Prospects of CMB studies

Paweł Bielewicz

NARODOWE CENTRUM BADAŃ JĄDROWYCH ŚWIERK

Outline

- Status of CMB studies
- Future: CMB polarisation, spectral distortions
- Physics of CMB polarisation
- Search for primordial B-modes
- Search for neutrino mass and light relics
- Next generation CMB experiments
- Conclusions

Status of CMB studies

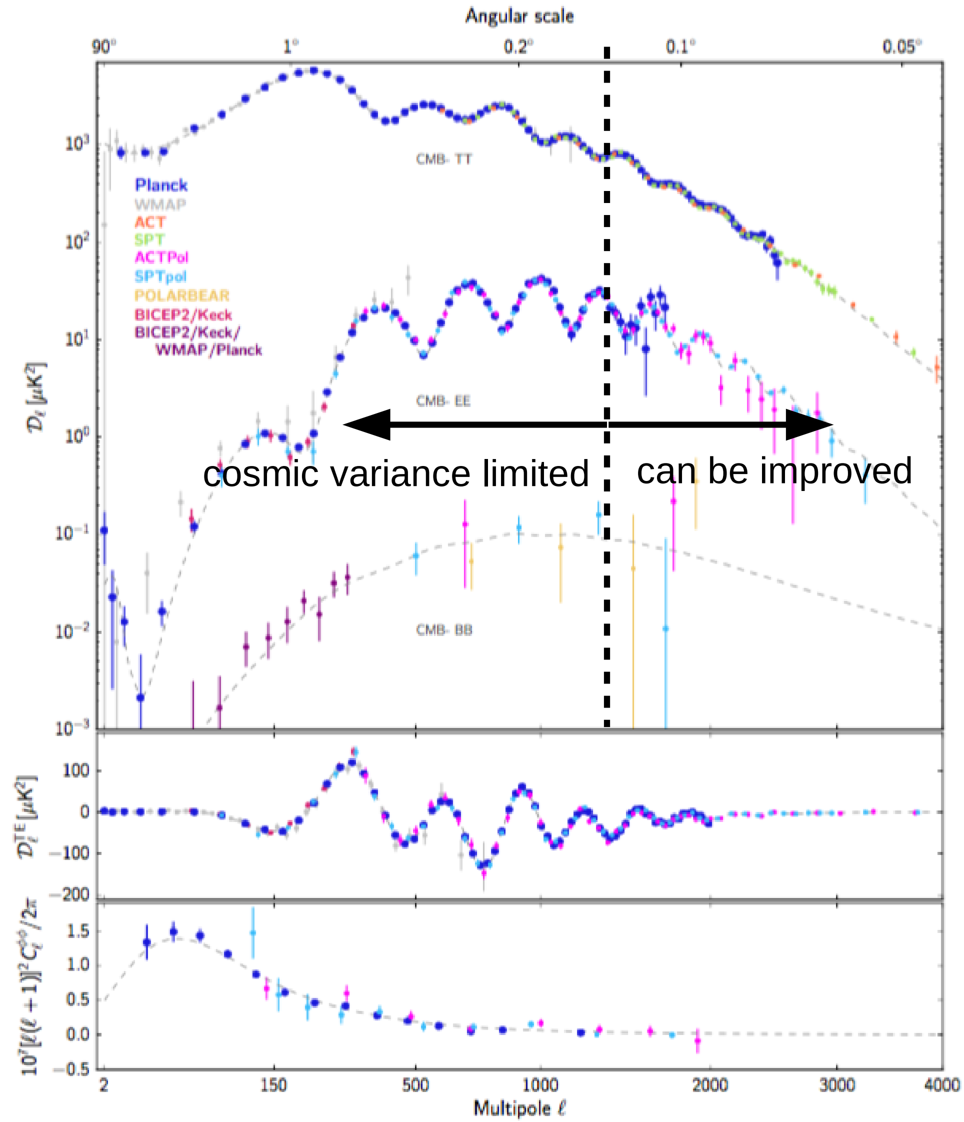
- The Planck satellite has performed almost final measurement of primary CMB temperature anisotropy

$$\Delta T(\hat{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{n})$$

$$C_\ell = \frac{\sum_m |a_{\ell m}|^2}{2\ell + 1} \qquad \theta \sim \frac{\pi}{\ell}$$

$$\frac{\Delta C_\ell}{C_\ell} = \sqrt{\frac{2}{(2\ell+1)\, f_{\rm sky}}} \left(1 + \frac{N_\ell}{C_\ell}\right)$$

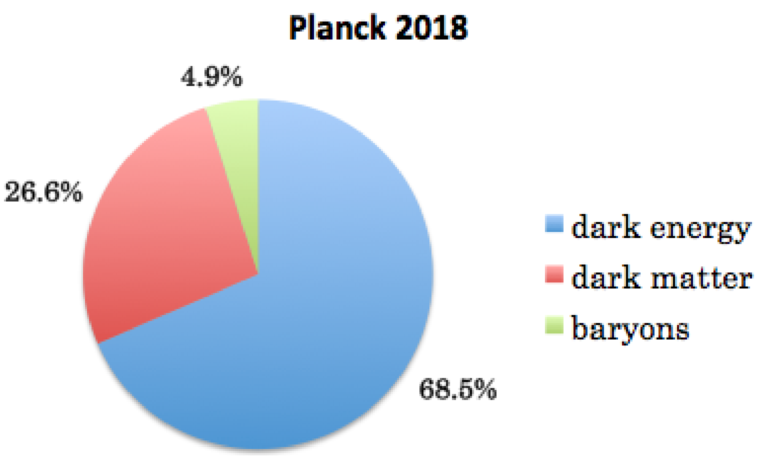
$$N_\ell = N_0 \exp\left(\frac{\ell(\ell+1)\,\theta^2}{2\sqrt{2\ln 2}}\right)$$



Planck collaboration et al. (2020)

Status of CMB studies

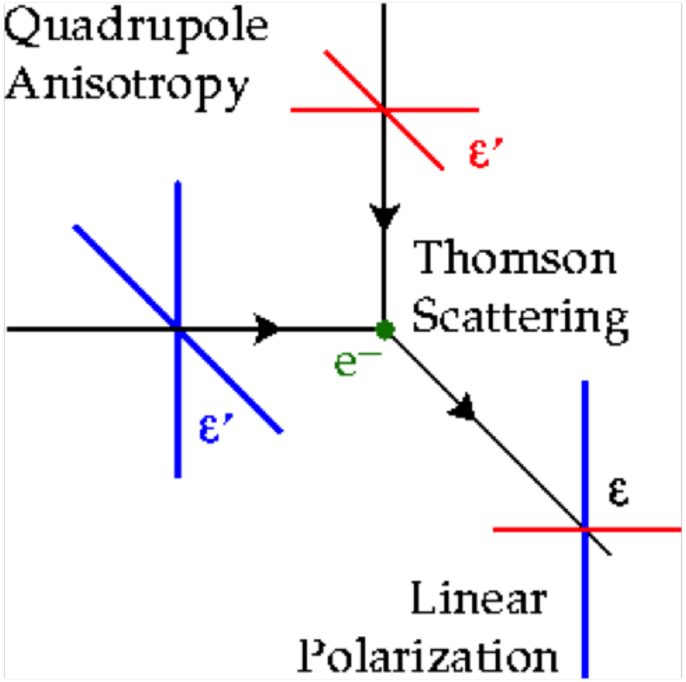
- The Planck satellite has performed almost final measurement of primary CMB temperature anisotropy
- CMB data sufficiently well described by six parameter model
- Cosmological parameters estimated with precision of order percent or smaller



Parameter	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}]	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056

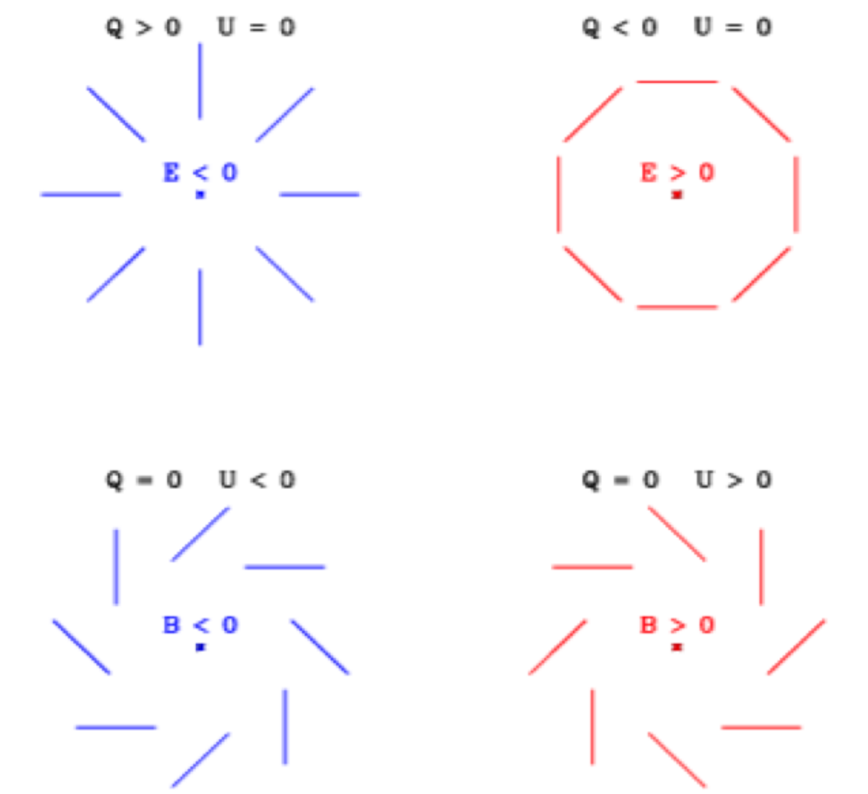
Planck collaboration et al. (2020)

