The standard cosmological model and beyond

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The main scientific questions in Cosmology are . . .

- What is the Universe made of?

- What are the fundamental laws the governs the evolution of its behavior in space and time and how do they back-react on the evolution of spacetime ?

- *Initial conditions ?*

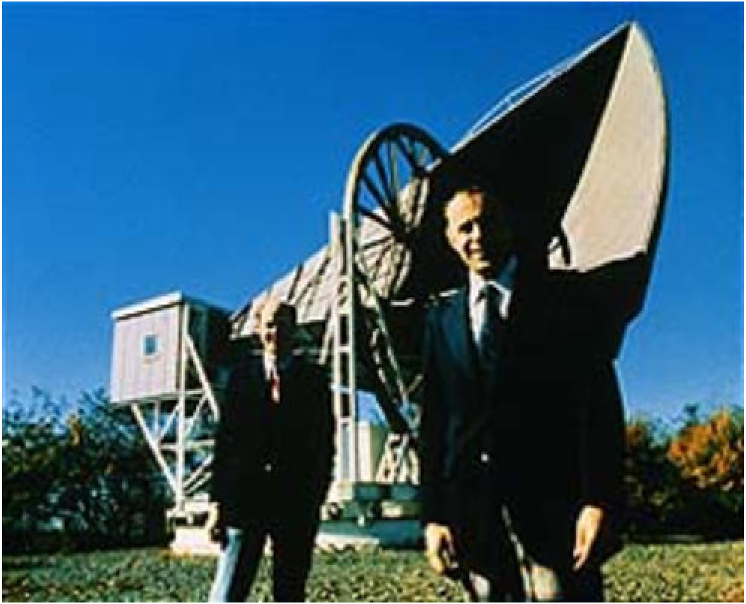
Introduction

On of the main difference between cosmology (astroparticle physics) and other branches of physics is that in cosmology we can only observe. We cannot prepare an experiment and control all possible effects. $\Rightarrow$ Model dependence! Therefore we usually want different independent observations showing the same before coming to conclusions.

At present, most of the precise information about cosmology comes from CMB experiments. An important reason for this is that the theory of the CMB is quite simple and elegant, and we can compute its anisotropies & polarisation very precisely. This has led to the amazing success story of the CMB which helped us to determine the parameters describing the present Universe with 1% precision.
Therefore I shall spend half of my time talking about the CMB. Especially, I want to emphasize that it is not over, there is more to come.

Another very important dataset is the distribution of galaxies and their shapes. To this large scale structure, LSS, (galaxy distribution and weak lensing) I devote the second half of the talk. This dataset is much more difficult to interpret since we usually calculate the fluctuations of the matter density and we observe individual galaxies.

The cosmic microwave background discovery 1965 by Penzias & Wilson



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- At $z \sim 7$–8 the Universe was re-ionized (probably due to uv radiation from the first stars).

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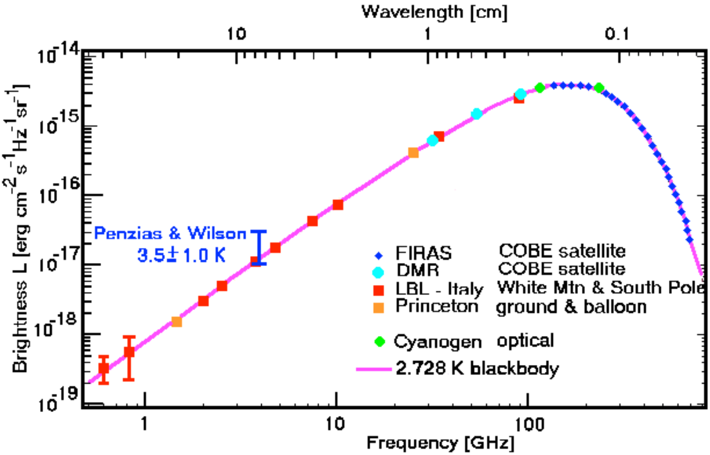
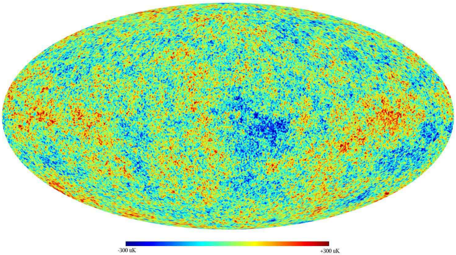
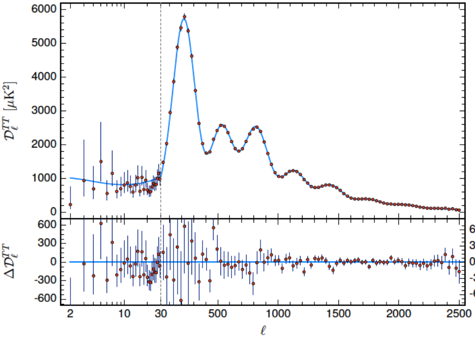


