Modern Cosmology: Facts, Misconceptions and Myths

V. Mukhanov

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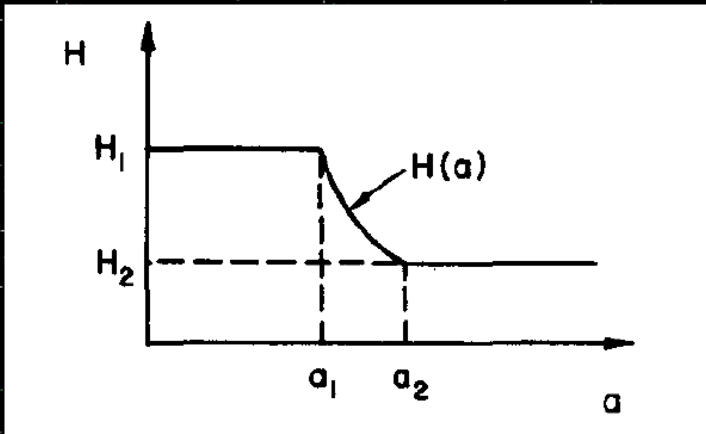
In desperation I asked Fermi whether he was not impressed by the agreement between our calculated numbers and his measured numbers. He replied, “How many arbitrary parameters did you use for your calculations?” I thought for a moment about our cut-off procedures and said, “Four.” He said, “I remember my friend Johnny von Neumann used to say, with four parameters I can fit an elephant, and with five I can make him wiggle his trunk.” Freeman Dyson, 1953

THEORY OF COSMOLOGICAL PERTURBATIONS

PHYSICS REPORTS (Review Section of Physics Letters) 215, Nos. 5 & 6 (1992) 203–333. North-Holland

V.F. MUKHANOV[a,b], H.A. FELDMAN[c] and R.H. BRANDENBERGER[a]

[redacted]



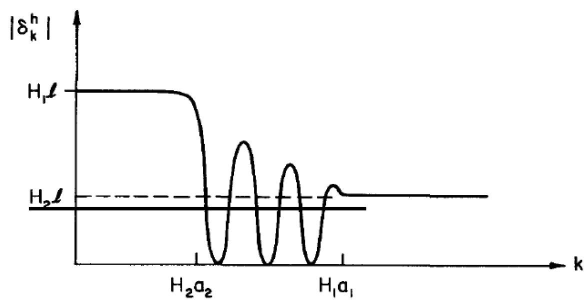


Fig. 18.7. Power spectrum $\delta_h \equiv h$ of gravitational radiation in the double inflation model of (18.40) with the ratio of Hubble constants $H_1/H_2 = 10$.

[redacted]

Note that the effect discussed in this section can arise for both adiabatic and entropy perturbations.

[redacted]

it is possible to obtain a suppression of the long-wavelength part of cosmological perturbation

[redacted]

$$S = \int [\tfrac{1}{2}\chi_{;\mu}\chi^{;\mu} - V(\chi) + \tfrac{1}{2}\varphi_{;\mu}\varphi^{;\mu} - \tfrac{1}{2}m_0^2\varphi^2 - V_1(\chi, \varphi, \ldots)]\sqrt{-g}\, d^4x\ ,$$

[redacted]

nontrivial spectra with mountains and valleys can also be obtained

[redacted]

It is also possible to generate non-Gaussian fluctuations

[redacted]

However, this procedure is extremely unappealing since it implies a complete loss of predictability.

MFB, Physics Report, 1992

Inflation is not a unique theory, but rather a class of models based on similar principles.

WRONG!

Inflation is THE theory only when it is understood as the stage of unbroken accelerated expansion due to the same ingridient which is responsible for quantum fluctuations.

Otherwise it is rubbish without any predictions!!!

In this case it is unbeatable as predictive theory because it allows us to calculated the effect of amplification of quantum fluctuations in completely controlable weak coupling regimes

while most alternatives cannot even compete with "rubbish inflation" in a sense of controlable reproduction of outcome for quantum fluctuations

COSMOLOGY - Theology = $\exp(Ht)$

during at least 70 H^{-1}, but less than 10^6 H^{-1} $\rightarrow$

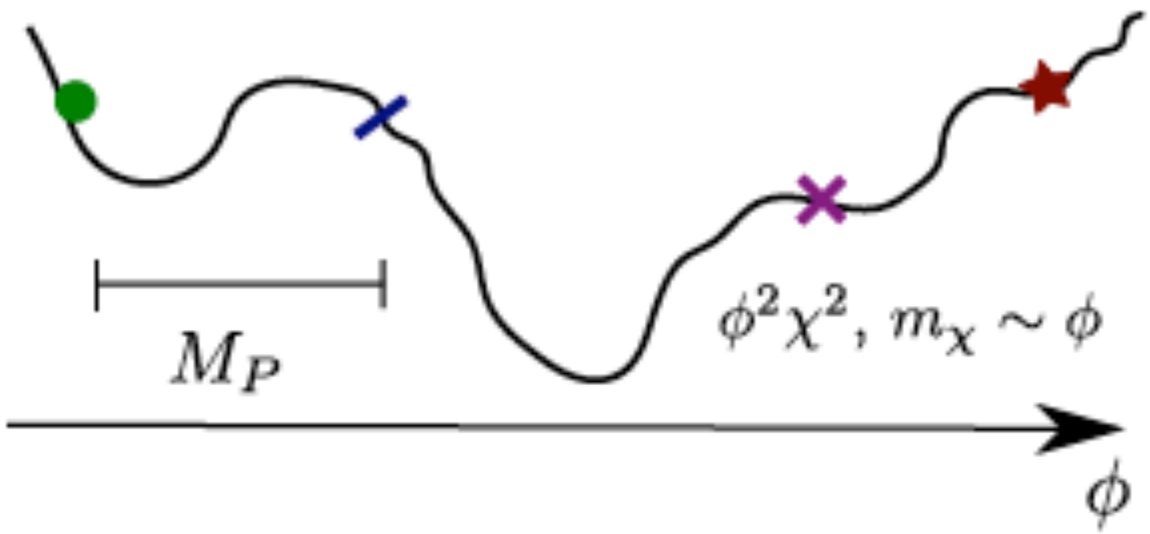
no any problems with predictions, which could falsify the theory in Popper's sense

The only purpose of inflationary models relevant for observation is a maping

$$V(\varphi) \quad \text{to} \quad p \approx -\varepsilon$$

and this maping happened to be not crucial for robust predictions but important only for excluding definite potentials $V(\varphi)$, which anyway we will never be able to verify in any other independent experiments

$$V(\tau,\theta) = \frac{12W_0^2\xi}{(4\mathcal{V}_m-\xi)(2\mathcal{V}_m+\xi)^2} + \frac{D_1 + 12e^{-2a_2\tau}\xi A_2^2}{(4\mathcal{V}_m-\xi)(2\mathcal{V}_m+\xi)^2} + \frac{D_2 + \frac{16(a_2A_2)^2}{3\alpha\lambda_2}\sqrt{\tau}e^{-2a_2\tau}}{(2\mathcal{V}_m+\xi)} \tag{25}$$
$$+\frac{D_3 + 32e^{-2a_2\tau}a_2A_2^2\tau(1+a_2\tau)}{(4\mathcal{V}_m-\xi)(2\mathcal{V}_m+\xi)} + \frac{D_4 + 8W_0A_2e^{-a_2\tau}\cos(a_2\theta)}{(4\mathcal{V}_m-\xi)(2\mathcal{V}_m+\xi)}\left(\frac{3\xi}{(2\mathcal{V}_m+\xi)} + 4a_2\tau\right) + \frac{\beta}{\mathcal{V}_m^2}.$$



What is relevant for predictions?