- CMB is polarised owing to **Thomson scattering** of photons at last scattering (or after reionisation)



CMB polarisation

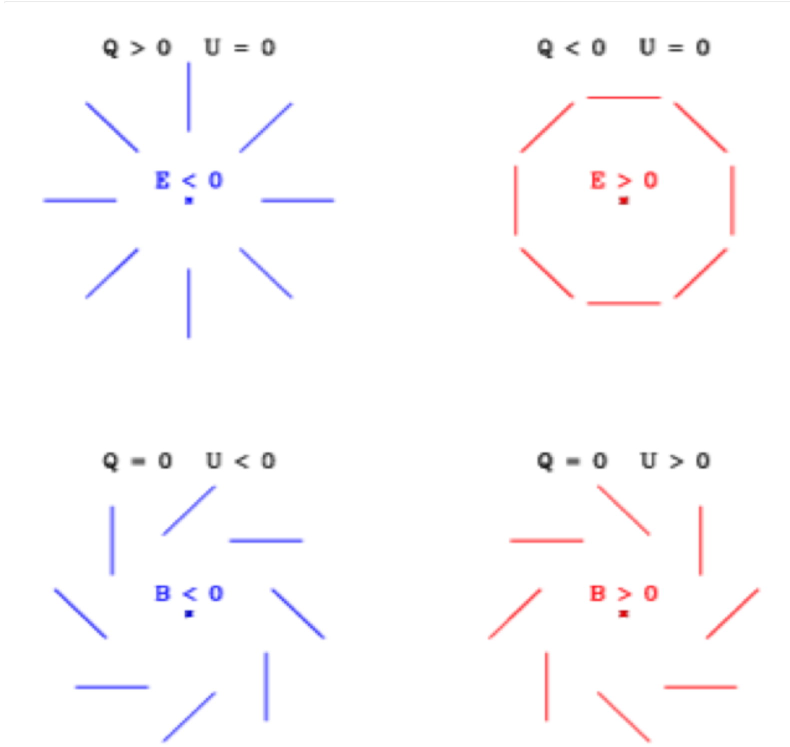
- CMB is polarised owing to **Thomson scattering** of photons at last scattering (or after reionisation)
- Decomposition of the Stokes parameters Q, and U into **E** (curl-free) and **B** (divergence-free) modes by analogy with electromagnetic field



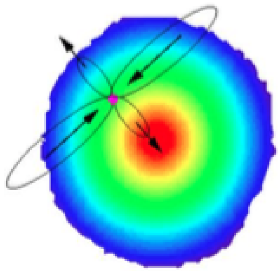
Zaldarriaga (2003)

CMB polarisation

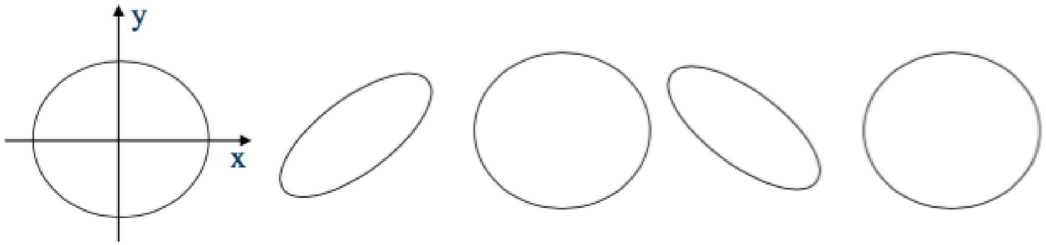
- Scalar perturbations generate E-mode polarisation
- Tensor perturbations (gravitational waves) generate E and B-mode polarisation



Scalar perturbations



Tensor perturbations



Search for primordial B-modes

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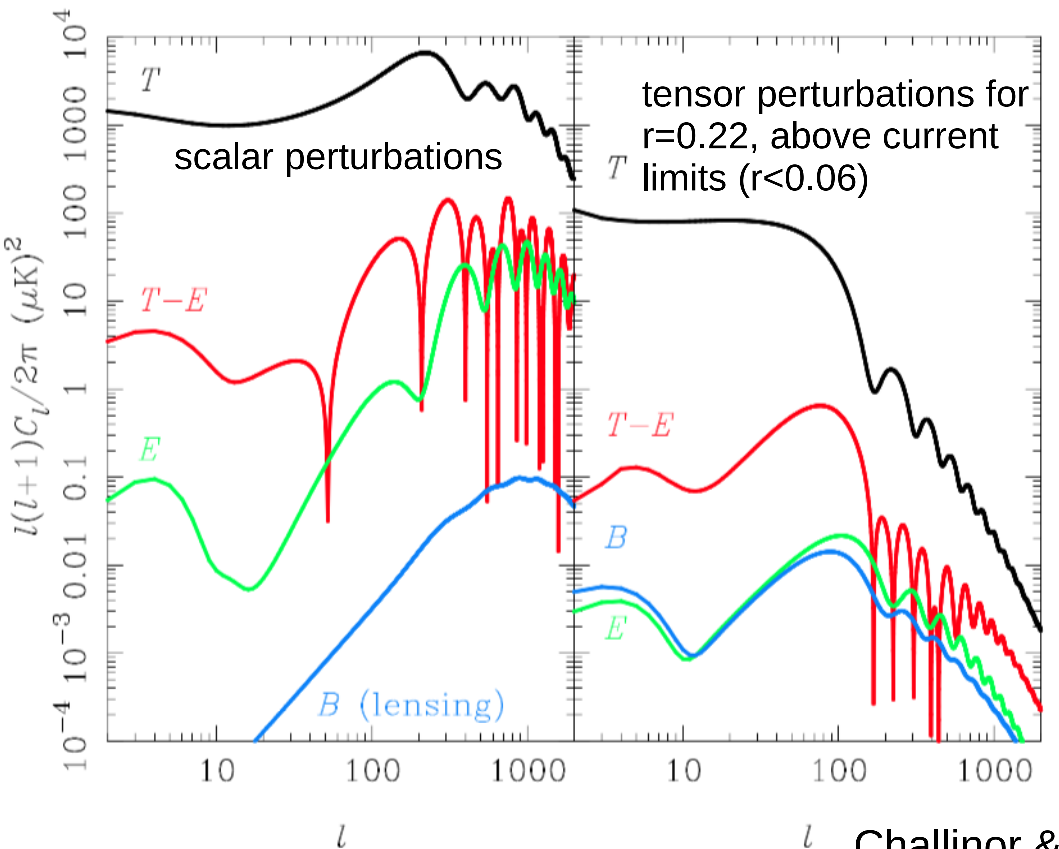

Challinor & Peiris (2009)

Search for primordial B-modes

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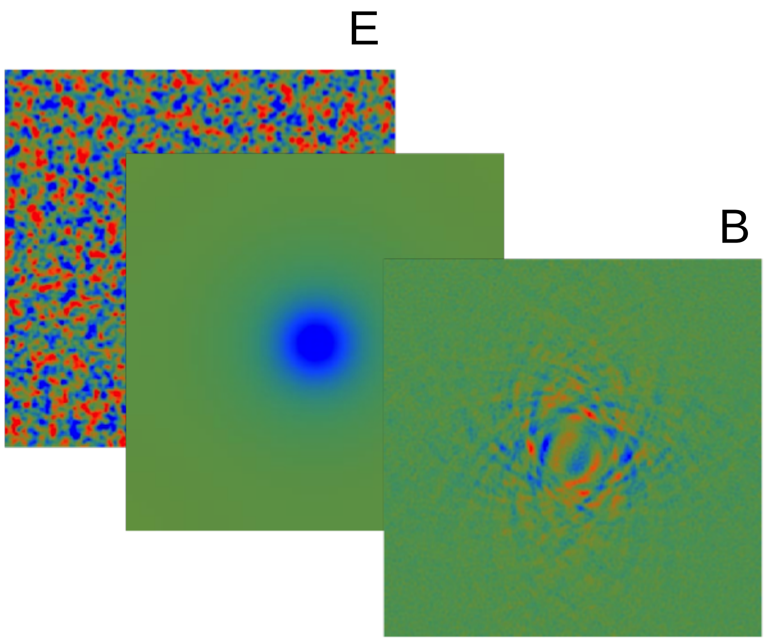
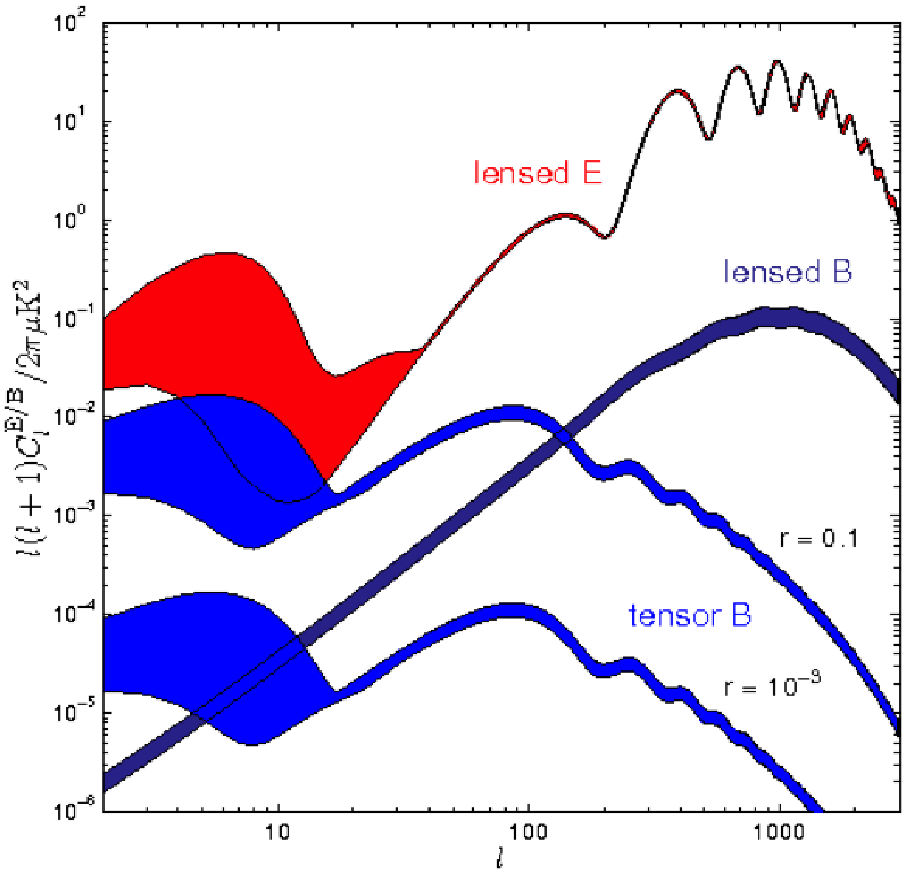
- B-modes also generated by CMB lensing effect



