上州無智亦無才
剛毅木訥易被欺
唯以正直接萬人
至誠依神期勝利

鑑三

Prof Kodama (KEK cosmophysics group)

Prof Suto

Me(70kg)

Suto's students

Me(62kg)

Prof. K. Sato's group as of 1986
(6 years after proposing inflation)

(Part of) UTAP/RESCEU as of 2008

Sarujima (Monkey Island) in Tokyo Bay

On this slot of the symposium, originally Virginia Trimble was supposed to give a talk on the history of the concept Multiverse with the title "APERIO KOSMOI: Multiple Universes from the Ancients to 1981"
but she could not come here in the end, because she could not pass through the security check at Los Angels Airport……???

1981?

Inflation based on the first-order phase transition
K. Sato MNRAS 195(1981)467; PLB99(1981)66, A. Guth PRD23(1981)347

cf New inflation A. Linde PLB108(1982)389, Albrechet & Steinhardt PRL 48(1982)1220
R^2 theory A. Starobinskiy PLB91(1980)99
Chaotic inflation A. Linde PLB129(1983)177

Volume 108B, number 2 PHYSICS LETTERS 14 January 1982

MULTI-PRODUCTION OF UNIVERSES BY FIRST-ORDER PHASE TRANSITION OF A VACUUM

Katsuhiko SATO, Hideo KODAMA, Misao SASAKI [a] and Kei-ichi MAEDA

Department of Physics, Kyoto University, Kyoto 606, Japan

[a] *Research Institute for Fundamental Physics, Kyoto University, Kyoto 606, Japan*

1981

Received 8 June 1981

Revised manuscript received 6 October 1981

Gauge theories with spontaneously broken symmetries give rise to a cosmological phase transition of a vacuum. We show that if the phase transition is strongly of first order, such gauge theories combined with general relativity yield a surprising prediction; although the Creator might have made a unitary universe, many mini-universes are produced sequentially afterward as a result of the phase transition.

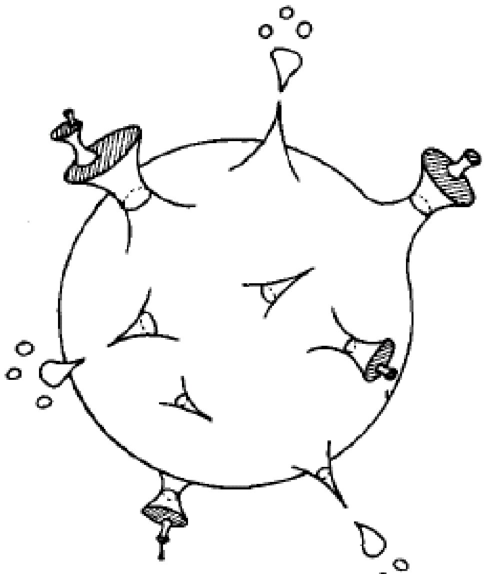


Fig. 2.

→ eternal inflation of Vilenkin and Linde

佐藤勝彦氏に仁科賞

Reporting that Professor Sato won Nishina Memorial Prize

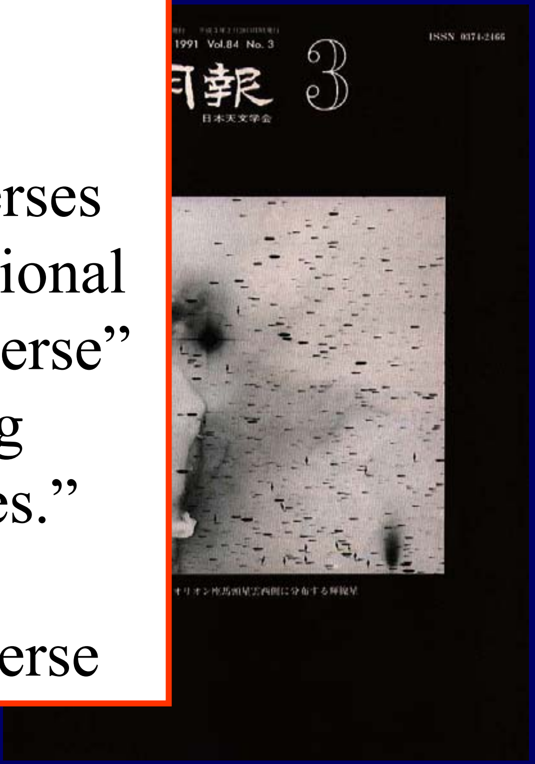
The paper of the multiproduction of the Universes was epoch-making in the sense that the conventional cosmology dealing with "the one and only Universe" was replaced by the new cosmology pushing "our Universe among many possible universes."

⬇

triggered a transition of the vision of the Universe

され，我々の宇宙が実現する確率まで議論されるようになっているが，こうした研究の背景には，佐藤氏を嚆矢とする上述のような宇宙観の変遷があることを忘れてはならない．

天文月報1991年3月号



Astronomical Herald
March, 1991
(by Astronomical Society of Japan)

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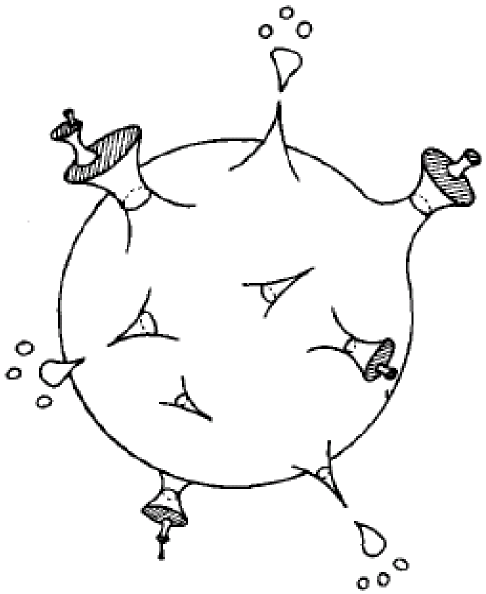


Fig. 2.

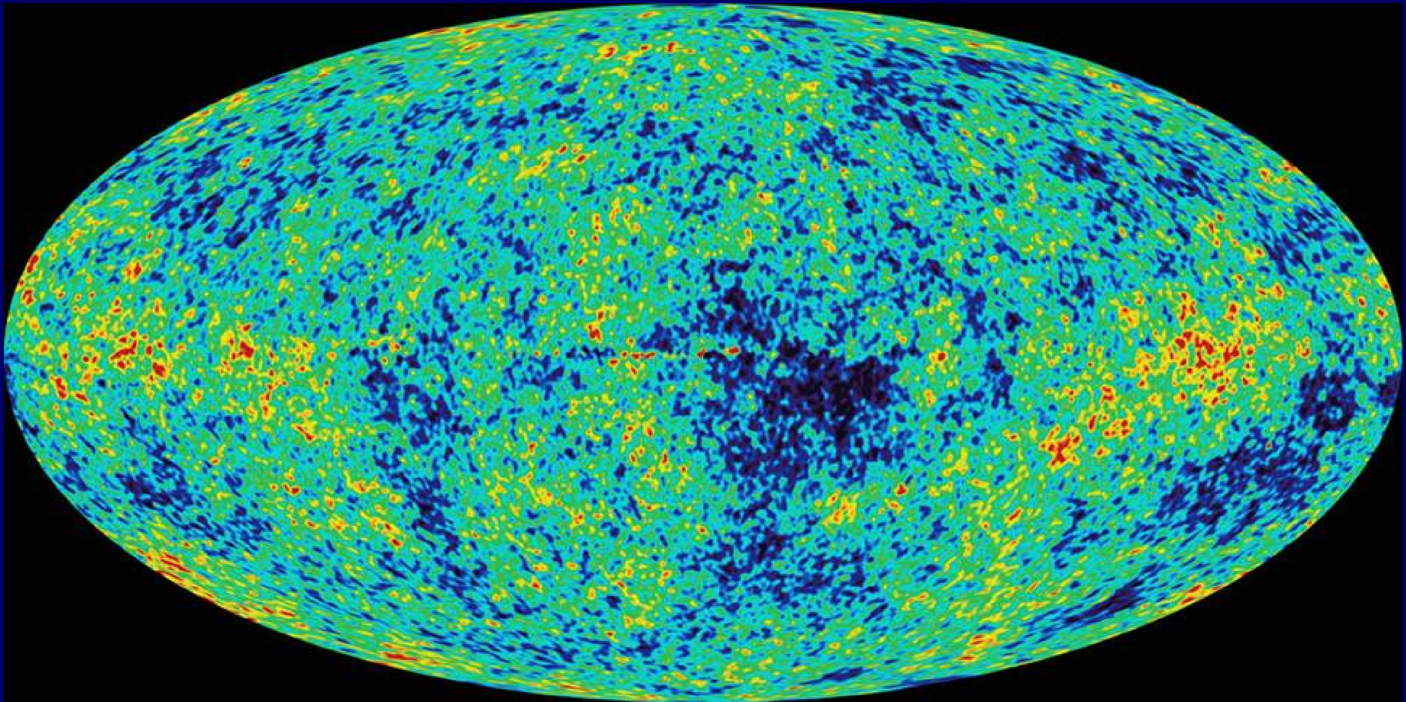
→ eternal inflation of Vilenkin and Linde

So much for the Multiverse

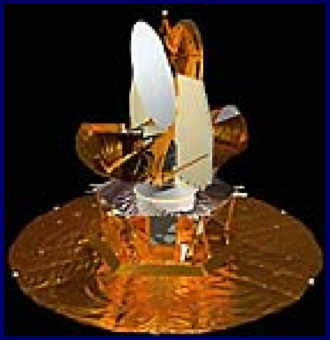
In the current paradigm of Inflationary Cosmology, in which the seeds of large scale structures and the anisotropy of CMB are explained in terms of quantum fluctuations of scalar fields,

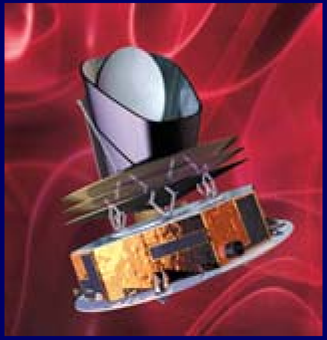
We must deal with the quantum ensemble of the universes whether there are many universes or only one.

We are observing one realization of the ensemble from a single point.



What can we learn about cosmophysics by observing only one Universe?





RESEARCH CENTER FOR THE EARLY UNIVERSE
THE UNIVERSITY OF TOKYO
RESCEU

東京大学 大学院
理学系研究科·理学部
SCHOOL OF SCIENCE, THE UNIVERSITY OF TOKYO

Jun'ichi Yokoyama

(RESCEU, U. Tokyo)

横山順一

Theories predict an ensemble average, and at best statistical distribution around it.

We can observe only one realization of the ensemble.

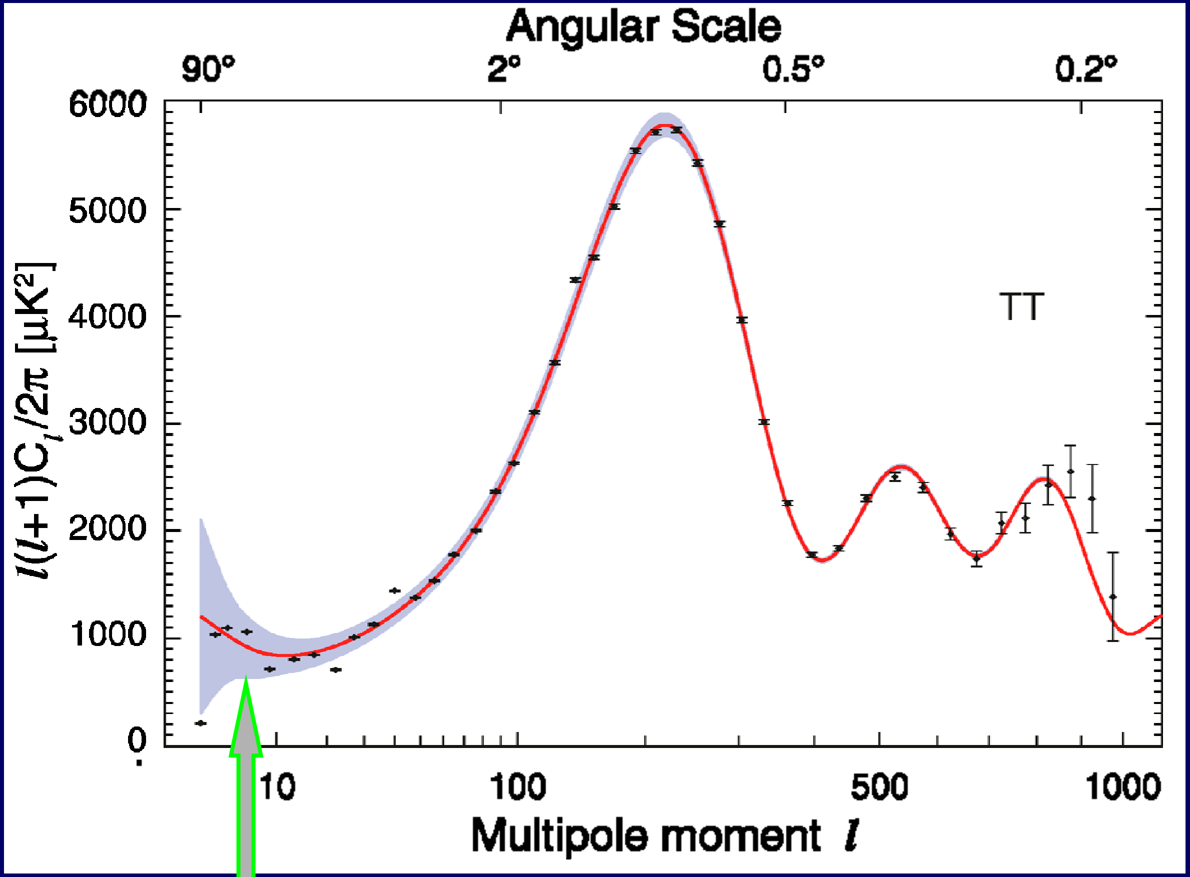
Comparison between theories and observations is done incorporating the cosmic variance.

