H_0 tension or T_0 tension?: Ivanov, Ali-Haimoud & Lesgourgues, arXiv:2005.10656

....

Perhaps a better title: Three new ways to measure $(H_0, T_0)_{\Lambda CDM}$ without using COBE-FIRAS

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A true way to measurement c/H_0 and a true way to measure T_0

"True" means completely independent of cosmological model.

c/H_0: Distance ladder (SH0ES)

1. Radar measurement of Earth-Sun distance
2. $\Rightarrow$ parallax measurement of stellar distances
3. $\Rightarrow$ measurement of Cepheid luminosities
4. $\Rightarrow$ measurement of SNIa luminosities

$\Rightarrow$ measurement of $c/H_0 = D_{SNIa}/z_{SNIa}$ $(z \ll 1)$

T_0: COBE-FIRAS: Comparison of CMB spectrum with spectrum from calibrated blackbody

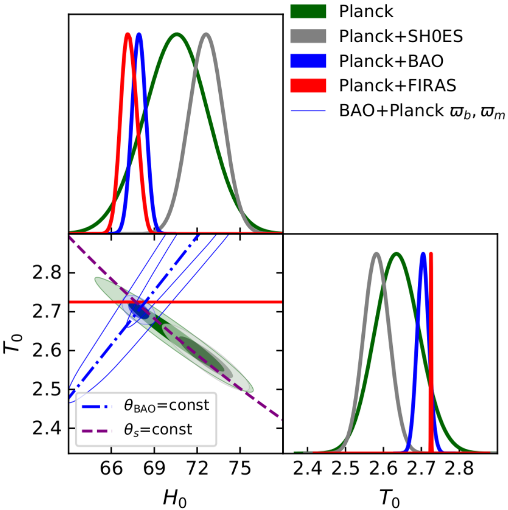
Because both H_0 and T_0 have (SI) units, each requires the measurement of a dimensioned quantity.

Other true measurements of T_0 arXiv:0911.1955

CMB Source	Temp (K)	Uncertainty (mK)	Reference
CN	2.700	40	Meyer & Jura (1985)
CN	2.740	50	Crane et al. (1986)
Balloon	2.783	25	Johnson & Wilkinson (1987)
CN	2.750	40	Kaiser & Wright (1990
Rocket	2.736	17	Gush et al. (1990)
S Pole	2.640	39	Levin et al. (1992)
Balloon	2.712	20	Schuster et al. (1993)
CN	2.796	39	Crane et al. (1994)
CN	2.729	31	Roth et al. (1995)
Balloon	2.730	14	Staggs et al. (1996)
ARCADE1	2.694	32	Fixsen et al. (2004)
ARCADE1	2.721	10	Fixsen et al. (2004)
ARCADE2	2.731	5	Fixsen et al. (2009)
FIRAS	2.7249	1.0	Mather et al. (1999)
FIRAS	2.7255	0.85	Fixsen et al. (1996)
FIRAS	2.7260	1.3	This Work
Mean	2.72548	.57	

TABLE 2
MEASUREMENTS AND UNCERTAINTIES OF THE CMB TEMPERATURE.

Five measurements of (H_0, T_0)



FIRAS-SH0ES: not shown

FIRAS-Planck:
(The standard result)

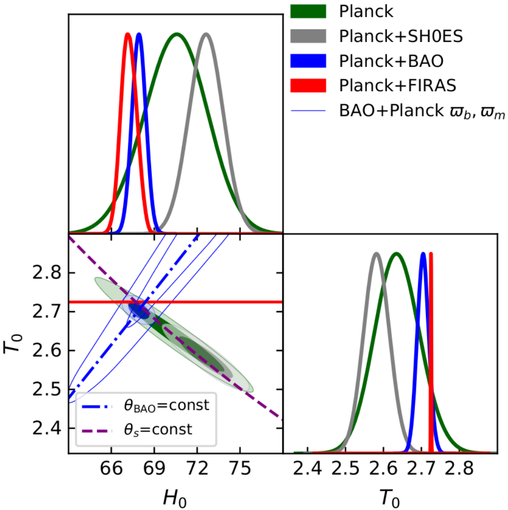
FIRAS-Planck-BAO-SN:
(The best result)

BAO-Planck:
New

SH0ES-Planck:
New T_0 measurement

Planck only:
New

All but FIRAS-SH0ES and FIRAS-Planck-BAO-SNIa assume ΛCDM.



Assuming ΛCDM:

FIRAS-Planck:
(The standard result)

BAO-Planck:
(New result)

SH0ES-Planck:
New T_0 measurement

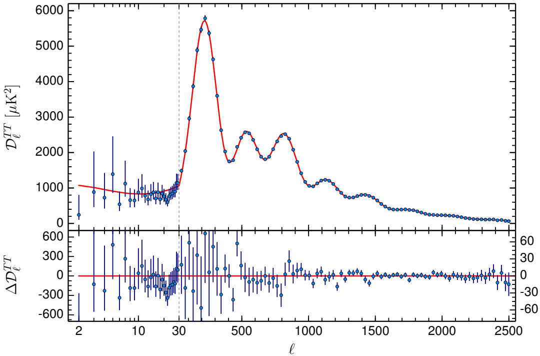
Planck only:
New T_0 and H_0 meas.

