gov/

You can find everything you need!



温度揺らぎ

温度揺らぎ
と偏光の
相関



Polarization

Produced by

Anisotropic Component of Thomson Scattering

need quadrupole component in temperature

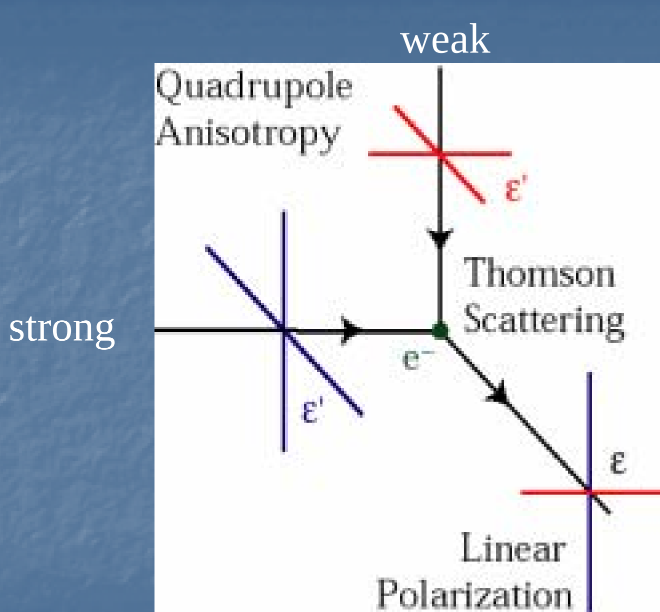
1) Phase difference between Temp. & Pol.

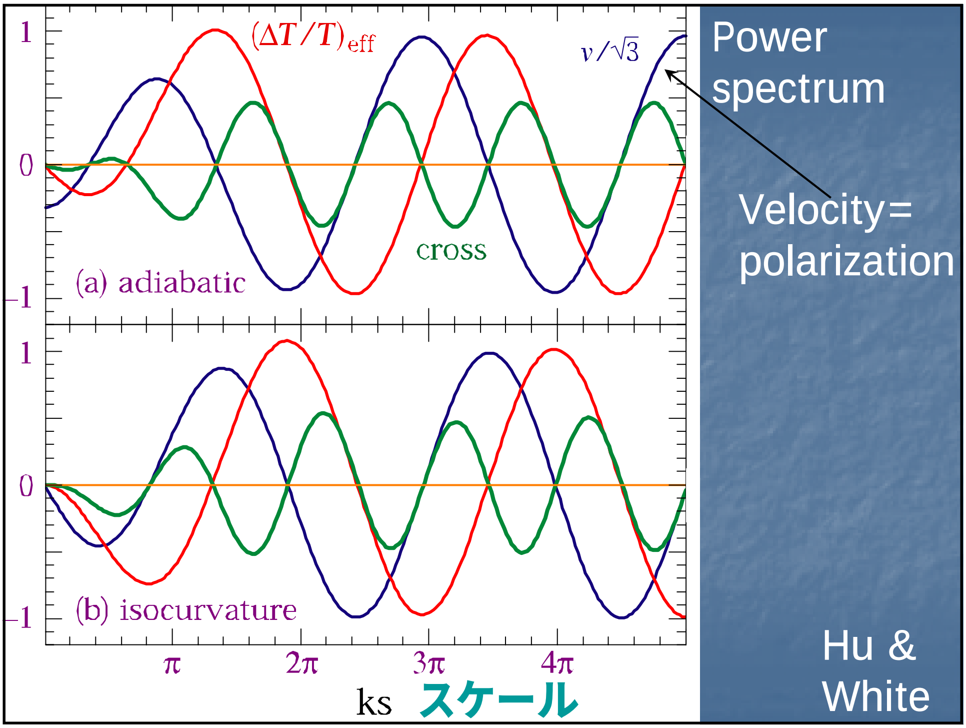
: polarization is generated by velocity

2) E-mode (parity even) & B-mode (parity odd)