We would be happy if
our theory agrees with observation
within the cosmic variance.

What should we do if it doesn't?

It depends on the degree of deviation,
of course.

5-year WMAP data. TT angular power spectrum



Theoretical curve of the best-fit ΛCDM model with a power-law initial spectrum

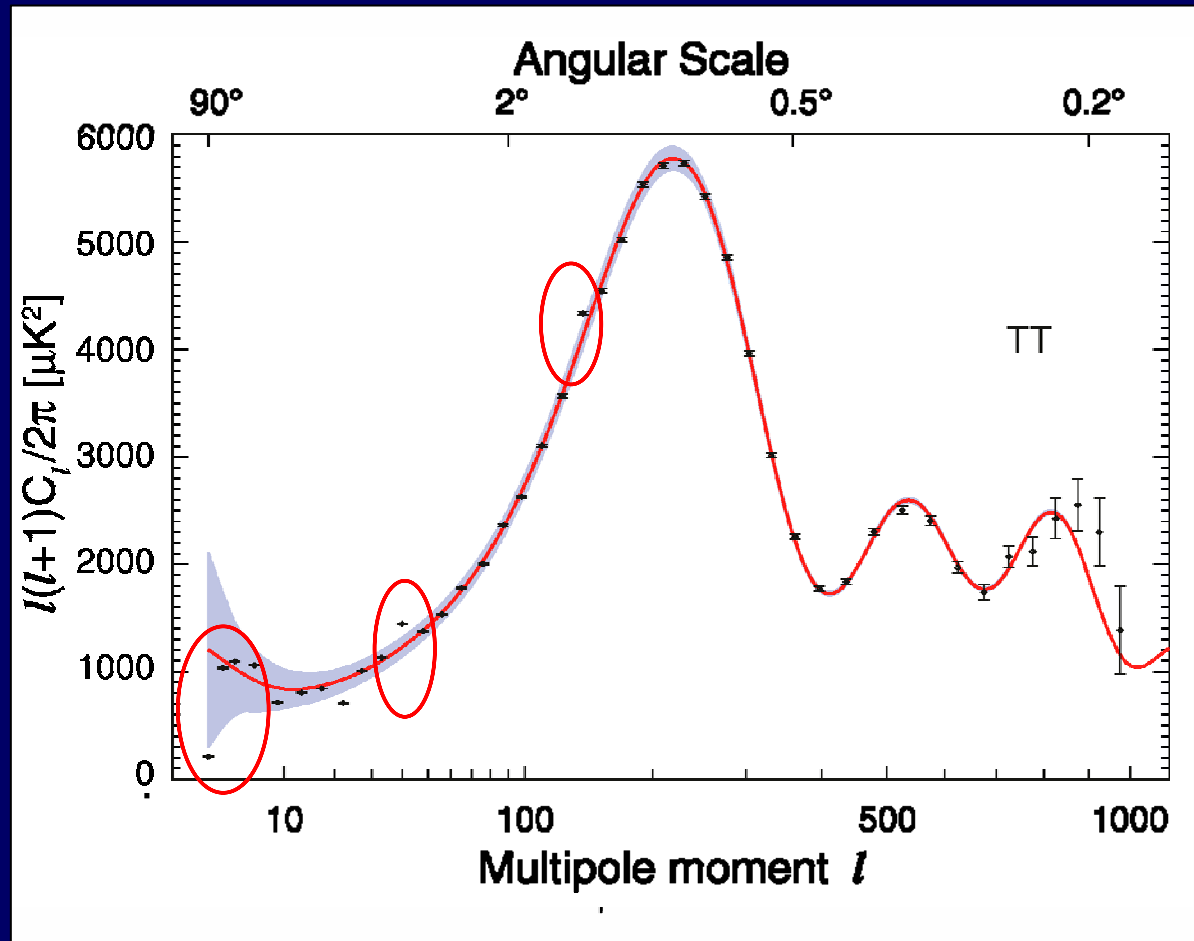
Even the binned data have some deviations from the power-law model.

Errors are dominated by the cosmic variance up to ℓ=407.

Is a simple power-law primordial fluctuation spectrum sufficient?

$$C_\ell \Rightarrow P(k)$$

Cosmic Inversion



From the viewpoint of observational cosmology, the spectral shape of primordial curvature perturbation should be determined purely from observational data without any theoretical prejudice.

Plan

Inverse Analysis

Shown at Poster #C07 by Ryo Nagata

Maximum Likelihood Matrix Method

Forward Analysis

Markov-Chain Monte-Carlo Method

Conclusion

Maximum Likelihood Matrix Method

As confirmed by WMAP observation, temperature fluctuation $\frac{\delta T}{T}(\theta,\varphi) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\varphi)$ is Gaussian distributed.

$$\langle a_{\ell m}\rangle = 0, \quad \langle a_{\ell m} a^*_{\ell' m'}\rangle = C_\ell \delta_{\ell\ell'}\delta_{mm'},$$

with

$$C_\ell = \int \frac{d^3k}{(2\pi)^3}\frac{4\pi}{(2\ell+1)^2}|X_\ell(k)|^2 P(k)$$

Primordial Power spectrum

The probability distribution function (PDF) for each multipole is given by

$$\mathcal{P}[a_{\ell m}|P(k)] = \frac{1}{\pi C_\ell}\exp\left(-\frac{|a_{\ell m}|^2}{C_\ell}\right) \quad (m \neq 0),$$

$$\mathcal{P}[a_{\ell 0}\,|P(k)] = \frac{1}{\sqrt{2\pi C_\ell}}\exp\left(-\frac{|a_{\ell 0}|^2}{2C_\ell}\right),$$

$P(k)$

The likelihood function is their products.

$$\mathcal{L}[\{a_{\ell m}\}|P(k)] = \prod_{\ell,\, m\geq 0} \mathcal{P}[a_{\ell m}|P(k)].$$

Maximum Likelihood analysis

We insert the observed values

$$C_\ell^{obs} \equiv \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2 - N_\ell$$

to the above PDF and regard it as a PDF for the power spectrum $P(k)$.

(N_ℓ : dispersion of observational noises)

$$\mathcal{S} \equiv -2 \ln \mathcal{L}[\{C_\ell^{obs}\}|P(k)]$$

$$= \sum_{\ell=\ell_{\min}}^{\ell_{\max}} (2\ell+1) \left[\frac{C_\ell^{obs} + N_\ell}{C_\ell + N_\ell} + \ln \left(\frac{C_\ell + N_\ell}{C_\ell^{obs} + N_\ell} \right) \right] + (const.)$$

Likelihood function for $P(k)$

$$\mathcal{S} \equiv -2\ln\mathcal{L}[\{C_\ell^{obs}\}|P(k)]$$

$$= \sum_{\ell=\ell_{\min}}^{\ell_{\max}} (2\ell+1)\left[\frac{C_\ell^{obs}+N_\ell}{C_\ell+N_\ell} + \ln\left(\frac{C_\ell+N_\ell}{C_\ell^{obs}+N_\ell}\right)\right] + (const.)$$

should be multiplied by the sky coverage factor f_{sky}.

with

$$C_\ell^{obs} \equiv \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell}|a_{\ell m}|^2 - N_\ell$$

χ^2 distribution with degree $2\ell+1$

We assume the values of global cosmological parameters are fixed (to the WMAP best-fit values), and maximize the likelihood function with regard to the power spectrum $P(k)$.

We solve
$$\frac{\delta \mathcal{S}}{\delta P(k)} = \sum_\ell f_{sky} \frac{k^2}{\pi} \frac{|X_\ell(k)|^2}{2\ell+1} \frac{C_\ell - C_\ell^{obs}}{(C_\ell + N_\ell)^2} = 0,$$

cf
$$\frac{\delta C_\ell}{\delta P(k)} = \frac{2k^2}{\pi} \frac{|X_\ell(k)|^2}{(2\ell+1)^2}$$

$$\sum_{\ell=\ell_{min}}^{\ell_{max}} \underbrace{\frac{k^2 f_{sky}}{\pi (C_\ell + N_\ell)^2} \frac{|X_\ell(k)|^2}{2\ell+1}}_{D_{k\ell}} \int dk' \underbrace{\frac{2k'^2}{\pi} \frac{|X_\ell(k')|^2}{(2\ell+1)^2}}_{G_{\ell k'}} \underbrace{P(k')}_{P_{k'}} = \sum_{\ell=\ell_{min}}^{\ell_{max}} \underbrace{\frac{k^2 f_{sky}}{\pi (C_\ell + N_\ell)^2} \frac{|X_\ell(k)|^2}{2\ell+1}}_{D_{k\ell}} \underbrace{C_\ell^{obs}}_{C_\ell^{obs}}$$

We obtain a matrix equation.

$$\sum_{\ell,\ k'} D_{k\ell} G_{\ell k'} P_{k'} = \sum_\ell D_{k\ell} C_\ell^{obs}.$$

$$\sum_{\ell,\,k'} D_{k\ell} G_{\ell k'} P_{k'} = \sum_{\ell} D_{k\ell} C_\ell^{obs}.$$

$$\left[D_{k\ell} \right]_{k\ell} \left[G_{\ell k'} \right]_{\ell k} \left[P_{k'} \right]_{k} = \left[D_{k\ell} \right]_{k\ell} \left[C_\ell^{obs} - N_\ell \right]_{\ell}$$

#k dimensional square matrix

but we cannot invert it as it is, because the transfer function contained there act as a smoothing function.

⇩

If we introduce some appropriate prior to the power spectrum, we can reconstruct it.

Bayes theorem

$$\mathcal{P}\left[P(k)|\{C_\ell^{obs}\}\right] = \frac{\mathcal{P}\left[\{C_\ell^{obs}\}|P(k)\right]\mathcal{P}\left[P(k)\right]}{\mathcal{P}\left[\{C_\ell^{obs}\}\right]}$$

Prior

Prior for $P(k)$: "smoothness condition" *cf* (Tocchini-Valentini, Hoffman &Silk 05)

$$\mathcal{P}\left[P(k)\right] \propto \exp\left[-\epsilon \int dk \left(\frac{dk^3 P(k)}{dk}\right)^2\right] \equiv e^{-\epsilon \mathcal{J}[P(k)]}$$

With this prior, the maximum likelihood equation

$$\frac{\delta \mathcal{S}}{\delta P(k)} = \sum_\ell f_{sky} \frac{k^2}{\pi} \frac{|X_\ell(k)|^2}{2\ell+1} \frac{C_\ell - C_\ell^{obs}}{(C_\ell + N_\ell)^2} = 0,$$

is modified to

$$\frac{\delta}{\delta P(k)} \left(\mathcal{S}[P(k)] + \epsilon \mathcal{J}[P(k)]\right) = 0$$

