Modified Gravity, Dark Matter and Dark Energy: Deep Mysteries of the Universe

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1. Einstein’s Gravity Theory and Dark Matter

• In 1916, Einstein published his new theory of gravity called General Relativity. It generalized his Special Theory of Relativity which did not include gravity.

• Why would we want to modify Einstein’s outstanding intellectual achievement?
• Since the 1970s and early 1980s, a growing amount of observational data has been accumulating that shows that Newtonian and Einstein gravity cannot describe the motion of the outermost stars and gas in galaxies correctly, if only their visible mass is accounted for in the gravitational field equations.
• Galaxy data that show that Newtonian and Einstein gravity do not fit the observed speed of stars in orbits inside a galaxy such as NGC 6503.
• To save Einstein’s and Newton’s theories, many physicists and astronomers have postulated that there must exist a large amount of “dark matter” in galaxies and also clusters of galaxies that could strengthen the pull of gravity and lead to an agreement of the theories with the data. This invisible and undetected matter removes any need to modify Newton’s and Einstein’s gravitational theories. Invoking dark matter is a less radical, less scary alternative for most physicists than inventing a new theory of gravity.
Physics Poster Competition 2006
Kevin Angus, Kay Copland, Victoria Mutch, Frances Shaw
Banff Academy

DARK MATTER...

Without it planets and galaxies would fly apart

90%+ of the universe is made of dark matter

IT'S OUT THERE!

It could be rock or some unknown planet but we don't know what it is.

DO YOU?

Matter and Energy in the Universe: A Strange Recipe

Baryons: 4 ±1%
Neutrinos: 0.1% – 5%
CMB: 0.01%

Cold Dark Matter: 29 ± 4%

Dark Energy: 67 ± 6%
• Exotic dark matter is invisible (no visible protons and electrons)

• Dark Matter is “cold” (CDM) meaning the dark matter particles are heavy, or it can be “warm” meaning dark matter particles are light

• Dark Matter does not interact with visible matter through electricity (photons)

• Preferred model of dark matter is WIMPS (weakly interacting massive particles), although warm dark matter has recently become more popular

• Dark matter particles have never been detected in spite of years searching for them in underground experiments and in astronomical experiments
• If dark matter is not detected and does not exist, then Einstein’s and Newton’s gravity theories must be modified.

• Can this be done successfully?

• Yes! My modified gravity (MOG) can explain the astrophysical, astronomical and cosmological data without dark matter.
2. Cosmology

Ingredients of the standard cosmology:

• General Relativity
• Large-scale homogeneity and isotropy
• 5% ordinary matter (baryons and electrons)
• 25% dark matter
• 70% dark energy
• Uniform CMB radiation, $T \sim 2.73$ degrees
• Scale-free adiabatic fluctuations $\Delta T/T \sim 10^{-5}$ in CMB

CMB is the cosmic microwave background radiation discovered serendipitously by Arno Penzias and Robert Wilson in 1964 (Nobel Prize 1978). It is the afterglow of the big bang.
Evolution of the universe in standard cosmology model.
• The dark matter and dark energy are the most puzzling parts of the standard cosmology.

25 % Dark matter is collisionless

Dark Energy ~ 70 % is smooth and appears about 9 billion years after the Big Bang (supernovae measurements). It is claimed that the Dark Energy accelerates the expansion of the universe.
3. Dark Matter and Modified Gravity (MOG)

• Dark matter is inferred from the motions of visible matter in a gravitational field. It is possible that dark matter doesn’t exist and that Einstein’s General Relativity (GR) has to be modified.

• In my MOG I add new fields to Einstein’s theory. These fields make gravity stronger at the distance scales of galaxies, clusters of galaxies and the large distance scales of the universe.

• The new fields are dynamically sourced by ordinary matter (baryonic matter) such as protons and electrons – in the absence of visible matter the gravitational field and the new fields vanish. For dark matter theories the gravitational field does not vanish in the presence of dark matter and in the absence visible matter. This is a significant difference between dark matter theories and MOG.
• The fully relativistic modified gravity (MOG) called Scalar-Tensor-Vector-Gravity (STVG) (JWM, JCAP 2006, 004 (2006), arXiv:gr-qc/0506021), leads to a gravity theory that can describe solar system, astrophysical and cosmological data.