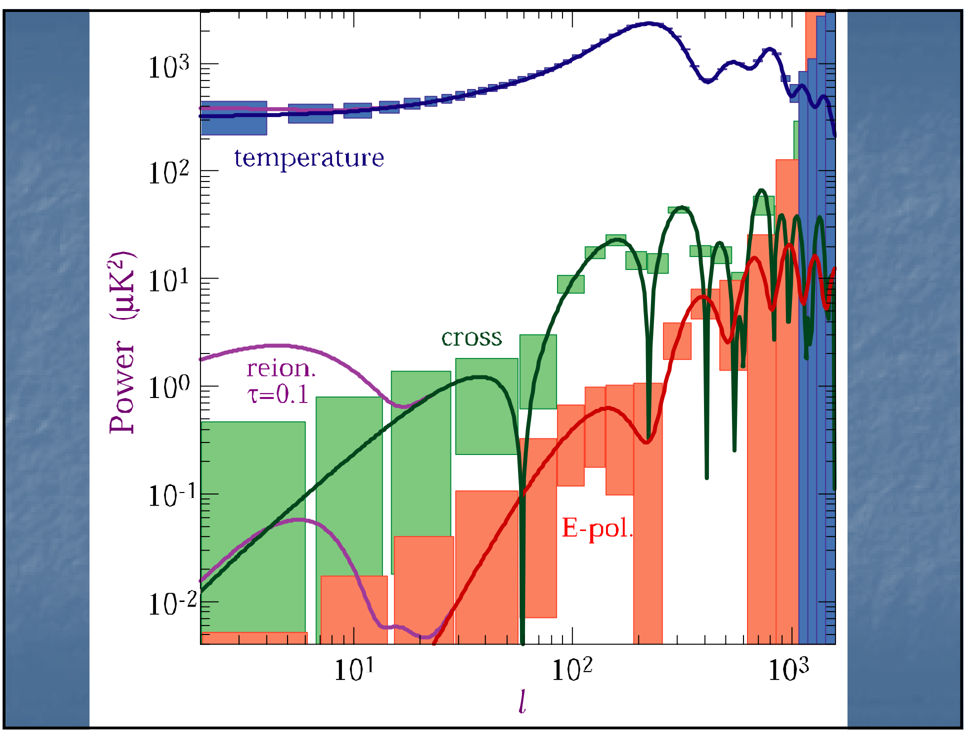
3) Temperature-Polarization (TP) correlation

Larger Signal





$(\Delta T/T)_{eff}$
$v/\sqrt{3}$
Power spectrum
Velocity= polarization
cross
(a) adiabatic
(b) isocurvature
π
2π
3π
4π
ks スケール
Hu & White



temperature
cross
reion.
τ=0.1
E-pol.
Power (μK²)
l

What can we learn?