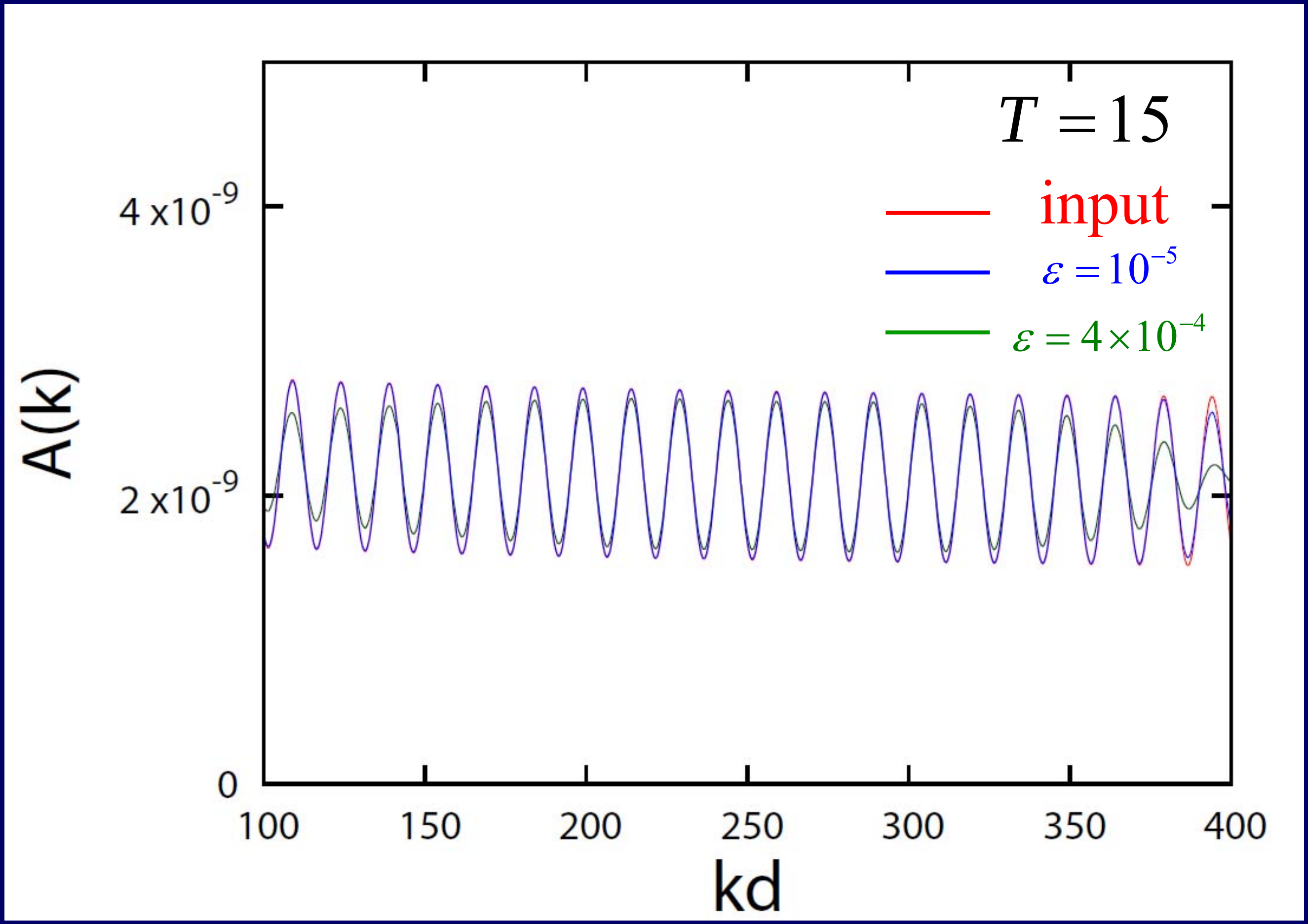
The value of ε is chosen so that the reconstructed power spectrum does not oscillate too much (in particular, to negative values) and that recalculated C_ℓ's agree with observation well.

Test Calculations

d : distance to LSS (13.4Gpc)

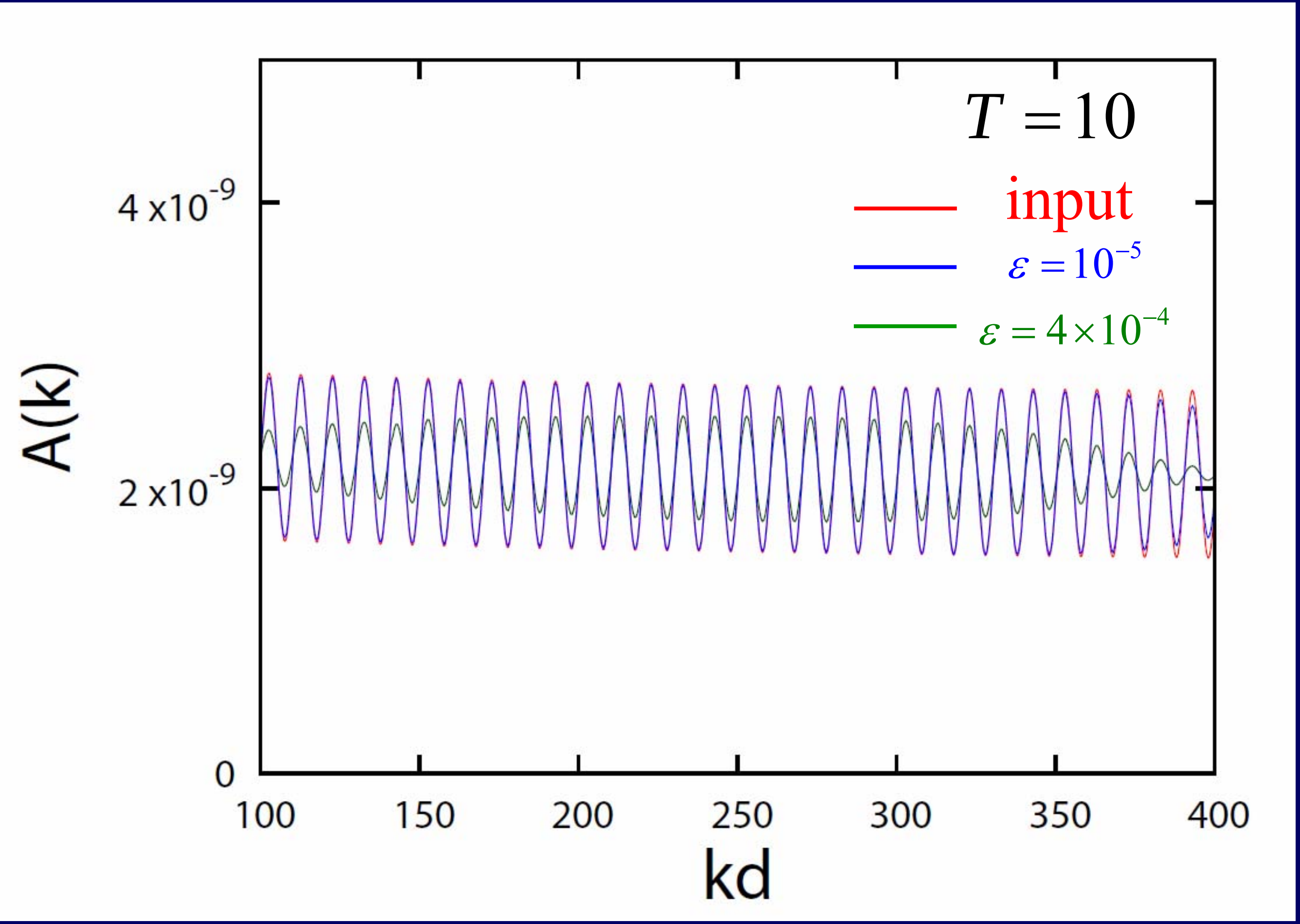
start with a power spectrum with oscillatory modulation → calculate C_ℓ → reconstruct $A(k)$

$$A(k) \equiv k^3 P(k) = A(k/k_0)^{n-1} + B \sin\left(\frac{2\pi}{T} kd\right)$$



Test Calculations

$$A(k) \equiv k^3 P(k) = A\left(k/k_0\right)^{n-1} + B\sin\left(\frac{2\pi}{T}kd\right) \Rightarrow C_\ell \Rightarrow A(k)$$



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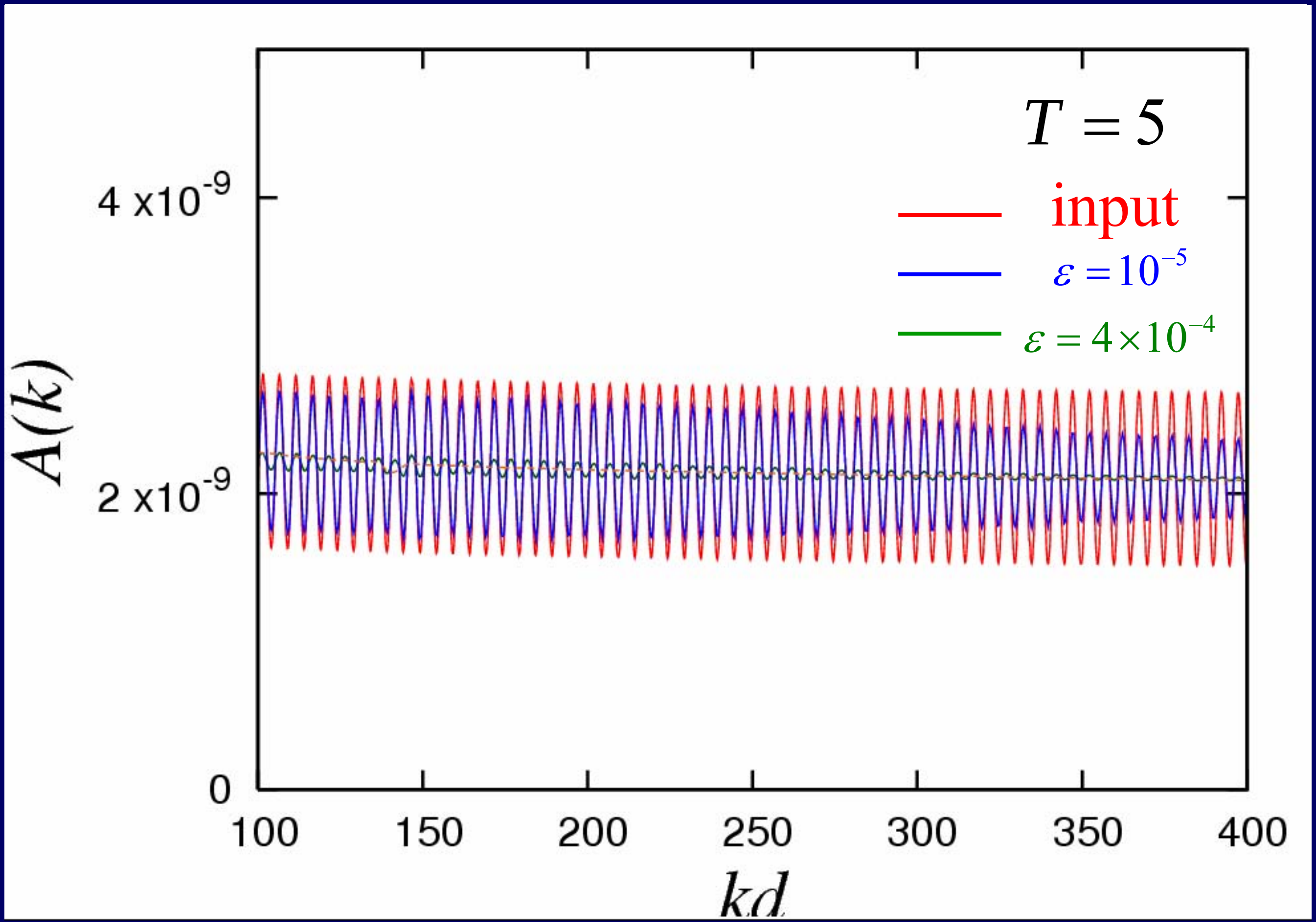
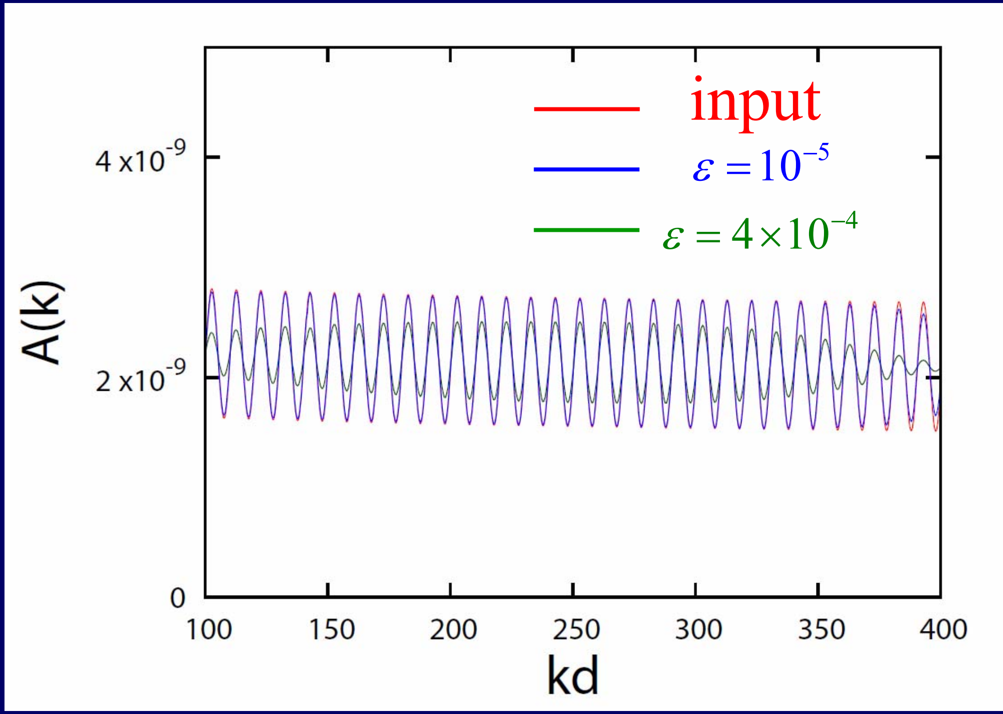


Test Calculations : Summary

- Resolution depends on ε .
- Locations of peaks/dips are reproduced quite accurately.
- Always returns equal or smaller amplitudes = smoothed spectrum.
- Gives a conservative bound on any deviation from the power law
- If we find some deviation, actual power spectrum should have even larger deviation.