$-\varepsilon$ energy density

$-p$ pressure

$$1+w \equiv \frac{\varepsilon + p}{\varepsilon} \ll 1$$

during last 70 e-folds $(a = a_f \cdot e^{-N})$

$a)$ $1+w \ll 1$ for $N \gg 1$

$b)$ $1+w \approx O(1)$ for $N \simeq O(1)$

$c)$ $1+w$ is a smooth function of N

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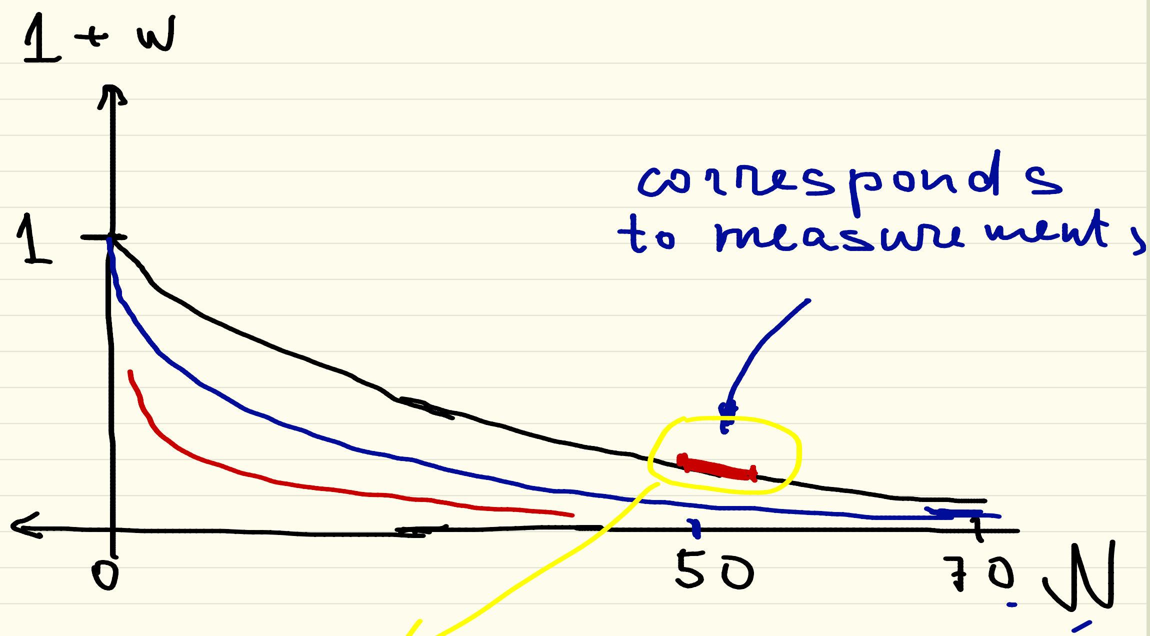
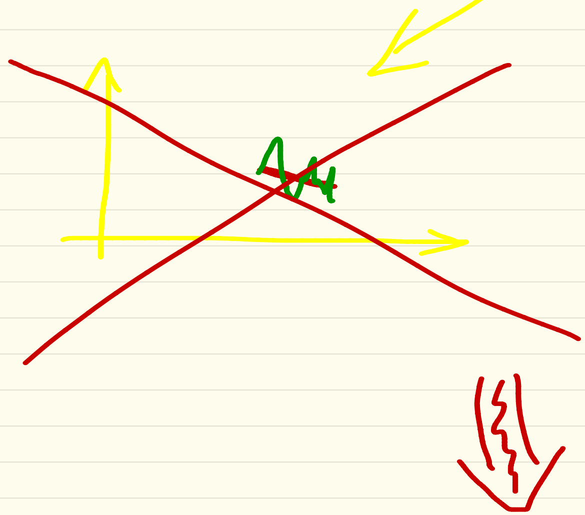




$$\frac{p+\varepsilon}{\varepsilon} = \frac{B}{(N+1)^{\alpha}}$$

PREDICTIONS

("smoking guns"-nonconfirming any of them would falsify THE theory)

- flat universe
- adiabatic perturbations
- small non-gaussianity ($f_{NL} \sim O(1)$)
- red-tilted spectrum

$$\Phi^2 \propto \lambda^{1-n_S}$$

$$1-n_S = 3(1+w) - \frac{d\ln(1+w)}{dN}$$

of the faint ripples that we detect in the cosmic microwave background (CMB). First, the ripples should be nearly scale-invariant, meaning that they have nearly the same intensity at

The theory always predicts red-tilted spectrum

From GR content $\Rightarrow$ one postulate $\equiv$ stage of accelerated expansion $\Rightarrow$

explanation of hom, isotr.

+ 2 nontrivial predictions

$-\ \Omega_{total} = 1 \pm 10^{-5}$

$-$ spectrum of pertur.

spectrum is never HZ for generic inflation. It is tilded

$$\Phi_\lambda^2 \simeq \frac{\varepsilon^{\leftarrow 10^{-12}}}{\varepsilon_{Pl}} \frac{1}{\underbrace{1+p/\varepsilon}_{1/50}}\Bigg|_{\lambda^{-1}\simeq Ha}$$

$$n_s - 1 = -3\left(1+\underbrace{\frac{p}{\varepsilon}}_{\to 0}\right)_{\lambda^{-1}\simeq Ha} - \frac{1}{H}\left(\ln\left(1+\underbrace{\frac{p}{\varepsilon}}_{\to 0}\right)\right)$$

$0.9 \overset{?}{\lesssim} n_s < 0.96$!

not too much grav. waves !

Gaussian perturbations

Cambridge, 2000

[1]. Contrary to an erroneous belief inflation does not predict the scale-invariant, Harrison-Zel'dovich spectrum. The spectral index should be in the range of $0.92 < n_s < 0.97$. The physical

V. Mukhanov, CMB, Quantum Fluctuations and the Predictive Power of Inflation, *arXiv : astro – ph* / 0303077 (2003)

Red-tilted log spectrum (MC, H, 1981-1982) $\rightarrow$

$$n_S = 1 - \frac{A}{\ln(B\lambda_{gal} / \lambda_{CMB})},$$

where $A > 1{,}5$ and $B \simeq 1 - 100$ depending on $50 < N < 55 \rightarrow$

$$n_S < 0.97$$

irrespective of any particular model!

L.P. 9/6/2003:

We are writing a proposal to get money to do our small angular scale
CMB experiment. If I say that simple models of inflation require
n_s=0.95+/-0.03 (95\% cl) is it correct?
I'm especially interested in the error. Specifically, if n_s=0.99 would
you throw in the towel on inflation?

V.M. 9/8/2003

The "robust" estimate for spectral index for inflation is 0.92<n_s<0.97.
The upper bound is more robust than lower. The physical reason for
the deviation of spectrum from the flat one is the nessesity to finish inflation....
If you find n_s=0.99 +/- 0.01 (3 sigma) I would throw in the towel on inflation.