1) Thermal History

- standard recombination

  ⇒ Peak at horizon scale at z=1000: ℓ= 100-1000

- re-ionization

  ⇒ Peak at horizon scale at z_i: ℓ= 10-100

2) Adiabatic vs. Isocurvature

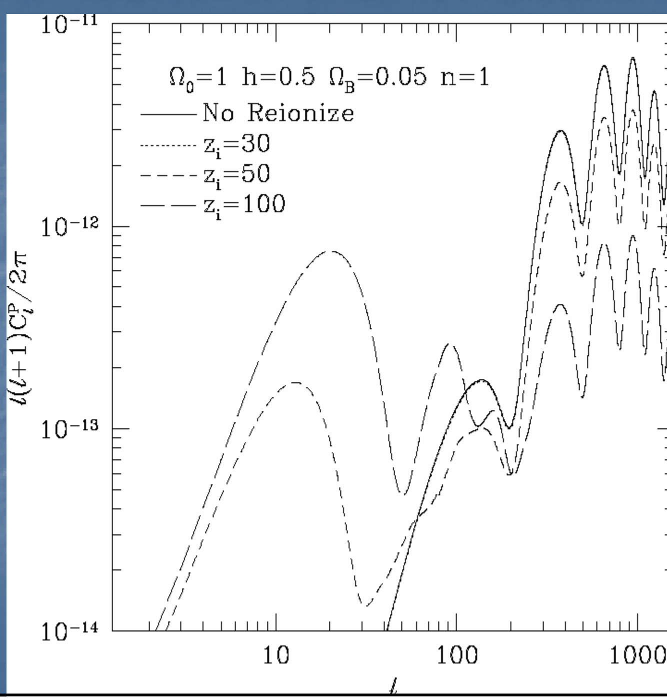
3) Scalar vs. Tensor

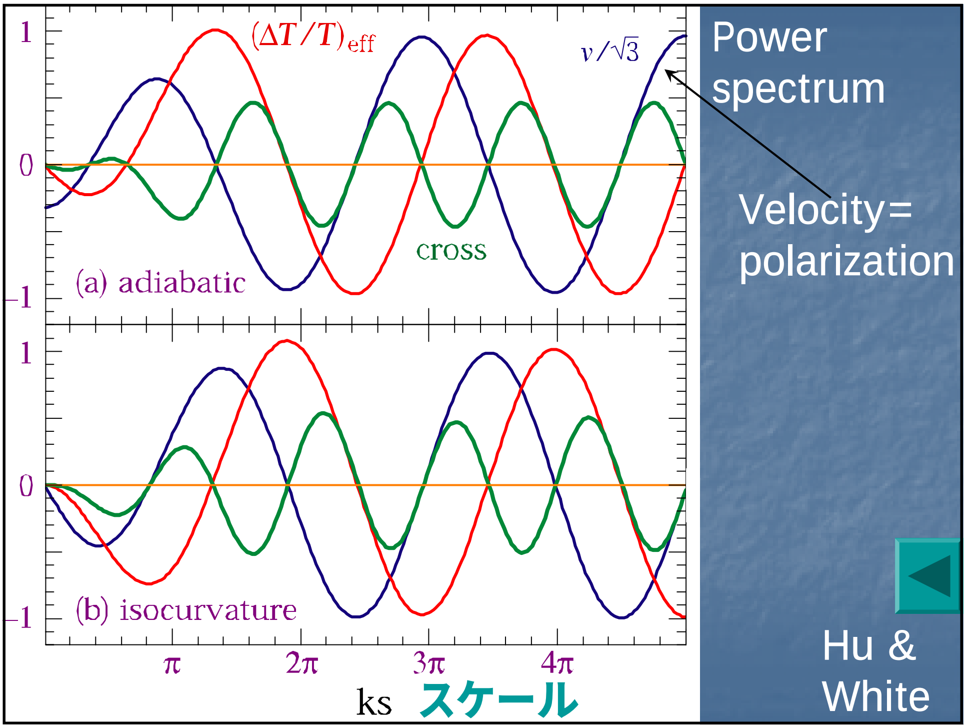
scalar: only E-mode

tensor: E+B modes

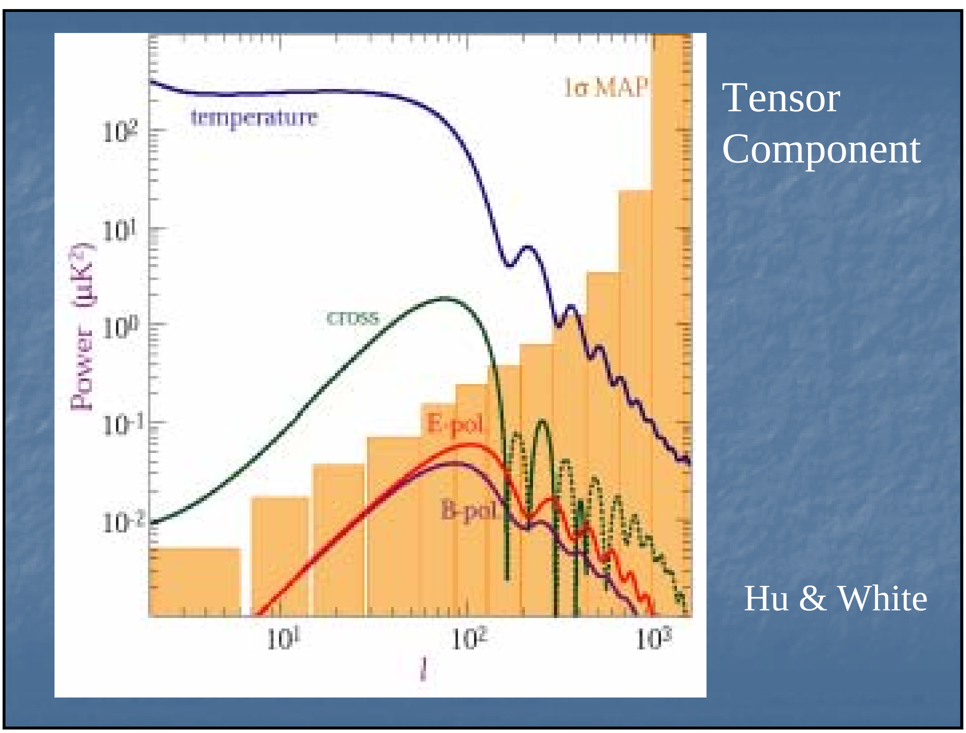
