Sunyaev-Zeldovich effect as tool to probe fundamental physics and modified gravity

Ivan de Martino

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Outline

1. Standard cosmological model vs new physics
2. Data and Methodology
3. Results
4. Modified Gravity
5. Conclusions

The concordance cosmological model: ΛCDM

Modern Astrophysics and Cosmology are entirely based on **General Relativity** + **DM** + Λ. Due to its simplicity and capacity to explain the observations, the ΛCDM model is currently the Standard Cosmological Model.

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Comptes Rendus Physique, 18, 275-291 (2017)

Do We *really* Understand the Cosmos?

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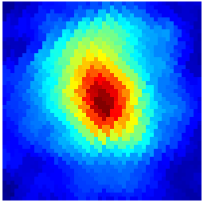
Abstract

Our *knowledge* about the universe has increased tremendously in the last three decades or so — thanks to the progress in observations — but our *understanding* has improved very little. There are several fundamental questions about our universe for which we have no answers within the current, operationally very successful, approach to cosmology. Worse still, we do not even know how to address some of these issues within the conventional approach to cosmology. This fact suggests that we are missing some important theoretical ingredients in the overall description of the cosmos. I will argue that these issues — some of which are not fully appreciated or emphasized in the literature — demand a paradigm shift: We should not think of the universe as described by a specific solution to the gravitational field equations; instead, it should be treated as a special physical system governed by a different mathematical description, rooted in the quantum description of spacetime. I will outline how this can possibly be done.

SZ effect: How to....

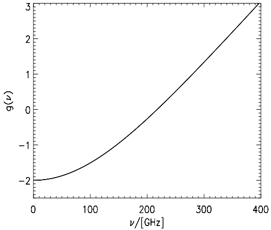
Temperature anisotropies due to SZ effects are given by



$$\frac{\Delta T_{TSZ}}{T} = g(\tilde{\nu})\frac{k_B\sigma_{\mathrm{T}}}{mc^2}\int_l T_{\mathrm{e}}(l)n_{\mathrm{e}}(l)dl = g(\tilde{\nu})Y_c$$

and their frequency dependence by

$$\tilde{\nu} = \frac{h\nu(z)}{k_B T_{CMB}(z)} \qquad g(\tilde{\nu}) = \tilde{\nu}\coth(\tilde{\nu}) - 4.$$



Assuming that the CMB temperature at a given redshift is unknown

$$g(\tilde{\nu}) \longmapsto g(\nu, T_{CMB}(z))$$

We can estimate $T_{CMB}(z)$ using multi-frequencies measurements of the TSZ effect.

WHY?

[Battistelli et al, 2016, Int. J. Mod. Phys. D 25, 1630023]

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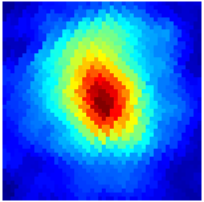

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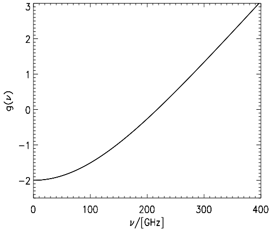

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Standard cosmological model vs new physics

ΛCDM-model: adiabatic evolution

$$T_{\rm CMB}(z) = T_0(1+z)$$

No adiabatic evolution: phenomenological parameterization

$$T_{\rm CMB}(z) = T_0(1+z)^{1-\beta}$$

No adiabatic evolution

In models where an evolving scalar field is coupled to the Maxwell F^2 term in the matter Lagrangian, photons can be converted into scalar particles violating the photon number conservation. Thus, there will be both variations of the fine-structure constant and violations of the standard $T_{CMB}(z)$ law. These can usually be written as

$$\frac{T_{CMB}(z)}{T_0} \sim (1+z)\left(1+\epsilon\frac{\Delta\alpha}{\alpha}\right),$$

[Avgoustidis, et al. JCAP 06 62(2014)]

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X-ray Cluster Catalog

Our cluster sample contains almost 618 clusters outside galactic plane.

- ROSAT-ESO Flux Limited X-ray catalog (REFLEX)
- extended Brightest Cluster Sample (eBCS)
- Clusters in the Zone of Avoidance (CIZA)

All three surveys are X-ray selected and X-ray flux limited. All quantities of interest for our analysis are measured, or derived from measured quantities.