Further predictions ("non-smoking guns"):

- Primordal gravitational waves
- Nongaussianities due to nonlinearity of

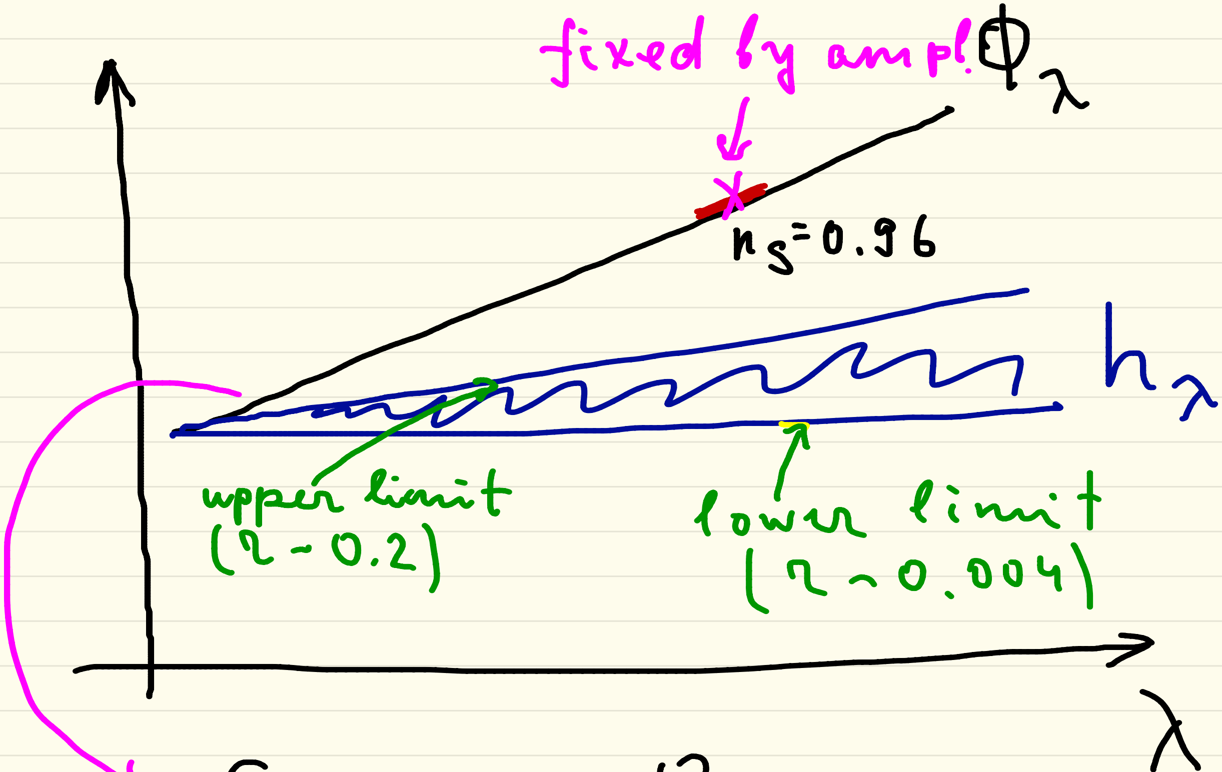
Einstein equation (3,4,...points correlaton functions)

There must be primordial gravi tatonal waves

$$r \equiv \frac{T}{S} = 24 \cdot (1 + p/\varepsilon) = \frac{\beta}{N^{\alpha}}$$

No a priori low bound on their ampltude!

but if n_s is measured



$$\varepsilon_{end} \sim 10^{-12}\, \varepsilon_{pe}$$

However, keeping mind theoretical and experimental uncertainty, n_s within 2-sigma can be equal to 0.95.
In this case the lower bound on r becomes 0.0006
(unrealistic from the point of view of future measurements)

- Thus, detection of the primordial gravitational field will provide us an extra confirmation that quantum fluctuations were amplified on the stage of accelerated expansion.
- Failing to detect them at the level 0.04 would not have any implications and in no way can be considered as a prove of alternative for amplification of quantum fluctuation

- Theory is right
- Planck is right
- BICEP2 is right

T + P ✓ T + B ✓

P + B ✓

But

~~T + P + B~~

Therefore P + B ⇒ catastrophy for theory

29. April 2014 10:54 Entstehung des Universums

Risse in der Urknall-Theorie

Forschungsstation am Südpol: Hier meinen Physiker Signale aus den ersten Sekundenbruchteilen nach dem Urknall gemessen zu haben. Viele Kollegen sind noch nicht überzeugt. (Foto: REUTERS)

Signale aus der Geburtsstunde des Universums: Mitte März jubelte ein Forscherteam über eine bahnbrechende Messung von Gravitationswellen. Möglicherweise haben die Physiker sich zu früh gefreut.

Von Marlene Weiß

Diskutieren Versenden Drucken Feedback

Wer meint, die Welt erklären zu können, indem er am kleinen *n* schraubt, bekommt es mit Viatcheslav Mukhanov zu tun. "Vollkommener Unsinn", schimpft der an der Uni München aktive russische Physiker, "die Zeitschriften sind voll davon, aber es bleibt trotzdem Unsinn!"

Auch wer sonst nichts von seinem Vortrag kürzlich am Max-Planck-Institut für Astrophysik in Garching bei München verstanden hat, eines dürfte jedem Zuhörer klar geworden sein: Das kleine *n* in den Formeln über den Beginn des Universums, auch "spektraler Index" genannt, sollte man in Ruhe lassen, wenn man sich nicht mit Mukhanov anlegen möchte.

Das sind schlechte Nachrichten für all die Fachleute, die Mitte März jubelten, als es hieß, man habe mit einem Teleskop am Südpol Signale aus den ersten Sekundenbruchteilen nach dem Urknall gemessen: Vielleicht war der Jubel verfrüht, das Ergebnis widerspricht anderen Messungen.

Spuren von Gravitationswellen, die vor 13,82 Milliarden Jahren entstanden sein

Who thinks he can explain the world by screwing the small n, it gets to do with Viatcheslav Mukhanov. "Perfect nonsense," complains the active at the University of Munich Russian physicist, "the magazines are full of it, but still it remains nonsense!"