Polと

reionization

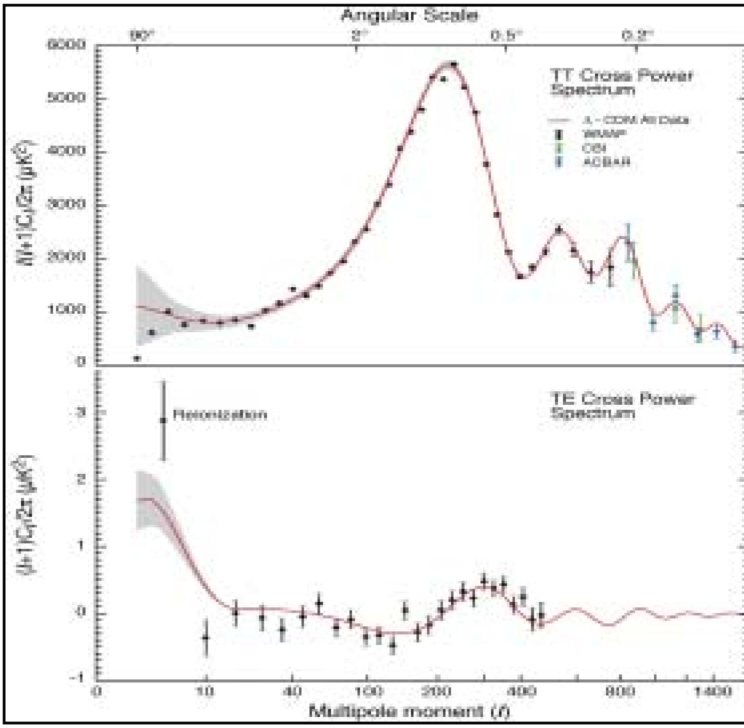




(ΔT/T)eff
v/√3
cross
(a) adiabatic
(b) isocurvature
1
0
−1
π
2π
3π
4π
ks スケール
Power spectrum
Velocity= polarization
Hu & White



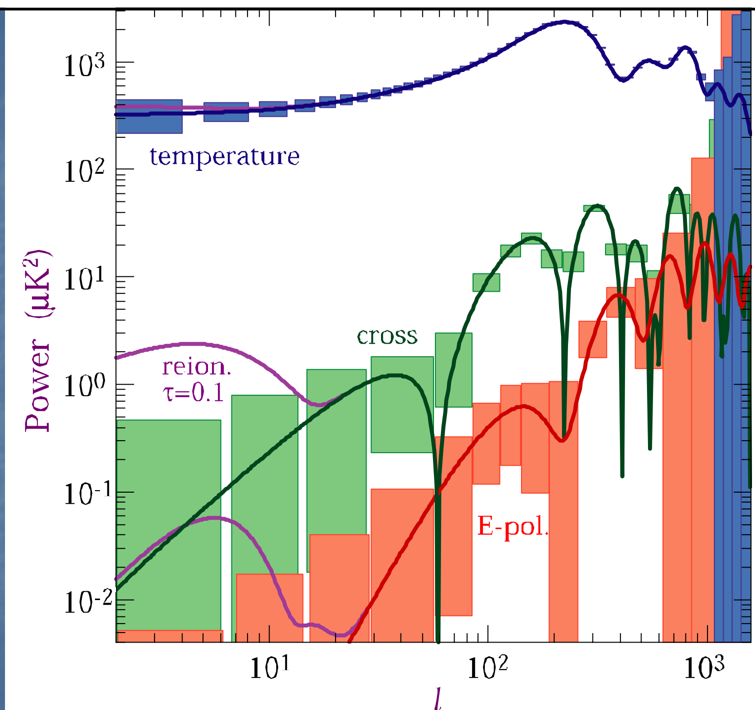
1σ MAP
temperature
cross
E-pol
B-pol
Power (μK²)
10²
10¹
10⁰
10⁻¹
10⁻²
10¹
10²
10³
l
Tensor Component
Hu & White