Hu & Okamoto (2002)



Lewis & Challinor (2006)

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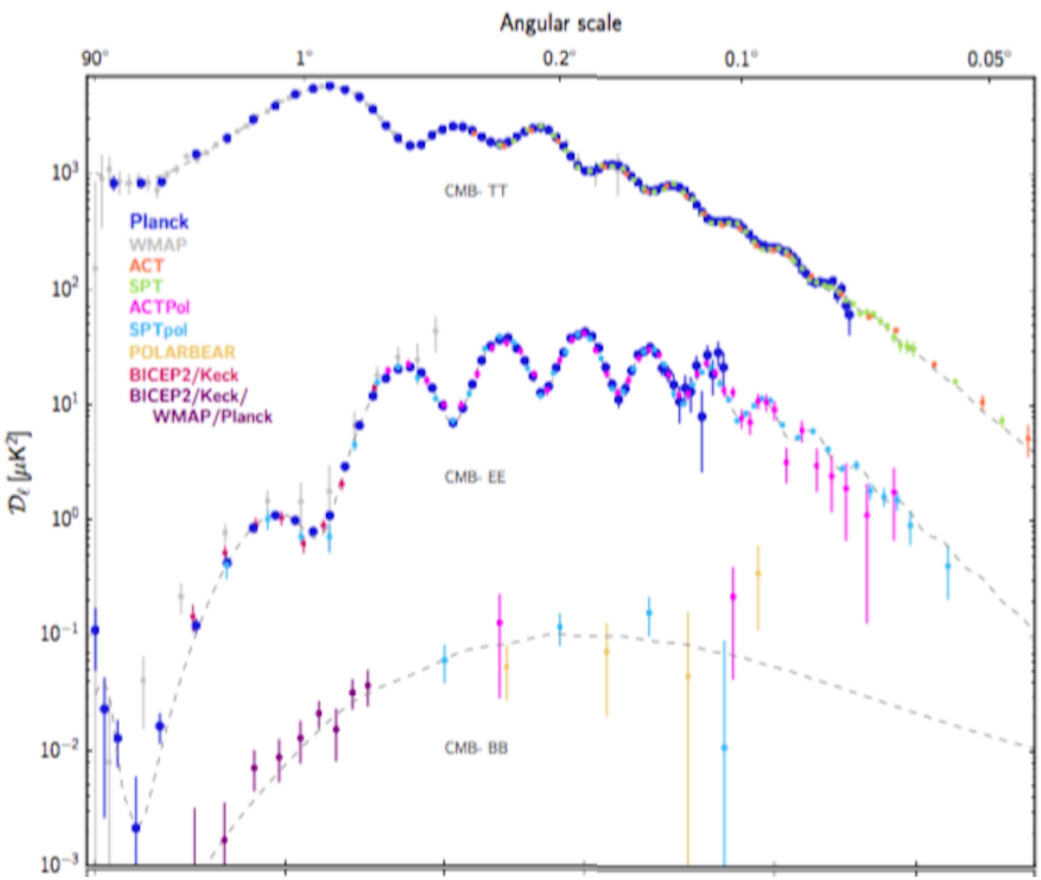
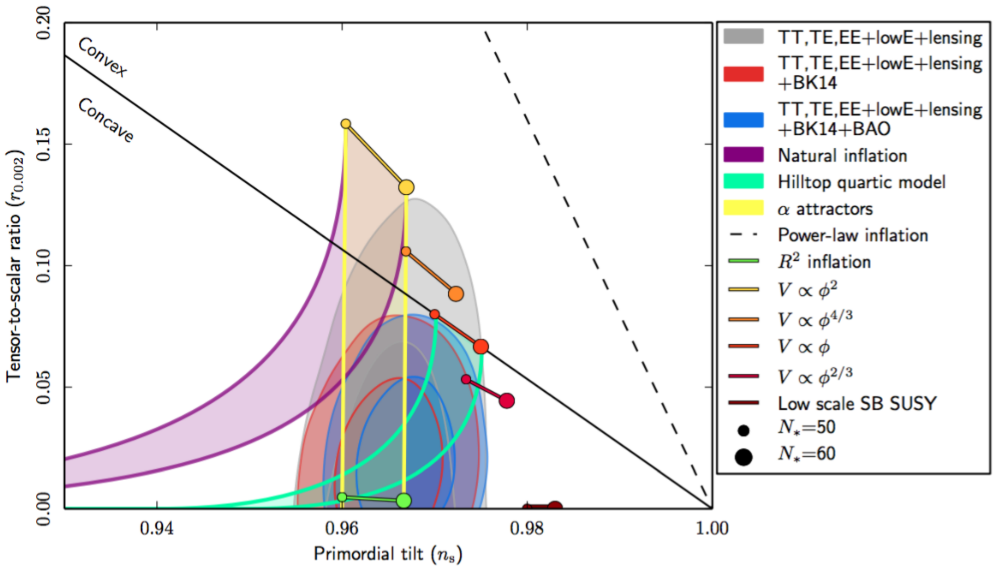


Planck collaboration et al. (2020)

Current constraints on primordial gravitational waves

- Tensor-to-scalar ratio $r \equiv \dfrac{P_t(k_0)}{P_R(k_0)}$
- No detection of B-mode polarisation generated by tensor modes
- Upper bound based on contribution of tensor modes to the temperature and E-mode polarisation anisotropy (indirect constraint, dependent on theoretical model)



$$r_{0.002} < 0.10 \quad (95\%;\ \text{Planck TT,TE,EE} + \text{lowE} + \text{lensing})$$

Planck collaboration et al. (2020)

- Upper bound including BICEP2 data (direct constraint on B-mode polarisation)

$$r_{0.002} < 0.058 \quad (95\%;\ \text{Planck TT,TE,EE} + \text{lowE} + \text{lensing} + \text{BK14} + \text{BAO})$$

$$E_{\text{inf}} < 1.7 \times 10^{16}\ \text{GeV} \quad (95\%)$$

- Slow-roll single-field inflationary models preferred ($n_s < 1$)