• The STVG theory has an extra degree of freedom, a vector field called a “phion” field ($\phi_\mu$) whose curl is a skew field that couples to matter (“fifth force”). The gravitational field is described by a symmetric Einstein metric tensor.

• The classical theory allows the gravitational coupling “constant” $G$ to vary as a scalar field with space and time. The effective mass ($\mu$) of the phion field also varies with space and time as a scalar field.
• The MOG must explain the following:

• MOG must fit the accurate solar system experiments;

• The CMB data including the power spectrum data. Essentially, the power spectrum is a measure of the fluctuation of temperature or density against the angular size;

• The formation of proto-galaxies in the early universe and the growth of galaxies;

• Gravitational lensing data for galaxies and clusters of galaxies. The lensing is the bending of light by massive bodies such as a star or a galaxy;

• The merging Bullet Clusters 1E0-657-588 and Abell 520;

• The accelerating expansion of the universe (Dark Energy?).
4. Modified Gravity (MOG)


$$S = S_G + S_\phi + S_S + S_M.$$ 

$$S_G = -\frac{1}{16\pi} \int \frac{1}{G} (R + 2\Lambda) \sqrt{-g} d^4 x,$$

$$S_\phi = -\int \omega \left[ \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{2} \mu^2 \phi_\mu \phi^\mu + V_\phi(\phi) \right] \sqrt{-g} d^4 x,$$

$$S_S = \int \frac{1}{G} \left[ \frac{1}{2} g^{\mu\nu} \left( \frac{\nabla_\mu G \nabla_\nu G}{G^2} + \frac{\nabla_\mu \mu \nabla_\nu \mu}{\mu^2} \right) - \frac{V_G(G)}{G^2} - \frac{V_\mu(\mu)}{\mu^2} \right] \sqrt{-g} d^4 x.$$ 

• In addition to the metric $g_{\mu\nu}(x)$, we have a massive vector field $\varphi_\mu(x)$, and two scalar fields $G(x)$ and $\mu(x)$. $B_{\mu\nu} = \partial_\mu \varphi_\nu - \partial_\nu \varphi_\mu$ and $V_\phi(\phi)$, $V_G(G)$ and $V_\mu(\mu)$ denote self-interaction potentials. $\omega$ is a dimensionless coupling constant.
The spherically symmetric MOG solution is given by

\[ d\tau^2 = B dt^2 - Adr^2 - r^2(d\theta^2 + \sin^2 \theta d\phi^2), \]

\[ A \simeq B^{-1}, \]

\[ B \simeq 1 - \frac{2G_0M}{r} + \frac{\omega G_0 Q_5^2}{r^2}, \]

\[ G \simeq G_0 = G_N + (G_\infty - G_N)\frac{M}{(\sqrt{M} + E)^2}, \]

\[ \mu \simeq \mu_0 = \frac{D}{\sqrt{M}}, \]

\[ \omega = \frac{1}{\sqrt{12}}, \]

\[ \phi_t \simeq -Q_5 \frac{e^{-\mu r}}{r}, \]
The constants of integration are
\[ \kappa = \sqrt{\frac{G_N}{\omega}}, \]
\[ D \simeq 6250 \ M_{\odot}^{1/2} \text{kpc}^{-1}, \]
\[ E \simeq 25000 \ M_{\odot}^{1/2}, \]
\[ G_\infty \simeq 20G_N. \]

The modified Newtonian acceleration is given by
\[ \ddot{r} = - \left[ 1 + \alpha - \alpha(1 + \mu r)e^{-\mu r} \right] \frac{G_N M}{r^2}. \]

\[ \alpha = \frac{G_0 - G_N}{G_N} = \left( \frac{G_\infty}{G_N} - 1 \right) \frac{M}{(\sqrt{M} + E)^2}. \]

The rotation velocity of a star in a galaxy is
\[ v = \sqrt{\left[ 1 + \alpha - \alpha(1 + \mu r)e^{-\mu r} \right] \frac{G_N M}{r}}. \]

At \( r = \mu^{-1} \) and \( \mu = D/\sqrt{M} \) we get the Tully-Fisher law: \( v^4 \propto M. \)

\[ v = \sqrt{\left[ 1 + \alpha(1 - 2e^{-1}) \right] D G_N} \sqrt[4]{M}, \]
Fitting Galaxy Rotation Curves and Clusters

• Galaxy rotation curves (101 galaxies) are fitted to photometric data (J. R. Brownstein and JWM, Astrophys. J. 636, 721 (2006), arXiv:astro-ph/0506370). Only one parameter, the mass-to-light ratio M/L, is used for the fitting once two parameters $\alpha$ and $\lambda$ are universally fixed for galaxies and dwarf galaxies. No dark matter is needed to fit the data.

