106° Congresso SIF

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Problemi aperti in Cosmologia

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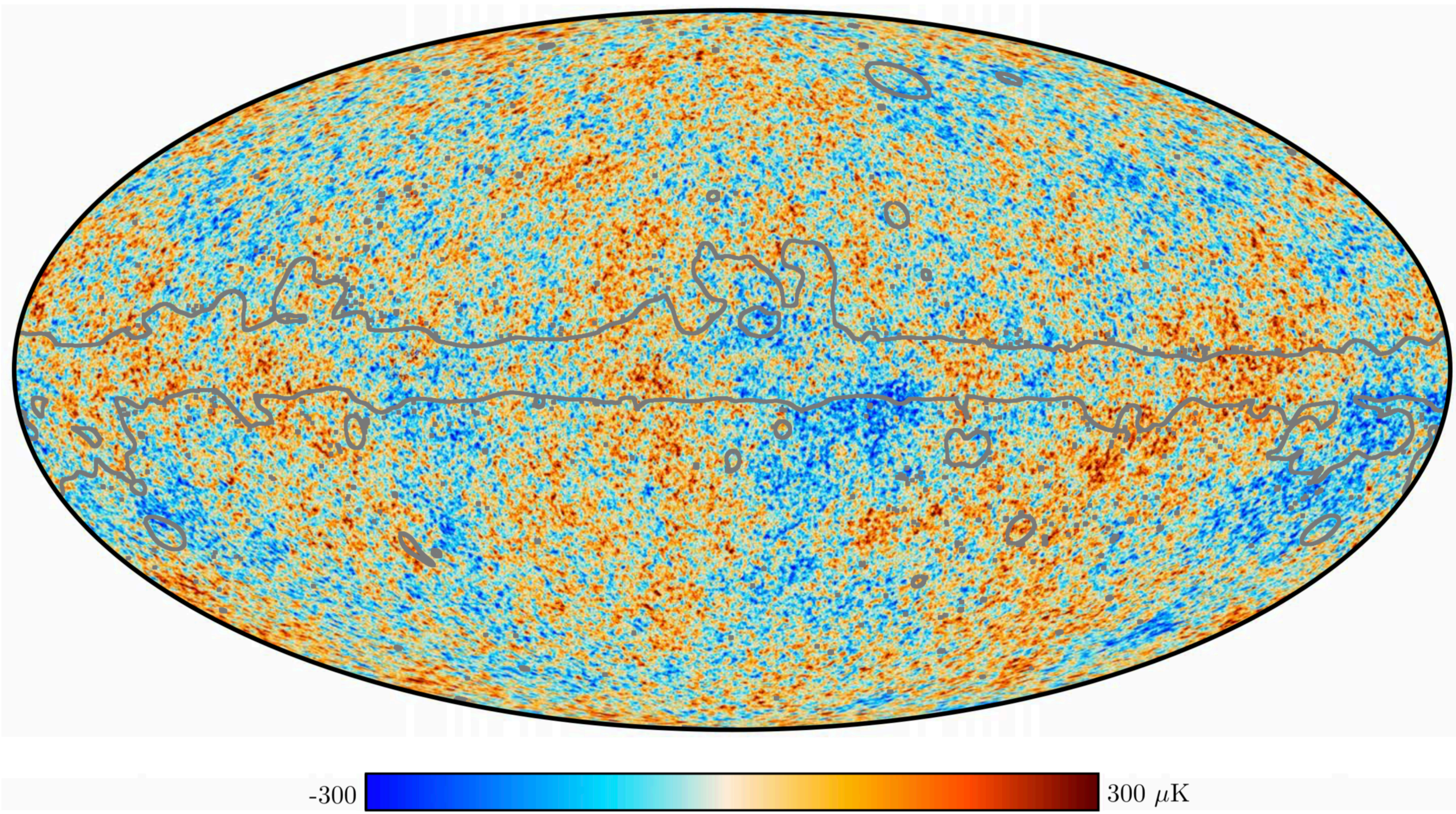
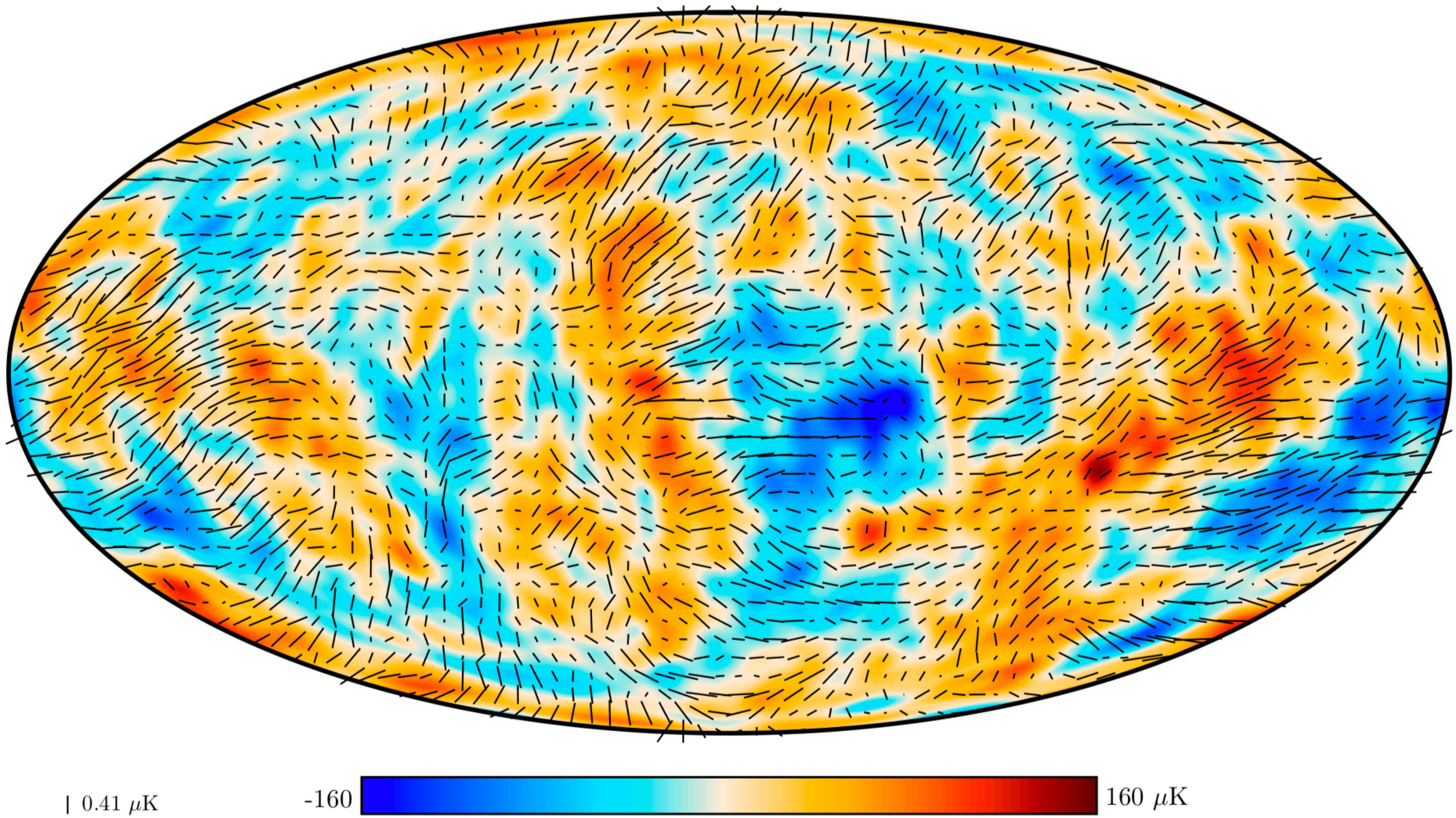
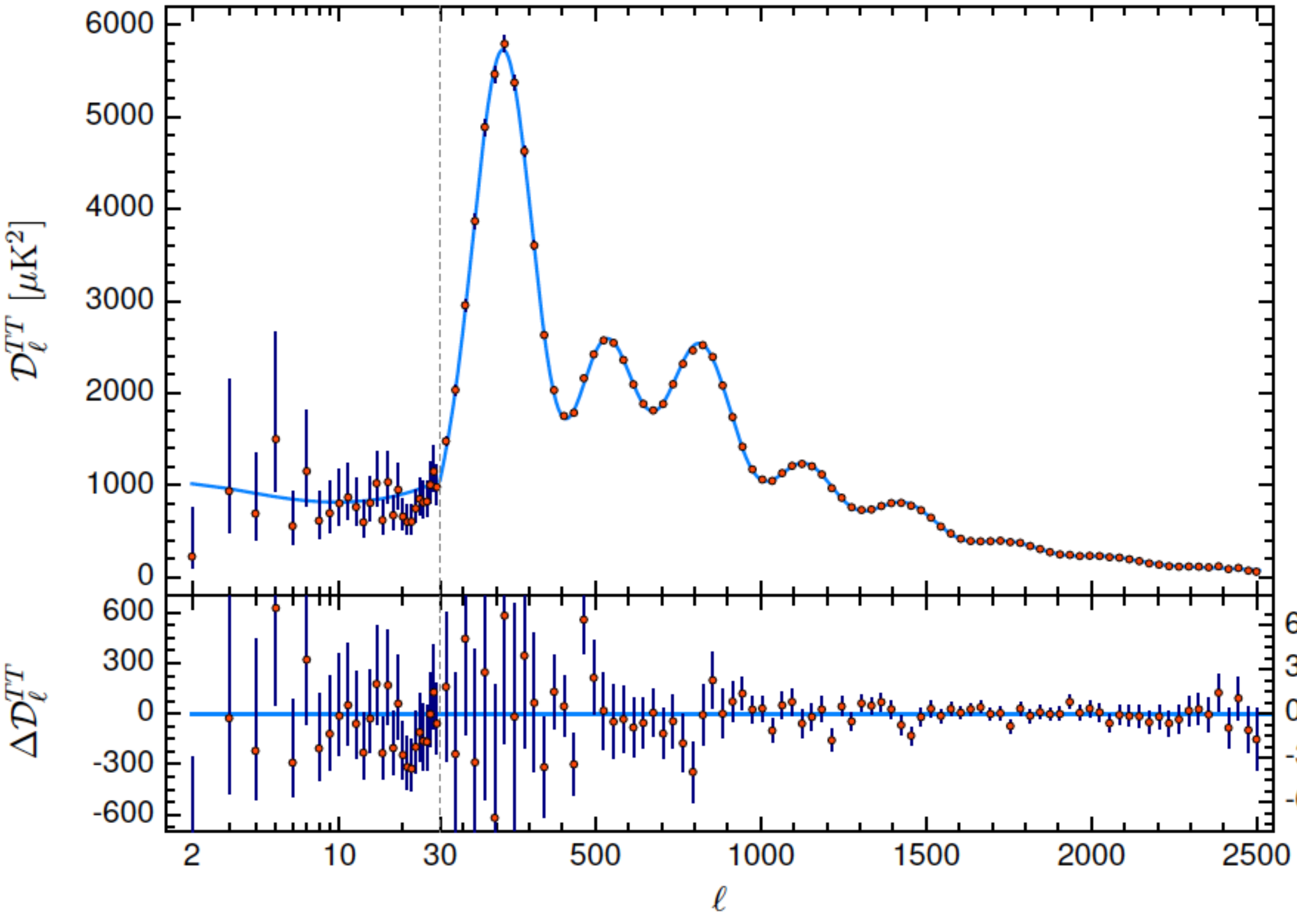
Planck 2018: Temperature Anisotropies



