Frontiers of CMB research

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I will talk about. . . Umm?

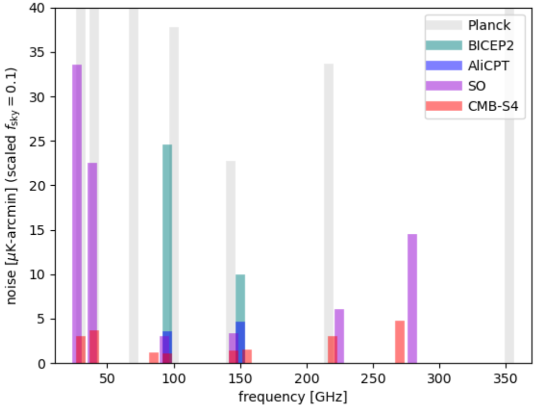
Everything about primary CMB

Everything about secondary CMB (and cross correlations with everything else)

Umm???

Is CMB a dead subject (for grad students)?

There will be more CMB experiments, but...



- AliCPT: $\sigma(r) = 0.01$
- Simons Observatory: $\sigma(r) = 0.003$
- CMB-S4: $\sigma(r) = 0.0005$

Why stake career on a single number r that may or may not be measurable? Might as well let the old dudes (老登们) do it?

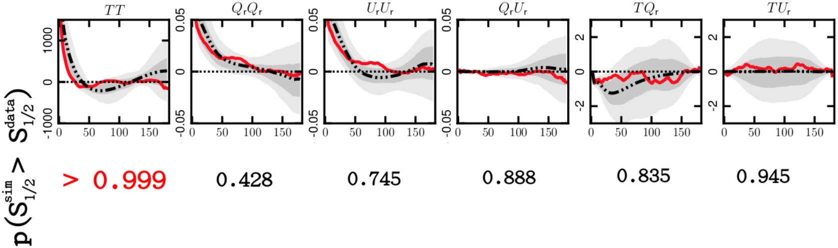
I am still into CMB because

- There are puzzles in current CMB data.
- There is more (than r) to be observed from CMB.
- ~~I am an old dude.~~

Puzzles in current CMB data

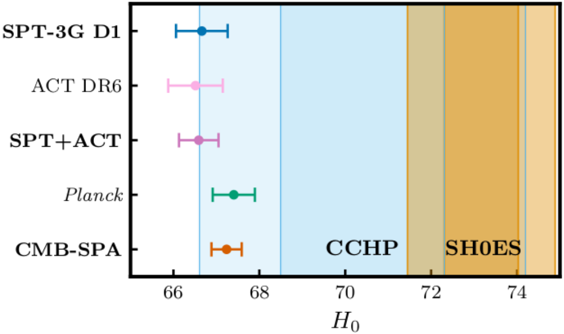
Lack of large-angle correlation ($> 3\sigma$, Planck18)

$$S_{1/2}^{XY} = \int_{-1}^{1/2} \left[C^{XY}(\arccos \mu) \right]^2 \mathrm{d}\mu.$$



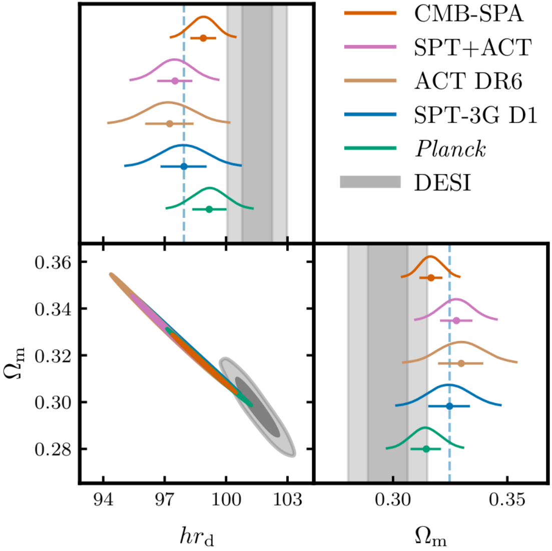
 What physical process can suppress temperature fluctuations but not polarisation?