• A large sample of X-ray mass profile cluster data (106 clusters) has also been well fitted (J. R. Brownstein and JWM, 2005; JWM and V. T. Toth, 2007, 2008; J. R. Brownstein, 2008).

• The strength of gravity increases as we go from the center of a galaxy to its edge. The rotational velocity curves become the Kepler-Newtonian curves at large distances from the galaxies. The strength of gravity diminishes in MOG as we go to large distances from massive bodies such as galaxies.

• The modified acceleration law is consistent with the solar system data (JWM & V. T. Toth, Int. J. Mod. Phys. D21, 1250084 (2012), arXiv:1001.1564). The strength of gravity in MOG decreases as we go to small distance scales such as the solar system.
Photometric fits to galaxy rotation curves. There are 4 benchmark galaxies presented here; each is a best fit via the single parameter \((M/L)_{\text{stars}}\) based on the photometric data of the gaseous (HI plus He) and luminous stellar disks. The radial coordinate (horizontal axis) is given in kpc and the rotational velocity (vertical axis) in km/s. The red points with error bars are the observations, the solid black line is the rotation curve determined from MOG, and the dash-dotted cyan line is the rotation curve determined from MOND. The other curves are the Newtonian rotation curves of the various separate components: the long-dashed green line is the rotation curve of the gaseous disk (HI plus He) and the dotted magenta curve is that of the luminous stellar disk.

MOND is an alternative non-relativistic modified Newtonian dynamics (M. Milgrom, 1983).
5. Gravitational Lensing: Einstein Rings, the Bullet Cluster and Abell 520

The deflection angle of light passing a massive body is given in MOG (JWM 2006, JWM and V. T. Toth, MNRAS 397, 1885 (2009), arXiv:0805.4774 [astro-ph]) by

\[ \Delta \phi_\gamma = \frac{4GM}{r_0} = \frac{4(1 + \alpha)G_NM}{r_0} \]

The effective lensing mass is \( M_L = (1 + \alpha)M \). \( \alpha=\alpha(M) \) is a function of the baryon mass \( M=M_b \) we have

\[ M_L = \left( 1 + \frac{G_\infty - G_N}{G_N} \frac{M}{(\sqrt{M} + E)^2} \right) M. \]

\[ E \simeq 25000 \ M_\odot^{1/2}, \]
\[ G_\infty \simeq 20G_N. \]
Gravitational Lensing

1. A Distant Source
   Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

2. A Lens of ‘Dark Matter’
   Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter’s gravity acts like a lens, bending the incoming light.

3. Focal Point: Earth
   Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.
TABLE I: Data for 21 strong lensing objects. Lensing mass and stellar luminosity estimates are from [16]. The value of the baryonic mass-to-light ratio under MOG, $\Upsilon_{\text{MOG}}$, is predicted, as described in the text.

