Cosmological Constraints on Newton’s Gravitational Constant for Matter and Dark Matter

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Cosmological measurements of $G_N$

- Very different scale than the lab experiments!
  
  Ken-ichi Umezu, K. Ichiki and M. Yahiro  
  S. Galli, A. Melchiorri, G.F. Smoot and O. Zahn  

We (ONLY!) know DM interacts with Gravity, but is it the same Gravity?

- Long Range Forces  
  
  A. Nusser, S.S. Gubser and P.J.E. Peebles  
  R. Bean, E.E. Flanagan, I. Laszlo and M. Trodden  

- Dark Matter Equivalence Principle ($M_{grav} = M_{iner}$)
Cosmological linear theory
0-order (homogeneous and isotropic), \( \Omega_i \equiv \rho_i / \rho_{\text{crit}}, \ \rho_{\text{crit}} = \frac{3H^2}{8\pi G} \)

- Matter \( \rightarrow \Omega_m \rightarrow \Omega_{\text{cdm}}, \Omega_b \)
- Radiation \( \rightarrow \Omega_r \rightarrow \Omega_\gamma \) (fixed by \( T_{\text{CMB}} \), \( N_{\text{rel}} \))
- Reionization optical depth \( \rightarrow \tau \)
- Hubble parameter today \( \rightarrow H_0 \rightarrow \Omega_\Lambda \)

1-order, initial conditions for \( \delta \rho / \rho \) are determined by the primordial power spectrum from inflation,

- Primordial spectrum amplitude \( \rightarrow A_s \)
- Spectral index \( (n_s = 1 \Rightarrow \text{flat spectra}) \) \( \rightarrow n_s \)

\[
P(k) = A_s \frac{k^{1-n_s}}{k^3} \rightarrow C_l, P_{\text{gal}}(k)
\]
How can we measure the gravitational constant $G_N$?

- Gravitational acceleration depends only on the product of Newton’s Constant $G_N$ and the central body mass $M$.

$$a_{\text{grav}} = -\frac{G_N M}{r^2}$$

- To break this degeneracy and measure $G_N$, an additional force is required to define the central body mass.

How can we use cosmology to constrain $G_N$?

- Almost all can be absorbed redefining $\tau \rightarrow \lambda_G \tau$ and $k \rightarrow k/\lambda_G$.

- The baryons interact electromagnetically with the photons.

$$\dot{\delta}_b = -\theta_b + 3\dot{\phi}$$

$$\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_s^2 k^2 \delta_b + \frac{4\bar{\rho}_\gamma}{3\bar{\rho}_b} a n_e \sigma_T (\theta_\gamma - \theta_b) + k^2 \psi$$

- The Thomson scattering term is the only one that cannot be absorbed.

- Varying $G$ now yields an observable change in cosmological evolution.
- Cosmological equations integrated and CMB spectra computed using the publicly available CLASS code.
Analysis Method

Markov Chain Monte Carlo (MCMC) using the publicly available MontePython code (written to work with CLASS).

\[ P(\theta_i|D) = \frac{\mathcal{L}(D|\theta_i)\pi(\theta_i)}{\int \mathcal{L}(D|\theta_i) d\theta_1 \ldots d\theta_N} \]

1. Planck 2013 & 2015 Data Release
2. 3 Yr, High-\(\ell\) TT polarization from the Atacama Cosmology Telescope (ACT) and the South Pole Telescope (SPT).
3. BAO data from Sloan Digital Sky Survey (SDSS) (Data Releases 7 and 9) and Six degree Field Galaxy Survey (6dFGS).
4. \(H_0\) measurement from Wide Field Camera 3 on HST (0.01 < \(z\) < 0.1)
Planck Constraint on $\lambda_G$

- Planck 2015 gives a result consistent with lab experiments at $1\sigma$

<table>
<thead>
<tr>
<th>Data</th>
<th>$\lambda_G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck 2013</td>
<td>$1.062^{+0.0309}_{-0.0311}$</td>
</tr>
<tr>
<td>Planck+Lensing+BAO</td>
<td>$1.041^{+0.024}_{-0.027}$</td>
</tr>
<tr>
<td>Planck+Lensing+BAO+HST</td>
<td>$1.046^{+0.026}_{-0.027}$</td>
</tr>
<tr>
<td>Planck+Lensing+BAO+BBN</td>
<td>$1.046^{+0.021}_{-0.021}$</td>
</tr>
<tr>
<td>Planck+ACT/SPT</td>
<td>$1.026^{+0.013}_{-0.014}$</td>
</tr>
<tr>
<td>Planck+Lensing+BAO+HST+ACT/SPT</td>
<td>$1.038^{+0.022}_{-0.023}$</td>
</tr>
<tr>
<td>Planck+Lensing+BAO+BBN+ACT/SPT</td>
<td>$1.043^{+0.019}_{-0.019}$</td>
</tr>
<tr>
<td>Planck 2015</td>
<td>$1.025^{+0.025}_{-0.026}$</td>
</tr>
</tbody>
</table>
DM sector Long Range Force Model