温度揺らぎ

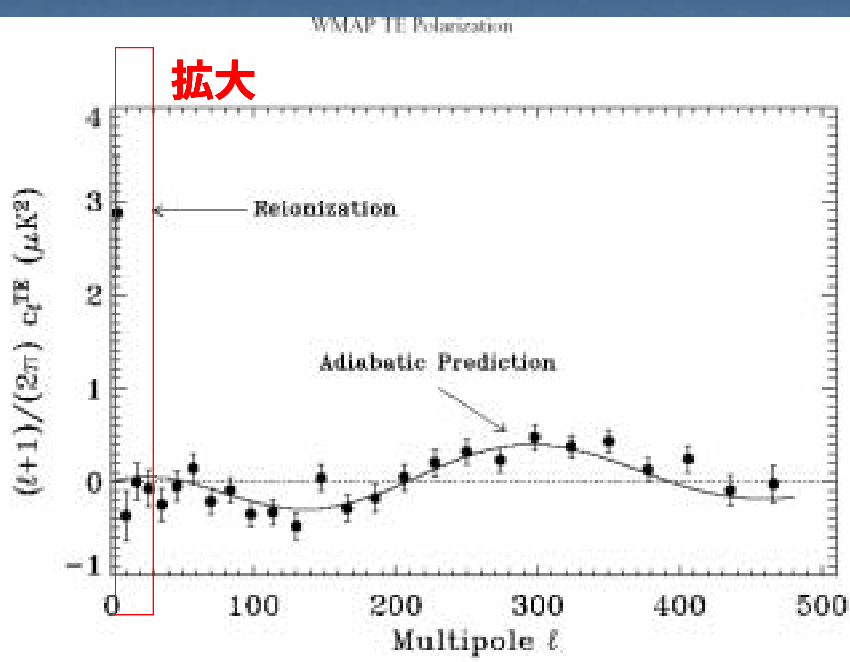
WMAP
の観測

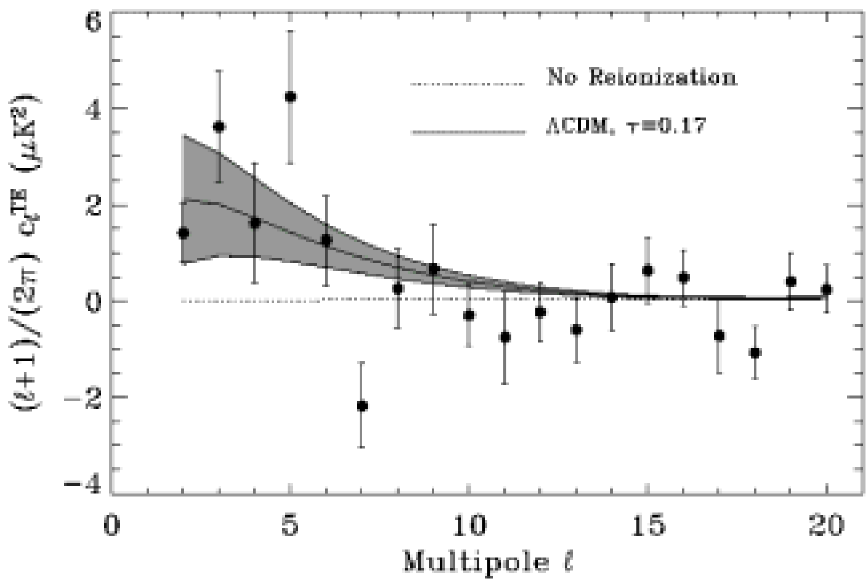
温度揺らぎ
と偏光の
相関



WMAPのpolarization

- adiabaticゆらぎ
- E-mode
- reionization of the universe after recombination





WMAPの結果の意味するところ

Spergel et al.

注意すべき点は、WMAP**のみの結果と、**
WMAP+fine scale CMB+2dF+Lyα+running ns
の結果若干異なる：後者を以下ではall**と略**
また、平坦な宇宙を仮定