Search for primordial B-modes

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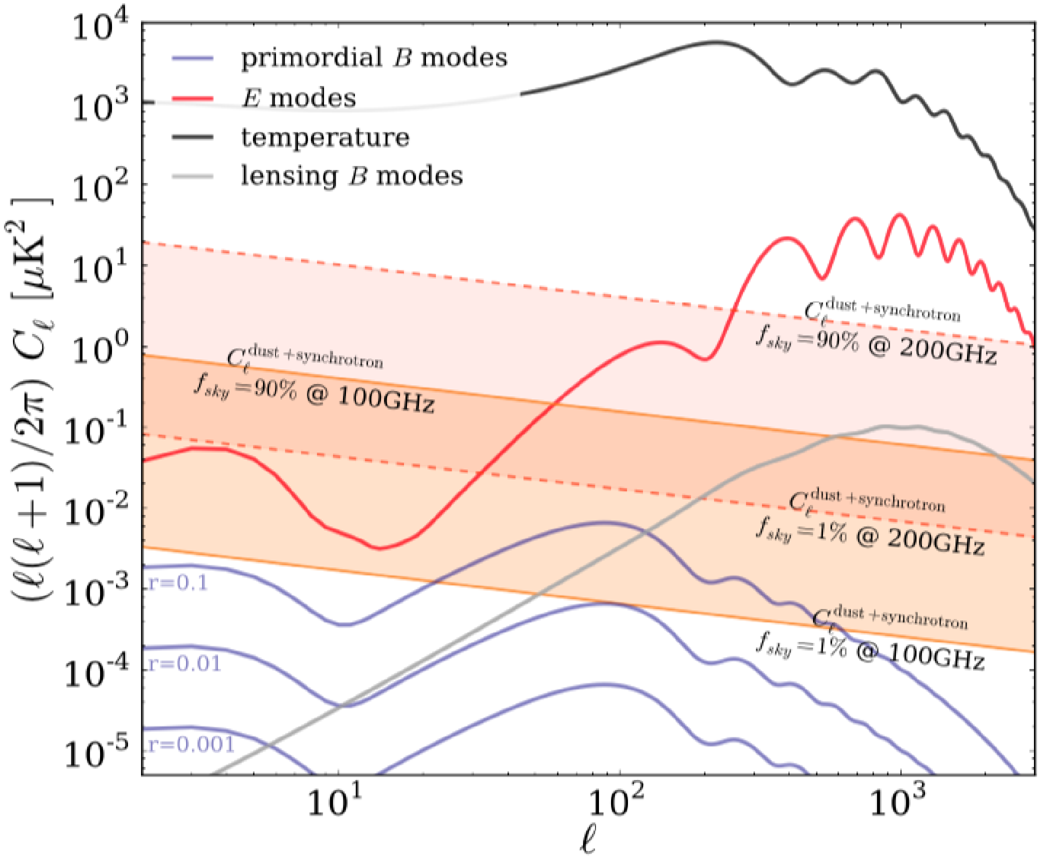

CMB-S4 collaboration et al. (2016)

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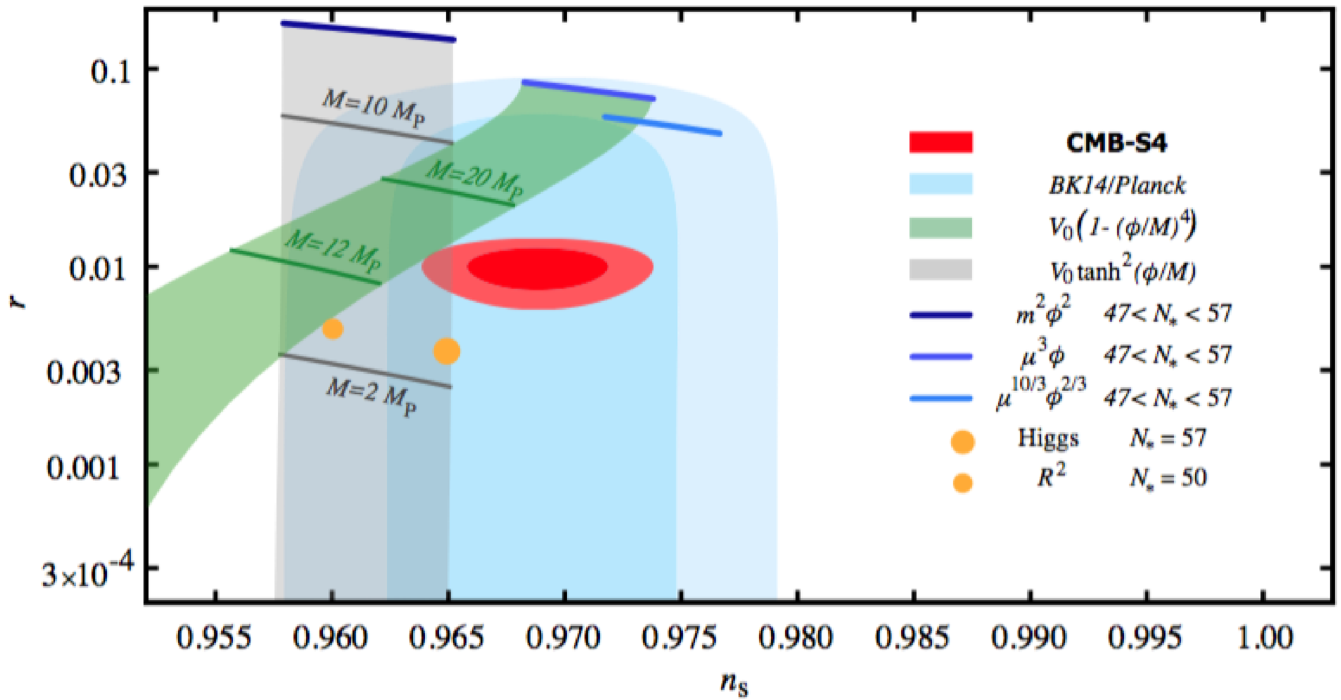
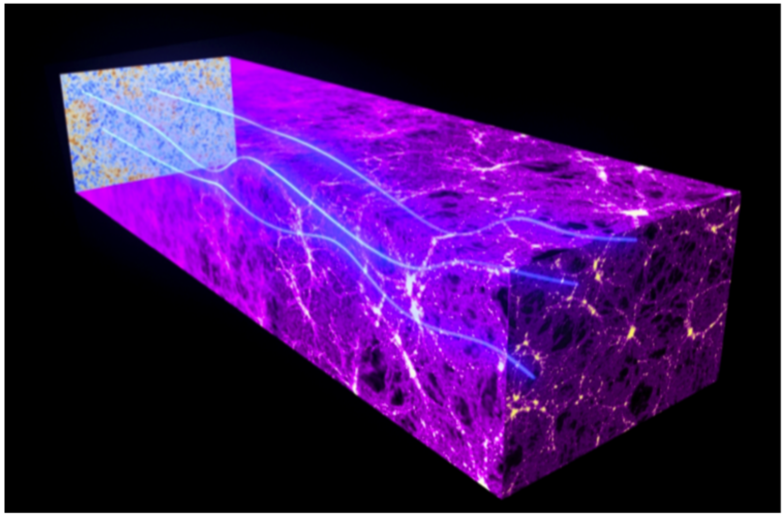


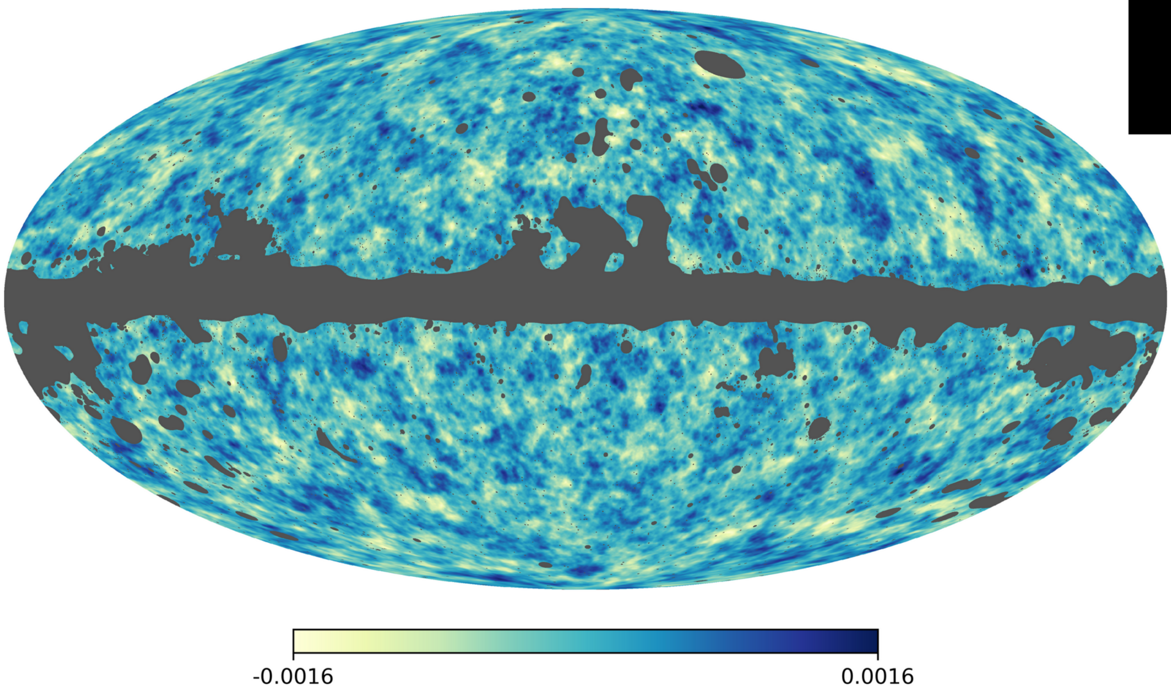
CMB-S4 collaboration et al. (2016)

CMB lensing

- Deflection of the CMB photon paths by the large scale structure of the Universe (~3’)
- Correlation of deflection angles over the sky
- Reconstruction of lensing potential from perturbations of statistical properties of CMB anisotropy



$$\phi(\hat{n}) = -\frac{2}{c^2}\int_0^{\chi_{rec}} d\chi \frac{D_{ls}}{D_l D_s}\Psi(\chi_0-\chi, \chi\hat{n})$$