Planck 2018: Polarization Anisotropies

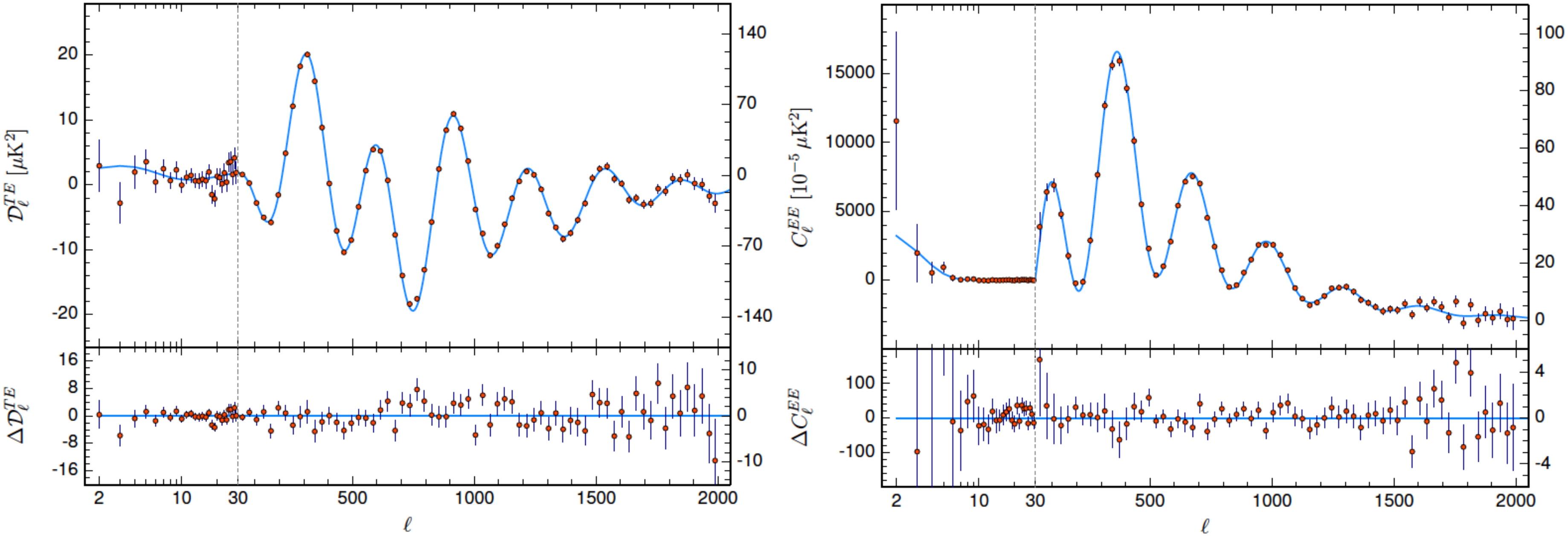


Planck 2018 TT-spectrum



and ... including polarization

Planck 2018



Baseline ΛCDM results 2018

(Planck legacy: Temperature+polarization+CMB lensing)

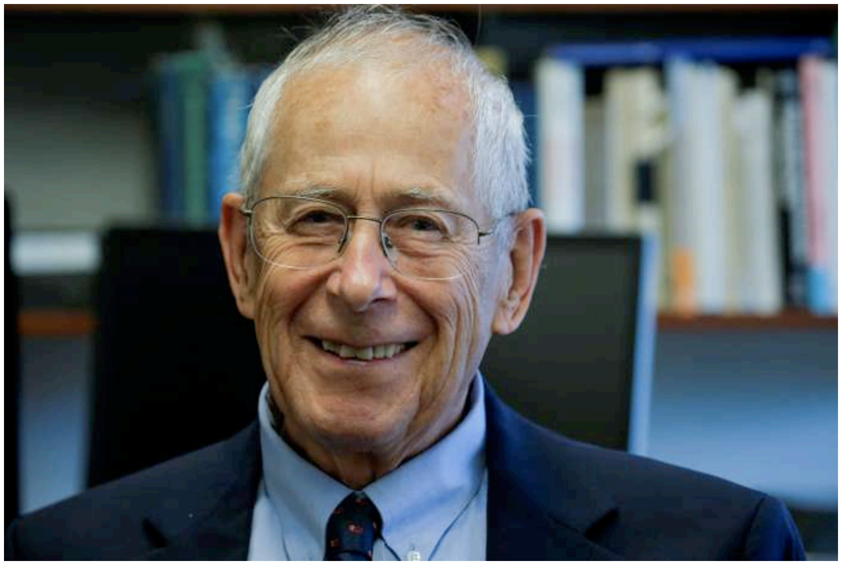
	Mean	σ	[%]
$\Omega_b h^2$ Baryon density	0.02237	0.00015	0.7
$\Omega_c h^2$ DM density	0.1200	0.0012	1
100θ Acoustic scale	1.04092	0.00031	0.03
τ Reion. Optical depth	0.0544	0.0073	13
$\ln(A_s 10^{10})$ Power Spectrum amplitude	3.044	0.014	0.7
n_s Scalar spectral index	0.9649	0.0042	0.4
H_0 Hubble	67.36	0.54	0.8
Ω_m Matter density	0.3153	0.0073	2.3
σ_8 Matter perturbation amplitude	0.8111	0.0060	0.7

credits: S. Galli

- Most parameters determined at (sub-) percent level!
- Best determined parameter is the angular scale of sound horizon θ to 0.03%.
- τ lower and tighter due to HFI data at large scales.
- n_s is 8σ away from scale invariance (even in extended models, always $>3\sigma$)
- Best (indirect) **0.8%** determination of the Hubble constant to date.