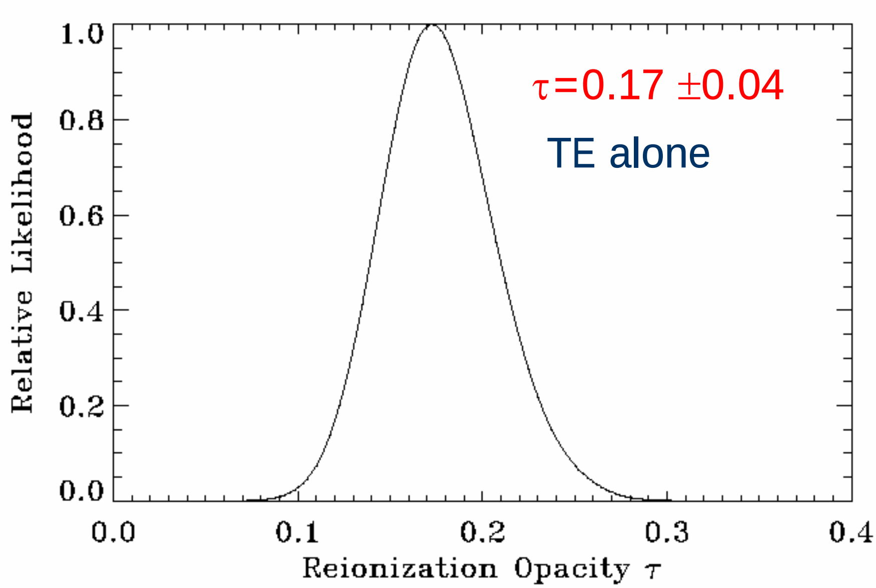
インフレーションからはじまった宇宙を支持する

- polarization**から**adiabatic fluctuations**確認**
- **揺らぎの統計：**non-Gaussian **の証拠はない**
- n_s=0.99±0.04(WMAP**のみ**)
- n_s=0.93±0.03(all)
- dn_s/dlnk=-0.031+0.031-0.017(all)

•最初の天体形成は

$$\tau = 0.166^{+0.076}_{-0.071}(\mathrm{WMAP})$$
$$= 0.17 \pm 0.04(\mathrm{all})$$
$$z_{reio} = 20^{+10}_{-9}(95\%CL)$$
$$t_{rio} = 180^{+220}_{-80}(95\%)$$