H_0 tension (6.4σ, Camphuis25)

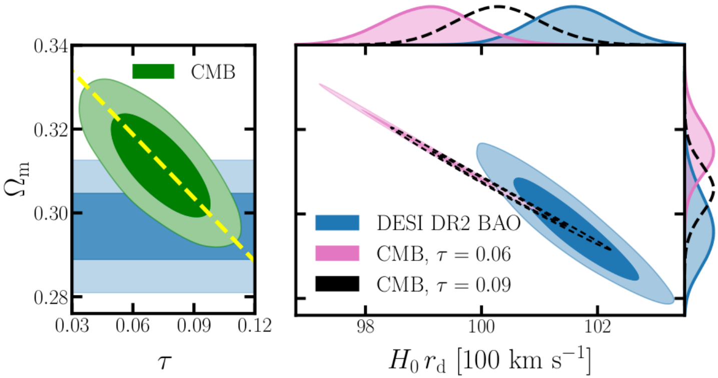


Planck+ACT+SPT ($67.24 \pm 0.35\,\mathrm{km/s/Mpc}$) v.s. SH0ES ($73.17 \pm 0.86\,\mathrm{km/s/Mpc}$, Breuval24)

Ω_m tension (2.8σ, Camphuis25)



A larger optical depth? (Sailer25, Jhaveri25)



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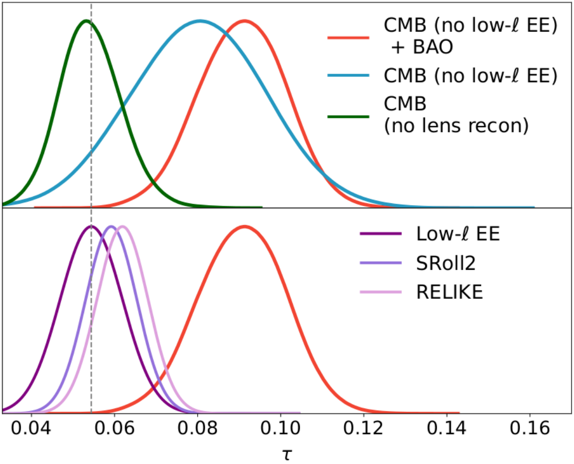
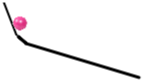
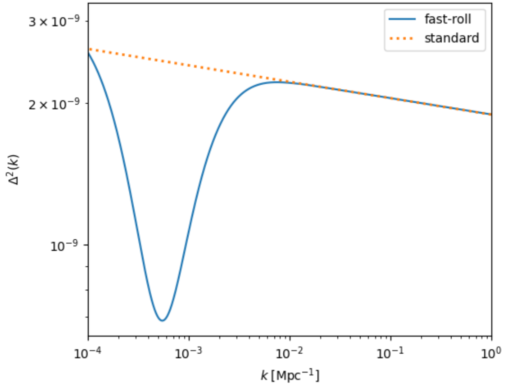


Fast-roll at the beginning of inflation?