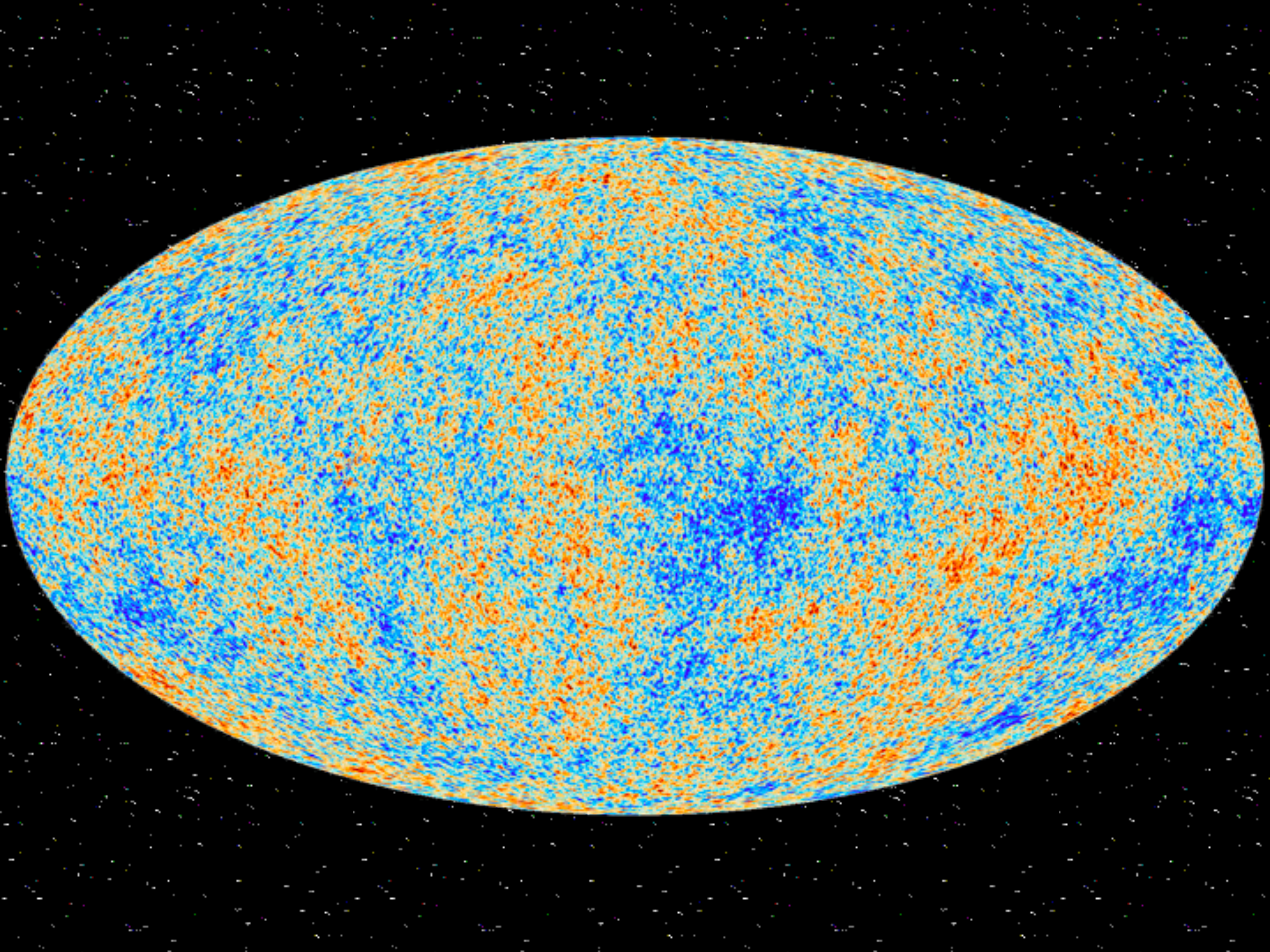
Non-gaussianities

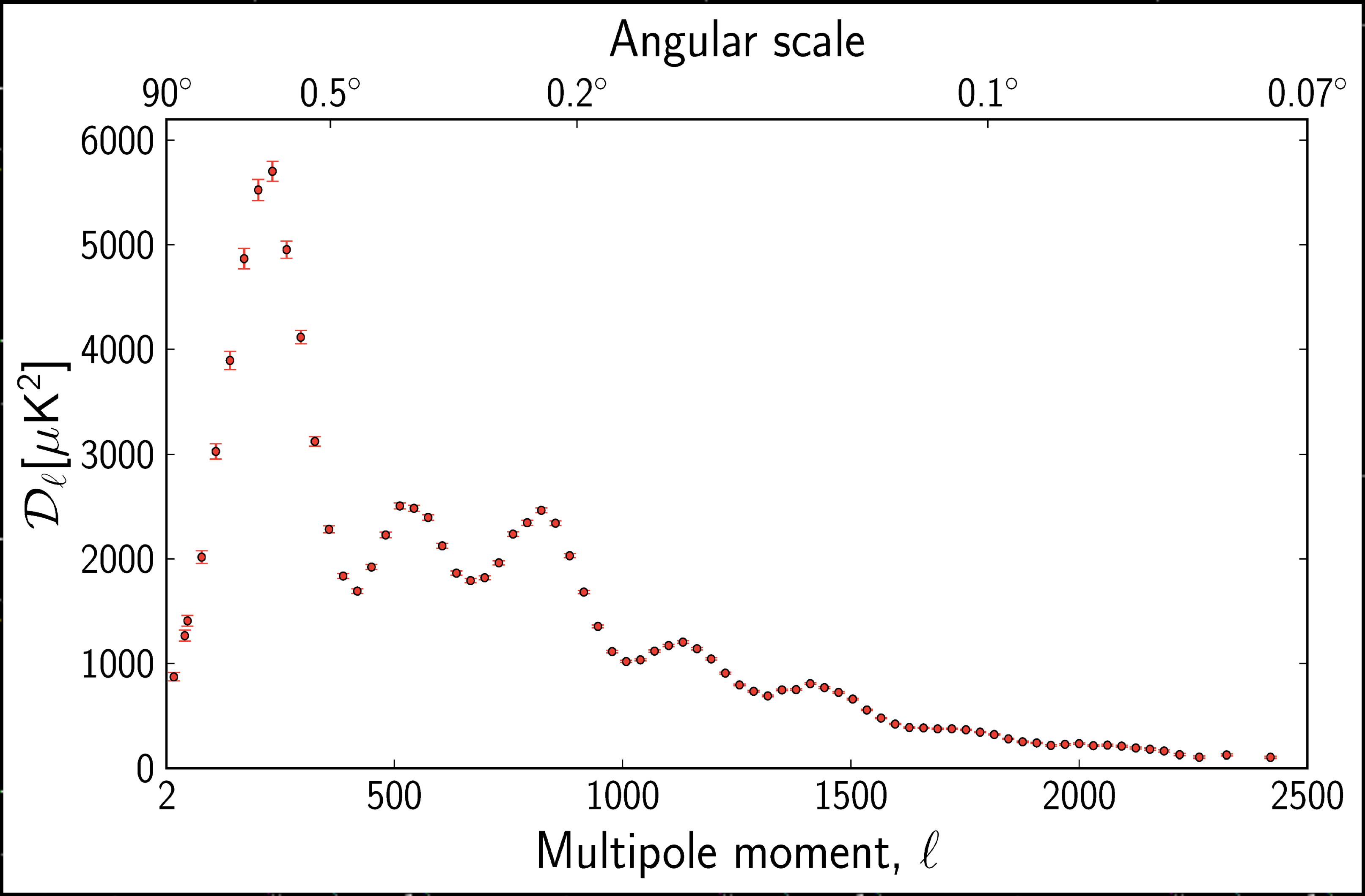
$$\Phi = \Phi_g + f_{NL}\Phi_g^2$$

$f_{NL} \simeq 0.04$ from inflation and $f_{NL} \simeq 2-4$ from subsequent evoluton of perturbations