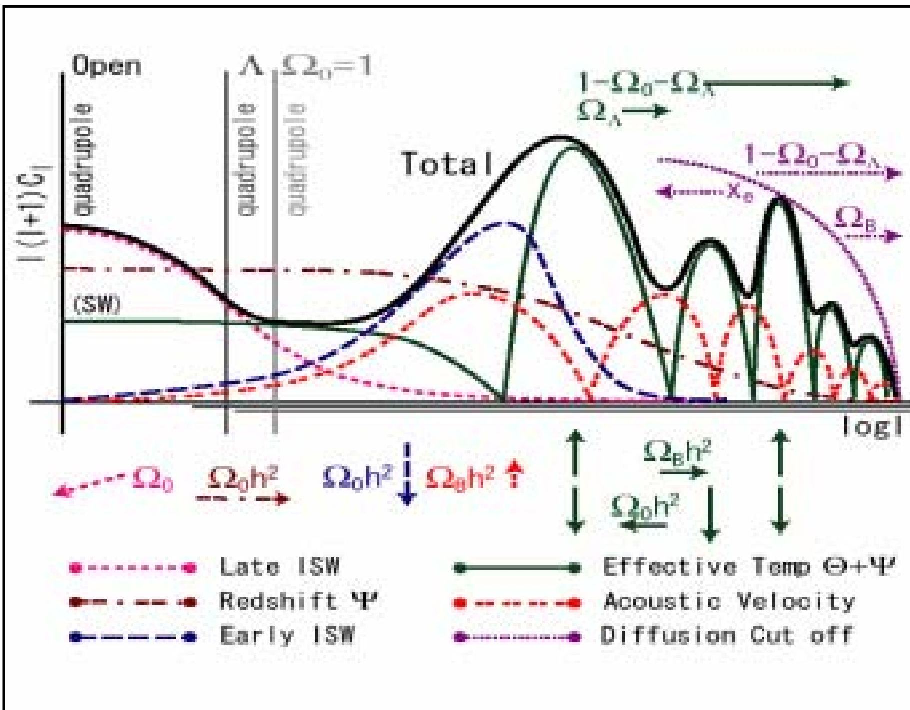
Reionizationをpolarizationから測定した

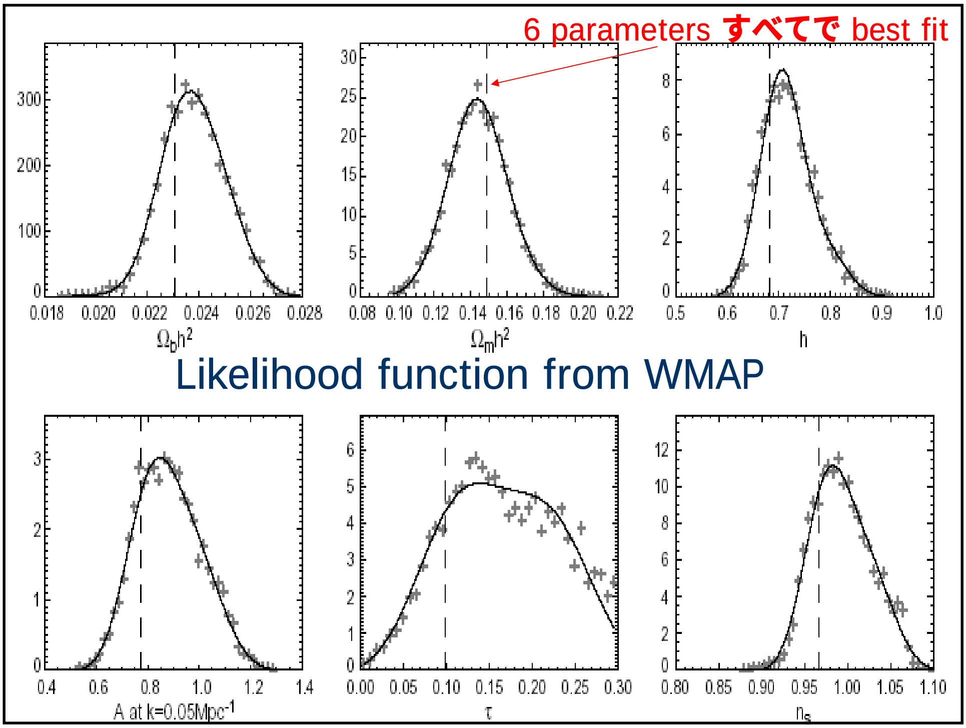


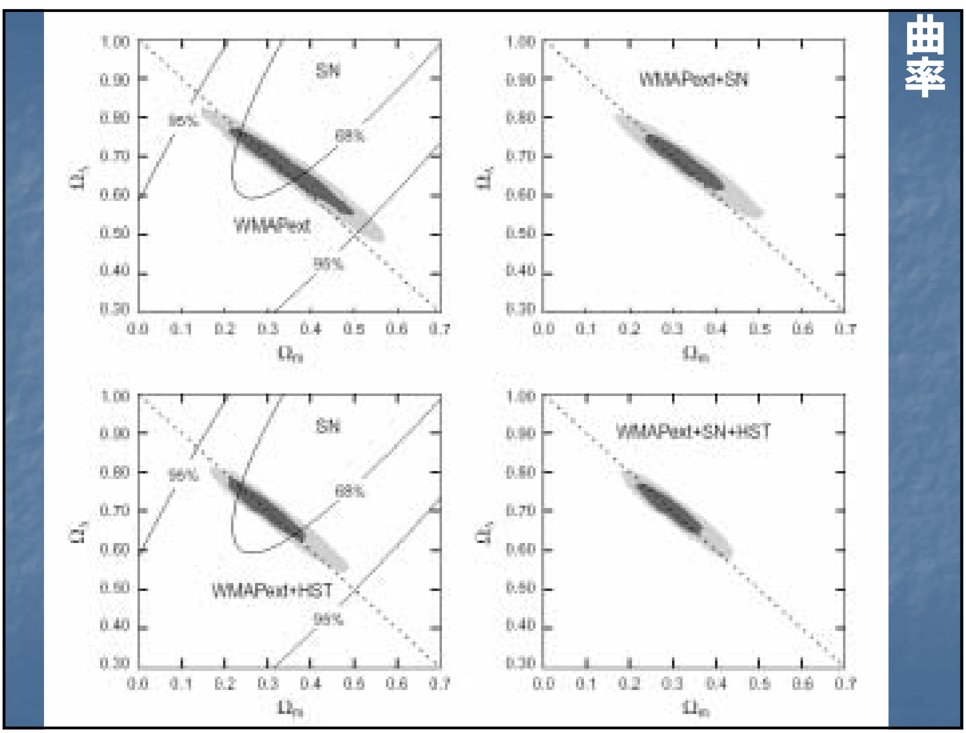
Optical depth from TE(temp-pol) Kogut et al.