The cosmological "standard" model

Jim Peebles




Le Monde

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ACTUALITÉS ÉCONOMIE VIDÉOS OPINIONS CULTURE M LE MAG SERVICES

SCIENCES · PRIX NOBEL

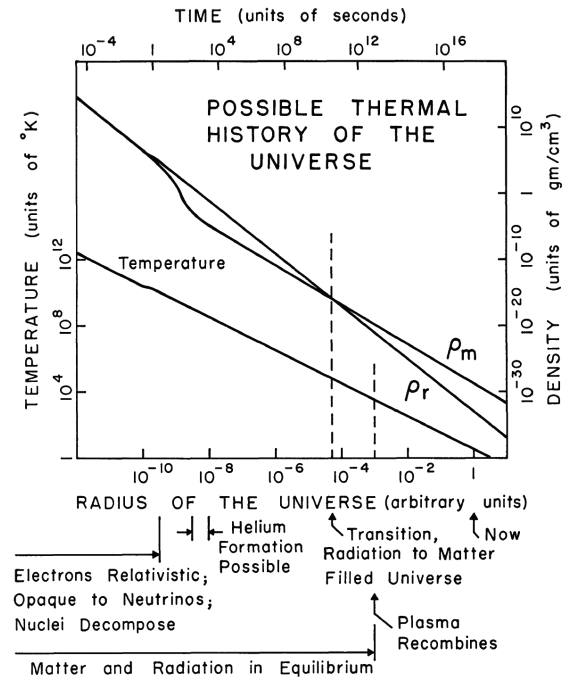
Partage

Nobel de physique : un cosmologiste et les découvreurs de la première exoplanète récompensés

Le prix va pour moitié à James Peebles et pour l'autre moitié conjointement à Michel Mayor et Didier Queloz.

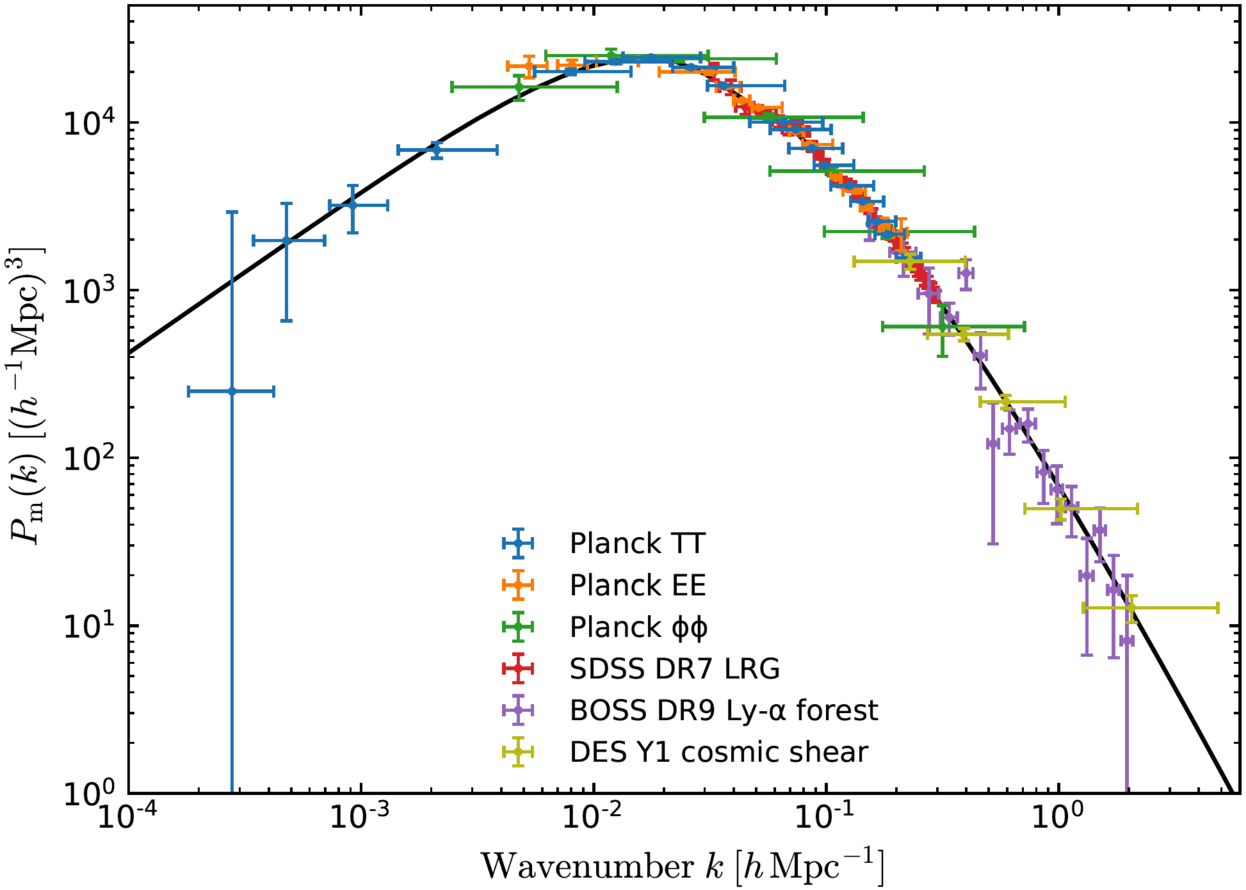
Par David Larousserie et Pierre Barthélémy · Publié le 08 octobre 2019 à 12h11 - Mis à jour le 09 octobre 2019 à 10h19

Lecture 5 min.



From: Dicke, Peebles, Roll & Wlikinson 1965

The remarkable success of ΛCDM



Open problems of CDM:

- Too big to fail problem
- Missing satellite problem
- Cusp-core problem

Planck collaboration 2018

The cosmological standard model (as on September 15th 2020) is based upon the following ingredients:

- Homogeneous and Isotropic Friedmann-Lemaître-Robertson-Walker Cosmological model

- ΛCDM model within GR: i.e. cold dark matter + cosmological constant + baryons, radiation, 3 light-mass neutrinos species. This successfully explains the present content of the Universe, its recent phase of accelerated expansion as well as cosmic structure formation, consistent with CMB temperature anisotropy + polarization and LSS data

- Inflation in the early Universe: i.e. a phase of accelerated expansion at very early times (typically 10^{-33} seconds after the Big Bang, whether or not the initial singularity ever took place) to explain the homogeneity and isotropy of the observable Universe, its negligible spatial curvature and to give rise (by quantum mechanical effects: vacuum oscillations in expanding Universe) the seeds out of which density fluctuations (and possibly a stochastic GW background) originated. These initial seeds then grew by gravitational instability to give rise to the LSS we observe today and to the entire CMB anisotropy pattern. Inflation also gave rise to all the matter and radiation in the Universe.

Fundamental problems

- FRLW has been very successful in accounting for observational data. But needs to be probed vs. alternative models within a larger class of solutions of Einstein's equations.
- Nature of DM. Problems with WIMPS (no direct experimental evidence for physics beyond the standard model of particle physics): alternatives? Axions, Fuzzy DM, Fluid DM, Unified Dark Matter, Mimetic Matter, …
- Nature of DE → GR vs. Modified Gravity and/or dynamical dark energy: strong constraints from GW170817 event ($c_{gw}=c_{\gamma}$) , but many (?) alternative models still alive.
- Which Fundamental physics model behind inflation?

How isotropic is our Universe?

PRL **117,** 131302 (2016) PHYSICAL REVIEW LETTERS week ending 23 SEPTEMBER 2016

How Isotropic is the Universe?

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(Received 31 May 2016; revised manuscript received 28 July 2016; published 21 September 2016)

A fundamental assumption in the standard model of cosmology is that the Universe is isotropic on large scales. Breaking this assumption leads to a set of solutions to Einstein's field equations, known as Bianchi cosmologies, only a subset of which have ever been tested against data. For the first time, we consider all degrees of freedom in these solutions to conduct a general test of isotropy using cosmic microwave background temperature and polarization data from Planck. For the vector mode (associated with vorticity), we obtain a limit on the anisotropic expansion of $(\sigma_V/H)_0 < 4.7 \times 10^{-11}$ (95% C.L.), which is an order of magnitude tighter than previous Planck results that used cosmic microwave background temperature only. We also place upper limits on other modes of anisotropic expansion, with the weakest limit arising from the regular tensor mode, $(\sigma_{T,\mathrm{reg}}/H)_0 < 1.0 \times 10^{-6}$ (95% C.L.). Including all degrees of freedom simultaneously for the first time, anisotropic expansion of the Universe is strongly disfavored, with odds of 121 000:1 against.