<table>
<thead>
<tr>
<th>Lens</th>
<th>$M_L$ ($10^{10} M_\odot$)</th>
<th>$L_V$ ($10^{10} L_\odot$)</th>
<th>$\sigma_\parallel$ (km/s)</th>
<th>$\Upsilon_{\text{MOG}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q0047</td>
<td>$33.27^{+3.80}_{-3.03}$</td>
<td>$2.30^{+0.59}_{-0.47}$</td>
<td>$250(30)$ [17]</td>
<td>$0.97^{+0.25}_{-0.20}$</td>
</tr>
<tr>
<td>Q0142</td>
<td>$45.81^{+3.31}_{-5.00}$</td>
<td>$4.59^{+2.32}_{-1.61}$</td>
<td>—</td>
<td>$0.65^{+0.35}_{-0.22}$</td>
</tr>
<tr>
<td>MG0414</td>
<td>$102.76^{+15.65}_{-19.04}$</td>
<td>$3.54^{+2.01}_{-1.31}$</td>
<td>—</td>
<td>$1.74^{+1.02}_{-0.63}$</td>
</tr>
<tr>
<td>B0712</td>
<td>$16.13^{+2.55}_{-2.04}$</td>
<td>$1.67^{+0.50}_{-0.49}$</td>
<td>—</td>
<td>$0.71^{+0.22}_{-0.17}$</td>
</tr>
<tr>
<td>HS0818</td>
<td>$36.88^{+8.69}_{-5.48}$</td>
<td>$1.74^{+0.57}_{-0.44}$</td>
<td>—</td>
<td>$1.40^{+0.48}_{-0.34}$</td>
</tr>
<tr>
<td>RXJ0911</td>
<td>$73.04^{+1.15}_{-1.36}$</td>
<td>$4.85^{+2.47}_{-1.69}$</td>
<td>—</td>
<td>$0.93^{+0.30}_{-0.21}$</td>
</tr>
<tr>
<td>BRI0852</td>
<td>$14.76^{+5.67}_{-5.87}$</td>
<td>$1.79^{+0.57}_{-0.44}$</td>
<td>—</td>
<td>$0.61^{+0.20}_{-0.15}$</td>
</tr>
<tr>
<td>Q0957</td>
<td>$151.29^{+15.67}_{-1.95}$</td>
<td>$8.29^{+2.51}_{-1.95}$</td>
<td>$288(9)$ [18]</td>
<td>$1.06^{+0.33}_{-0.25}$</td>
</tr>
<tr>
<td>LBQS1009</td>
<td>$64.73^{+21.19}_{-11.97}$</td>
<td>$3.09^{+1.86}_{-1.20}$</td>
<td>—</td>
<td>$1.31^{+0.83}_{-0.50}$</td>
</tr>
<tr>
<td>B1030</td>
<td>$55.09^{+2.11}_{-3.52}$</td>
<td>$4.61^{+2.24}_{-1.58}$</td>
<td>—</td>
<td>$0.76^{+0.39}_{-0.25}$</td>
</tr>
<tr>
<td>HE1104</td>
<td>$72.80^{+6.68}_{-3.22}$</td>
<td>$4.11^{+1.82}_{-1.29}$</td>
<td>—</td>
<td>$1.09^{+0.50}_{-0.33}$</td>
</tr>
<tr>
<td>PG1115</td>
<td>$16.80^{+1.31}_{-1.23}$</td>
<td>$1.52^{+0.94}_{-0.62}$</td>
<td>$281(25)$ [19]</td>
<td>$0.81^{+0.35}_{-0.31}$</td>
</tr>
<tr>
<td>B1152</td>
<td>$30.43^{+4.23}_{-5.86}$</td>
<td>$3.02^{+0.92}_{-0.72}$</td>
<td>—</td>
<td>$0.68^{+0.22}_{-0.16}$</td>
</tr>
<tr>
<td>B1422</td>
<td>$5.72^{+4.03}_{-0.24}$</td>
<td>$0.46^{+0.17}_{-0.13}$</td>
<td>—</td>
<td>$1.11^{+0.44}_{-0.34}$</td>
</tr>
<tr>
<td>SBS1520</td>
<td>$41.98^{+1.49}_{-1.82}$</td>
<td>$4.37^{+2.64}_{-1.69}$</td>
<td>—</td>
<td>$0.63^{+0.40}_{-0.24}$</td>
</tr>
<tr>
<td>B1600</td>
<td>$16.38^{+0.82}_{-1.67}$</td>
<td>$0.62^{+0.22}_{-0.16}$</td>
<td>—</td>
<td>$1.94^{+0.69}_{-0.50}$</td>
</tr>
<tr>
<td>B1608</td>
<td>$42.49^{+14.23}_{-26.50}$</td>
<td>$11.5^{+3.49}_{-2.67}$</td>
<td>$247(35)$ [20]</td>
<td>$0.24^{+0.07}_{-0.06}$</td>
</tr>
<tr>
<td>MG2016</td>
<td>$52.05^{+14.23}_{-5.13}$</td>
<td>$7.12^{+6.58}_{-3.75}$</td>
<td>$304(27)$ [21]</td>
<td>$0.47^{+0.52}_{-0.22}$</td>
</tr>
<tr>
<td>B2045</td>
<td>$173.07^{+21.02}_{-34.20}$</td>
<td>$5.76^{+2.01}_{-1.50}$</td>
<td>—</td>
<td>$1.74^{+0.60}_{-0.45}$</td>
</tr>
<tr>
<td>HE2149</td>
<td>$26.82^{+2.19}_{-0.58}$</td>
<td>$5.42^{+2.12}_{-1.57}$</td>
<td>—</td>
<td>$0.34^{+0.14}_{-0.10}$</td>
</tr>
<tr>
<td>Q2237</td>
<td>$2.76^{+0.86}_{-0.58}$</td>
<td>$0.26^{+0.14}_{-0.10}$</td>
<td>$215(30)$ [22]</td>
<td>$1.08^{+0.61}_{-0.39}$</td>
</tr>
</tbody>
</table>