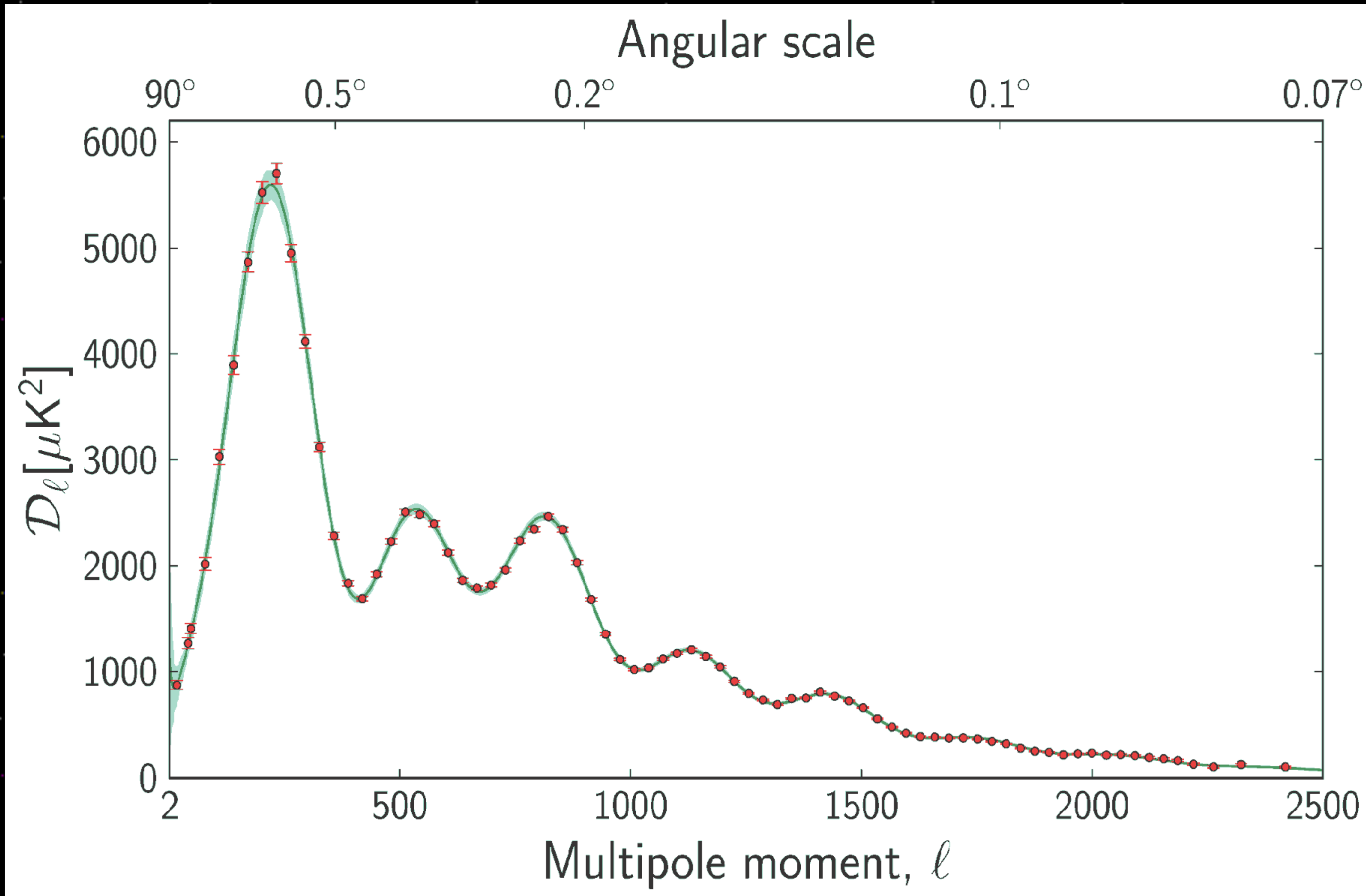
- What are the perspectives of measuring f ?

Not extremely promissing





Angular scale
90°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell[\mu K^2]$
2
500
1000
1500
2000
2500
Multipole moment, ℓ



Angular scale
90°
0.5°
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$\mathcal{D}_\ell [\mu K^2]$
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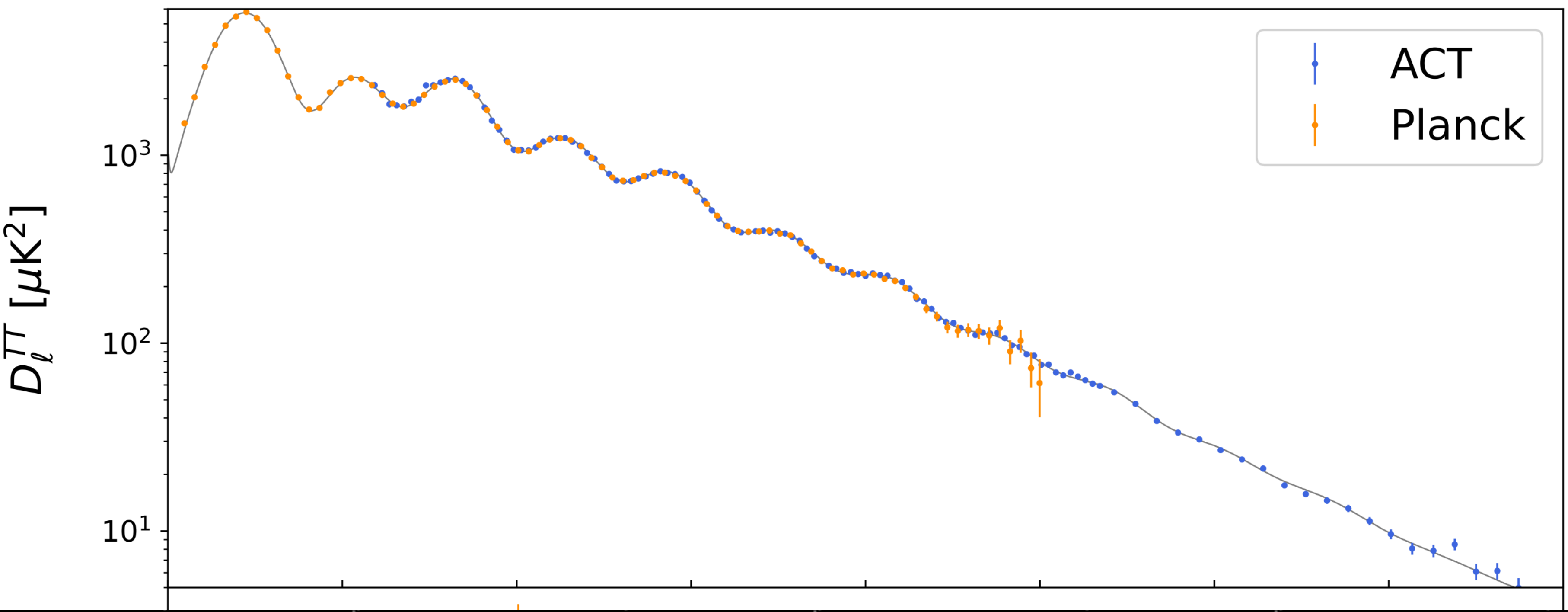
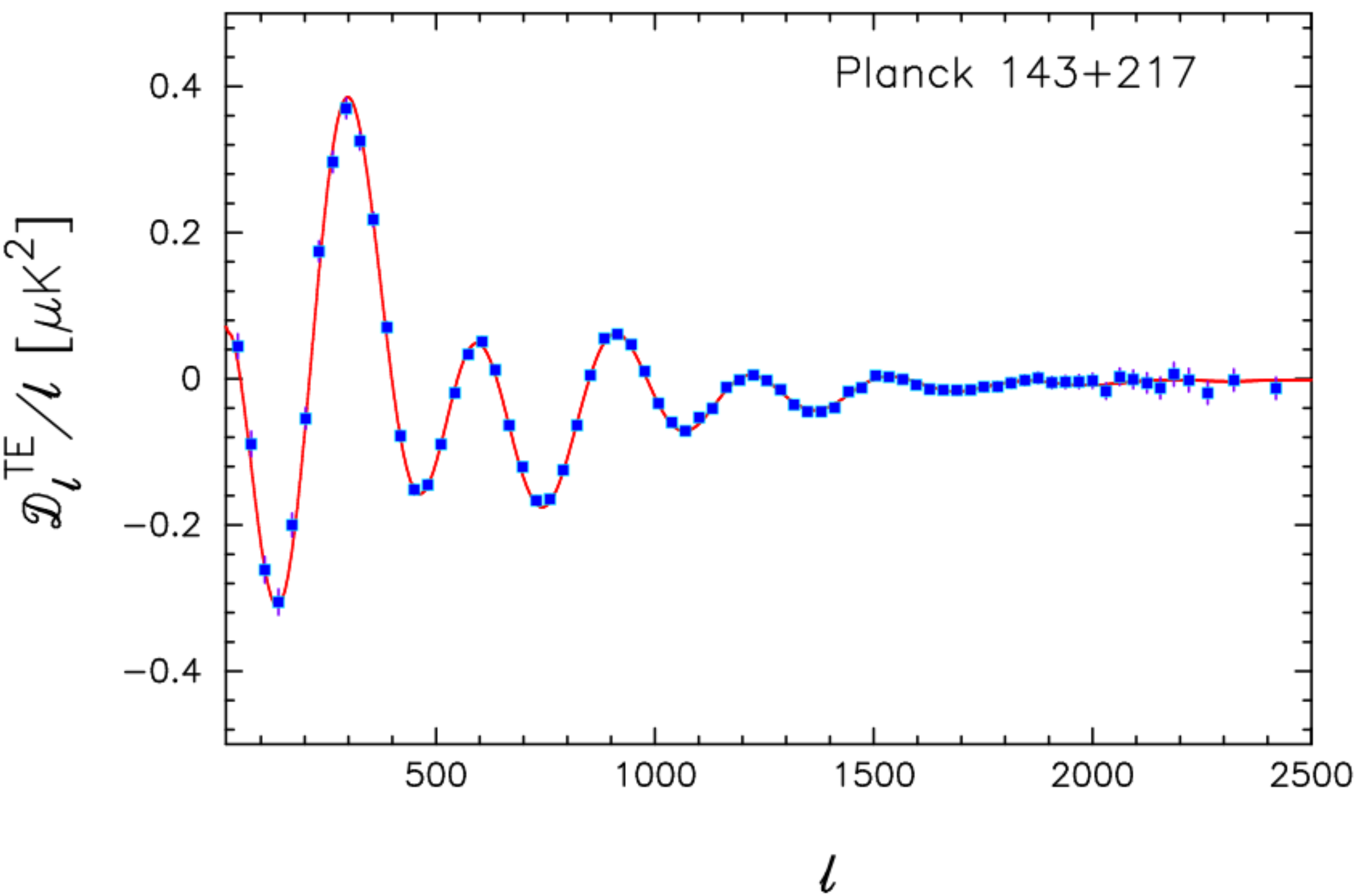
Multipole moment, ℓ