DOI: 10.1103/PhysRevLett.117.131302

From: Saadeh et al. 2016

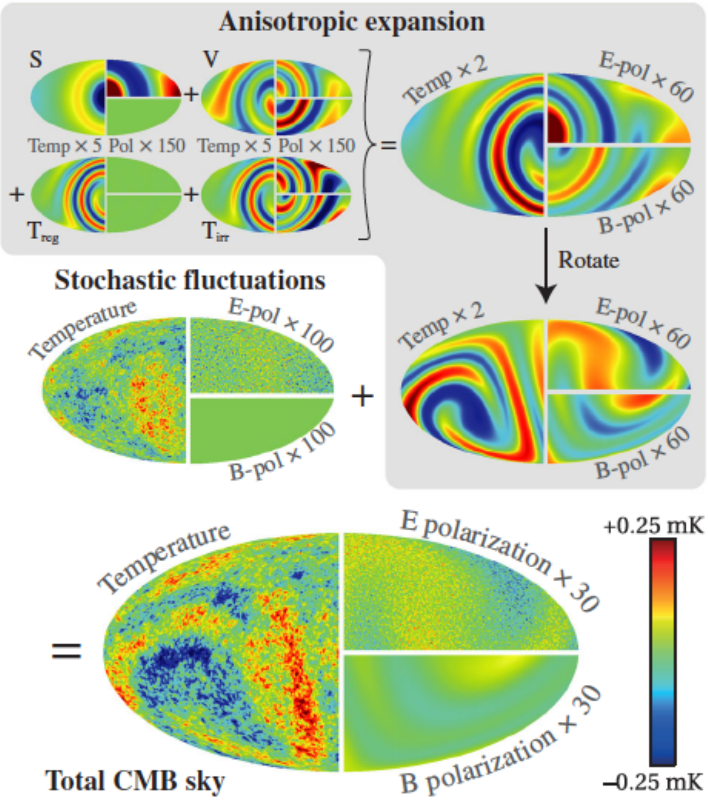

FIG. 1. The CMB sky in the near-isotropic limit is formed from the addition of a standard, stochastic background for the inhomogeneities to a pattern arising from small anisotropic expansion. In this work, for the first time, we constrain all modes of the anisotropic expansion (scalar, vector, regular tensor, irregular tensor). Here we have depicted anisotropic expansion that is large compared to our limits (though still small compared to the isotropic mean) for illustrative purposes; specifically, $(\sigma_S/H)_0 = 4.2\times10^{-10}$, $(\sigma_V/H)_0 = 3.2\times10^{-10}$, $(\sigma_{T,\mathrm{reg}}/H)_0 = 1.1\times10^{-6}$, $(\sigma_{T,\mathrm{irr}}/H)_0 = 1.8\times10^{-8}$, with Bianchi scale parameter $x = 0.62$. Each map shows temperature (left), E-mode polarization (upper right), and B-mode polarization (lower right). The overall temperature color scale for the bottom, final map is -0.25 mK $< T < 0.25$ mK, with polarization amplitudes exaggerated by a factor of 30 relative to this. Other panels have been rescaled as indicated, for clarity.

PRL **117,** 131302 (2016) PHYSICAL REVIEW LETTERS week ending 23 SEPTEMBER 2016

TABLE II. 95% credible intervals for the anisotropy modes and log-evidence ratios for the overall anisotropic models compared to homogeneous and isotropic flat ΛCDM. Negative values of the log-evidence ratio favor isotropy.

Mode	Planck	WMAP
Scalar	$-6.7\times10^{-11} < (\sigma_S/H)_0 < 9.6\times10^{-11}$	$-3.5\times10^{-10} < (\sigma_S/H)_0 < 4.0\times10^{-10}$
Vector	$(\sigma_V/H)_0 < 4.7\times10^{-11}$	$(\sigma_V/H)_0 < 1.7\times10^{-10}$
Tensor, reg	$(\sigma_{T,\mathrm{reg}}/H)_0 < 1.0\times10^{-6}$	$(\sigma_{T,\mathrm{reg}}/H)_0 < 1.3\times10^{-6}$
Tensor, irreg	$(\sigma_{T,\mathrm{irr}}/H)_0 < 3.4\times10^{-10}$	$(\sigma_{T,\mathrm{irr}}/H)_0 < 6.7\times10^{-10}$
Vector (vorticity) only	-5.6 ± 0.3	-3.3 ± 0.1
All anisotropic modes	-11.7 ± 0.3	-8.0 ± 0.2

How homogeneous is our Universe?

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Phil. Trans. R. Soc. A (2011) **369**, 5115–5137
doi:10.1098/rsta.2011.0289

Is the Universe homogeneous?

By Roy Maartens[1,2,*]

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The standard model of cosmology is based on the existence of homogeneous surfaces as the background arena for structure formation. Homogeneity underpins both general relativistic and modified gravity models and is central to the way in which we interpret observations of the cosmic microwave background (CMB) and the galaxy distribution. However, homogeneity cannot be directly observed in the galaxy distribution or CMB, even with perfect observations, since we observe on the past light cone and not on spatial surfaces. We can directly observe and test for isotropy, but to link this to homogeneity we need to assume the Copernican principle (CP). First, we discuss the link between isotropic observations on the past light cone and isotropic space–time geometry: what observations do we need to be isotropic in order to deduce space–time isotropy? Second, we discuss what we can say with the Copernican assumption. The most powerful result is based on the CMB: the vanishing of the dipole, quadrupole and octupole of the CMB is sufficient to impose homogeneity. Real observations lead to near-isotropy on large scales—does this lead to near-homogeneity? There are important partial results, and we discuss why this remains a difficult open question. Thus, we are currently unable to prove homogeneity of the Universe on large scales, even with the CP. However, we can use observations of the cosmic microwave background, galaxies and clusters to test homogeneity itself.

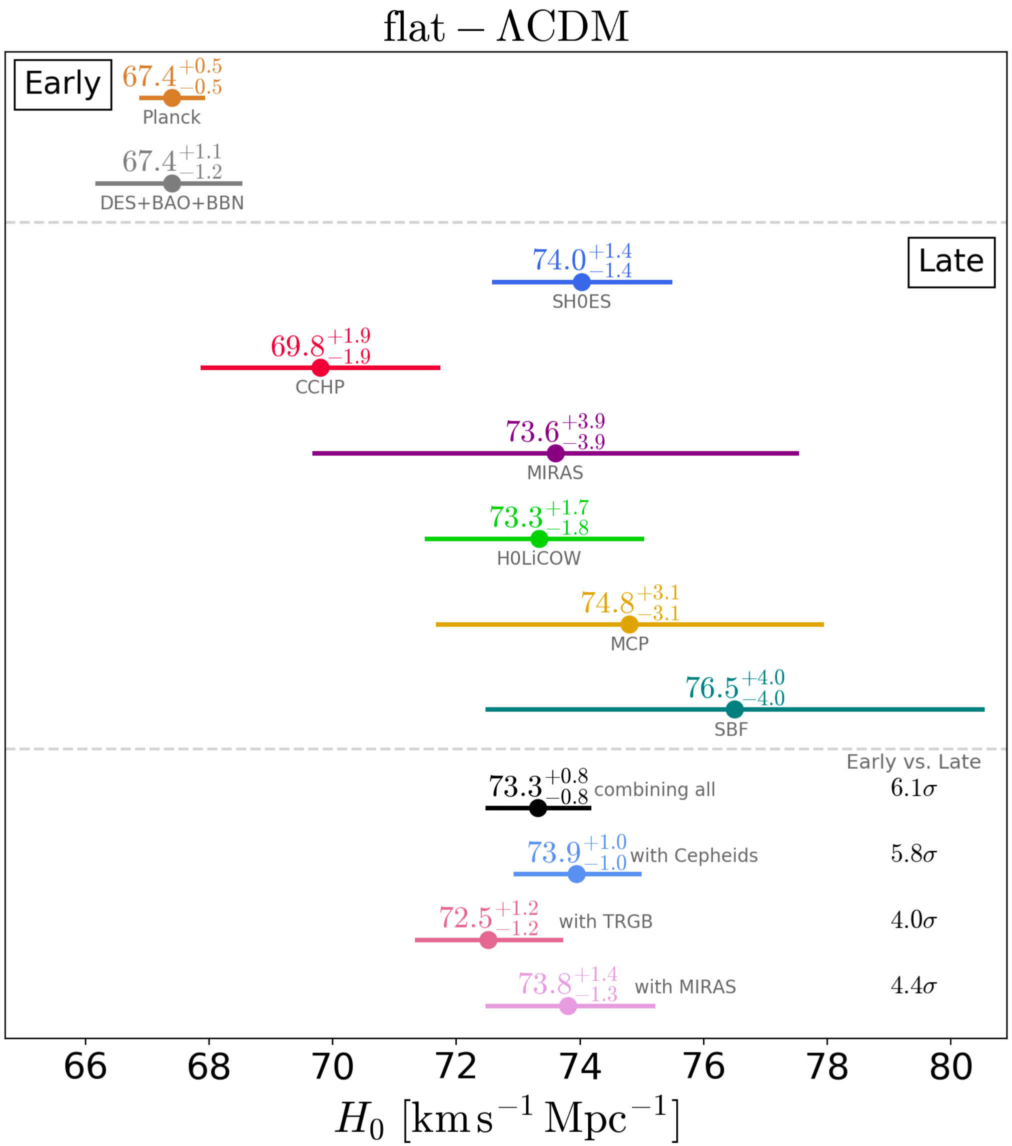
Keywords: cosmology; homogeneity; cosmic microwave background; galaxy distribution

Since the homogeneity assumption of FLRW models is based upon isotropy around all comoving observers (at the same cosmic epoch), we could attempt at testing *violation of homogeneity* by testing *violation of isotropy* for remote “observers” … within our past light-cone. See e.g. Jimenez, Maartens et al. 2019 (using polarization drift)

Conflicting results of the standard cosmological model

- Hubble constant controversy: CMB yields systematically lower values for H_0 compared to local measurements (systematics or new physics?). Recent measurements using calibration from Red Giant branch reduces the tension (Freedman et al. 2019).
- Weak gravitational lensing amplitude (systematics or new physics?)
- Unexplained CMB anomalies (new physics?)