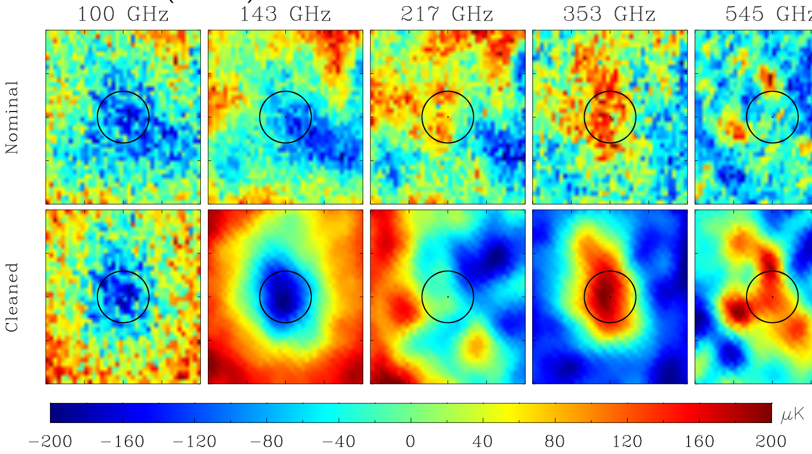
Warning!!!

Be careful if you are using SZ selected cluster. They will bias your analysis since they will mimic the underlying $T_{CMB}(z)$ scaling

Reference: Kocevski, D. and Ebeling, H. (2006). ApJ, 645:1043

Cleaning procedure: $\mathcal{P}(\nu, \mathbf{x}) = P(\nu, \mathbf{x}) - w(\nu) P(857\mathrm{GHz}, \mathbf{x})$

Coma Cluster (A1656): $l = 57.8°$; $b = 88.0°$; $z = 0.02310$



Diego, J. M., et al. 2002, MNRAS, 336, 1351

de Martino, I. et al. 2015, ApJ, 808, 128

Obtaining T_{CMB} from the data

For each channel, we measure the TSZ emission over disc of radius θ_{500}: $\delta\bar{T}/T_0$. Then, we predict the theoretical averaged TSZ anisotropies at the same apertures

$$\Delta\bar{T}(\mathbf{p},\nu_i)/T_0 = g(\nu_i, T_{CMB}(z))\langle Y_c\rangle_{\theta_{500}},$$

where

$$\mathbf{p} = [T_{CMB}(z), \langle Y_c\rangle_{\theta_{500}}].$$

We explore the 2D parameter space with Monte Carlo Markov Chain (MCMC) technique. We run four independent chains employing the Metropolis-Hastings sampling algorithm with different (randomly set) starting points. The chains stop when contain at least 30,000 steps and satisfy the Gelman-Rubin criteria.

References:

de Martino, I. et al. 2015, ApJ, 808, 128.

de Martino, I. et al. 2016, PRD, 94, 083008.

Estimating $\frac{\Delta\alpha}{\alpha}$ from the data

Once we have extracted the $T_{CMB}(z)$ from the data, we are ready to estimate the variation of the fine structure constant at cluster location:

$$\left(\frac{\Delta\alpha}{\alpha}\right)_{obs} = \epsilon^{-1}\left(1 - \frac{T_{CMB}(z)}{T_0(1+z)}\right),$$

and to compare it with

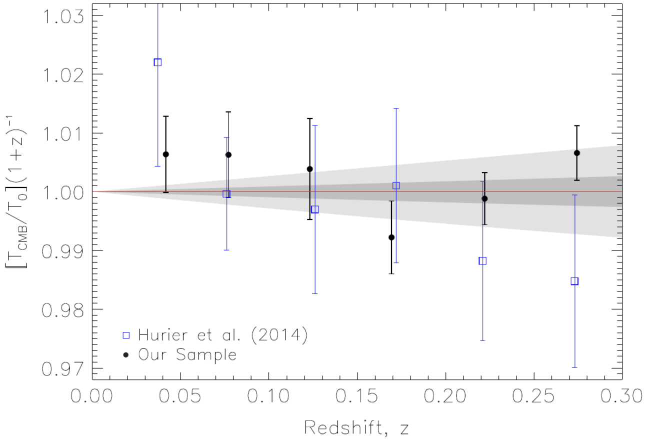
Model 1. $\left(\frac{\Delta\alpha}{\alpha}\right)_{th} = m + d\cos(\Theta),$

Model 2. $\left(\frac{\Delta\alpha}{\alpha}\right)_{th} = m + dr(z)\cos(\Theta),$

where m and d are the monopole and dipole amplitudes, Θ is the angle on the sky between the line of sight of each cluster and the best fit dipole direction, and $r(z)$ is the look-back time in the concordance ΛCDM model.