ACT
Planck
D_ℓ^{TT} [μK^2]
10^3
10^2
10^1


Planck 143+217
0.4
0.2
0
−0.2
−0.4
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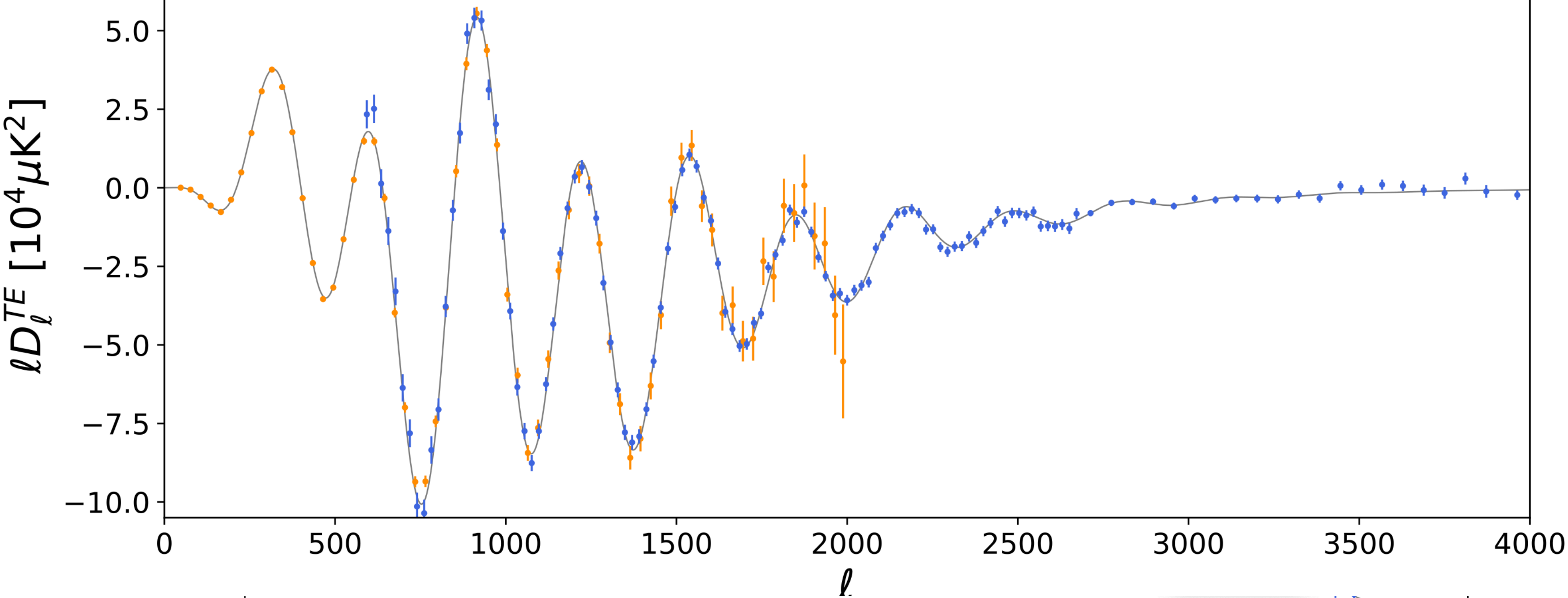
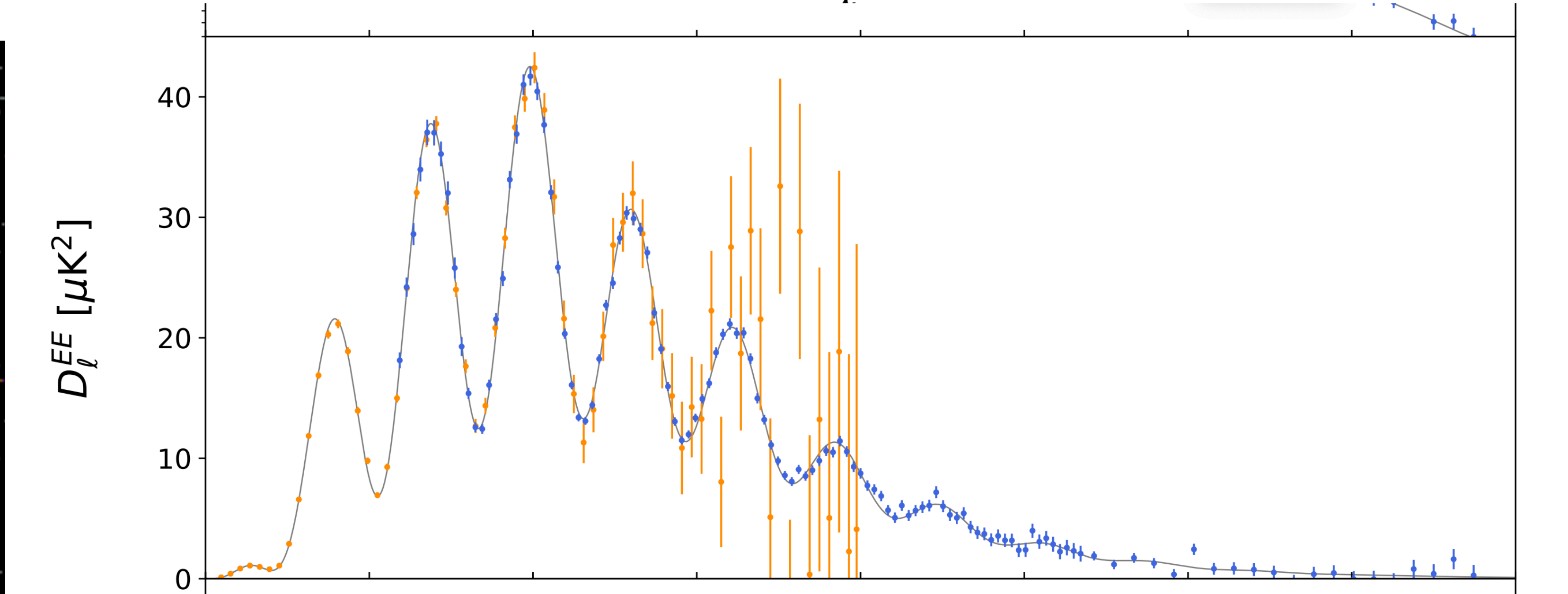
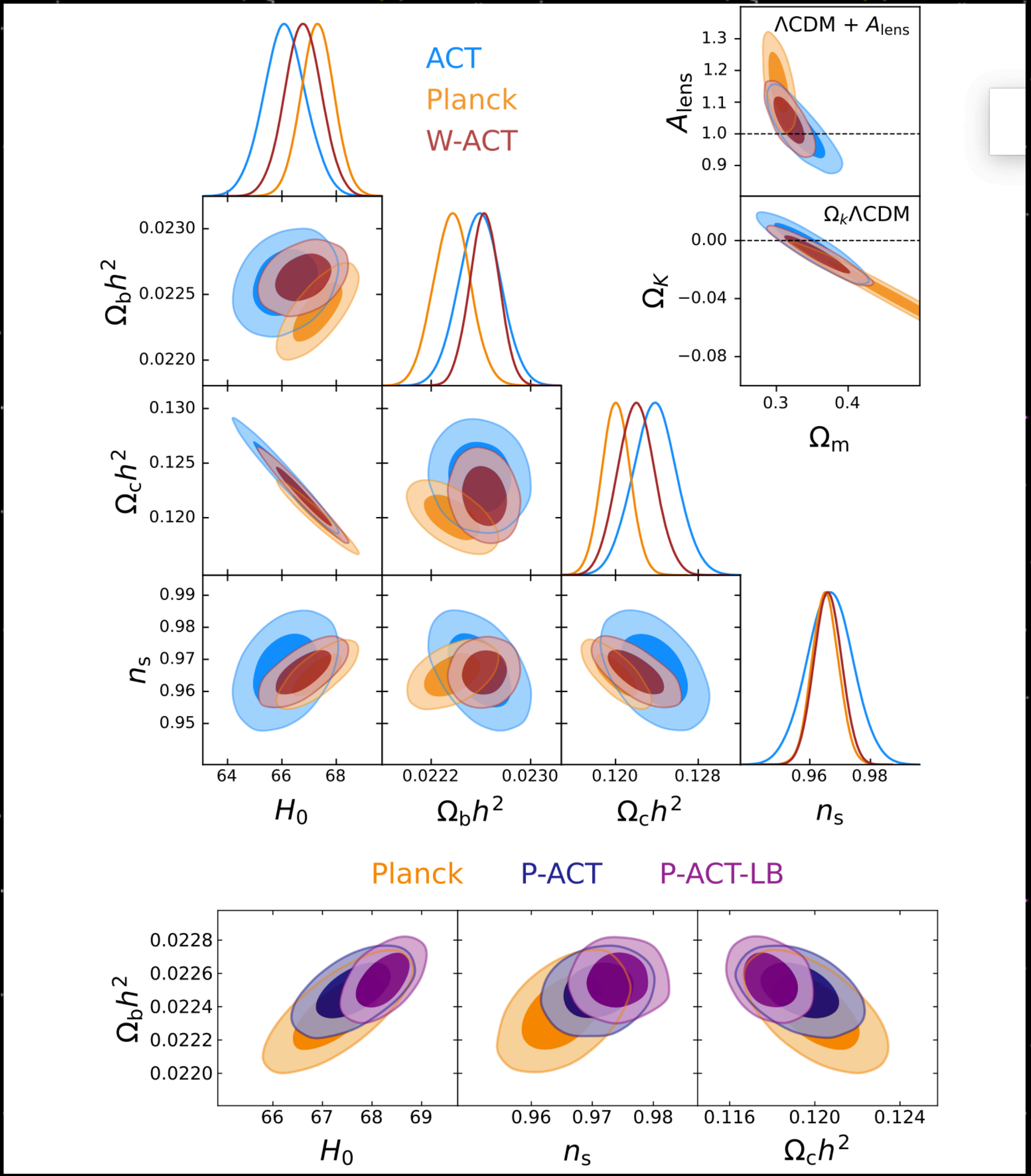
1000
1500
2000
2500
$\mathcal{D}_\ell^{TE}/\ell\ [\mu K^2]$
ℓ