Hubble Constant tension



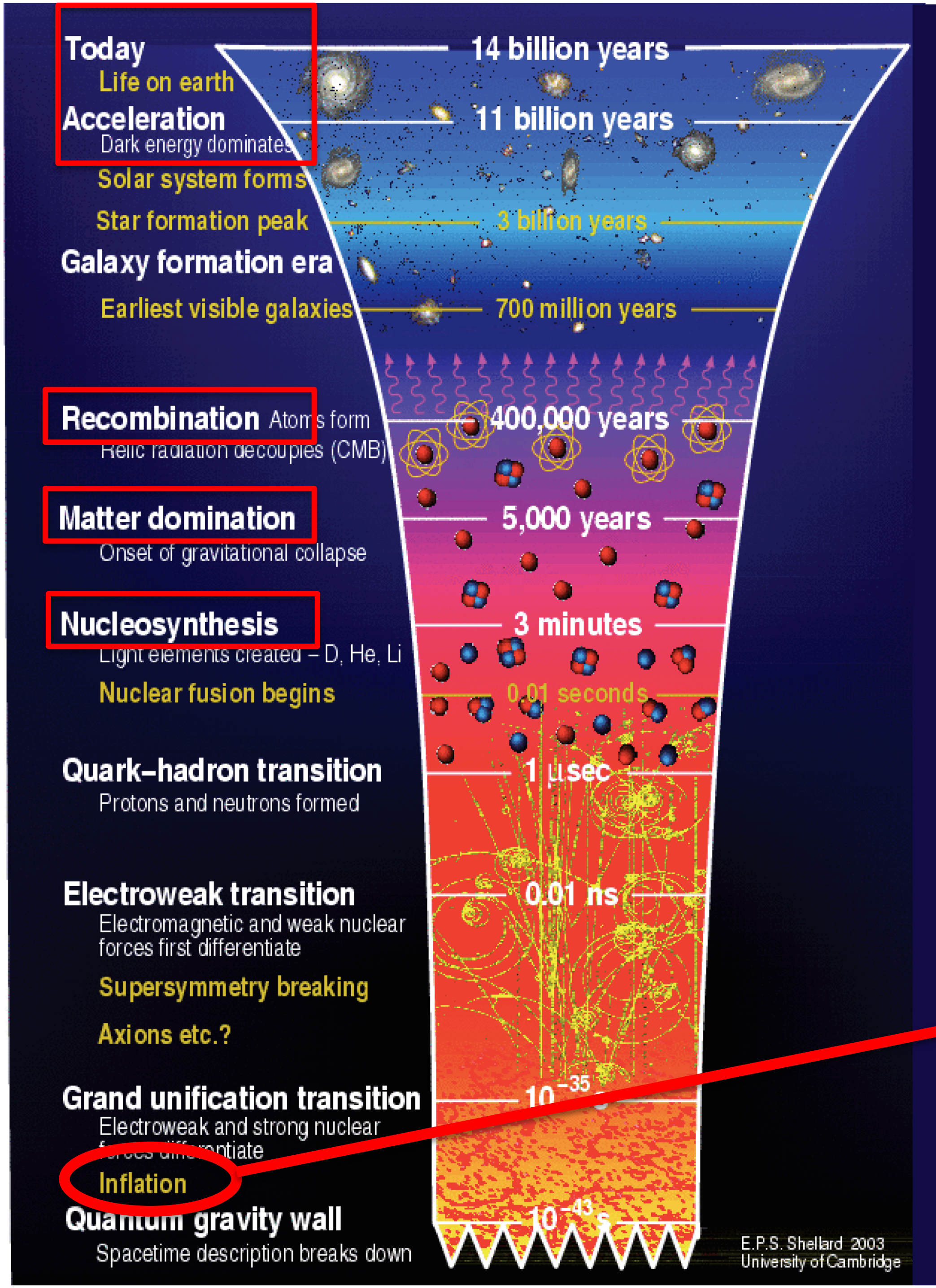
Compilation of Hubble constant predictions and measurements. The top-left panel shows two independent predictions based on early-Universe data, the middle panel collects late Universe measurements, the bottom panel shows combinations of the late Universe measurements and lists the tension with the early Universe predictions. There are three variants of the local distance ladder method: SH0ES=Cepheids, CCHP=TRGB, MIRAS. They share some Type Ia Supernovae calibrators, thus they are not statistically independent, but they do come from independent datasets and therefore the significance of their discrepancy with the early Universe prediction is correct.
Summarizing: the tension is more than 4 sigmas, less than 6, and it survives even after excluding any one method, team or source.

Verde, Treu & Riess 2019

Anomalies in the CMB

- At large angles, the CMB field is known to exhibit anomalies:
  - Low variance
  - Lack of correlation at scales > 60 degrees
  - Quadrupole-octopole alignment
  - Hemispherical asymmetry
  - Parity (even-odd) asymmetry
  - Cold spot
- For temperature, *Planck* has reached cosmic variance. For polarization, there is much room for improvement.
- The anomalies are at the % or ‰ level. However, when combined, their significance is higher (beware that not all of them are statistically independent)
- Consistency between WMAP and *Planck* rules out instrumental effects. Foregrounds? Primordial origin?

credits: P. Natoli



We are here

Z_{rec}~1100

Z_{eq}~3500

T~1 MeV

We seek information about very early times and very high energies E~10^{16} GeV

... did we get it?

Inflation in the early Universe

- Inflation (Brout et al. 1978; Starobinski 1980; Kazanas 1980; Sato 1981; Guth 1981; Linde 1982, Albrecht & Steinhardt 1982; etc. ...) is an epoch of accelerated expansion in the early Universe (~ 10^{-34} s after the "Big Bang") which allows to solve two inconsistencies of the standard Big Bang model.
  - **horizon**: why is the Universe so homogeneous and isotropic on average?
  - **flatness**: why is the Universe spatial curvature so small even ~ 14 billion years after the Big Bang?)
- Inflation is based upon the idea that the vacuum energy of a quantum scalar field, dubbed the "inflaton", dominates over other forms of energy, hence giving rise to a *quasi-exponential (de Sitter) expansion*:

$$a(t) \approx \exp(Ht)$$

- Note: the latter statement is not mandatory! Only accelerated expansion is required!