SH0ES-Planck in H_0 and T_0 tension with Firas-Planck
BAO-Planck not in tension with Firas-Planck
⇒ Disfavors either SH0ES or FIRAS or ΛCDM

Outline

- FIRAS-Planck (the standard result)
- Rewrite the standard formulas using T rather than z
- BAO-Planck
- SH0ES-Planck
- Planck alone

Power spectrum shape $\Rightarrow (\Omega_{\rm M} h^2, \Omega_{\rm B} h^2)$



Spectrum shape (relative peak heights) gives $\rho_{\rm M}/\rho_\gamma$, $\rho_{\rm B}/\rho_\gamma$

$$\Omega_{\rm M} H_0^2 = \frac{8\pi G}{3} \frac{\rho_M}{\rho_\gamma} \rho_\gamma$$

The (simplified) primary effects [Hu et al. 2001 ApJ 549, 669]:

- Power($\ell < 30$) $\Rightarrow A_s$ (primordial fluctuations)
- Power(peak 1)/Power($\ell < 30$) $\Rightarrow \Omega_{\rm M} h^2 / \Omega_{\rm R} h^2$
- Power(even peaks)/Power(odd peaks)$\Rightarrow \Omega_{\rm B} h^2 / \Omega_{\rm M} h^2$
- Power($\ell > 1000$)/Power(peak 1)$\Rightarrow N_\nu$

Calculation of the sound horizon

Same as "particle horizon" except $c_s < c$
$c_s = (c/\sqrt{3})f(\rho_{\rm B}/\rho_\gamma)$ (baryon inertia slows sound)

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)dz}{H(z)} = \sqrt{\frac{3}{8\pi G}} \int_{z_d}^{\infty} \frac{c_s(z)dz}{\sqrt{\rho_{\rm M} + \rho_\gamma + \rho_\nu}}$$

We normalize to the present photon density

$$r_d = \sqrt{\frac{3}{8\pi G \rho_\gamma(0)}} \int_{z_d}^{\infty} \frac{c_s(\rho_{\rm B}/\rho_\gamma)dz}{(1+z)^2\sqrt{\rho_{\rm M}(z)/\rho_\gamma(z) + 1 + \rho_\nu(z)/\rho_\gamma(z)}}$$

COBE gives us $\rho_\gamma(0)$ and the CMB spectrum shape (Planck) gives us the density ratios $\rho_{\rm M}/\rho_\gamma$, $\rho_{\rm B}/\rho_\gamma$, ρ_ν/ρ_γ.

r_d from COBE-Planck

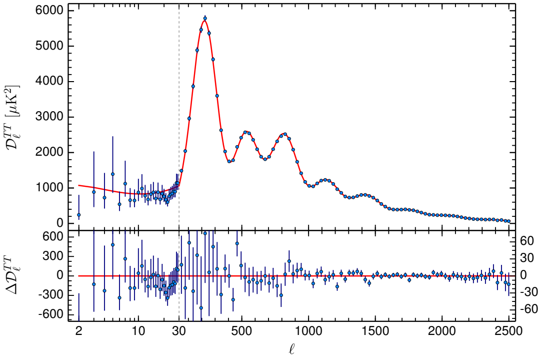
Imposing three neutrino families ($\rho_\nu = 0.23 N_\nu \rho_\gamma$) gives

$$r_d = (147.3 \pm 0.5)\mathrm{Mpc}$$

Fitting the CMB spectrum for N_ν gives $N_\nu = 2.99 \pm 0.2$ and

$$r_d = (147.4 \pm 1.5)\mathrm{Mpc}$$

Peak positions $\Rightarrow H_0$ (assuming $\Omega_k = 0$)



Spectrum shape (relative peak heights) gives $\rho_{\rm M}/\rho_\gamma$, $\rho_{\rm B}/\rho_\gamma$

$\Rightarrow \Omega_{\rm M} H_0^2, \Omega_{\rm B} H_0^2$

$\Rightarrow r_d$

First peak: $\ell_1 \sim 200 \sim 1/\theta_{BAO} \sim D(z=1090)/r_d$:

$$\theta_{BAO}^{-1} = D(z)/r_d \; = r_d^{-1} \int_0^z \frac{dz}{\left[H_0^2 + \Omega_{\rm M} H_0^2[(1+z)^3 - 1]\right]^{1/2}} \qquad \Rightarrow H_0$$

($\sim 10\%$ of integral in H_0 dominated region)