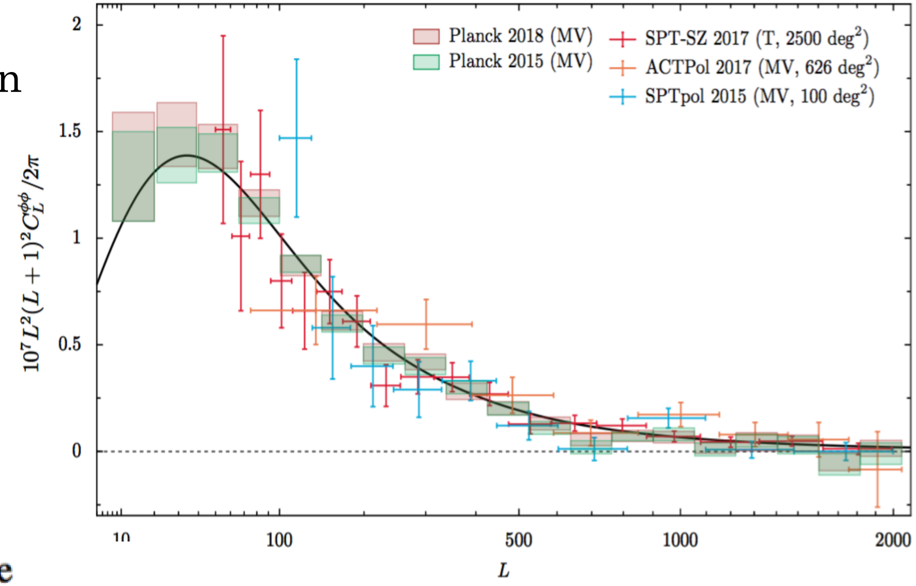
Planck collaboration et al. (2020)

CMB lensing - neutrinos

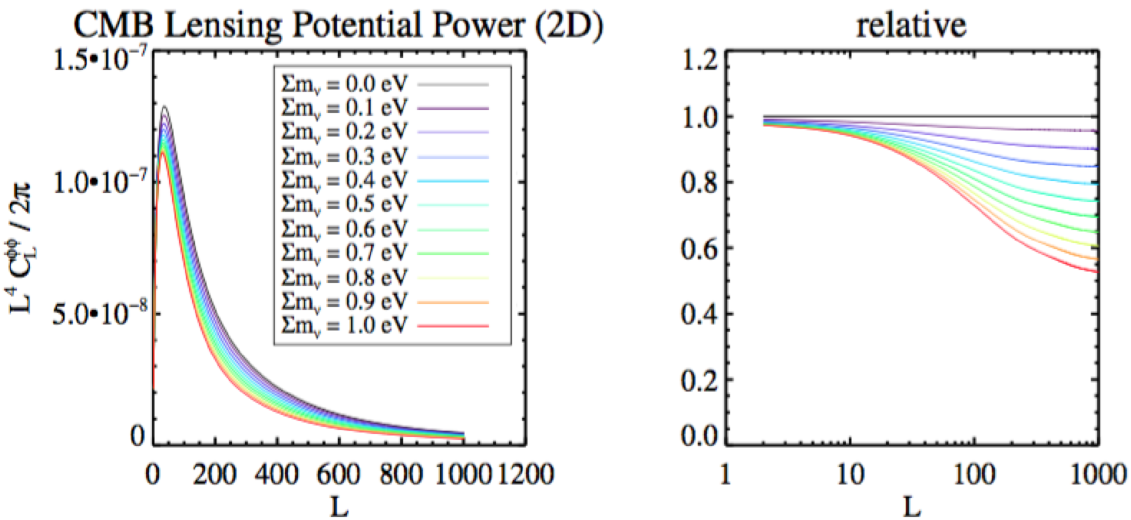
- CMB lensing power spectrum sensitive to the sum of neutrino masses (current constraint

$$\sum m_\nu < 0.12\ \text{eV}\ \ (95\%; \text{Planck temp.} + \text{polar.} + \text{lensing} + \text{BAO})$$

- Neutrinos: relativistic at decoupling, transition to non-relativistic matter today



Planck collaboration et al. (2020)



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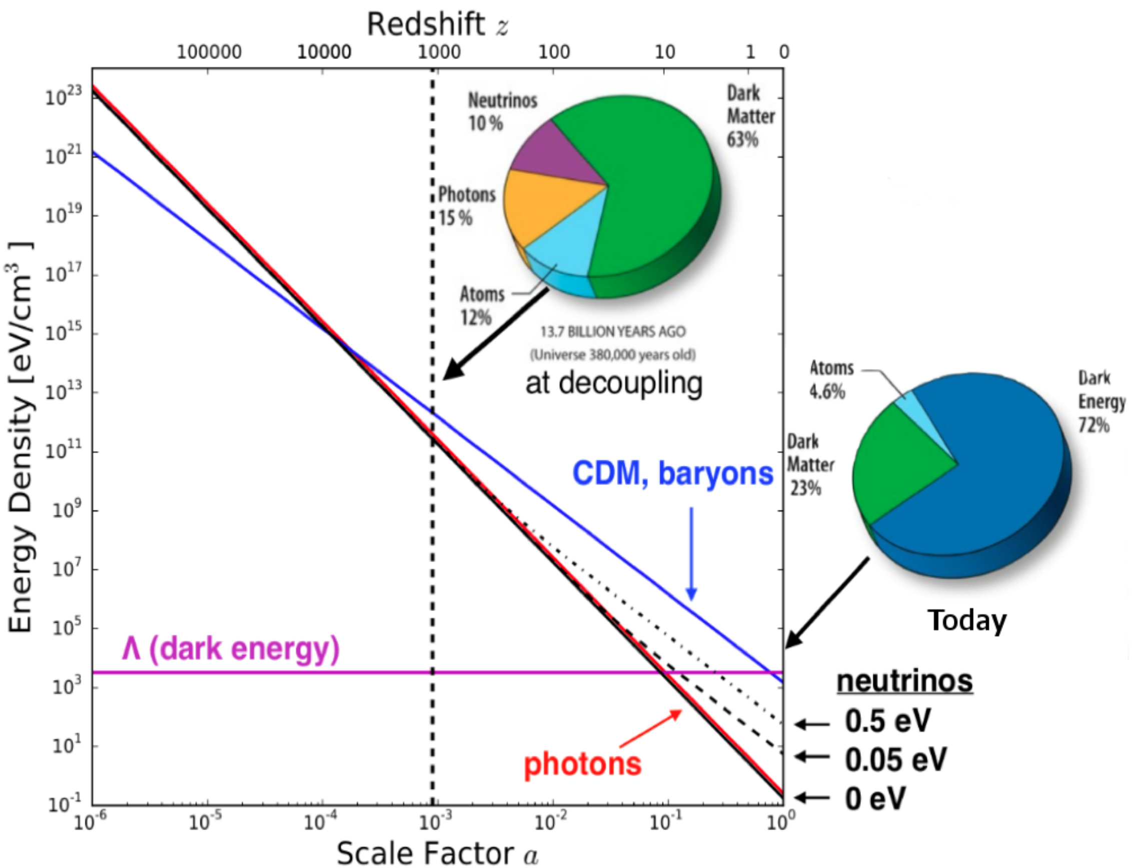
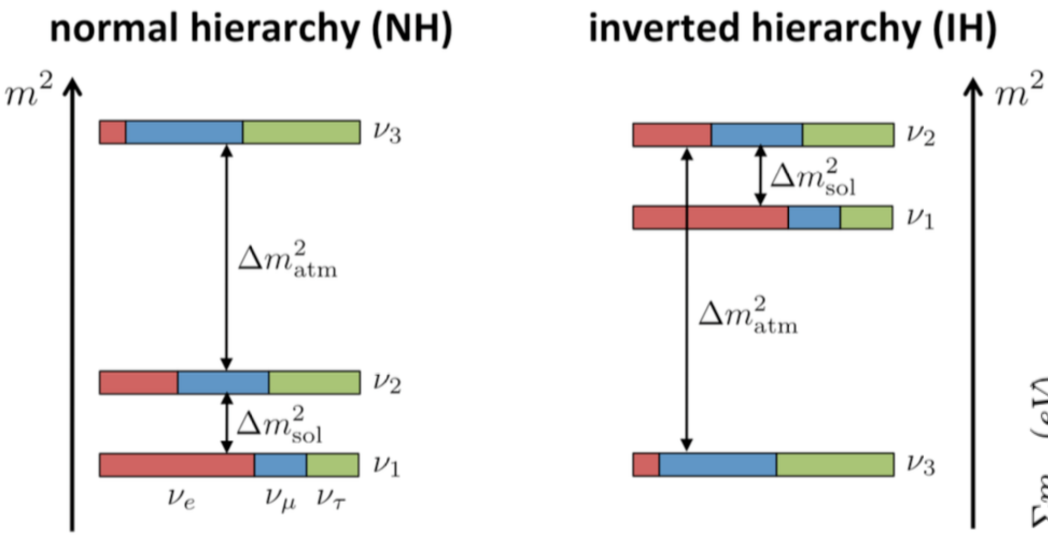