Application to WMAP5 data

- We fix cosmological parameters to the best fit values of the power-law ΛCDM model based on WMAP5.

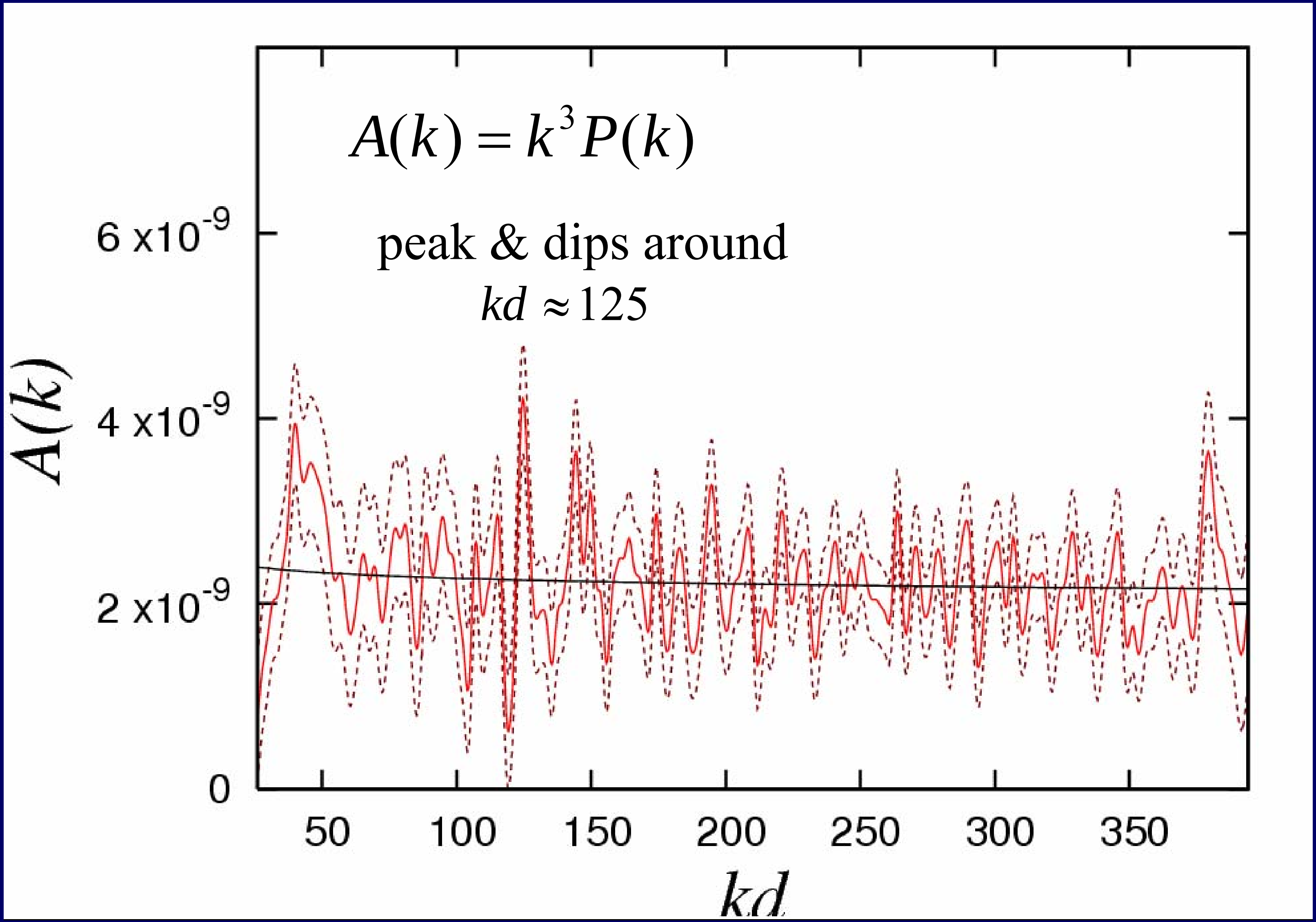
$$h=0.723,\ \Omega_m=0.249,\ \Omega_b=0.0432,$$

$$\Omega_\Lambda=0.751,\ \tau=0.089$$

distance to the last scattering surface $d=13.4\mathrm{Gpc}$

- We make 50000 samples of C_ℓ based on observed mean values and scatters around them based on the proper likelihood function of WMAP and perform inversion for each sample.

Application to WMAP5 data: Results

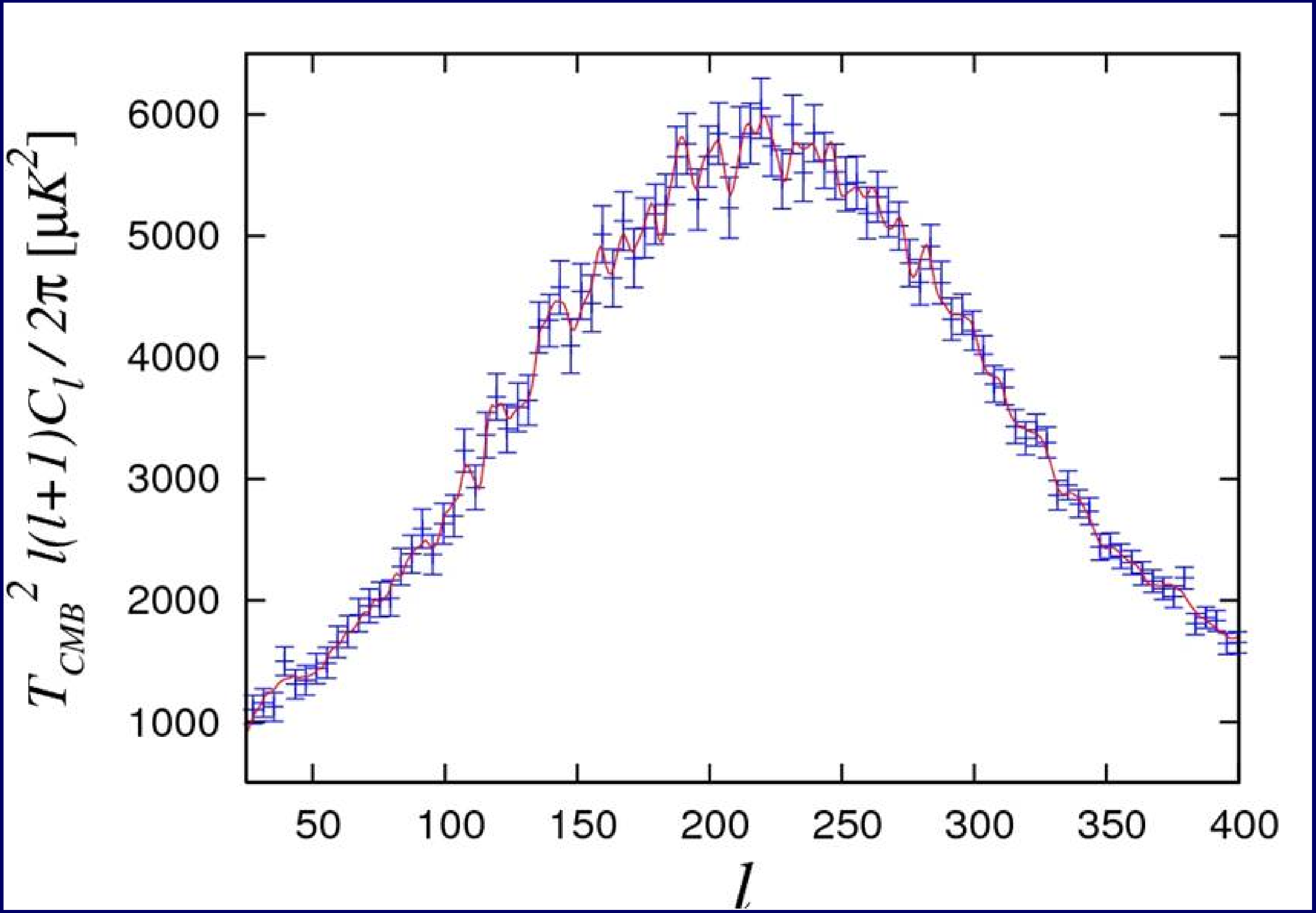


$kd \approx \ell$

$2.1\times10^{-3}\,\mathrm{Mpc}^{-1} \le k \le 2.7\times10^{-2}\,\mathrm{Mpc}^{-1}$

$d = 13.4\mathrm{Gpc}$

Recalculate the angular power spectrum



fits the observational data with binning $\Delta\ell = 4$ well.

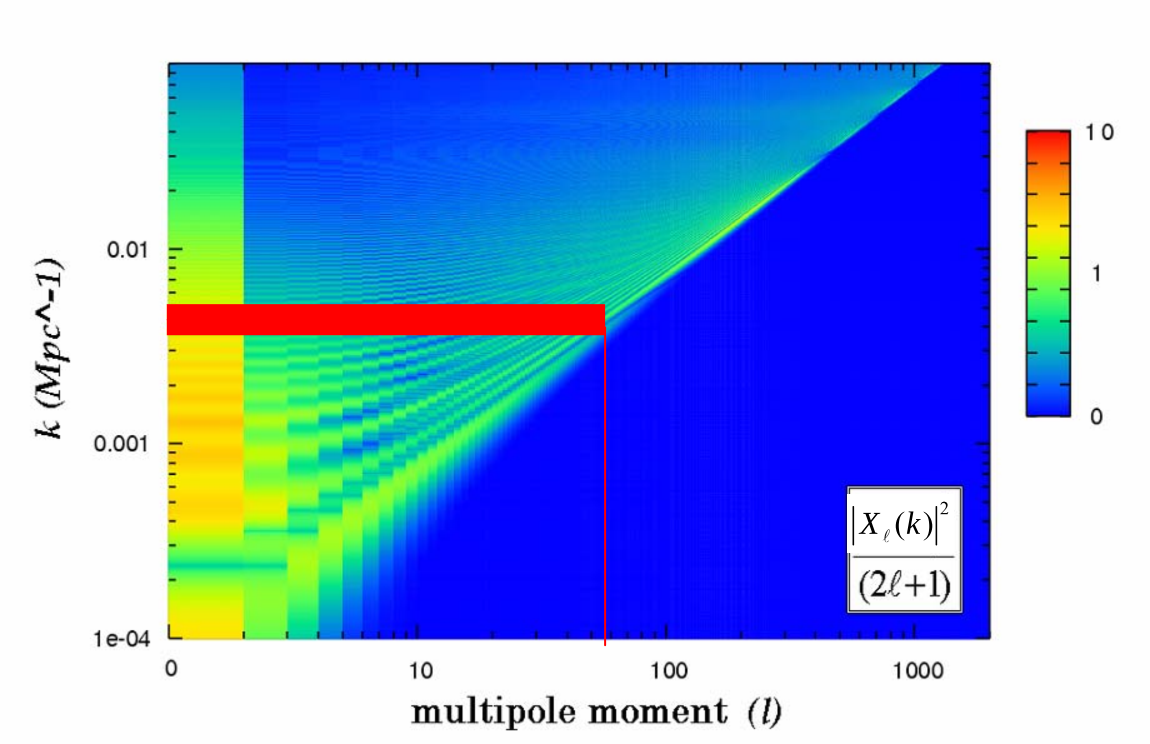
- Theoretically, different *k* modes are uncorrelated.

$$\left\langle \Phi_{\mathbf{k}}(t)\Phi_{\mathbf{k}'}^{*}(t)\right\rangle = P(k,t)\,\delta^3(\mathbf{k}-\mathbf{k}')$$

- Observationally reconstructed spectrum is correlated with nearby *k*-modes.