$$T_0 = (2.72548 \pm 0.00057)K$$

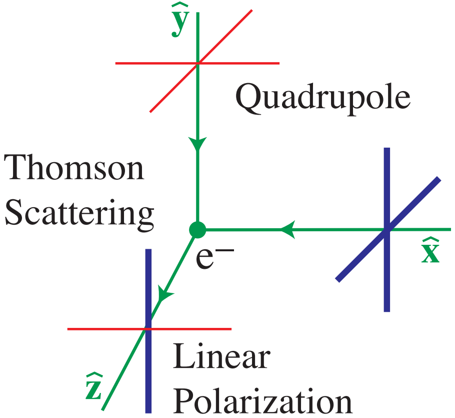


$T_0 = (2.72548 \pm 0.00057)K$
$\Delta T(\mathbf{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\mathbf{n})$
$C_\ell = \langle |a_{\ell m}|^2 \rangle,$
$D_\ell = \ell(\ell+1)C_\ell/(2\pi)$



From the Planck Collaboration
Planck 2018 Results VI
arXiv:1807.06209

Polarisation of the CMB



Thomson scattering depends on polarisation.
A local quadrupole induces linear polarisation,
$Q \neq 0$ and $U \neq 0$.

Polarisation

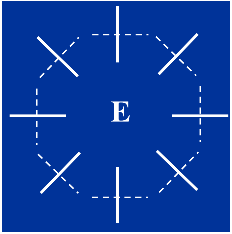
Polarisation defines a tensor field on the CMB sky which is split into a parity even component called E-polarisation and parity odd component called B-polarisation.

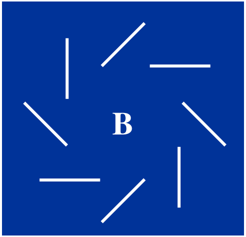
At first order, scalar perturbations only generate E-polarisation.

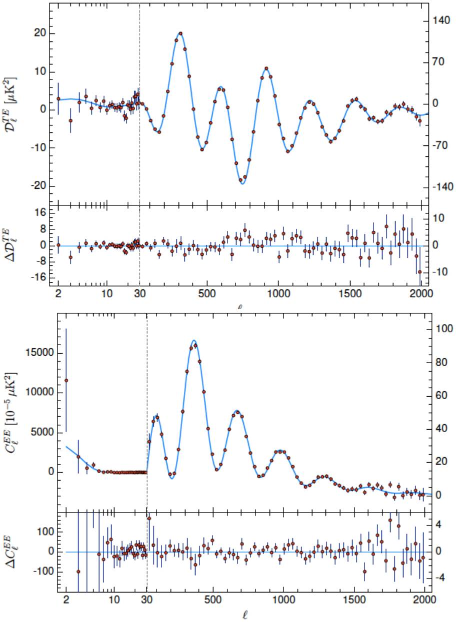
B-polarisation is generated by (vector and) tensor perturbations and at higher order scalar perturbations.

E-polarisation is correlated with temperature anisotropies.

B-polarisation has opposite parity to E polarisation and temperature anisotropies, hence in a parity conserving Universe $\langle EB \rangle = \langle TB \rangle = 0$







T-E correlation

$$\mathcal{D}_\ell^{TE} = \frac{\ell(\ell+1)}{2\pi} C_\ell^{TE}$$

E-E spectrum

CMB lensing

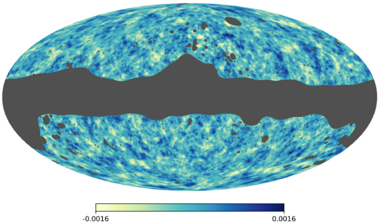
Due to the foreground gravitational potential the CMB temperature anisotropies and polarisation are lensed:

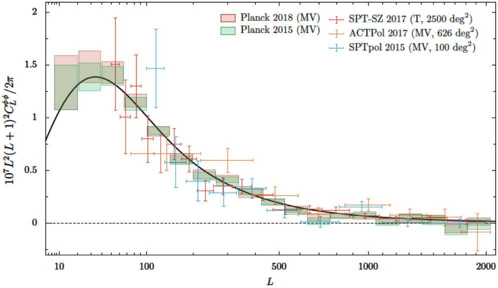
$$T_{\rm obs}(\mathbf{n}) = T(\mathbf{n} + \delta\mathbf{n}), \qquad \delta\mathbf{n} = \nabla\phi,$$

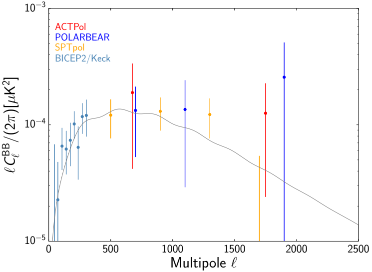
$$\phi(\mathbf{n}) = -\int_0^{r_*} dr \frac{(r_* - r)}{r_* r}(\Phi + \Psi)(r\mathbf{n}, \tau_0 - r)$$

Lensing of the CMB is a second order effect. Lensing E polarisation induces B polarisation.

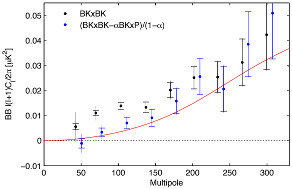
$$\phi(\mathbf{n}) = -\int_0^{r_*} dr \frac{(r_* - r)}{r_* r} (\Phi + \Psi)(r\mathbf{n}, \tau_0 - r)$$

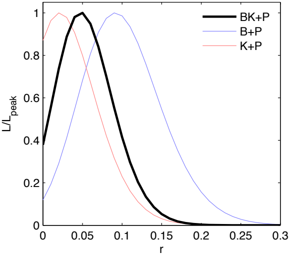






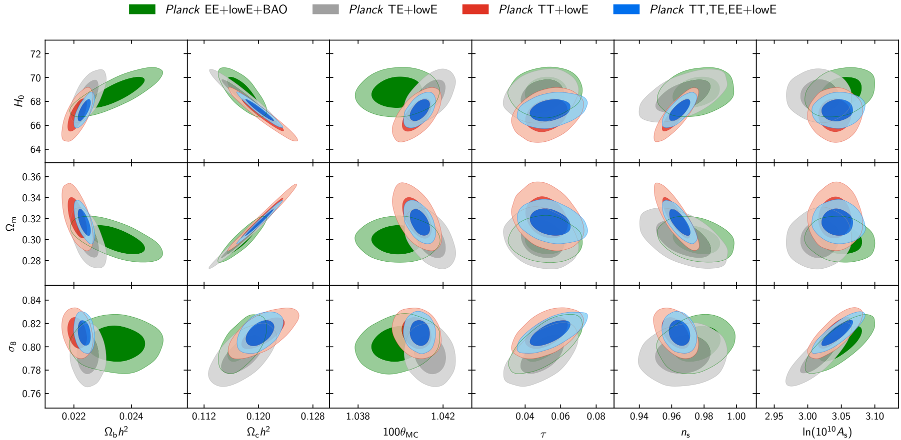
Atacama telescope array
[arXiv:1610.02360]





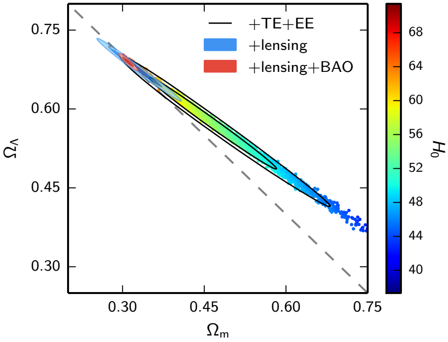
Bicep2 – KeckArray – Planck [arXiv:1502.00612]

Cosmological parameters from Planck 2018 arXiv:1807.06209



$$\theta_* = 10^{-2}(1.04089 \pm 0.00031) \qquad 68\%$$

Lensing breaks degeneracies



(Planck 1502.01589)