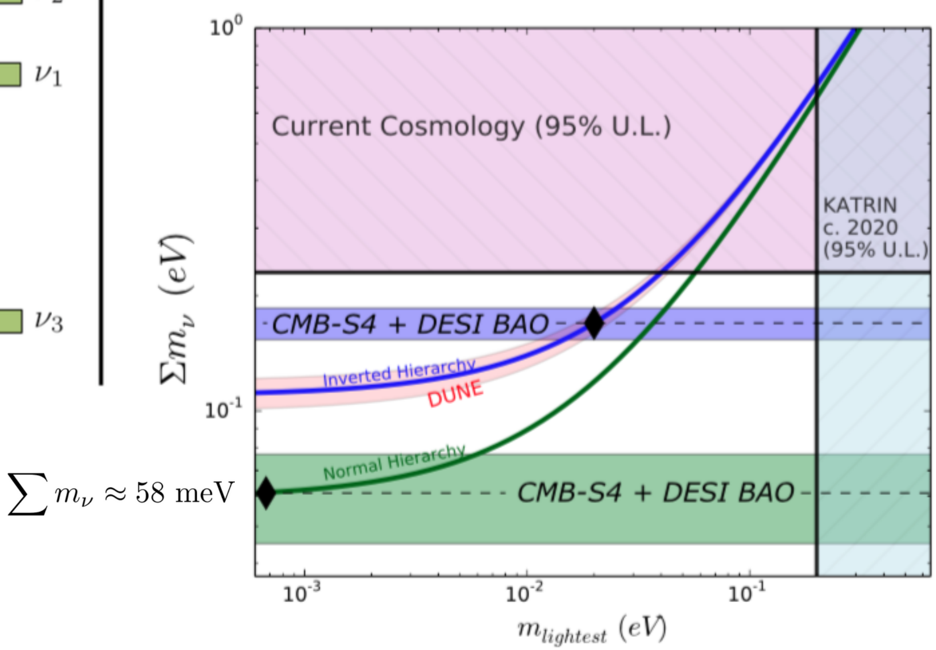
Carlstrom (2017)

CMB lensing - neutrinos

- Neutrinos: relativistic at decoupling, transition to non-relativistic matter today
- Future CMB experiments sensitive to hierarchy of neutrino masses

$$\sigma\left(\sum m_\nu\right) \approx 20 - 30 \text{ meV}$$





CMB-S4 collaboration et al. (2016)

Light relics

- Light relics (axions, sterile neutrinos, ...) can contribute to total energy density of radiation

$$\rho_{\rm rad} = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)\rho_\gamma$$

- Effective number of relativistic species $N_{\rm eff}$ ($N_{\rm eff} \approx 3.046$ in the standard model)

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33}\ (95\%; \text{Planck temp.} + \text{polar.} + \text{lensing} + \text{BAO})$$

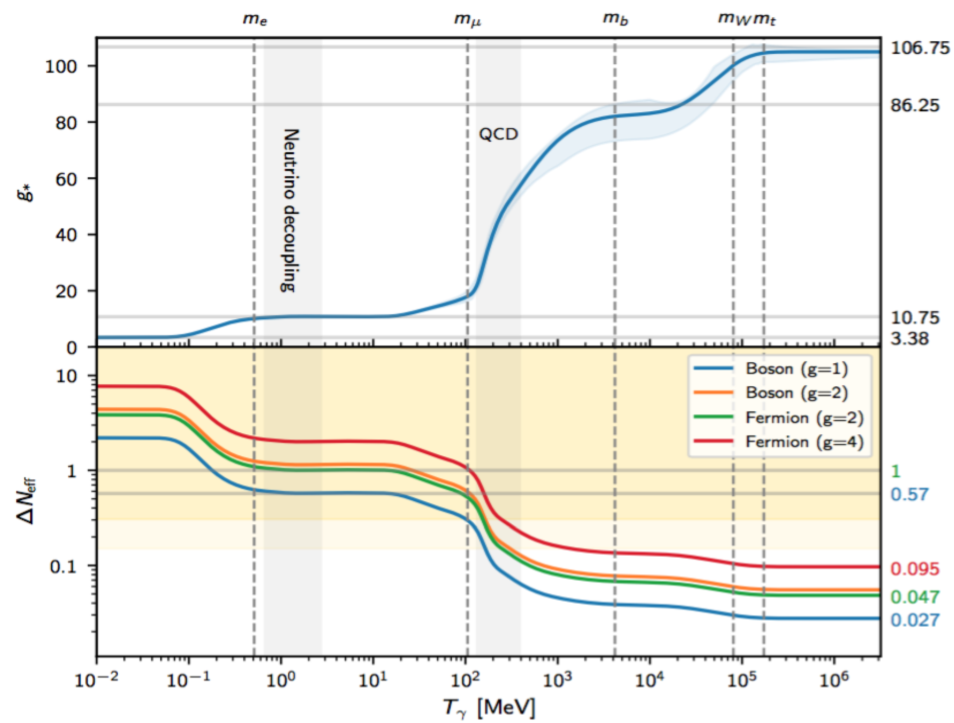
- For particles that were in thermal equilibrium for $T > T_F$

$$\Delta N_{\rm eff} \equiv N_{\rm eff} - 3.046$$

$$\Delta N_{\rm eff} = g\left(\frac{43}{4\, g_*(T_F)}\right)^{4/3} \times \begin{cases} 4/7 \text{ boson} \\ 1/2 \text{ fermion} \end{cases}$$

- Errors for future CMB experiments

$$\sigma(N_{\rm eff}) \sim 0.02 - 0.03$$



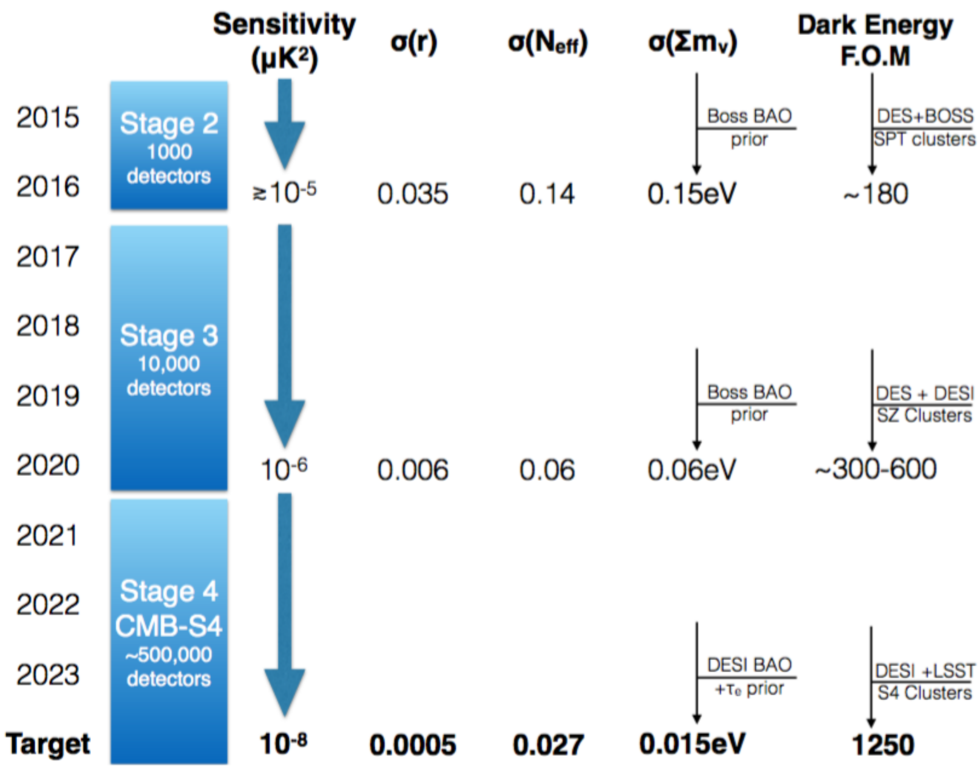
Planck collaboration et al. (2020)

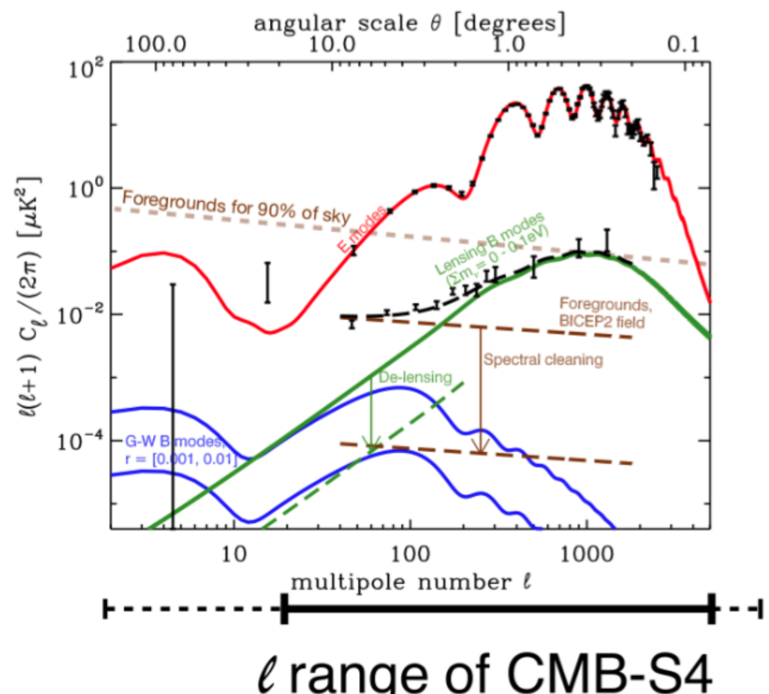
Future CMB projects

- CMB-S4 (ground-based, 30-300 GHz)
- Simons Observatory (ground-based, 30-280 GHz)
- LiteBIRD (space-based, 50-320 GHz)
- PIXIE (space-based, 30-6000 GHz)