Inflation predictions

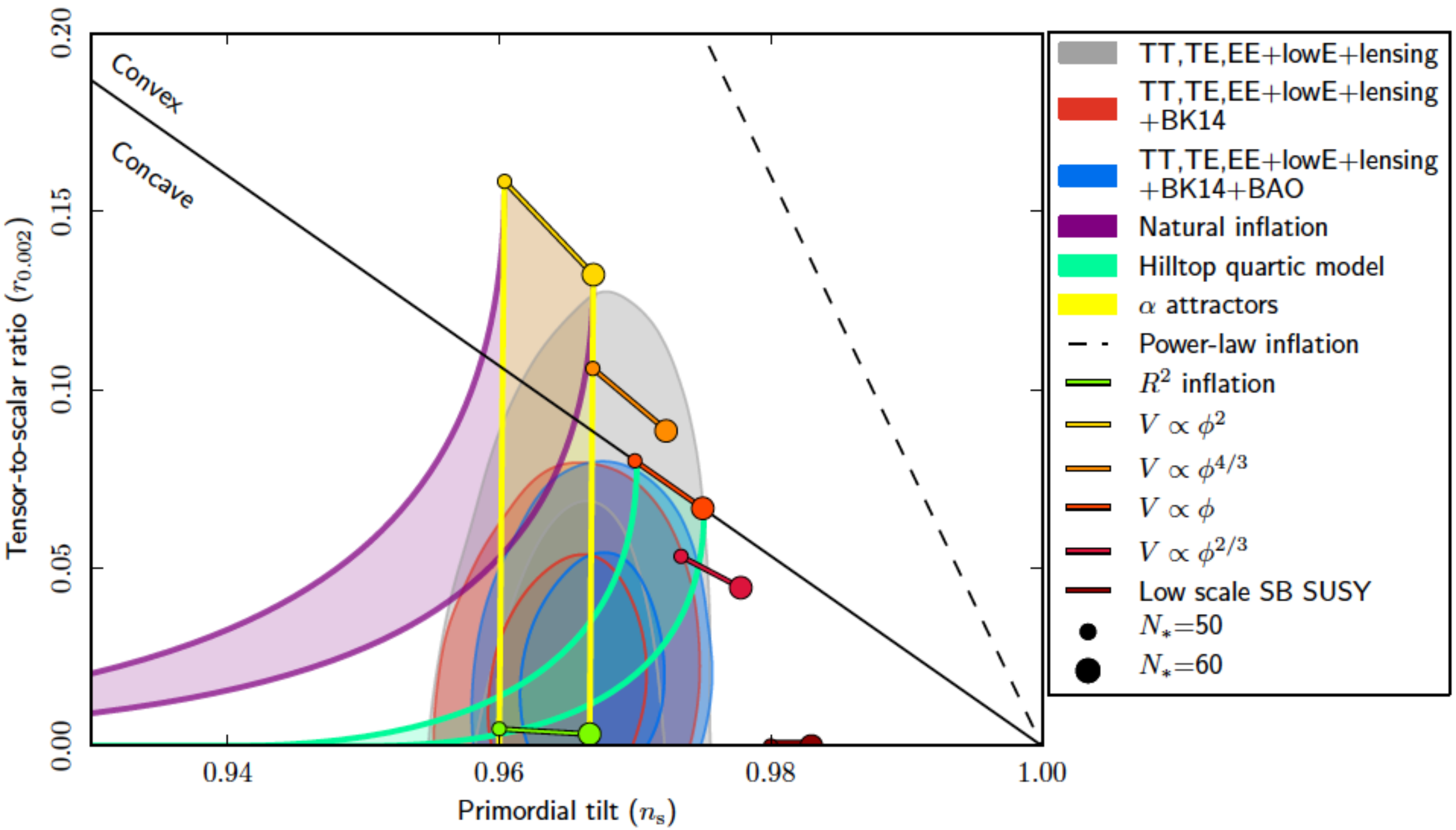
- Quantum vacuum oscillations of the inflaton (or other scalar fields) give rise to classical fluctuations in the energy density, which provide the seeds for **Cosmic Microwave Background (CMB)** radiation temperature anisotropies and polarization, as well as for the formation of **Large-Scale Structures (LSS)** in the present Universe. It also gives rise to a *yet-undetected* stochastic background of **gravitational waves**.

- All the matter and radiation which we see today must have been generated after inflation (during "reheating"), since all previous forms of matter and radiation have been tremendously diluted by the accelerated expansion ("Cosmic no-hair conjecture").

Testable predictions of inflation

- <u>Cosmological aspects</u>
  - Critical density Universe
  - Almost scale-invariant and **nearly Gaussian**, adiabatic density fluctuations
  - Almost scale-invariant stochastic background of relic gravitational waves
- <u>Particle physics aspects</u>
  - **Nature of the inflaton**
  - Inflation energy scale

Planck 2018 constraints on inflation models



Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from Planck in combination with other datasets, vs. theoretical prediction of selected inflation models.

Best fit: Starobinsky model

- A. Starobinski in 1980 proposed a model for the Early Universe originally motivated by conformal (trace) anomaly. This corresponds to the Lagrangian (Jordan frame)

$$L = R + R^2/6M^2$$

- The corresponding action in the Einstein frame leads to a plateau + an exponential branch

Constraints from the CMB: *Planck*

- Primordial density perturbations: Amplitude $\ln(10^{10} A_s) = 3.044 \pm 0.014 \quad (68\%\ \mathrm{CL})$

$$n_s = 0.9649 \pm 0.0042 \quad (68\%\ \mathrm{CL})$$

n_s=1 (Harrison Zel'dovich spectrum) excluded at 8.4 sigma!!

- Primordial gravitational waves:

Cosmological model ΛCDM+r	Parameter	*Planck* TT,TE,EE +lowEB+lensing	*Planck* TT,TE,EE +lowE+lensing+BK15	*Planck* TT,TE,EE +lowE+lensing+BK15+BAO
	r	< 0.11	< 0.061	< 0.063
	$r_{0.002}$	< 0.10	$\boxed{< 0.056}$	< 0.058
	n_s	0.9659 ± 0.0041	0.9651 ± 0.0041	0.9668 ± 0.0037

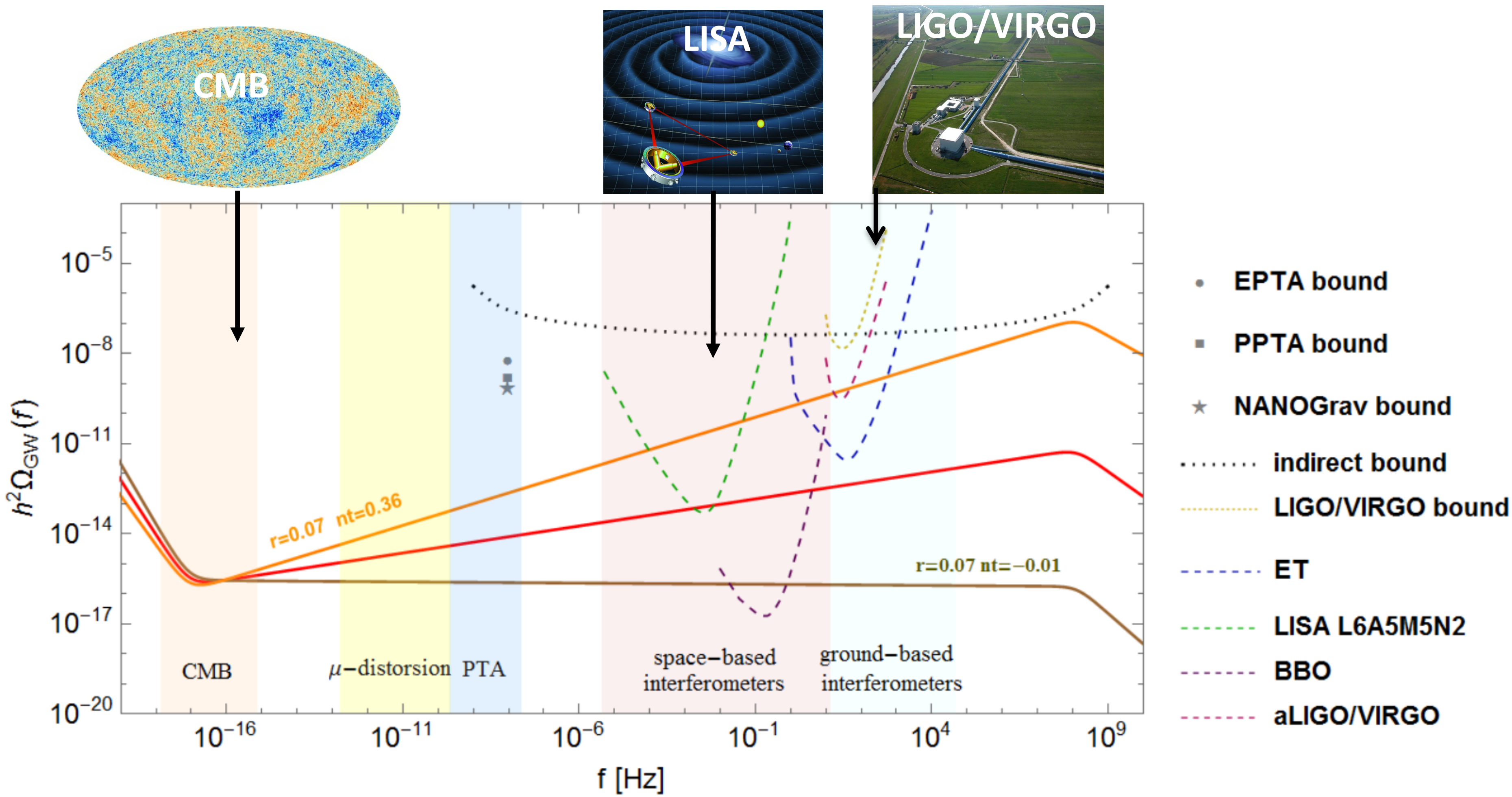
Energy scale of inflation $V^{1/4} < 1.7 \times 10^{16}\ \mathrm{GeV}$

Target of future CMB experiments: r <10^{-3}

Credits: N. Bartolo

Prospects for PGWB direct detection

Complements main road: CMB B-mode polarization (indirect) detection: **LiteBIRD**



From: Guzzetti, Bartolo, Liguori, Matarrese, ``Gravitational waves from Inflation'', arXiv:1605.01615

Primordial non-Gaussianity (PNG)