$$C_\ell = \int \frac{d^3k}{(2\pi)^3}\frac{4\pi}{(2\ell+1)^2}|X_\ell(k)|^2 P(k)$$

limited by the transfer function

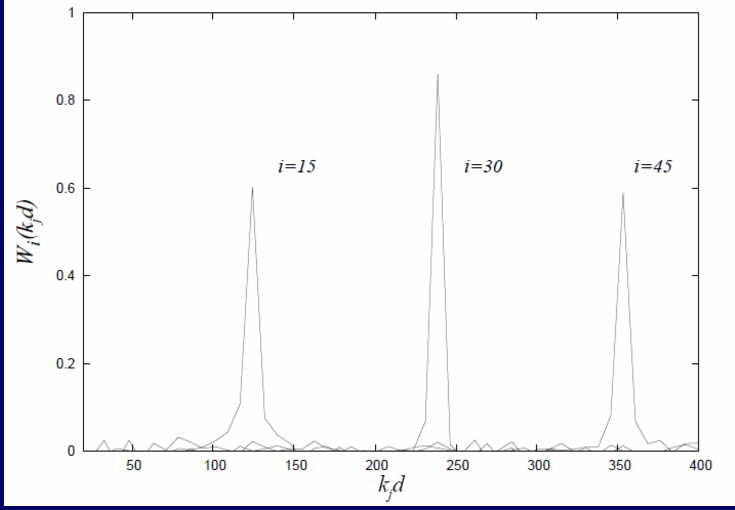


Error estimation

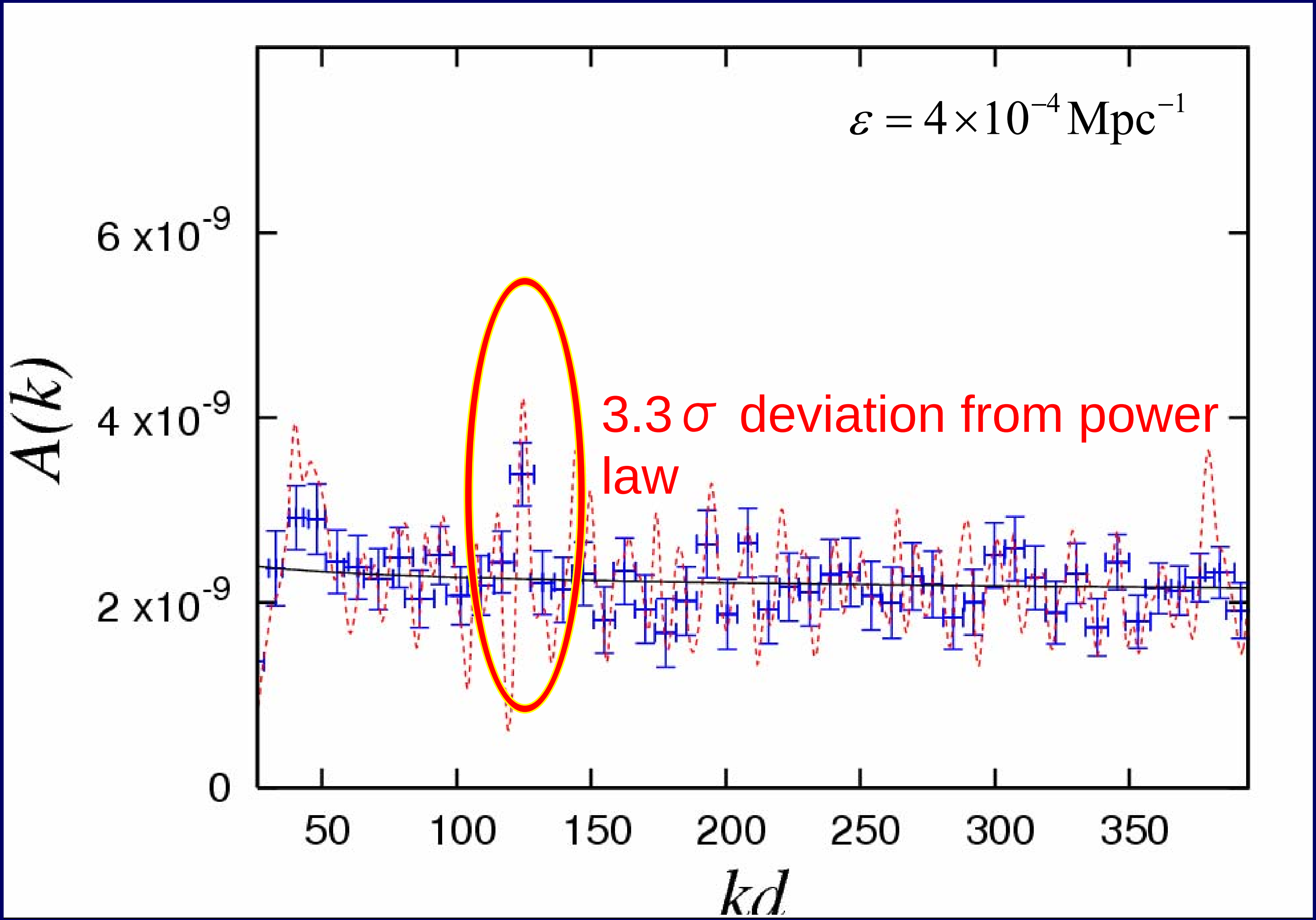
- Calculate the covariance matrix from $\mathcal{N}$=50000 samples of the reconstructed power spectra.

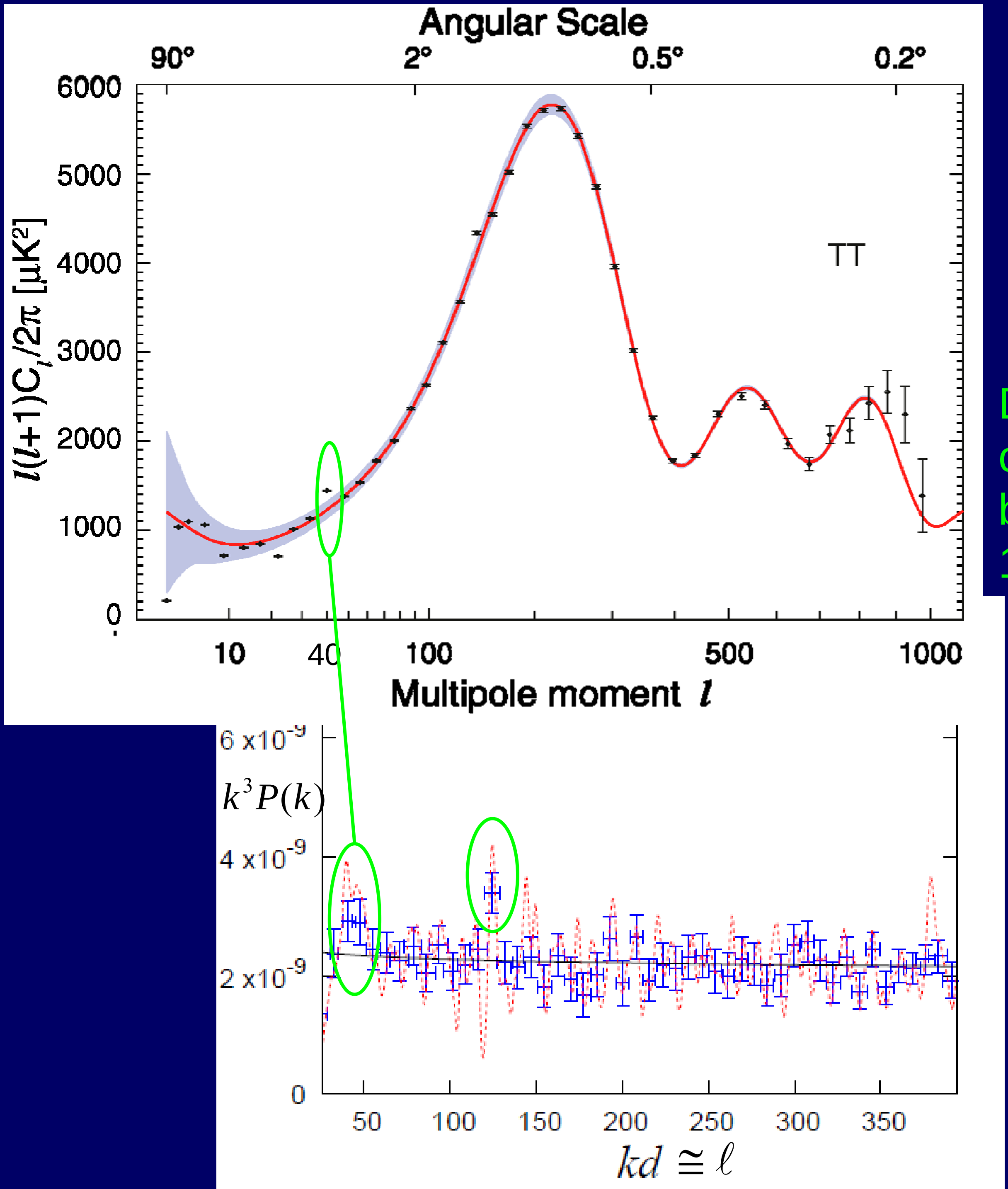
$$K_{ij} \equiv \frac{1}{\mathcal{N}} \sum_{\alpha=1}^{\mathcal{N}} A_\alpha(k_i) A_\alpha(k_j) - \frac{1}{\mathcal{N}} \sum_{\alpha=1}^{\mathcal{N}} A_\alpha(k_i) \frac{1}{\mathcal{N}} \sum_{\beta=1}^{\mathcal{N}} A_\beta(k_j)$$
$$\equiv \langle\langle A_\alpha(k_i) A_\alpha(k_j) \rangle\rangle_\alpha - \langle\langle A_\alpha(k_i) \rangle\rangle_\alpha \langle\langle A_\beta(k_j) \rangle\rangle_\beta ,$$

- Diagonalize the covariance matrix to constitute mutually independent band powers. The number of band powers is chosen so that their widths do not overlap with each other.



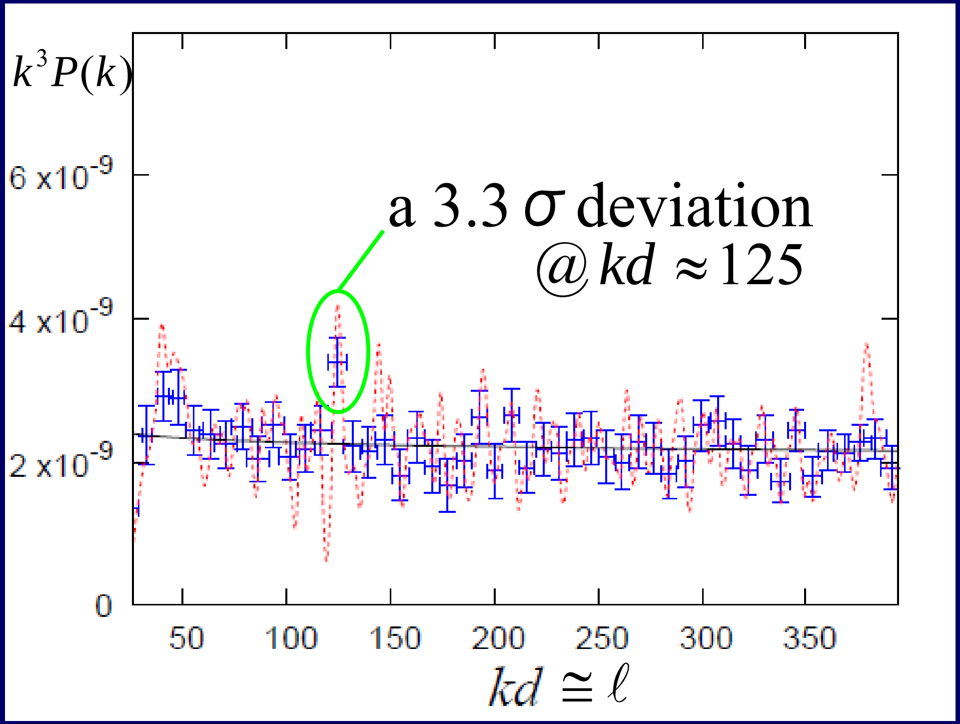
Result of band power decomposition

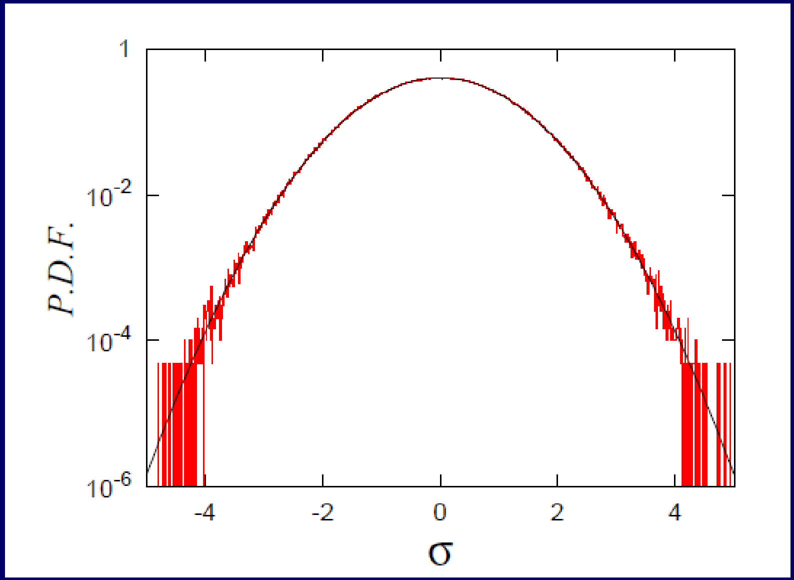




Deviation around $kd \approx \ell \approx 40$ can be seen even in the binned C_ℓ but those at 125 can not be seen there.