CMB-S4

- CMB-S4: CMB stage IV experiment
- Observations using multiple ground-base telescopes to map most of the sky
- Mission goals:
  - measurement of CMB polarisation on ~50 % of the sky with high angular resolution (~1-3 arcmin)
  - measurement of the tensor-to-scalar ratio r at σ(r) < 0.0005 precision

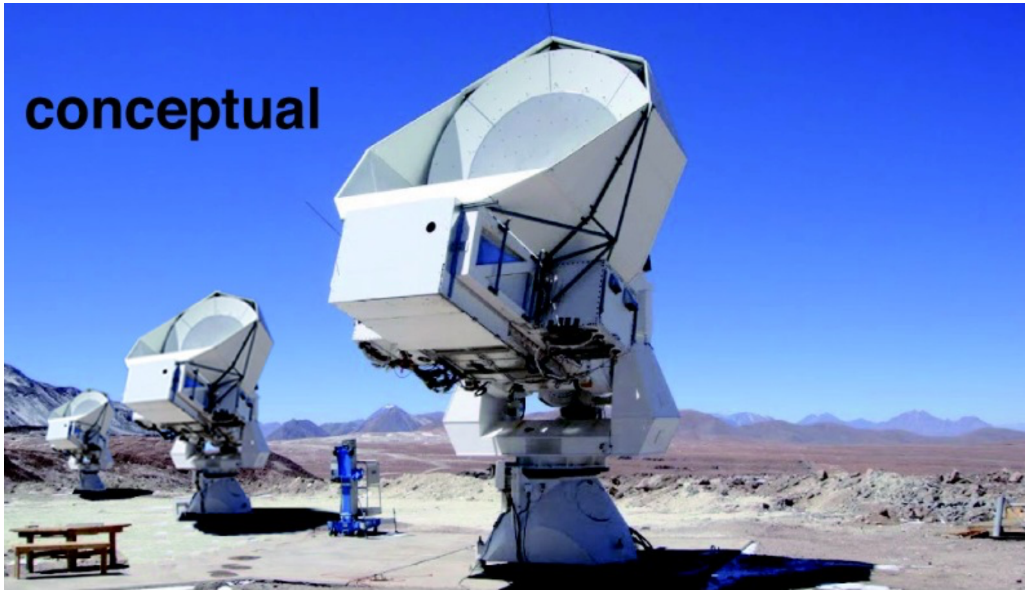




CMB-S4 collaboration et al. (2016)

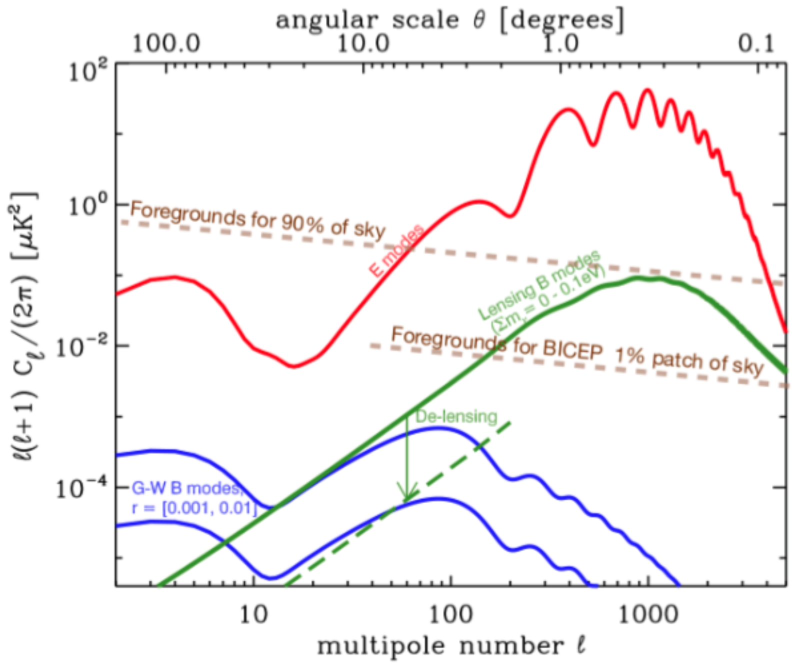
The Simons Observatory

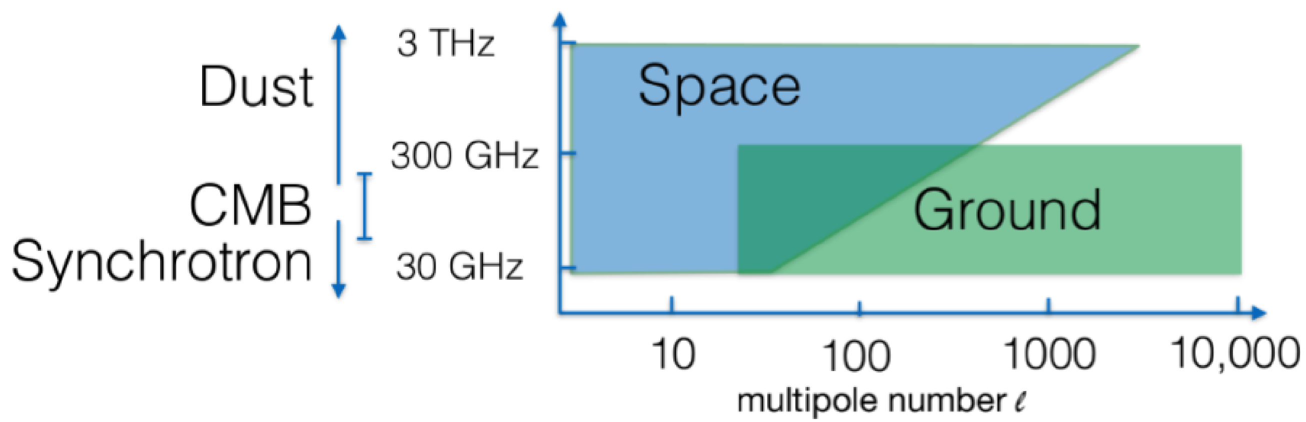
- CMB stage III experiment (~60 000 detectors)
- Mission goals:
  - measurement of CMB polarisation on ~40% of the sky with angular resolution of 1'-2'
  - measurement of the tensor-to-scalar ratio r at $\sigma(r) < 0.003$ precision



Ground-based versus space-based experiments

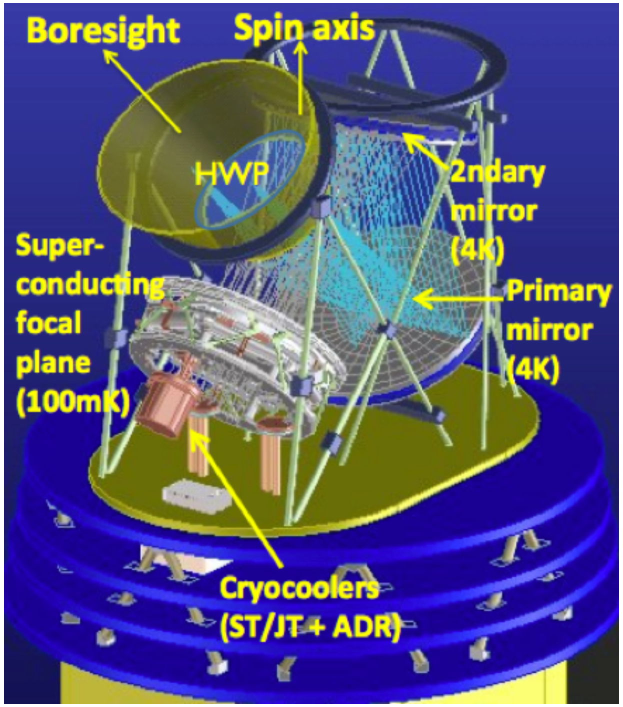
- **Ground-based**:
  - high angular resolution for CMB lensing, damping tail, clusters, …
  - higher sensitivity (more detectors)
  - limited number of frequency bands (atmosphere absorption)
  - larger number of systematic effects
- **Space-based**: all sky for reionization peak, high frequencies for thermal dust emission
- Complementarity of ground and space-based experiments (combination of data would improve constraints)