Rewrite cosmology

$$H(z)^2 = H_0^2 + \Omega_{\rm M} H_0^2[(1+z)^3 - 1] + \Omega_{\rm R}[(1+z)^4 - 1]$$

$$\rightarrow \quad H(T)^2 = H_0^2 + \frac{8\pi G}{3}\left[\alpha g T_{rec}(T^3 - T_0^3) + g(T^4 - T_0^4)\right]$$

$$D = \int \frac{dz}{H(z)} \qquad \rightarrow T_0^{-1} \int \frac{dT}{H(T)}$$

where:

- T_0 = today's temperature
- T_{rec} = temperature at recombination
- $\alpha = \rho_M/\rho_R$ at recombination (known from Planck)

CMB

$$\frac{r_d}{1+z_{rec}} = r_d \frac{T_0}{T_{rec}} \sim \frac{\overline{c_s}}{H(T_{rec})} \sim \frac{\overline{c_s}}{\sqrt{\alpha G}\, T_{rec}^2} \qquad r_d \sim \frac{\overline{c_s}}{\sqrt{\alpha G}\, T_{rec}\, T_0}$$

Physical r_d at recombination independent of (H_0, T_0) (not surprising).
Redshifted r_d proportional to T_0^{-1}.

$$D_{CMB} \sim \frac{1}{H_0^{1/3}} \left[\frac{1}{8\pi\alpha G T_{rec}\, T_0^3/3} \right]^{1/3} \quad \text{(JR approx.)}$$

$$D_{CMB} \sim \frac{1}{H_0^{0.19}} \frac{1}{T_0^{1.22}} \quad \text{(Ivanov et al.)}$$

$$\theta_{CMB} = \frac{r_d}{D_{CMB}} \propto H_0^{0.19}\, T_0^{0.22}$$

θ_{BAO}

$$D_{BAO} = (c/H_0)z_{BAO} \quad z_{BAO} \ll 1$$

$$\theta_{BAO} = \frac{r_d}{D_{BAO}} \sim \frac{H_0}{z_{BAO} G^{1/2} T_{rec} T_0}$$

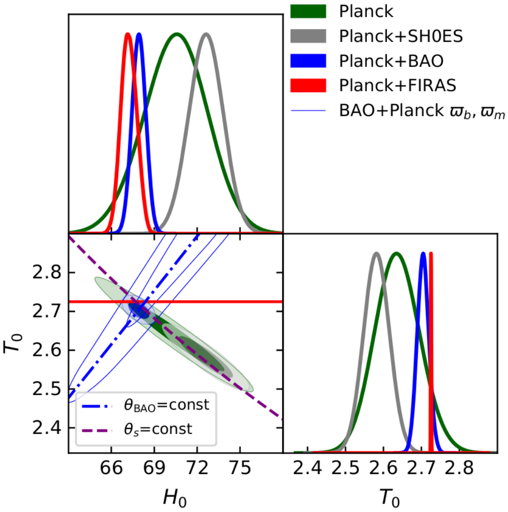
Planck-BAO (JR approximation)

$$T_0 \sim \frac{\theta_{CMB}^3}{z_{BAO}\theta_{BAO}} T_{rec} \qquad H_0 \sim \theta_{CMB}^3 \left[\frac{8\pi G T_{rec}^4}{3}\right]^{1/2}$$

My big question: How can observations of purely dimensionless quantities ($\Delta T/T$ for Planck and (z, ra, dec) for BAO) determine dimensioned quantities (H_0 and T_0).

Answer: T_{rec} is calculated from fundamental dimensioned constants with only a logarithmic dependence on cosmological parameters: $T_{rec} \propto \alpha^2 m_e c^2 \log(\Omega h^2.....)$

BAO-Planck and SH0ES-Planck



BAO-Planck:

$\theta_{CMB}, \theta_{BAO}(z \sim 0.5)$

$\Rightarrow T_0 = 2.704 \pm 0.016$

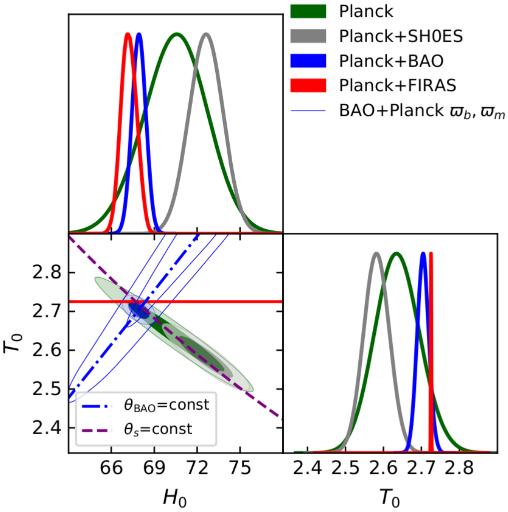
SH0ES-Planck:

$\theta_{CMB}, H_0^S = 73.5 \pm 1.4$

$\Rightarrow T_0 = 2.58 \pm 0.03$

4σ from FIRAS

Planck only



Decreasing T_0 increases time spent in vacuum domination.

$\Rightarrow$increased ISW and CMB-lensing

$H_0 = 70.5 \pm 2.3$

$T_0 = 2.64 \pm 0.06$