(Nagata & JY 08)

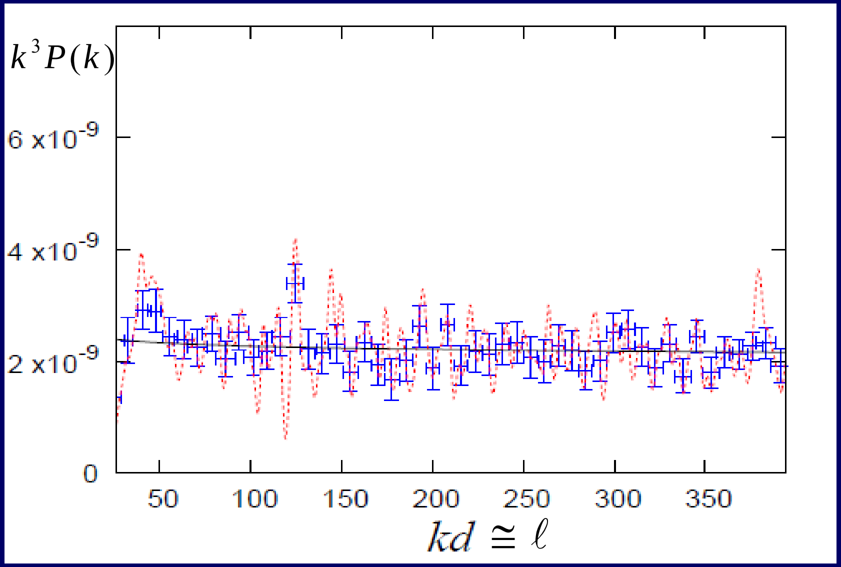




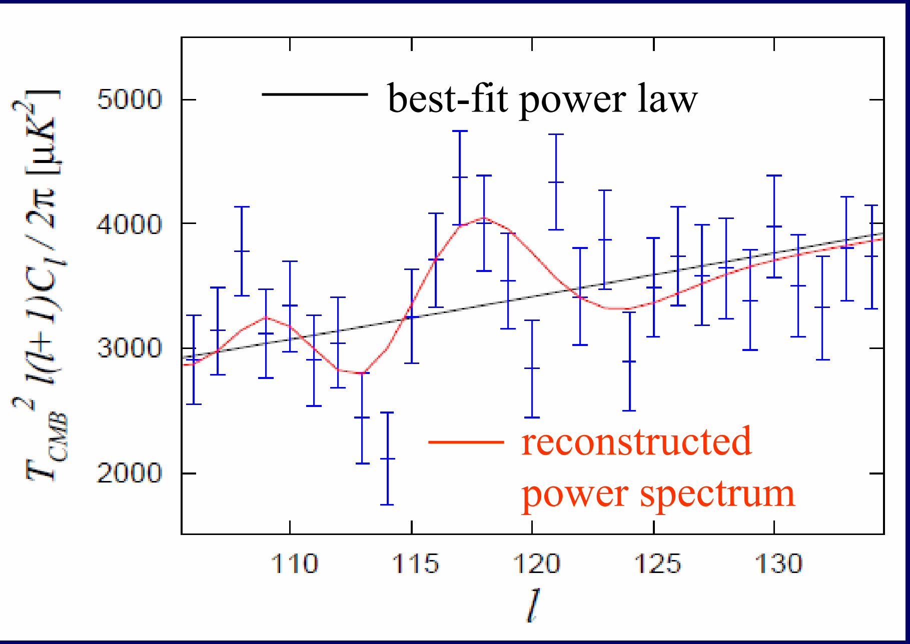
Statistical distribution according to WMAP likelihood function.

Statistical analysis of 50000 samples generated according to WMAP's likelihood function shows that the probability to find a deviation above 3.3σ is 10^{-3}. This is small.

But we have observed one such an event out of 40 band powers.
$10^{-3} \times 40 = 0.04$. This is large.
I would be happy to live in a Universe which is realized in a "standard" theory with the probability of 4%.

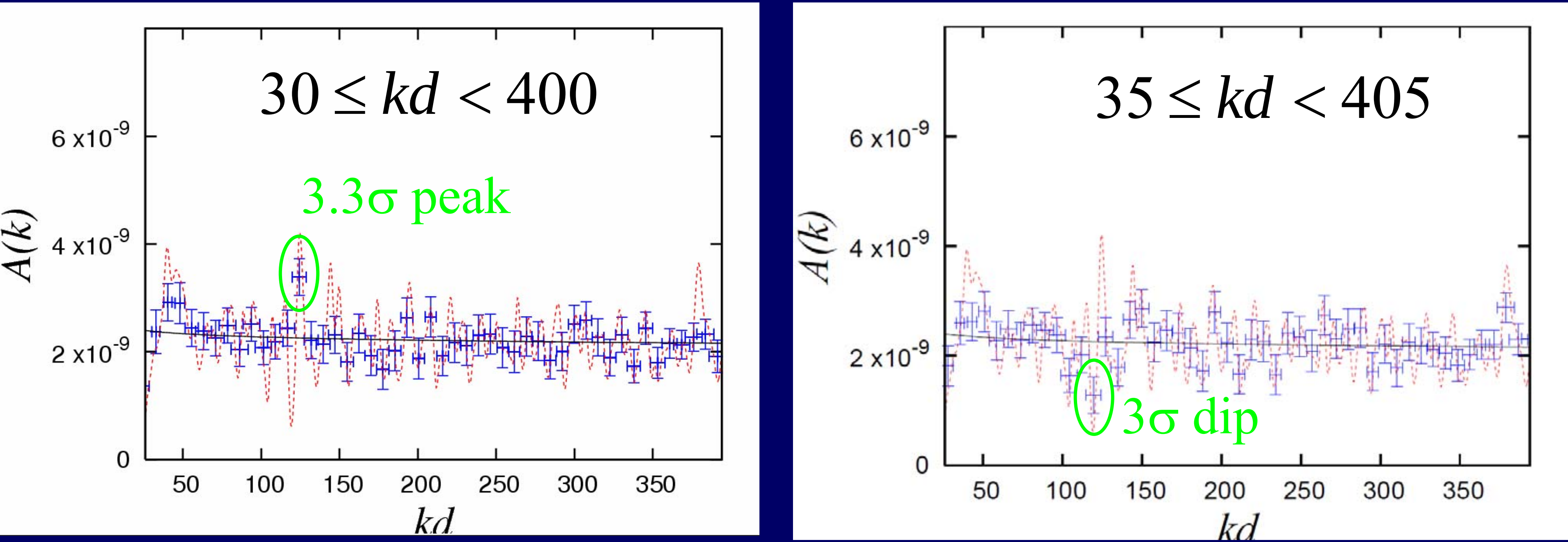


If we try to interpret the deviation from the band-power analysis only, we may well conclude that it is just a realization of a rare event among many random realizations of quantum ensemble.



But if we look at the original unbinned angular power spectrum we find some nontrivial oscillatory structures that may have originated in features in the primordial power spectrum.

NB Correlation between different multipoles is less than 1%.



In fact, if we change the wavenumber domain of decomposition slightly, we obtain a dip rather than an excess even for the band power analysis.

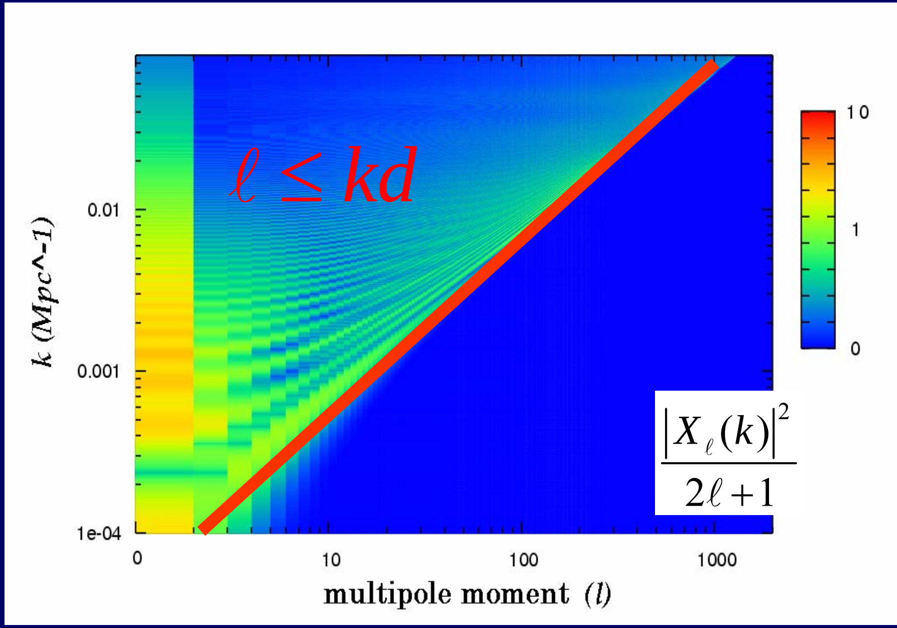
Forward Analysis

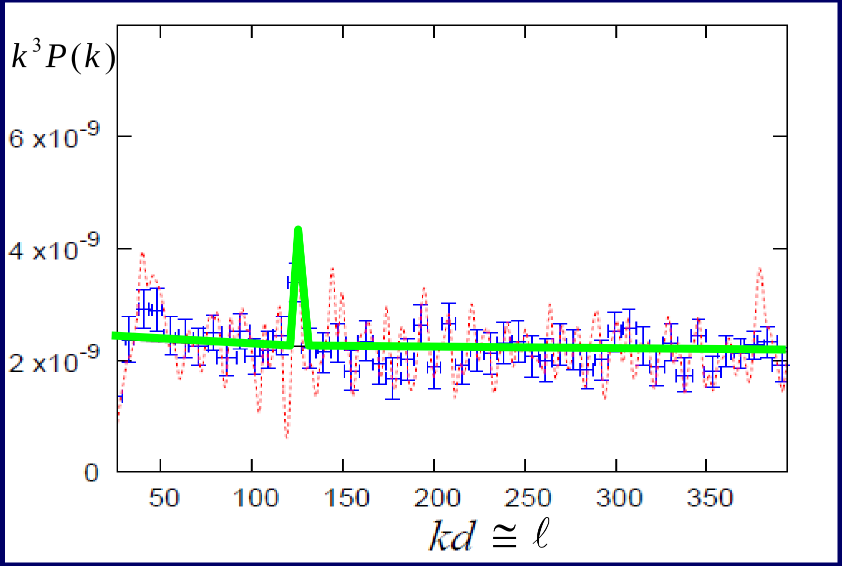
Assume various shapes of modified power spectrum $P(k)$ with three additional parameters in addition to the standard power-law.

Perform Markov-Chain Monte Carlo analysis with CosmoMC with these three additional parameters in addition to the standard 6 parameter ΛCDM model.

Transfer function shows that C_ℓ depends on $P(k)$ with $kd \geq \ell$.

$$C_\ell = \int \frac{d^3k}{(2\pi)^3} \frac{4\pi}{(2\ell+1)^2} |X_\ell(k)|^2 P(k)$$



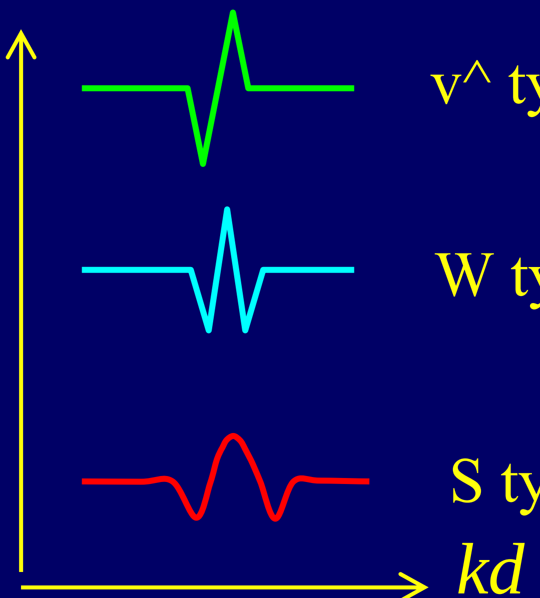


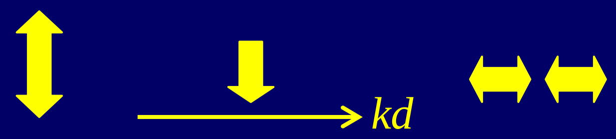
If we add some extra power on $P(k)$ at $kd \approx 125$, it would modify all C_ℓ's with $\ell \leq kd \approx 125$.

Simply adding an extra power around $kd \approx 125$ does not much improve the likelihood, because it modifies the successful fit of power-law model at smaller ℓ's.

Consider power spectra which change C_ℓ's only locally.