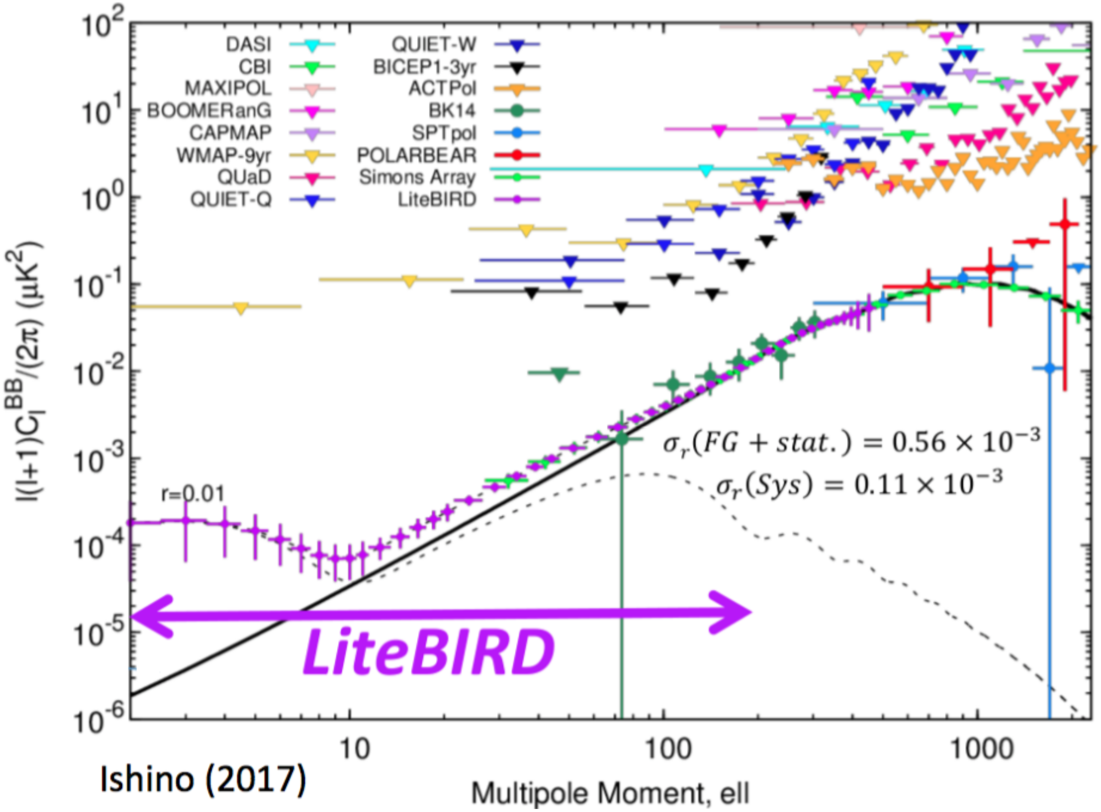




LiteBIRD

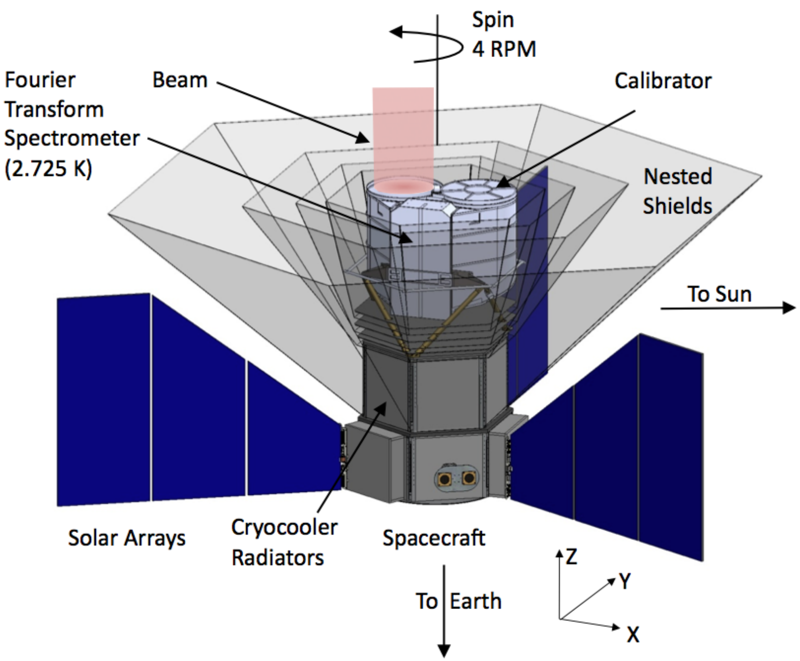
- LiteBIRD: Lite (Light) satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection
- Mission goals:
  - measurement of B-mode polarisation large angular scale (2< l <200) spectrum during three-year observation of all sky
  - measurement of the tensor-to-scalar ratio r at σ(r) < 0.001 precision

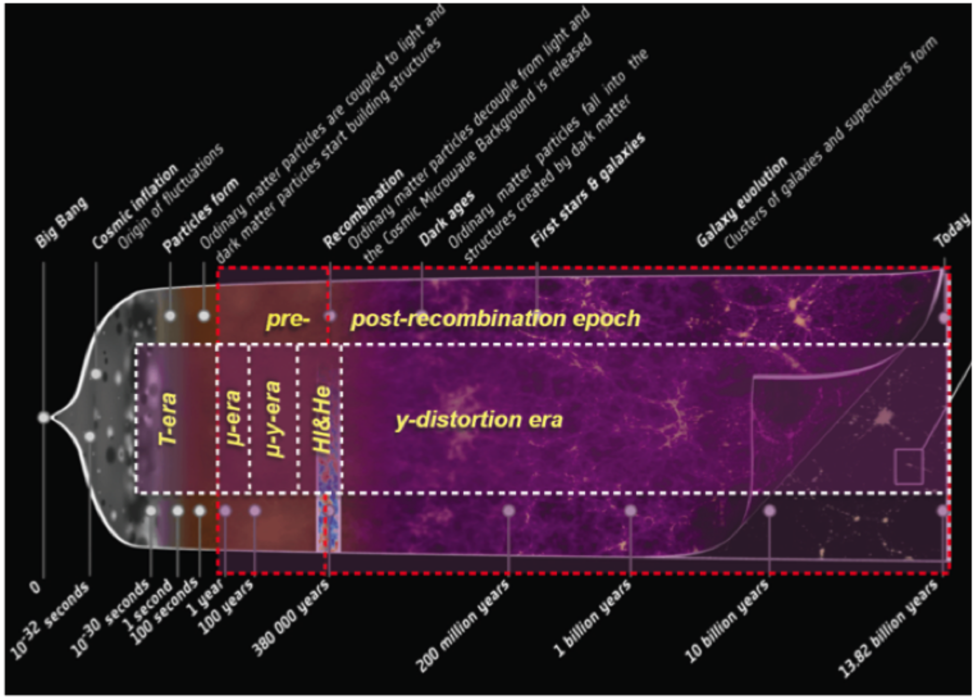




PIXIE

- PIXIE: Primordial Inflation Explorer
- Mission goals:
  - measurement of CMB polarisation and absolute spectrum with precision $\frac{\Delta I_\nu}{I_\nu} < 10^{-8}$ (current constraints from COBE FIRAS $\frac{\Delta I_\nu}{I_\nu} < 10^{-5}$)





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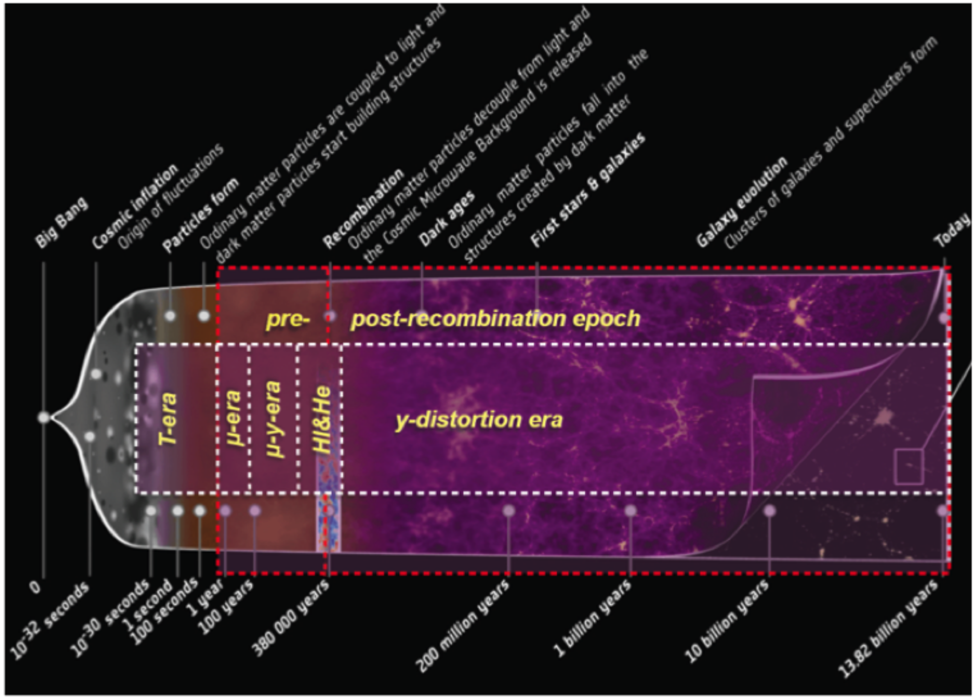
- Blackbody spectrum distortions:
  - Compton y-distortion (like for the thermal SZ effect) - studies of reionization and structure formation ($z < 20$)
  - μ-type distortion – studies of early Universe physics ($10^5 < z < 10^6$, $t > 1$ year after Big Bang)
  - Distortion introduced by recombination of H and He – direct measurements of recombination dynamics ($10^3 < z < 10^4$)
  - Limits on decaying and annihilating particles during the pre-recombination epoch



Conclusions

- The Planck satellite has performed almost final measurement of primary CMB temperature anisotropy
- Next generation CMB projects will be able to measure CMB E-mode polarisation down to cosmic variance limit over a wide range of angular scales
- Primordial B-modes provide a measure of the energy scale of order of 10^{16} GeV
- It will be possible to constrain primordial B-modes down to tensor-to-scalar ratio < 0.001
- Improved CMB lensing measurement may provide a determination of the neutrino mass hierarchy, constraints on the sum of neutrino masses and on possible light relics like axions or sterile neutrino
- Measurement of distortion of the CMB blackbody spectrum will allow to study early Universe physics (> 1 year after the Big Bang) and to constrain decaying and annihilating particles during the pre-recombination epoch