Cosmological Parameters

$$
\begin{aligned}
h &= 0.72 \pm 0.05 (\mathrm{WMAP}) \\
&= 0.71^{+0.04}_{-0.03} (\mathrm{all}) \\
\Omega_M h^2 &= 0.14 \pm 0.02 (\mathrm{WMAP}) \\
&= 0.135^{+0.008}_{-0.009} (\mathrm{all}) \\
\Omega_B h^2 &= 0.024 \pm 0.001 (\mathrm{WMAP}) \\
&= 0.0224 \pm 0.0009 (\mathrm{all}) \\
\Omega_{tot} &= 1.02 \pm 0.02 (\mathrm{WMAP + SN, or, HST, 2DF})
\end{aligned}
$$




6 parameters すべてで best fit
Likelihood function from WMAP
Ωbh2
Ωmh2
h
A at k=0.05Mpc-1
τ
ns


曲率
SN
95%
68%
WMAPext
WMAPext+SN
WMAPext+HST
WMAPext+SN+HST
Ωm
ΩΛ

- 宇宙はやはり平坦だった
- 宇宙の全エネルギーのうち、4%がbaryon、23%がnon-baryoninc dark matter、残り73%がdark energy
- 現在の宇宙年齢は

  134 ±3億歳 (WMAPのみ)

  137 ±2億歳 (all)
- Recombination epochは

  z=1089±1

  $\Delta z = 195 \pm 2$

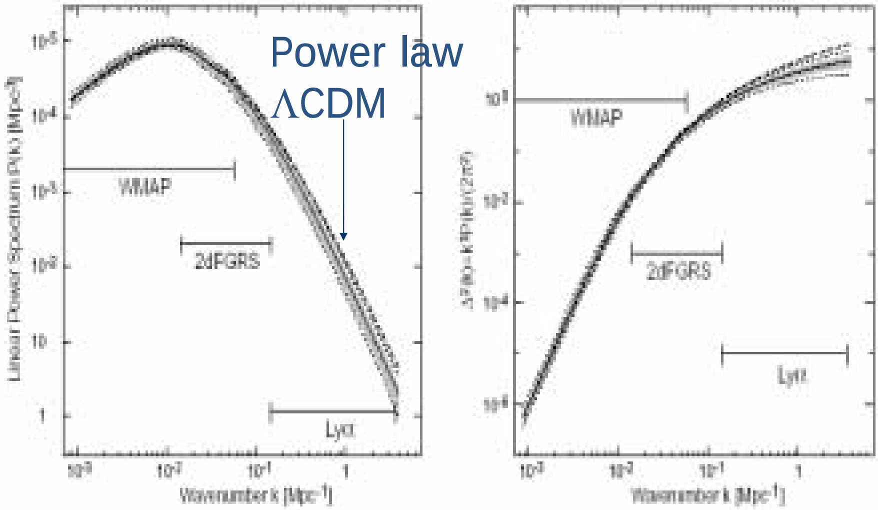
  t=379+8-7kyr.

その他おまけ

- 2dF Galaxy Redshift Survey, Ly-alphaとは有為にずれ：CMBの方がpower大きい

  Running spectral index?
- $w = p/\rho < -0.78$ (all data)

  Einsteinの宇宙項(w=-1)を示唆
- Tensor modeには $P_{tensor}/P_{scalar} < 0.71$
- neutrino mass: $m_\nu < 0.23$eV
- 極端にちいさなlow multipoleはなぜ？



すべて予想通り

(reionizationは早かった)

Stokes Parameters

$$E_x = a_x \sin(\omega t - \varepsilon_x(t))$$

$$E_y = a_y \sin(\omega t - \varepsilon_y(t))$$

$$I \equiv <a_x^2> + <a_y^2> = I_x + I_y$$

$$Q \equiv <a_y^2> - <a_x^2> = I_y - I_x$$

$$U \equiv <2a_x a_y \cos(\varepsilon_x - \varepsilon_y)>$$

$$V \equiv <2a_x a_y \sin(\varepsilon_x - \varepsilon_y)>$$

Rotational transformation: angle φ

$$Q' \pm iU' = \exp(\mp 2i\varphi)(Q \pm iU) \quad \Rightarrow \text{Spin 2}$$

Spin raising ∂_u and lowering ∂_d operators

$$\partial_d^2 (Q + iU) = \sum_{lm} \sqrt{(l+2)!/(l-2)!}\, a_{2,lm} Y_{lm}(\hat{n})$$

$$\partial_u^2 (Q - iU) = \sum_{lm} \sqrt{(l+2)!/(l-2)!}\, a_{-2,lm} Y_{lm}(\hat{n})$$

$$a_{E,lm} = -\frac{1}{2}(a_{2,lm} + a_{-2,lm})$$ E-mode; parity $(-1)^l$

$$a_{B,lm} = \frac{i}{2}(a_{2,lm} - a_{-2,lm})$$ B-mode; parity $(-1)^{l+1}$

Zaldarriaga, Seljak, PRD55 (97)1830