**Strong lensing MOG fits to 21 galaxies**
The Bullet Cluster and ABELL 520

When background objects are viewed through colliding clusters, significant weak lensing should be observable. The lensing is proportional to the gas mass at the locus of the collision. Lensing will be seen at the locus of the visible galaxies.

When two large clusters collide, much of the gas present in the galaxies slows down and heats up. This was observed using X-ray telescopes (hot gas ~ $10^7$ K). Stars and CDM halos of galaxies pass through each other in a collisionless manner and continue along the original trajectories of the colliding clusters, their path only influenced by gravitational interactions.
The case of the Bullet Cluster 1E0657-558 has been viewed as a vindication of DM. In contrast, the colliding clusters Abell 520 show weak lensing that in the DM scenario can only be explained if significant quantities of DM were present in the core (M. J. Jee et al., Ap. J.. 747, 96 (2012), arXiv:1202.6368). This contradicts the assumption that DM is collisionless, interacting only with gravity. DM attached to galaxies would have continued without collision and be detected through lensing where galaxies are visible. No visible galaxies are situated at the core of A520.

However, another group finds that the mass distribution of A520, after subtraction of the X-ray plasma mass, is in good agreement with the luminosity distribution of the cluster galaxies. They claim that A520 shows no evidence to contradict the collisionless dark matter scenario. D. Clowe et al., arXiv:1209.2143.

The amount of gas and non-exotic baryon mass in parts of the cluster are

\[ f_g = \frac{M_g}{M_L}, \quad M_b = M_g + M_\star = f_g M_L + \gamma_\star L. \]
Weak lensing for Abell 520 was explored using the Hubble space telescope wide field planetary camera. The authors conclude that this cluster **has a dark core that coincides with the peak X-ray luminosity** (A. Mahdavi et al. 2007; M. J. Jee et al. Ap. J. 747, 96 (2012), arXiv:1202.6368[astro-ph].)

### Applying MOG to Abell 520

<table>
<thead>
<tr>
<th>Component</th>
<th>$M_L$ ($10^{13} M_\odot$)</th>
<th>$f_g$</th>
<th>$L_\ast$ ($10^{11} L_\odot$)</th>
<th>$\alpha$</th>
<th>$\alpha(M_L)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main cluster</td>
<td>9.5(1.5)</td>
<td>0.09(1)</td>
<td>3.5</td>
<td>9.7$^{+1.3}_{-1.1}$</td>
<td>17.7</td>
</tr>
<tr>
<td>Subcluster</td>
<td>6.6(1.9)</td>
<td>0.04(1)</td>
<td>2.1</td>
<td>22.2$^{+7.6}_{-4.8}$</td>
<td>17.5</td>
</tr>
<tr>
<td>Main gas peak</td>
<td>10.8(6)</td>
<td>0.19(3)</td>
<td>N/A</td>
<td>4.3$^{+1.0}_{-0.8}$</td>
<td>18.6</td>
</tr>
</tbody>
</table>
TABLE III: Lensing mass, gas fraction, stellar luminosity and the MOG $\alpha$ parameter (estimated assuming a stellar mass-to-light ratio of 1) and the same parameter computed from $M_L$ for components of Abell 520 [3].