Many primordial (inflationary) models of non-Gaussianity can be represented in configuration space by the simple formula (Salopek & Bond 1990; Gangui et al. 1994; Verde et al. 1999; Komatsu & Spergel 2001)

$$\boldsymbol{\Phi = \phi_L + f_{NL} * (\phi_L^2 - \langle\phi_L^2\rangle) + g_{NL} * (\phi_L^3 - \langle\phi_L^2\rangle \phi_L) + \ldots}$$

where Φ is the large-scale gravitational potential (more precisely $\boldsymbol{\Phi = 3/5\, \zeta}$ on superhorizon scales, where $\boldsymbol{\zeta}$ is the gauge-invariant comoving curvature perturbation), $\boldsymbol{\phi_L}$ its linear Gaussian contribution and f_{NL} the dimensionless *__non-linearity parameter__* (or more generally *non-linearity function*). The percent of non-Gaussianity in CMB data implied by this model is

$$\mathrm{NG}\ \% \sim 10^{-5}\ |f_{NL}|$$

$$\sim 10^{-10}\ |g_{NL}|$$

< 10^{-5} from CMB & LSS

< 10^{-5} from CMB & LSS

PNG and bispectrum (shapes)

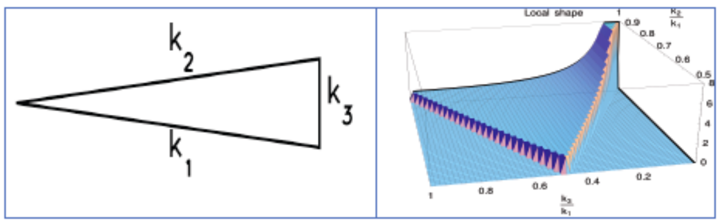
Bispectrum of primordial curvature perturbations

Amplitude

Shape

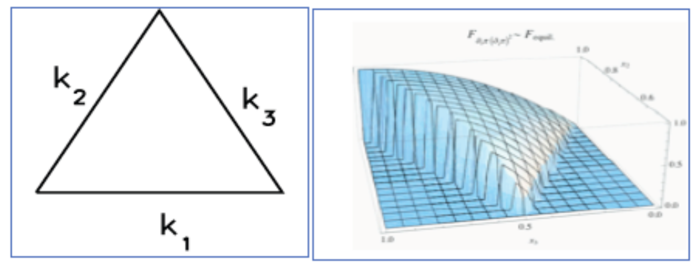
$$\langle \Phi(\vec{k}_1)\Phi(\vec{k}_2)\Phi(\vec{k}_3)\rangle = (2\pi)^3\delta^{(3)}(\vec{k}_1+\vec{k}_2+\vec{k}_3)f_{\rm NL}F(k_1,k_2,k_3)$$

Local NG



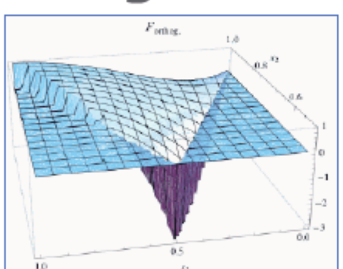
Multi-field models of inflation;
Cuvaton models;
Ekpyrotic/cyclic models

Equilateral NG



Single inflaton with non-standard kinetic term;
higher derivative interactions

Orthogonal NG



Single inflaton with non-standard kinetic term;
higher derivative interactions

Also: directionally dependent bispectra,
tensor bispectra and many others.

Bispectrum & PNG: theoretical expectations

- Primordial NG probes fundamental physics during inflation, being sensitive to ***(self-)interactions*** of fields present during inflation (different inflationary models predict different ***amplitudes and shapes*** of the bispectrum)

- Standard models of slow-roll inflation predict only ***tiny deviations from Gaussianity*** (Salopek & Bond ‘90; Gangui, Lucchin, Matarrese & Mollerach 1995; Acquaviva, Bartolo, Matarrese & Riotto 2003; Maldacena 2003), arising from ***non-linear gravitational interactions*** during inflation. Matarrese, Pilo & Rollo (2020) confirm that Maldacena’s “consistency relation” (*and GR effects on halo bias*) are gauge-independent hence physical and observable effects.

Planck results are ***fully consistent with such a prediction!***

- PNG can be thought as probing interactions among particles at inflation energy scales. E.g. probes string-theory via oscillatory PNG (Arkani-Hamed & Maldacena 2015 “Cosmological collider physics”; Silverstein 2017 “*The dangerous irrelevance of string theory*”).

f_{NL} from *Planck* 2018 bispectrum (KSW)

Shape	Independent	Lensing subtracted
	SMICA T	
Local	6.7 ± 5.6	-0.5 ± 5.6
Equilateral	4 ± 67	5 ± 67
Orthogonal	-38 ± 37	-15 ± 37
	SMICA $T+E$	
Local	4.1 ± 5.1	-0.9 ± 5.1
Equilateral	-25 ± 47	-26 ± 47
Orthogonal	-47 ± 24	-38 ± 24

Planck collaboration 2019

Clustering of peaks (DM halos) of NG density field

Start from results obtained in the 80's by Grinstein & Wise 1986, Matarrese, Lucchin & Bonometto 1986, Lucchin, Matarrese & Vittorio 1988) giving the general expression for the peak 2-point function as a function of N-point connected correlation functions of the background linear (i.e. ***Lagrangian***) mass-density field

$$\xi_{h,M}(|\mathbf{x}_1-\mathbf{x}_2|) = -1 + \exp\left\{ \sum_{N=2}^{\infty} \sum_{j=1}^{N-1} \frac{\nu^N \sigma_R^{-N}}{j!(N-1)!} \xi^{(N)} \begin{bmatrix} \mathbf{x}_1,\ldots,\mathbf{x}_1, & \mathbf{x}_2,\ldots\ldots,\mathbf{x}_2 \\ j\ times & (N-j)\ times \end{bmatrix} \right\}$$

(requires use of path-integral, cluster expansion, multinomial theorem and asymptotic expansion).

THE ASTROPHYSICAL JOURNAL, **330**: L21–L23, 1988 July 1

SCALE-INVARIANT CLUSTERING AND PRIMORDIAL BIASING

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Received 1987 December 14; accepted 1988 March 31

ABSTRACT

If cosmic objects formed around the maxima of a scale-invariant (either Gaussian or non-Gaussian) density perturbation field, their correlation length and mean distance are proportional as suggested by the observations. Since the typical density contrast of a peak is ν times greater than the field rms value, a size-independent, primordial threshold ν is obtained whose magnitude depends only on the statistics; late nonlinear evolution would mainly affect the clustering properties of objects like galaxies. In this framework we discuss a simple, phenomenological model for the power-spectrum and a "minimal," isocurvature perturbation model.

Subject headings: cosmology — galaxies: clustering — galaxies: formation

Recent analyses of the clustering properties of galaxies, groups, and clusters suggest that their coherence length is a growing function of the richness (Davis and Peebles 1983; Bahcall and Soneira 1983; Klypin and Kopylov 1983; Schectman 1985). All the observed two-point correlation functions are well described by a single power law, $\xi_i(r) \approx (r_i/r)^{1.8}$ in a suitable range of distances. The coherence lengths $r_g \approx 5h^{-1}$ Mpc (h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}) and $r_c \approx 25h^{-1}$ Mpc refer to galaxies and clusters, respectively. A similar trend seems to hold for superclusters, with $r_{sc} \approx 60h^{-1}$ Mpc (Bahcall and Burgett 1986). Szalay and Schramm (1985) have shown that the systematic change of r_i with the system richness approximately vanishes if r_i is made dimensionless using the mean interparticle distance l_i. They find $r_i/l_i \approx 0.56$, with the only exception of galaxies, which appear to have $r_g/l_g \approx 1$. Recent analyses (see, e.g., Sutherland 1988) seem to provide a smaller value for r_c and suggest that previous results would deserve some caution.

If the trend for r_i is confirmed it follows that different objects cannot be at once tracers of the overall density field. On the other hand, rich systems are rare and one can reconcile theory and observations by properly doing the statistics of rare events. This approach has been used to explain the different coherence lengths of galaxies and rich Abell clusters (Kaiser 1984; Politzer and Wise 1984; Bardeen *et al.* 1986; Martínez-González and Sanz 1988). It is plausible that the formation of objects is biased to occur around the maxima of the density field (i.e., the minima of the potential fluctuations). Peacock and Heavens (1985) found that the typical maxima of a Gaussian random field have a density contrast $\nu \approx 2$ times greater than the field rms value, independently of the proto-object size. This property can be easily generalized to non-Gaussian, scale-invariant distributions, although the numerical value of ν can be different. For a Gaussian random field the correlation of the up-crossing regions is well approximated by the Politzer and Wise (1984) formula, $\xi_{>\nu_i}(r; R_i) \approx \exp[\nu_i^2 \xi(r; R_i)/\sigma^2(R_i)] - 1$, for $\nu_i \gg 1$. Here $\xi(r; R_i) = (2\pi^2)^{-1} \int_0^\infty dk k^2 P(k) \exp(-k^2 R_i^2) \sin kr/kr$ is the correlation of the overall density field, smoothed on the typical proto-object size R_i, $\sigma^2(R_i)$ is the mass variance, and $P(k)$ is the power spectrum. By tuning R_i and ν_i it is possible to reproduce the observed coherence length of the distribution of objects of the ith richness class.