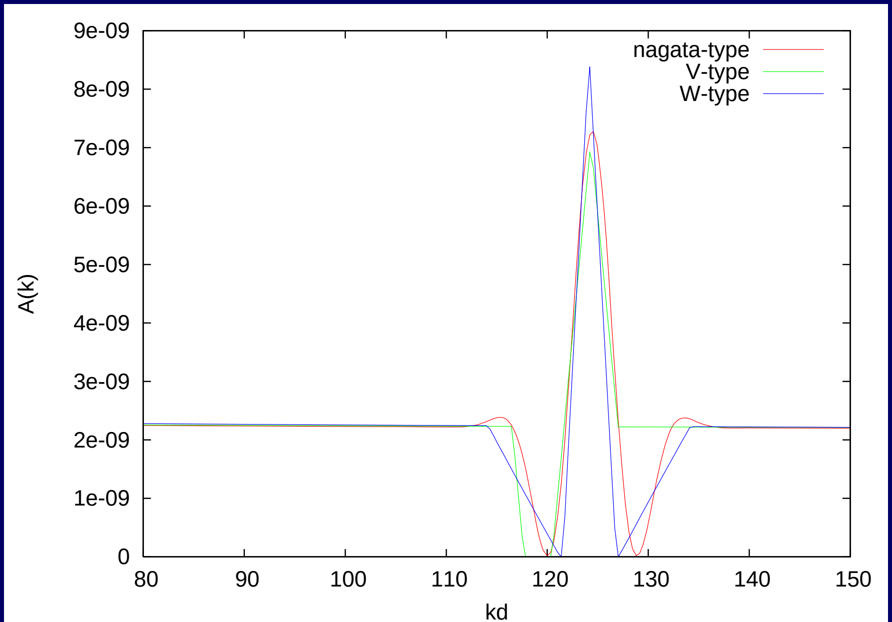
$$A(k) \equiv k^3 P(k)$$





Height, location, & width of the peak are 3 additional parameters.

$$k^3 P(k) = A\left(\frac{k}{k_0}\right)^{n-1} + B\left(\frac{k}{k_0}\right)^{n-1} \exp\left(-\frac{(k-k_*)^2}{\kappa^2}\right) \cos\left(\pi\frac{k-k_*}{\kappa}\right)$$



χ^2_{eff} improves as much as 21 by introducing 3 additional parameters.

	power law	$\sqrt{\Lambda}$ type	W type	S type	$\Delta_{\max}$	WMAP5	Planck
Ω_b	0.0438	0.0443	0.0435	0.0440	0.0005	0.0030	
Ω_m	0.256	0.260	0.257	0.256	0.004	0.027	
Ω_Λ	0.744	0.740	0.743	0.744	0.004	0.015	
H_0 [a]	72.1	71.8	72.0	72.1	0.3	2.7	
$\ln(10^{10}A_{0.002})$ [b]	3.173	3.155	3.187	3.146	0.027	0.047	
n_s	0.964	0.969	0.954	0.970	0.010	0.015	0.0045
$10^2\Omega_b h^2$	2.274	2.280	2.260	2.285	0.011	0.062	0.017
$\Omega_c h^2$	0.1094	0.1100	0.1096	0.1094	0.0006	0.0063	0.0016
τ	0.0864	0.0831	0.0786	0.0812	0.0078	0.017	0.005
$z_{\rm re}$	10.9	10.6	10.3	10.4	0.6	1.4	
$\Delta\chi^2_{\rm eff}$	0	−18	−16	−21			

(Ichiki, Nagata, JY, 08)

If χ^2 improves by 2 or more, it is worth introducing a new parameter, according to Akaike's information criteria (AIC).

Comparison with other non power-law, non standard models

(based on 3 year WMAP data)

Goodness of Fit, $\Delta\chi^2_{\rm eff} \equiv -2\ln\mathcal{L}$, for *WMAP* Data only Relative to a Power-Law ΛCDM Model

Model Number	Model	$\Delta\chi^2_{\rm eff} \equiv -\Delta(2\ln\mathcal{L})$	$N_{\rm par}$
M1	Scale-invariant fluctuations ($n_s = 1$)	6	5
M2	No reionization ($\tau = 0$)	7.4	5
M3	No dark matter ($\Omega_c = 0$, $\Omega_\Lambda \neq 0$)	248	6
M4	No cosmological constant ($\Omega_c \neq 0$, $\Omega_\Lambda = 0$)	0	6
M5	Power law ΛCDM	0	6
M6	Quintessence ($w \neq -1$)	0	7
M7	Massive neutrino ($m_\nu > 0$)	-1	7
M8	Tensor modes ($r > 0$)	0	7
M9	Running spectral index ($dn_s/d\ln k \neq 0$)	-4	7
M10	Nonflat universe ($\Omega_k \neq 0$)	-2	7
M11	Running spectral index and tensor modes	-4	8
M12	Sharp cutoff	-1	7
M13	Binned $\Delta^2_{\mathcal{R}}(k)$	-22	20

Note.—A worse fit to the data is $\Delta\chi^2_{\rm eff} > 0$.

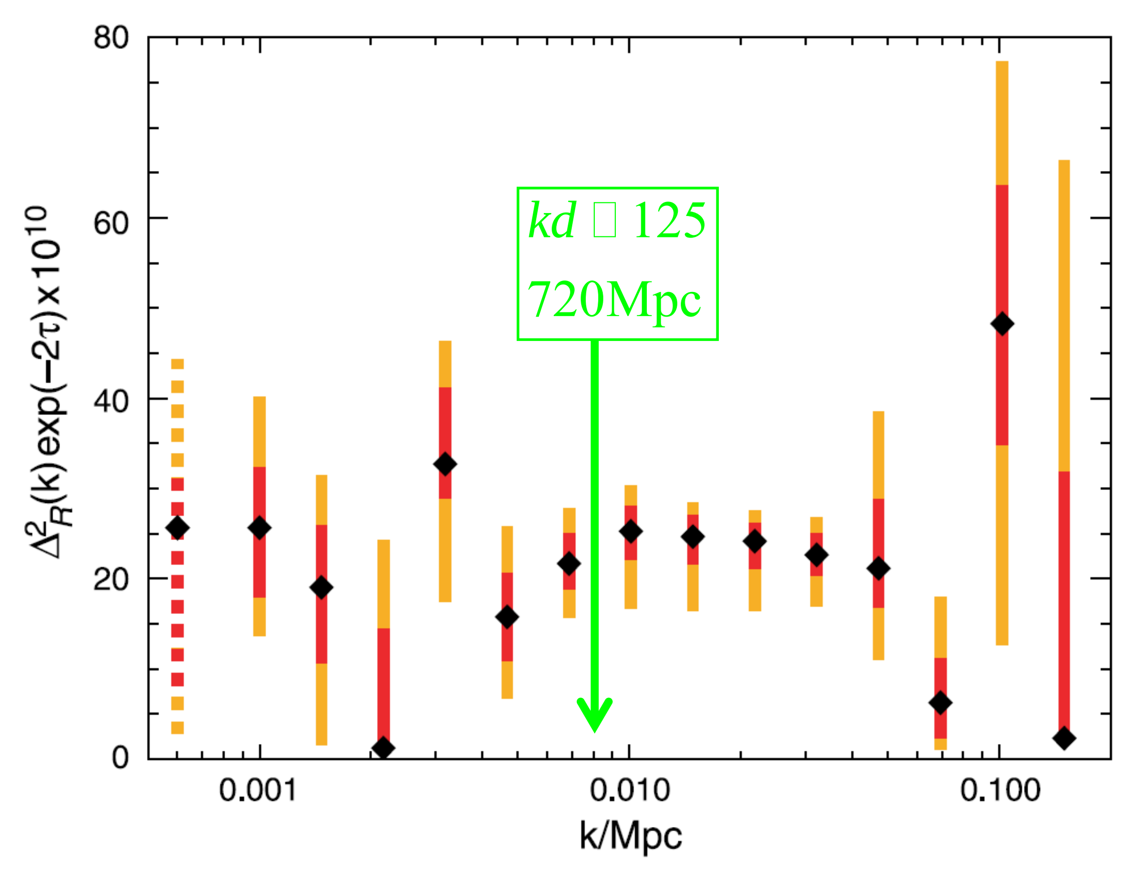
(Spergel et al 07)

Running spectral index improves χ^2_{eff} by 4. AIC OK

Running + tensor improve χ^2_{eff} by 4. AIC marginal

(Our analysis of 5 year WMAP data shows that Running improves χ^2_{eff} only by 1.8. AIC No)

...on standard models



...ATIVE TO A POWER-LAW ΛCDM MODEL

		$\Delta\chi^2_{\rm eff} \equiv -\Delta(2\ln\mathcal{L})$	$N_{\rm par}$
... = 1)		6	5
		7.4	5
... 0)		248	6
... $\neq 0$, $\Omega_\Lambda = 0$)		0	6
		0	6
		0	7
		−1	7
		0	7
... $k \neq 0$)		−4	7
		−2	7
...sor modes		−4	8
		−1	7
M13	Binned $\Delta^2_{\mathcal{R}}(k)$	−22	20

NOTE.—A worse fit to the data is $\Delta\chi^2_{\rm eff} > 0$.

Binned power spectrum does not improve χ^2_{eff} sufficiently,
if binning is done with no reference to the observational data.

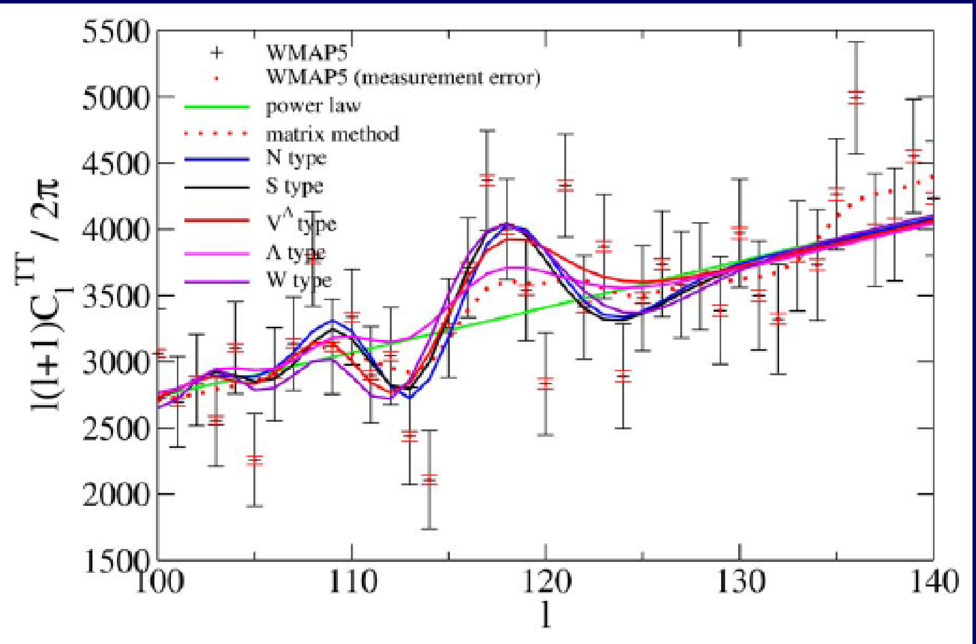
It is very difficult to improve the fit.
Inverse analysis is very important!

Unlike our reconstruction methods, MCMC calculations use not only TT data but also TE data.

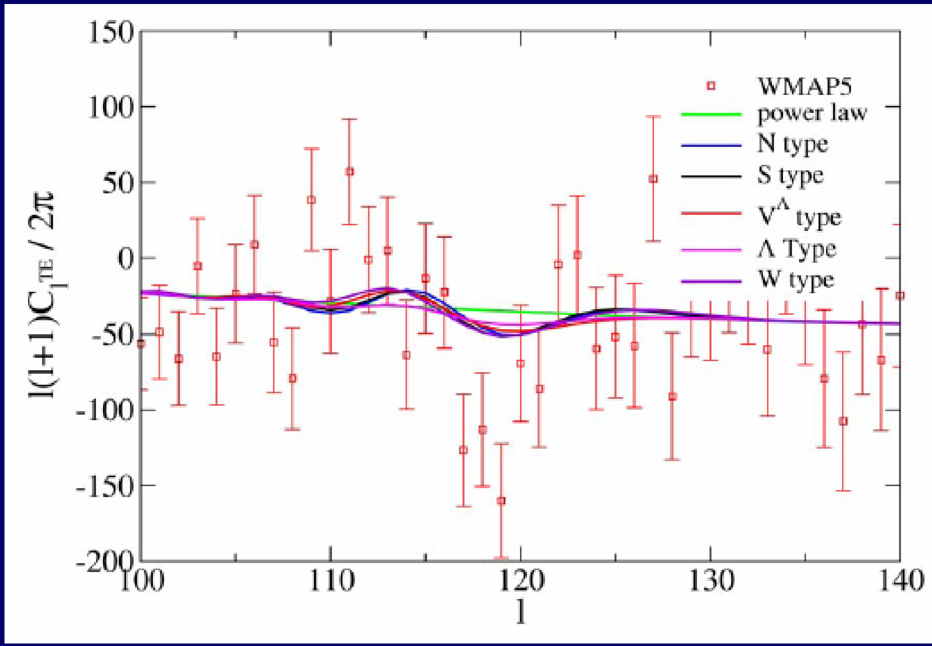
$$\Delta\chi^2_{eff} \text{ due to improvement of TT fit} = -12.5$$
$$\Delta\chi^2_{eff} \text{ due to improvement of TE fit} = -8.5$$

It is intriguing that our modified spectra improve TE fit significantly even if we only used TT data in the beginning.