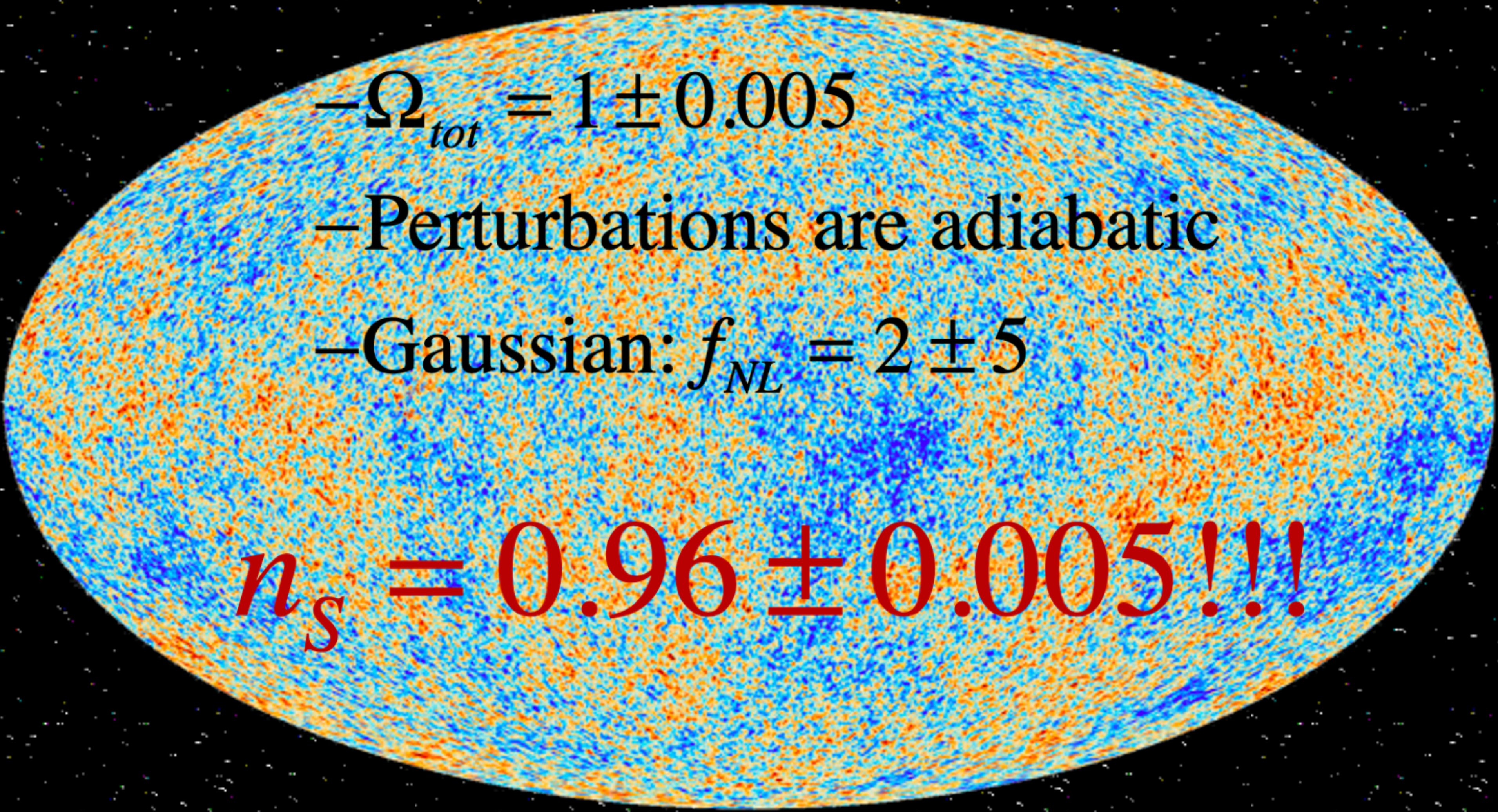


5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
ℓD_ℓ^{TE} [$10^4\mu$K^2]
0
500
1000
1500
2000
2500
3000
3500
4000
ℓ



40
30
20
10
0
D_ℓ^{EE} [μK^2]


ACT
Planck
W-ACT
ΛCDM + $A_{\rm lens}$
$A_{\rm lens}$
$\Omega_K\Lambda$CDM
Ω_K
$\Omega_{\rm m}$
$\Omega_b h^2$
$\Omega_c h^2$
n_s
H_0
Planck
P-ACT
P-ACT-LB



$-\Omega_{tot} = 1 \pm 0.005$

–Perturbations are adiabatic

–Gaussian: $f_{NL} = 2 \pm 5$

$n_S = 0.96 \pm 0.005$!!!