- Use a traditional long range “fifth force” to model different dynamics in the dark matter sector.

\[ \mathcal{L} \supset \frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi - \frac{1}{2} m_{\phi}^2 \phi^2 + \bar{\chi} \gamma_{\mu} \partial^{\mu} \chi - \left( 1 + \frac{\phi}{f} \right) m_{\chi} \bar{\chi} \chi \]

For scales smaller than \( r_s = m_{\phi}^{-1} \), the Yukawa interaction mediates a fifth force. This fifth force will be long ranged if the mediator \( \phi \) is nearly massless.

\[ V(r) = -\frac{G_N m_{D1} m_{D2}}{r} \left[ 1 + \alpha_f e^{-m_{\phi} r} \right] \]

- Attempt to constrain \( \alpha_f \) using the latest cosmological data.
Large effect at small multipoles.
We get a bound of $O(10^{-4})$ for $\alpha_s$.

The bound on the $\alpha_f$ is independent of $m_\phi$ in this range.
The Weak Equivalence Principle (WEP) states that all objects in a uniform gravitational field, independent of the mass or other compositional properties, will experience the same acceleration.

Modern experiments report that the difference between inertial and gravitational masses is zero at the $10^{-13}$ level. Thus, violations of the WEP in the visible sector are tightly constrained.

However, WEP violation in the Dark Matter sector is far less constrained.
DM sector WEP Violation

- We introduce WEP violation into the dark matter sector by allowing the gravitational charge of dark matter to differ from the inertial mass by a factor of $\lambda_D$

$$m_D^{\text{grav}} = \lambda_D m_D$$

- Consequently, if we have two matter particles $b_1$ and $b_2$ and two dark matter particles $D_1$ and $D_2$, the gravitational forces in terms of the particle inertial masses are

$$F_{b_1,b_2} = -\frac{G_N m_{b_1} m_{b_2}}{r^2}, \quad F_{b_i,D_j} = -\lambda_D \frac{G_N m_{b_i} m_{D_j}}{r^2},$$

$$F_{D_1,D_2} = -\lambda_D^2 \frac{G_N m_{D_1} m_{D_2}}{r^2}.$$
DM sector  Effect of dark WEP breaking on the CMB TT Spectrum

\[ \eta_D = \lambda_D - 1 \quad \text{Starting Redshift } z_T \]
DM sector **Allowed region for** $\lambda_D$ **as a function of** $z_T$

- Using just data from Planck, $\lambda_D - 1$ is consistent with zero at the $10^{-6}$ level or less for all $z_T \geq 10^3$.

- **Strong correlation with** $H_0$

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**Planck+Lensing+HST**

$z_T = 10^5 - 1$

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**Expansion Rate Today** $H_0$ [km s$^{-1}$ Mpc$^{-1}$]

**Hubble Parameter** $M_0$ [km s$^{-1}$ Mpc$^{-1}$]
Conclusions

- We used the latest cosmological data to derive a constraint on $G_N$ for all matter at the 2.7% level.

- We use the latest cosmological data to constrain a long range force between dark matter particles at the level of $10^{-4}$.

- Using this method, we can constrain WEP in the dark matter sector at the $10^{-6}$ level or less for all $z_T \geq 10^3$. 
THE END
Effect of dark WEP breaking on the CMB EE Spectrum

$$\eta_D = \lambda_D - 1$$

$$\eta_D = -10^{-6}$$

$$\eta_D = 0$$

$$\eta_D = +10^{-6}$$
Effect of dark WEP breaking on the CMB TE Spectrum

\[ \eta_D = \lambda_D - 1 \]
\[ C_{\ell}^E (\mu K)^2 = \frac{\ell (\ell + 1)}{2\pi} \]
CMB TE Power Spectrum

\[ \ell (\ell + 1)/2\pi \] C^E_\ell (\mu K)^2

\( \lambda_G = 0.25 \)  
\( \lambda_G = 0.50 \)  
\( \lambda_G = 1.00 \)  
\( \lambda_G = 1.50 \)  
\( \lambda_G = 2.00 \)
Ionization Fraction

- If $\lambda_G$ is increased (decreased), recombination takes place over a longer (shorter) period of time.