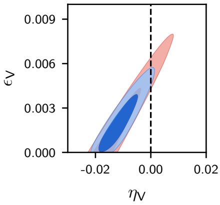
$$\Omega_K = \begin{array}{ll} -0.010 \pm 0.012 & \text{(TT,EE,TE, lensing)} \\ -0.0007 \pm 0.0037 & \text{add BAO's} \end{array} \quad 95\%$$

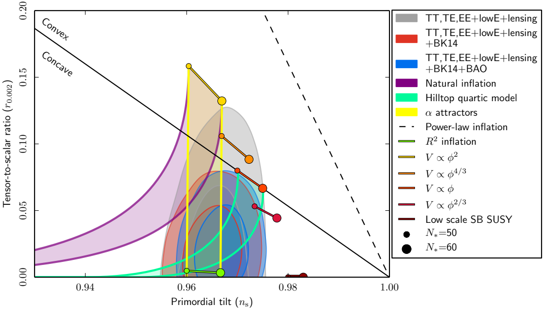
(Planck 1807.06209)

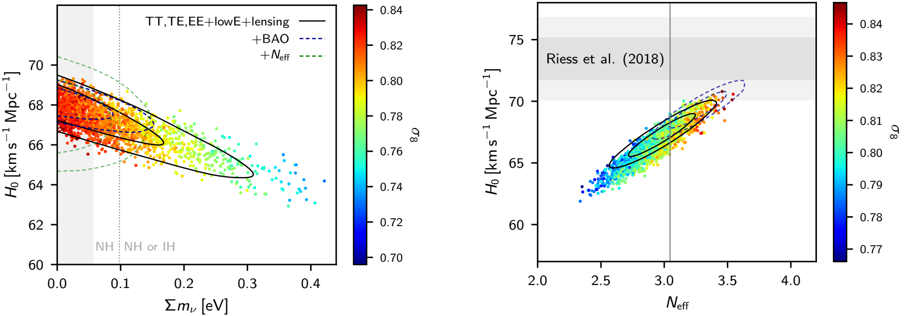
Slow-roll inflationary models can be described with a few (mainly 2) slow-roll parameters and the Hubble scale during inflation, H_*. The scalar and tensor spectra from inflation are given by

$$P_\zeta(k) \simeq \frac{H_*^2}{\epsilon M_p^2} k^{-6\epsilon+2\eta} \simeq 12.2 \times 10^{-9} \qquad P_h \simeq \frac{H_*^2}{M_p^2} k^{-2\epsilon} \simeq \left(\frac{E_*}{M_p}\right)^4$$

$$E_* = \left(\frac{r}{0.1}\right)^{1/4} 1.7 \times 10^{16}\text{GeV}\,, \qquad r = 16\epsilon$$





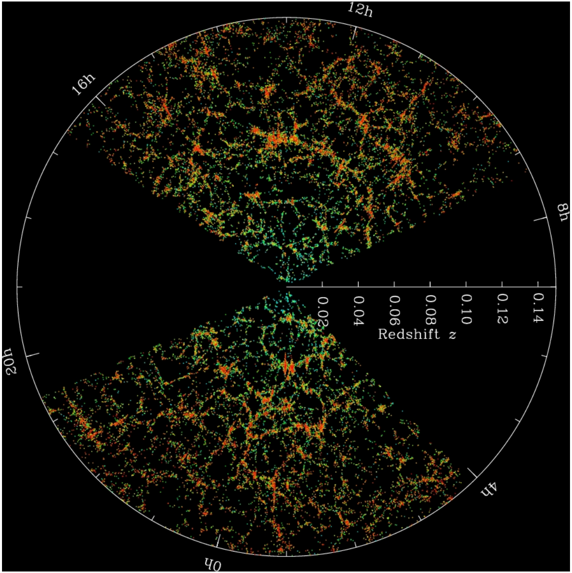


Single extension best constraints:

$\Sigma_i m_i < 0.12$ eV $\qquad N_{eff} = 2.99 \pm 0.33 \qquad$ Planck + BAO $\qquad$ 95%

Joint constraints:

$\Sigma_i m_i < 0.12$ eV $\qquad N_{eff} = 2.96 \pm 0.33 \qquad$ Planck + BAO $\qquad$ 95%