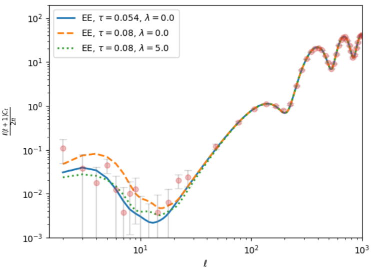


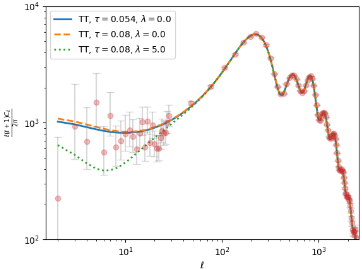


http://zhiqihuang.top/codes/compute_fastroll.f90

Fitting CMB data

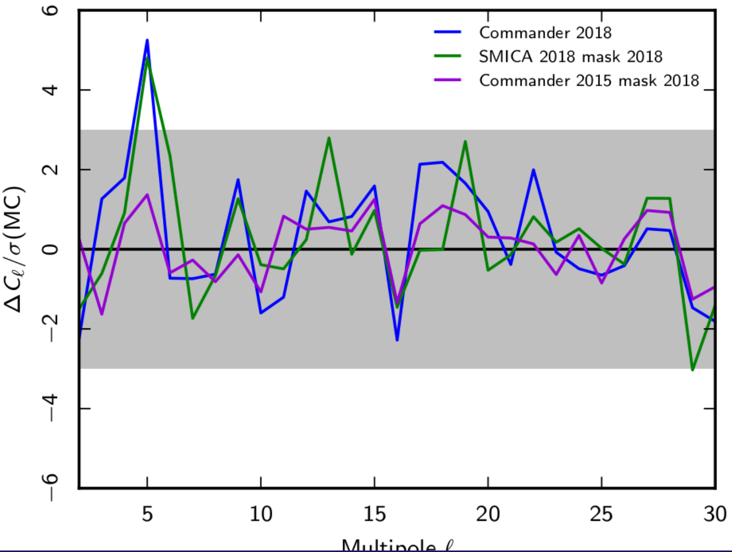
EE TT





Does not work that well for TT power at $\ell = 5$

The $\ell = 5$ anomaly between Planck18 and Planck15

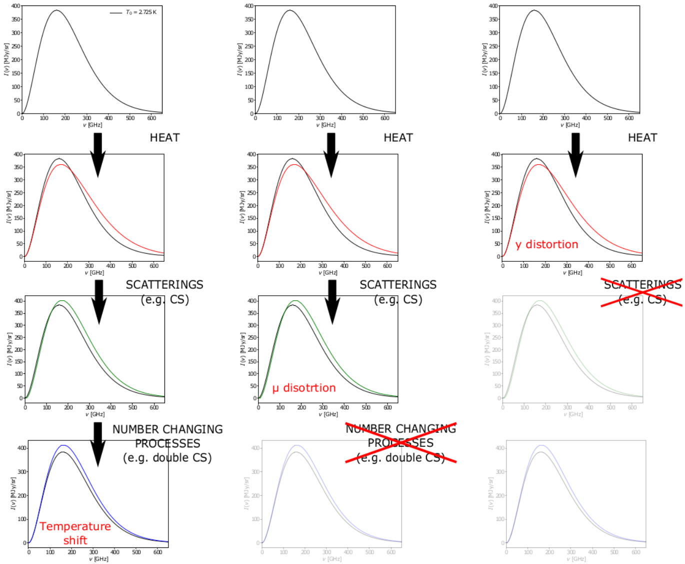


Possible indication of residual systematics

- $\sim 1.5\sigma$ shift of τ when low-ℓ EE likelihood is removed
- low-ℓ TE simulations did not pass the null test (no low-ℓ TE Planck likelihood released)
- $\ell = 5$ TT anomaly not fully understood (in my view)
- constraint on τ heavily relies on $\ell = 5$ EE
- The old dudes are making more efforts to understand Planck data better (see e.g. Cosmoglobe `https://wwww.cosmoglobe.uio.no`)

More (than r) to be observed

CMB spectral distortion (fig adapted from 2307.08513)



Spectral distortion

The blackbody spectrum with temperature T and chemical potential μ is

$$B(\nu;\mu,T) = \frac{1}{e^{\frac{\nu-\mu}{T}} - 1}.$$

In the very early universe when double Compton scattering is efficient. Photon numbers are not conserved, and therefore $\mu = 0$. The zeroth order CMB spectrum at redshift z is

$$f_0(\nu) = B\left(\nu;\mu = 0, T = T_{\mathrm{CMB}}(1+z)\right).$$

The true distribution of CMB, $f(\nu)$, is described by a spectral distortion

$$\Delta f(\nu) \equiv f(\nu) - f_0(\nu).$$

I am working with natural units $k_B = \hbar = c = 1$.

$z \gtrsim 2.e6$: thermalisation efficient (temperature shift)

$$\Delta f = \Delta T \frac{\partial B(\nu;\mu,T)}{\partial T}\Big|_{\mu=0} = \frac{\Delta T}{T}\frac{\frac{\nu}{T}e^{\frac{\nu}{T}}}{\left(e^{\frac{\nu}{T}}-1\right)^2},$$

where $T = T_{\rm CMB}(1+z)$.

$5.e4 \lesssim z \lesssim 2.e6$: CS efficient (chemical potential shift, μ distortion)

Chemical potential shift (from 0 to $\Delta\mu$) comes along with a temperature shift,

$$\Delta f = \Delta\mu \frac{\partial B(\nu;\mu,T)}{\partial\mu} + \Delta T \frac{\partial B(\nu;\mu,T)}{\partial T}.$$

The constraint that photon number is conserved gives $\Delta T \approx 0.4561\Delta\mu$ (pls. do this exercise), and therefore

$$\Delta f = \frac{\Delta\mu}{T}\left[\left(0.4561\frac{\nu}{T} - 1\right)\frac{e^{\frac{\nu}{T}}}{\left(e^{\frac{\nu}{T}} - 1\right)^2}\right],$$

where $T = T_{\rm CMB}(1+z)$.