Results for $\Delta T = T_0(1+z)^{1-\beta}$

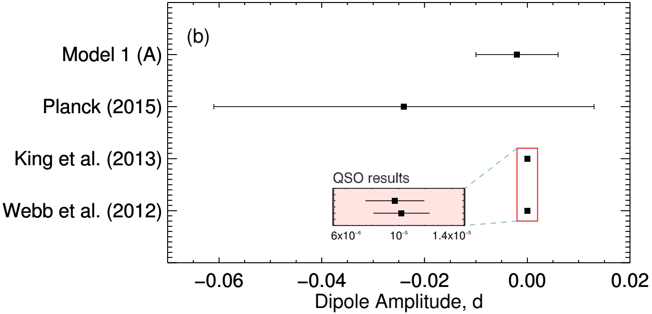
Best fit: $\beta = -0.007 \pm 0.013$



[de Martino, I. et al. 2015, ApJ, 808, 128]

Results for Model 1: $\left(\frac{\Delta\alpha}{\alpha}\right)_{th} = m + d\cos(\Theta)$

Analysis	m	d	RA ($^\circ$)	DEC ($^\circ$)
(A)	0	-0.002 ± 0.008	261.0	-58.0
(B)	0.006 ± 0.004	-0.008 ± 0.009	261.0	-58.0
(C)	0	-0.030 ± 0.020	255.1 ± 3.8	-63.2 ± 2.6
(D)	0.021 ± 0.029	-0.030 ± 0.014	255.9 ± 4.2	55.3 ± 5.8



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Testing modified gravity with TSZ cluster profiles

Model

$$i)\ \frac{\Delta T_{TSZ}}{T_0} = G(\nu)\frac{\sigma_{\rm T}}{mc^2}\int_l P_{\rm e}(l)dl,$$

$$ii)\ P_e(r) = P_c\mathbb{P}(r),$$

$$iii)\ \frac{d\mathbb{P}(r)}{dr} = -\rho_{gas}(r)\frac{d\Phi_{\rm eff}(r)}{dr},$$

$$iv)\ \mathbb{P}(r) \propto \rho_{gas}^{\gamma}(r),$$

$$v)\ \frac{dM(r)}{dr} = 4\pi\rho_{gas}(r).$$

de Martino I., et al. MNRAS, 442, 921 (2014)

de Martino I., PRD, 93, 4043 (2016)

de Martino I., de Laurentis M., PLB, 770, 440 (2017)

$f(R)$-gravity potential

$$\Phi_{\rm eff}(r) = \frac{\Phi_{\rm N}(r)}{1+\delta} - \frac{G\delta}{1+\delta}\int \frac{\rho(r')e^{-\frac{|r-r'|}{L}}}{|r-r'|}d^3r'$$

MOG potential

$$\Phi_{\rm eff}(r) = \Phi_{\rm N}(r)(1+\alpha) + G\alpha\int \frac{\rho(r')e^{-\frac{|r-r'|}{\mu^*}}}{|r-r'|}d^3r'$$

$\Phi_{\rm N}(r) = -\frac{GM(r)}{r}$ is the classical Newtonian potential.

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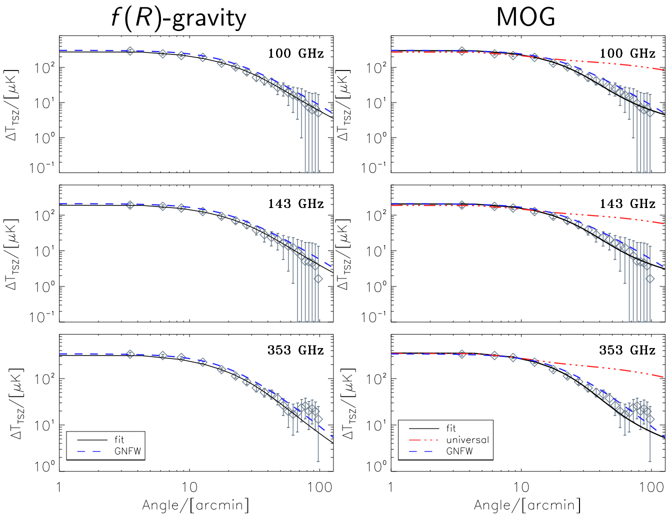

Conclusions

To sum up:

- Cluster could be a powerful tool to probe fundamental physics and modified gravity;

- They can used as cosmological probe: number counts, scaling relations, distance duality relations, dark energy models, $T_{CMB}(z)$, variation of fine structure constant, pressure profiles in modified gravity;

- Current SZ surveys carried out by ACT, SPT, and Planck offer a unique chance to perform new tests on $T_{CMB}(z)$ and variation of fine structure constant at redshift higher than $z \sim 0.3$;

- Waiting for the next generation of full sky CMB missions and X-ray satellites.

Thanks