M. Blanton and the Sloan Digital Sky Survey Team.

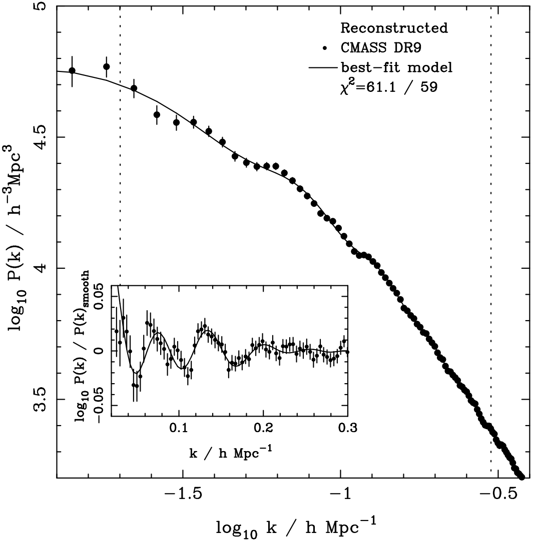
LSS

In principle LSS contains much more information since it is a 3d dataset while the CMB is essentially 2D. But

- At late times clustering becomes non-linear and must be calculated with costly and limited N-body simulations
- On small scales not only gravity is relevant but also hydrodynamical processes, radiative processes, magnetic fields?
- What is the relation between the matter density and the galaxy density (bias))

However

- Even if we do not have access to very small scales the 3d nature still make this dataset very interesting.
- With higher order perturbation theory and effective field theory methods we may have access at least to mildly non-linear scales, up to $k \sim 0.5h/\text{Mpc}$.
- Via redshift space distortions (RSD) and lensing magnification, in LSS observations we have access not only to the galaxy density but also to the velocity and the gravitational potential. This allows us to test GR with cosmological observations.
- Weak lensing from shape measurements also measures the gravitational potential directly with very different systematics .



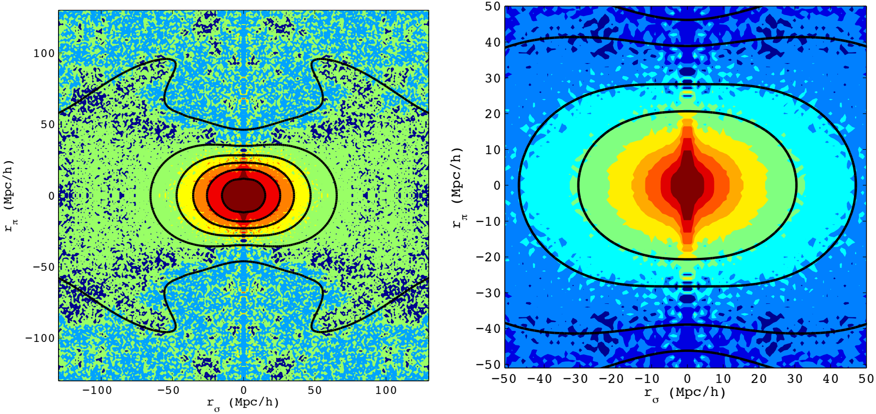
from Anderson et al. '12

SDSS-III (BOSS) power spectrum.

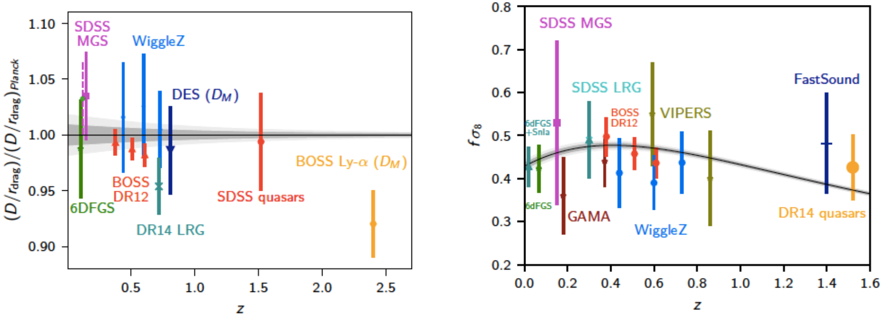
Galaxy surveys $\simeq$ matter density fluctuations, biasing and redshift space distortions.