TT(temp-temp) data and model

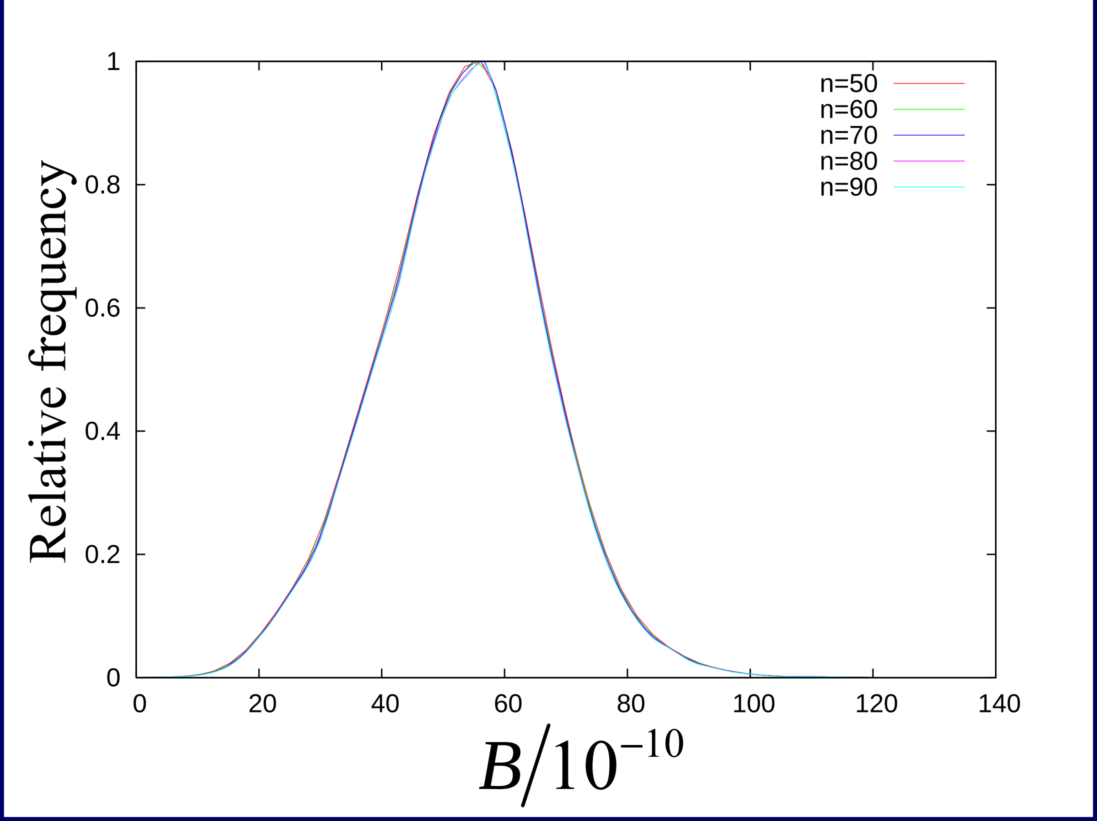


TE(temp-Epol) data and model



Posterior distribution in MCMC calculation with

$$k^3 P(k) = A\left(\frac{k}{k_0}\right)^{n-1} + B\left(\frac{k}{k_0}\right)^{n-1} \exp\left(-\frac{(k-k_*)^2}{\kappa^2}\right) \cos\left(\pi \frac{k-k_*}{\kappa}\right)$$



$A = 2.32 \times 10^{-9}$

Probability to find $B < 1.43 \times 10^{-10}$ is only 2.2×10^{-5}.

(for $k_* d = 100 \sim 150$) (tentative)

The tentative probability that the primordial power spectrum $P(k,t_i)=\left\langle |\Phi_k(t_i)|^2 \right\rangle$ has a nonvanishing modulation (at some wave number) is estimated to be ～99.98%.

Is it due to some
nontrivial physics during inflation??
or just a rare event (～0.02%)
in the standard theory?

The presence of such a fine structure changes the estimate of other cosmological parameters at an appreciable level.

Maximum of the shift from the power law

observed errors with WMAP5

Expected Errors by PLANCK

		modulated spectra					
	power law	$\sqrt{\Lambda}$ type	W type	S type	$\Delta_{\max}$	WMAP5	Planck
Ω_b	0.0438	0.0443	0.0435	0.0440	0.0005	0.0030	
Ω_m	0.256	0.260	0.257	0.256	0.004	0.027	
Ω_Λ	0.744	0.740	0.743	0.744	0.004	0.015	
H_0 (a	72.1	71.8	72.0	72.1	0.3	2.7	
$\ln(10^{10}A_{0.002})$ (b	3.173	3.155	3.187	3.146	0.027	0.047	
n_s	0.964	0.969	0.954	0.970	0.010	0.015	0.0045
$10^2\Omega_b h^2$	2.274	2.280	2.260	2.285	0.011	0.062	0.017
$\Omega_c h^2$	0.1094	0.1100	0.1096	0.1094	0.0006	0.0063	0.0016
τ	0.0864	0.0831	0.0786	0.0812	0.0078	0.017	0.005
$z_{\rm re}$	10.9	10.6	10.3	10.4	0.6	1.4	
$\Delta\chi^2_{\rm eff}$	0	−18	−16	−21			

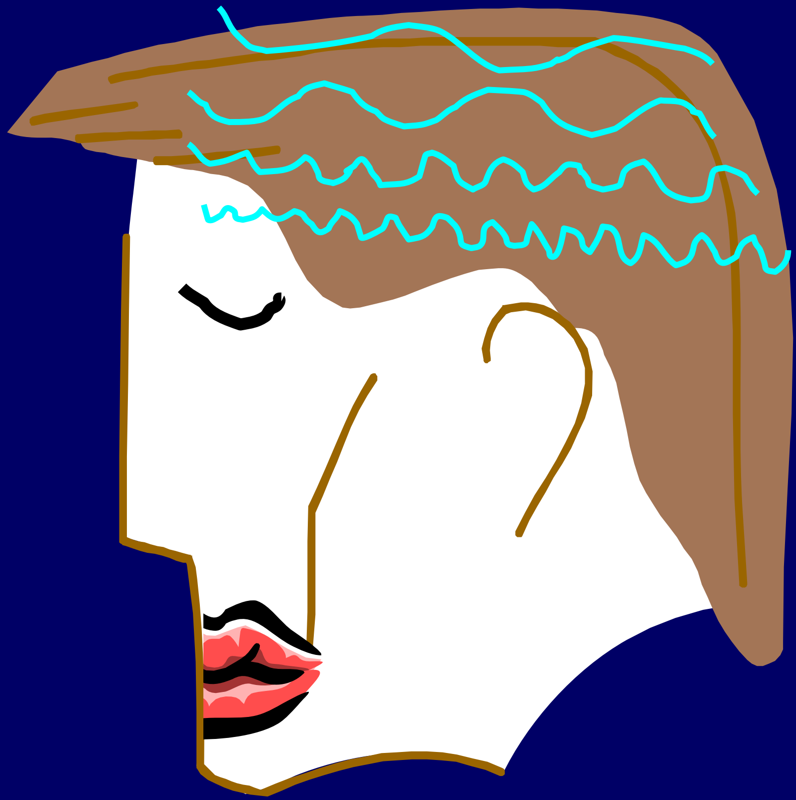
- If we wish to evaluate the values of the cosmological parameters of our current Universe with high accuracy, we should take possible nontrivial, non-power-law features into account.

- Whether they have any physical origin or are just a particular realization of random fluctuations,
  they are properties of our own Universe.

- We should investigate their characteristic features (and impact on other parameters), even if this may not be an physics issue.

Astronomer's Universe and Physicist's universe

To find something interesting



Abstract information by Fourier decomposition.

CONCLUSION

With the next generation (or perhaps next-to-next generation) of higher precision observations,
Cosmology will inevitably turn to Astronomy from Physics.
This could be regarded as a triumph of physics.

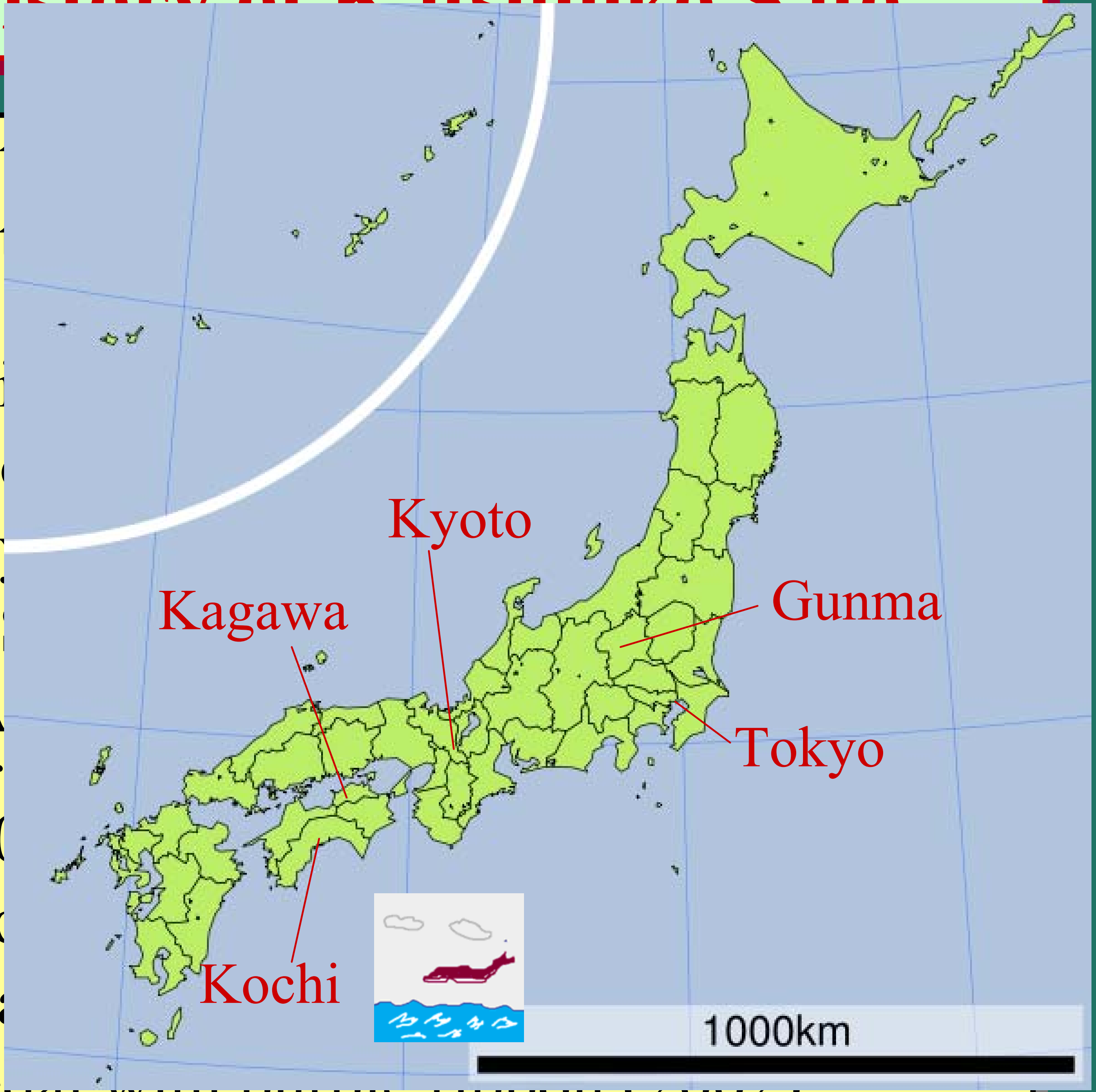
上州人

上州無智亦無才
剛毅木訥易被欺
唯以正直接萬人
至誠依神期勝利

鑑三

A brief hi

- born on August
- PhD from Kyo
  Hayashi)
- Kyoto Universi
  University of T
- Dean of Faculty
- Director of RE
- President of IA
  1988-1991), pr
  1998, 2005-200
- the 5th Inoue Fo
- the 36th Nishina
- 紫綬褒章　Medal with purple ribbon (2002)



A brief history of Katsuhiko Sato

- born on August 30, 1945
- PhD fr … Chushiro Hayash …
- Kyoto U …),
  Univers …
- Dean o …
- Directo … 2007)
- Preside … ogy; 1988-1 … n (1997-1998, 2 …
- the 5th I …
- the 36th …

- 紫綬褒章 Medal with purple ribbon (2002)

List of the graduate students supervised by Professor Sato

32 PhDs　4 PhD candidates　12 Masters

Thank you, Professor Sato.
We wish you a happy life after retirement from Physics Dept & RESCEU.