$z \lesssim 5.e4$: CS inefficient (y distortion)

Complicated collision equation (Kompaneets57),

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{T_e n_e \sigma_T}{m_e} \frac{\nu^2}{T^2} \left[\frac{T}{T_e} f(1+f) + T \frac{\partial f}{\partial \nu} \right].$$

Analytic solution in the case of small perturbation ($\Delta f \ll f$),

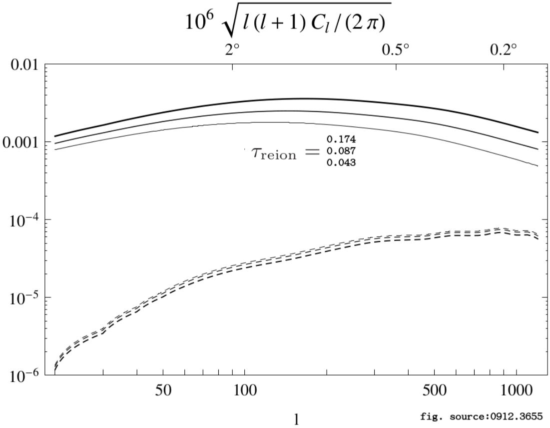
$$\Delta f = y \frac{\frac{\nu}{T} e^{\frac{\nu}{T}}}{\left(e^{\frac{\nu}{T}} - 1\right)^2} \left(\frac{\nu}{T} \frac{e^{\nu/T} + 1}{e^{\nu/T} - 1} - 4 \right),$$

where

$$y = \frac{T_e - T}{m_e} \int n_e \sigma_T \mathrm{d}t.$$

The factor $T_e - T$ encodes the direction of energy transfer; the optical depth $\int n_e \sigma_T \mathrm{d}t$ gives the probability of collision; the factor $\frac{1}{m_e}$ describes how hard it is to pass/gain energy to/from a heavy object.

Reionisation y-distortion anisotropy



μ distortion from early universe probes density perturbations at $k \sim$ 1-$10^4\mathrm{Mpc}^{-1}$

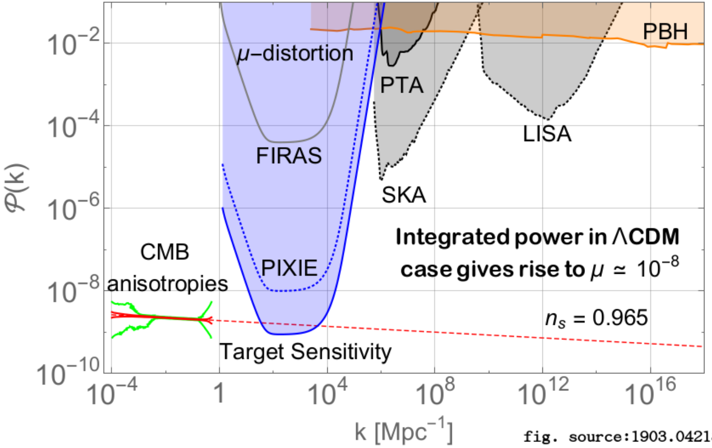


fig. source:1903.04218

Limit of SD measurement

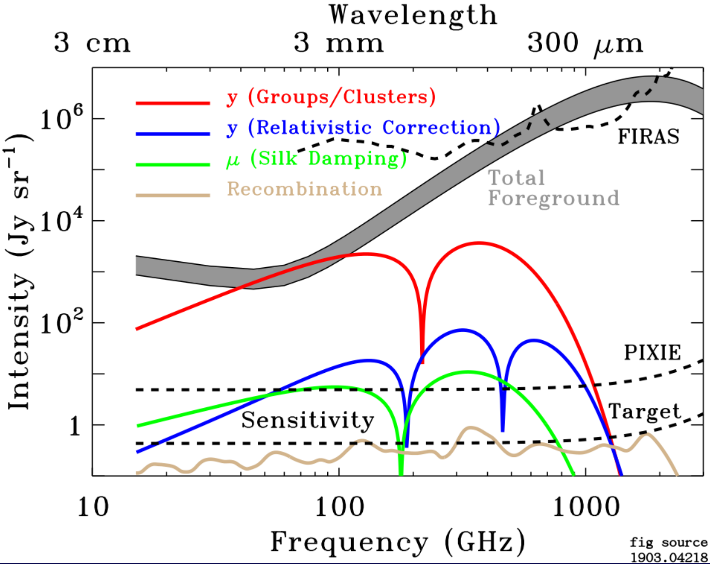


fig source: 1903.04218

Conclusions

- CMB is the experimental foundation of modern physical cosmology.
- The current cosmological crises may has to do with residual systematics in low-ℓ CMB polarization, if there is any.
- Future CMB is much more than measuring r. Spectral distortion is an exciting field for young ~~dudes~~ grad students.
- Related to this work shop: y-21cm correlation can be an interesting topic.