Redshift space distortions in the BOSS survey

(from Reid et al. '12)

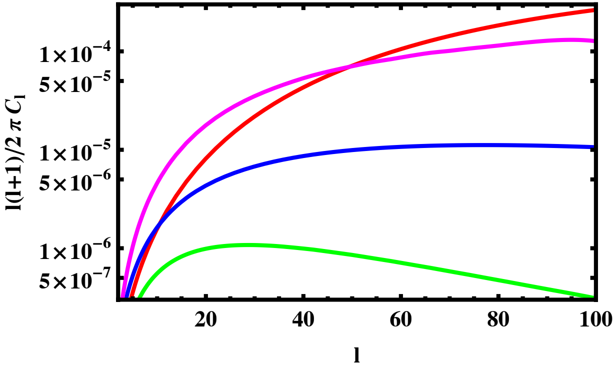


BAO & RSD



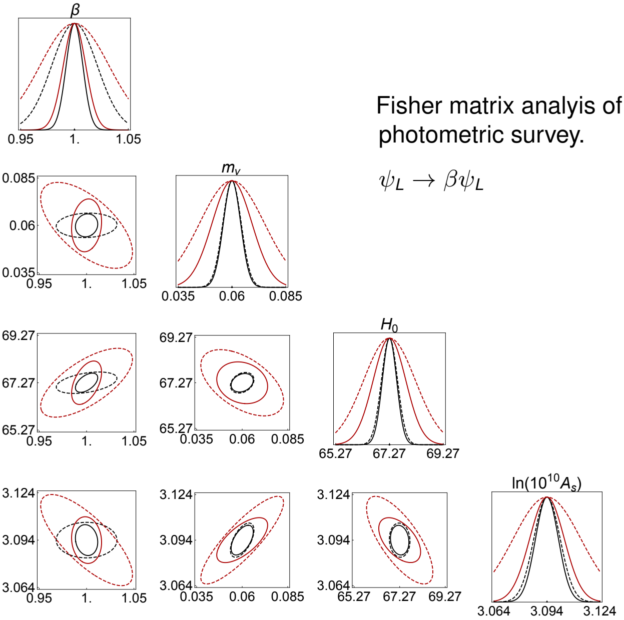
(From Planck arXiv:1807.06209)

Contributions to the transverse power spectrum at redshift $z = 3$, $\Delta z = 0.3$ (from Bonvin & RD '11)



C_ℓ^{DD} (red), C_ℓ^{zz} (green), $2C_\ell^{Dz}$ (blue), $C_\ell^{lensing}$ (magenta).

Measuring the lensing potential

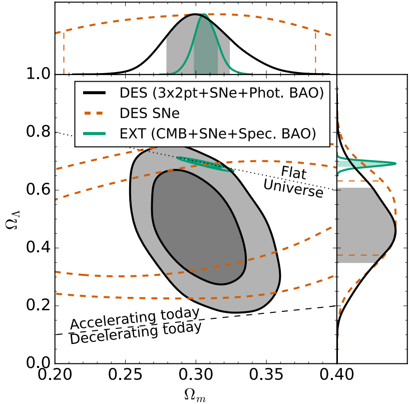


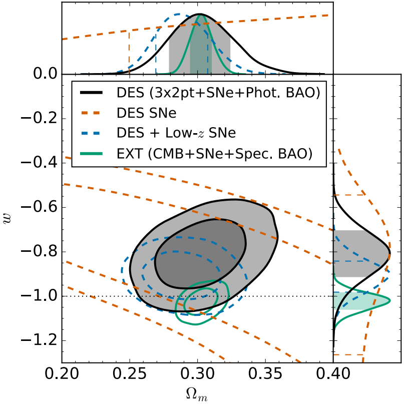
Fisher matrix analyis of an Euclid-like photometric survey.

$$\psi_L \to \beta\psi_L$$

(Montanari & RD) [1506.01369]

DES constraints (arXiv.1811.02375)





Conclusion

- Present day 'precision cosmology' is mainly due to CMB experiments
- We can still improve significantly CMB data to measure better the lensing potential and polarisation.
- This may yield to a measurement of the energy scale of inflation and will lead to much better constraints on $N_{\rm eff}$.
- CMB lensing correlated with LSS data can provide stringent tests of ΛCDM.
- Future LSS data is a most important independent cosmological probe. In addition to the sum of neutrino masses and other cosmological parameters, LSS data can be used to test GR.
- Apart from the neutrino masses, cosmology provides the only experimental evidence for physics beyond the standard model.
  - What is dark matter?
  - What is dark energy ?
  - What is the inflaton?