The purpose of this *Letter* is to show that a unique threshold ν for all the levels of the hierarchy would account for the scale-invariant (fractal) properties of the large-scale matter distribution suggested by observational data. As far as galaxies are concerned we attempt to recover their peculiar clustering properties by taking into account nonlinear gravitational effects on an initial Gaussian distribution. We discuss a simple, phenomenological model where $P(k) \propto k^{-1}$ and a "minimal," isocurvature perturbation model recently proposed by Peebles (1987).

Both the power-law behavior of all the observed correlation functions and the proportionality between the coherence length and the interparticle distance are commonly taken as an evidence for the scale-invariance of the underlying density fluctuation field. Under this assumption, the N-point (reduced) correlation functions obey to a simple scaling relation (Otto *et al.* 1986; Lucchin and Matarrese 1988):

$$\xi^{(N)}(\lambda \boldsymbol{x}_1, \ldots, \lambda \boldsymbol{x}_N; \lambda R_i) = \lambda^{-N(3+n)/2} \xi^{(N)}(\boldsymbol{x}_1, \ldots, \boldsymbol{x}_N; R_i), \quad (1)$$

n being the primordial spectral index. In this notation $\xi^{(2)}(0, 0; R)$ is the mass variance, which then scales according to $\sigma(\lambda R_i) = \lambda^{-(3+n)/2} \sigma(R_i)$. Independently of the assumed statistics, the correlation function of the up-crossing regions can be expressed as (Matarrese, Lucchin, and Bonometto 1986; Grinstein and Wise 1986)

$$1 + \xi_{>\nu_i}(|\boldsymbol{x}_1 - \boldsymbol{x}_2|; R_i) \approx \exp\left\{ \sum_{N=2}^{\infty} \sum_{j=1}^{N-1} \frac{\nu_i^N}{j!(N-j)!} \xi^{(N)}\Big[(\underbrace{\boldsymbol{x}_1, \ldots, \boldsymbol{x}_1}_{j\ \text{times}}, \underbrace{\boldsymbol{x}_2, \ldots, \boldsymbol{x}_2}_{N-j\ \text{times}}; R_i)\Big] \sigma^{-N}(R_i) \right\}. \quad (2)$$

This is the non-Gaussian generalization of the Politzer-Wise formula. If ν is kept fixed, equation (1) and equation (2) imply

Halo bias in NG models

First proposed by Dalal, Doré, Huterer & Shirokov 2007

Matarrese & Verde 2008 used clustering of peaks of NG fluctuations

$$\boxed{b_{\rm h}^{f_{\rm NL}} = 1 + \frac{\Delta_c(z)}{\sigma_R^2 D^2(z)}\left[1 + 2 f_{\rm NL}\frac{\Delta_c(z)}{D(z)}\frac{\mathcal{F}_R(k)}{\mathcal{M}_R(k)}\right]}$$

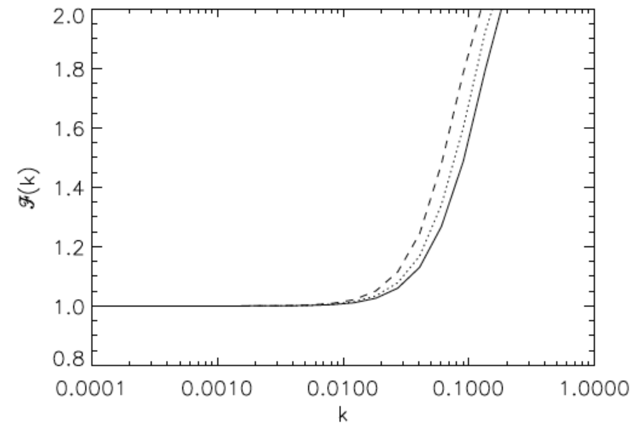


FIG. 1.— The function $\mathcal{F}_R(k)$ for three different masses: 1×10^{14} $M_\odot$ (solid), 2×10^{14} $M_\odot$ (dotted), 1×10^{15} $M_\odot$ (dashed).

form factor:

$$\mathcal{F}_R(k) = \frac{1}{8\pi^2\sigma_R^2}\int dk_1 k_1^2 \mathcal{M}_R(k_1) P_\phi(k_1)\times$$
$$\int_{-1}^{1} d\mu \mathcal{M}_R\left(\sqrt{\alpha}\right)\left[\frac{P_\phi\left(\sqrt{\alpha}\right)}{P_\phi(k)} + 2\right]$$

$$\alpha = k_1^2 + k^2 + 2k_1 k\mu$$

power-spectrum of a Gaussian gravitational potential

factor connecting the smoothed linear overdensity with the primordial potential:

$$\mathcal{M}_R(k) = \frac{2}{3}\frac{T(k)k^2}{H_0^2\Omega_{m,0}} W_R(k)$$

transfer function:

window function defining the radius R of a proto-halo of mass M(R):

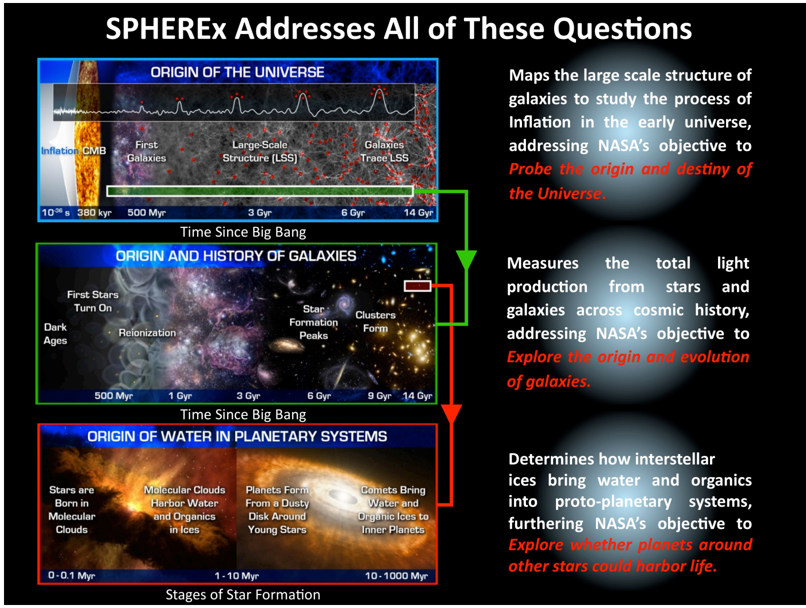
Searching for PNG with LSS: SPHEREx

The **bispectrum** could do better than the power-spectrum. Hence f_{NL} ~ 1 achievable with forthcoming surveys? Many issues, e.g. full covariance, accurate bias model, GR effects (Bertacca et al. 2017), survey geometry, estimator implementation … Still, great potential: 3D vs 2D (CMB).

SPHEREx is a proposed NASA Medium Explorer mission designed to:

- constrain the physics of inflation by measuring its imprints on the three-dimensional large-scale distribution of matter,
- trace the history of galactic light production through a deep multi-band measurement of large-scale clustering,
- investigate the abundance and composition of water and biogenic ices in the early phases of star and planetary disk formation.

SPHEREx will obtain near-infrared 0.75-5.0 um spectra every 6" over the entire sky. It implements a simple instrument design with a single observing mode to map the entire sky four times during its nominal 25-month mission. **SPHEREx** will also have strong scientific synergies with other missions and observatories, resulting in a rich legacy archive of spectra that will bear on numerous scientific investigations.



PNG and precision cosmology

- PNG is currently the highest precision test of Standard Inflation models.

- With *Planck*:
  - PNG constrained at better than ~ 0.01%
  - Flatness constrained at ~ 0.1%
  - Isocurvature mode constrained at ~ 1%

Standard inflation still alive … and kicking!

<u>Standard inflation</u>

- single scalar field (*single clock*)
- canonical kinetic term
- slow-roll dynamics
- Bunch-Davies initial vacuum state
- Einstein gravity

predicts tiny (up to $O(10^{-2})$, or even less??) primordial NG signal

→ No presently detectable PNG

Some open issues about inflation

- Is there a way to distinguish an exactly spatially flat cosmological background from an almost spatially flat one? (see also Jimenez et al. 2018)
- Is there a way to distinguish an exact cosmological constant from an almost constant DE?
- Can we go beyond the “quasi-de Sitter” inflation paradigm while preserving acceptable scalar and tensor perturbation properties?
- Is there a way to distinguish Higgs-inflation from Starobinski inflation?

Conclusions

- In spite of the many successes of the standard cosmological model, there are some very important open problems (e.g. the nature of the dark components) and conflicting results.
- In the last 40 years cosmology has been largely interconnected with high-energy particle physics. It is now time to open our doors to interaction with other branches of physics. This can only lead to profound and positive implications in the way we approach physical cosmology.