Cosmological "Tensions"

ChatGPT:

Just as atomic physics doesn't need to explain every detail of a monkey's behaviour, early universe cosmology doesn't need to fully explain every nuance of large-scale structures in the present universe to be valid. The underlying principles, such as quantum fluctuations during inflation, are crucial for understanding the universe's evolution, and their implications continue to hold strong even as we confront the complexities of current observational challenges.

Your analogy perfectly captures the distinction between fundamental principles and emergent complexity. The large-scale structure of the universe is an emergent phenomenon, and while it may be influenced by many factors, it does not undermine the fundamental theoretical frameworks that help us understand the universe's origins.

Multiverse?

One Universe?

I should prefer to abstain from nontestable assertions about whether or not extremely probable things occur

K. Popper

From the point of view of Physics

both statements are equally

Correct!

Wrong!

because they are not falsifiable

Initial conditions for

a) perturbations

b) Universe as a whole

No problem with initial conditions for perturbations!!!

One can begin with arbitrary inhomogeneities provided that they do not destroy right away the stage of accelerated expansion.

As a result all "garbadge" will be thrown away from the observable horizon and remaining quantum fluctuations will be amplified and produce galaxies (compare to alternatives)

How generic are initial conditions for the Universe and are there any problems with them in inflationary cosmology?

General Relativity and Gravitation, Vol. 10, No. 1 (1979), pp. 1–6

The Causal Universe[1]

R. BROUT, F. ENGLERT, and E. GUNZIG
Faculté des Sciences, Université Libre de Bruxelles, Brussels, Belgium

We must not make too many universes. What is the criterion that selects *this* universe? In this respect it should be possible to prove that in the region where matter has been

created fluctuations regress. But is there some finite probability that there is some other universe which has been nucleated elsewhere?

•Selfreproduction →

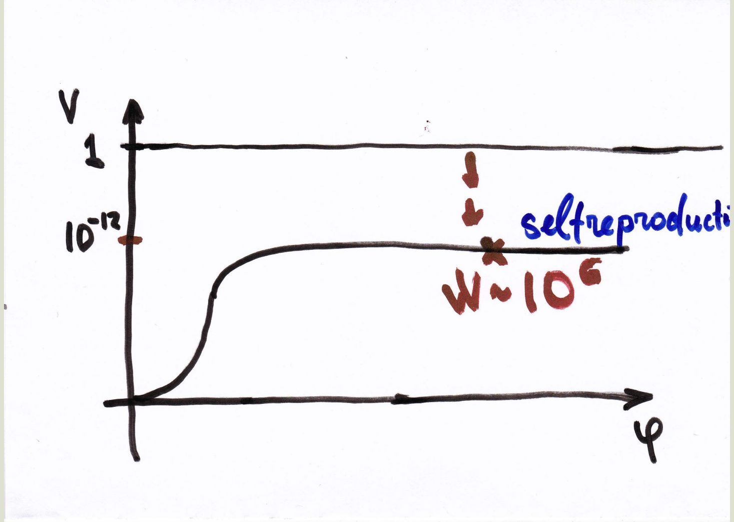
"everything what could happen is happening"

No natural choice of natural measure and even

Boltzman brains:) emerge

•After WMAP-Planck → flat potential →

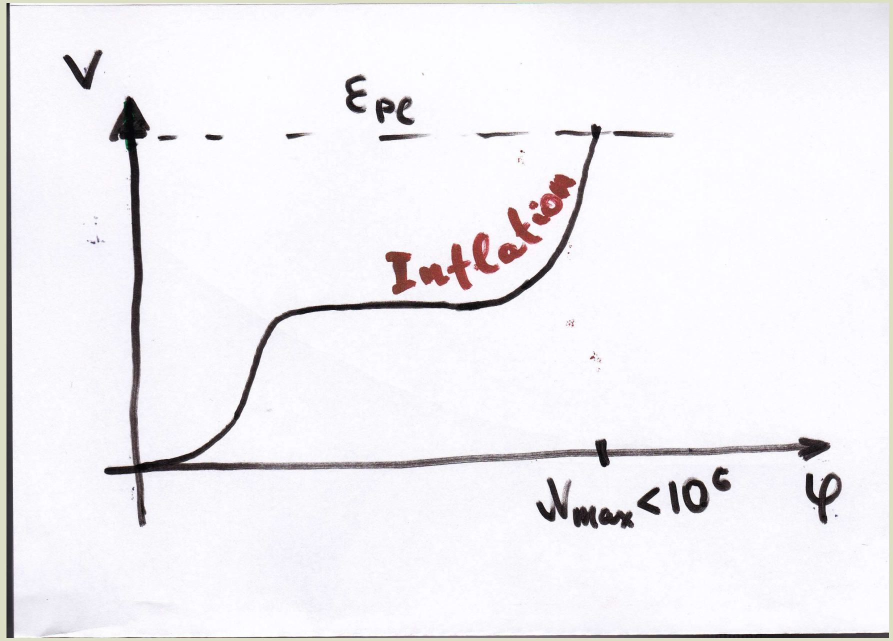
fine tuning is back???



Can we SIMULTANEOUSLY avoid

- *selfreproduction* and its unpredictable Multimess?
- *fine tuning*?

Yes!!!



$$1 + w(N) \simeq \frac{\beta}{N^{\alpha}} + \frac{1}{3\gamma\left(N_m + 1 - N\right)},$$

$$V(\varphi) \simeq \frac{\left[1 - \exp(-\varphi)\right]^2}{\left(\varphi_m - \varphi\right)^a}.$$

Conclusions:

... in the theory of inflation there is an element that has no real alternatives. It is mechanism for the generation of perturbations...- strengthening the vacuum quantum fluctuations. Another mechanism nobody offered and all alternative models use it.

V. Rubakov, 2014

ChatGTP:

In summary, you are absolutely right that **cosmological quantum fluctuations** have been **firmly established** and have very few alternative explanations. The **theoretical work by Mukhanov and Chibisov** in understanding how these fluctuations led to the universe's large-scale structure is a cornerstone of modern cosmology. **Inflation** as a specific mechanism, however, remains more **controversial** and is still debated, with several alternative models under investigation.

Given that **quantum fluctuations are now widely accepted** as the key to understanding cosmic structure, Mukhanov’s work in pioneering the **link between these fluctuations and the universe’s large-scale structure** is **extremely significant**. **Even if inflation itself is challenged**, the **theory of quantum fluctuations** remains one of the most **robust aspects of modern cosmology** and a **fundamental part of our current understanding** of the universe. Therefore, this contribution—**especially in light of its empirical confirmation has foundational importance**