<table>
<thead>
<tr>
<th>Component</th>
<th>$M_L$ ($10^{13} M_\odot$)</th>
<th>$f_g$</th>
<th>$L_B$ ($10^{11} L_\odot$)</th>
<th>$\alpha$</th>
<th>$\alpha(M_L)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>2.63(48)</td>
<td>&lt; 0.06</td>
<td>1.54</td>
<td>&gt; 13.8</td>
<td>18.2</td>
</tr>
<tr>
<td>P2</td>
<td>3.83(42)</td>
<td>&lt; 0.08</td>
<td>3.58</td>
<td>&gt; 9.7</td>
<td>18.3</td>
</tr>
<tr>
<td>P3 (dark core)</td>
<td>4.00(38)</td>
<td>&lt; 0.14</td>
<td>0.68</td>
<td>&gt; 6.0</td>
<td>18.4</td>
</tr>
<tr>
<td>P4</td>
<td>3.64(45)</td>
<td>&lt; 0.08</td>
<td>2.95</td>
<td>&gt; 9.9</td>
<td>18.3</td>
</tr>
<tr>
<td>P5</td>
<td>3.02(40)</td>
<td>&lt; 0.05</td>
<td>2.12</td>
<td>&gt; 15.5</td>
<td>18.3</td>
</tr>
<tr>
<td>P6</td>
<td>3.33(40)</td>
<td>&lt; 0.06</td>
<td>1.23</td>
<td>&gt; 14.3</td>
<td>18.3</td>
</tr>
</tbody>
</table>
• The infall velocity of the bullet cluster from infinity calculated from Newtonian gravity with dark matter is \( \sim 980 \) km/sec. This falls short of the required infall velocity \( \sim 3000 – 4000 \) km/sec needed to explain the 14 kev temperature of the hot central plasma (J. Lee & E. Komatsu, arXiv:1003.0939).

• MOG can solve this problem by predicting an infall velocity 3,300 km/s when the two clusters are 4.6 Mpc apart, assuming that they were at relative rest at infinity (JWM & V. T. Toth, arXiv:1005.2685).
Merging clusters: “Bullet Cluster” 1E 0657-558
JWM, Sohrab Rahvar and V. T. Toth, arXiv:1204.2985
Merging clusters: Abell 520. “Cosmic train wreck”. It does not show separation of dark matter! Constellation of Orion about 2.4 billion light years away. Large putative clump of dark matter should not be there.
Gravitational lensing contours mapping out matter distribution in Abell 520.
GLOBULAR CLUSTERS AS ASTRONOMICAL TEST OF MOG

- Globular clusters near the edge of our MILKY WAY galaxy are an excellent astronomical testing laboratory for MOG. (JWM and V. T. Toth, The Astrophysical Journal, 680:1158-1161, 2008.)
6. MOG Cosmology

Picture of the Universe ~ 380,000 years after the big bang at t=0. The “splotches” are thermal fluctuations in the cosmic microwave background radiation.
• The MOG cosmological field equations have been solved (JWM and V. T. Toth, arXiv:0710.0364; JWM and V. T. Toth, Class. Quantum Grav. 26 (2009) 085002, arXiv:0712.1796; V. T. Toth, arXiv:1011.5174). The universe “begins” an infinite time before $t=0$ and “bounces” at $t=0$ without an infinite matter density singularity. After the bounce the universe expands until the present time and beyond to $t = \infty$.

• Because the universe has an infinite past $t = -\infty$ there is no “horizon problem” and no need for inflation to solve this problem. In the commonly accepted inflation model, the universe expands exponentially fast for fractions of seconds after the big bang singularity, solving the horizon problem with no violation of causality to explain the uniformity of the CMB temperature. My variable speed of light cosmology (VSL) also solves the horizon problem without inflation (JWM, Int. J. Mod. Phys. D2, 351 (1993), arXiv:gr-qc/9211020).
About 380,000 years after the big bang protons and light (photons) interact before the photons decouple and stream away. The proton-photon interaction produces pressure waves that generate acoustical (sound) oscillations shown in the graph. The solid curve is the MOG fit to the data (WMAP data).
Type Ia supernova luminosity-redshift data and the MOG/ΛCDM predictions. The horizontal axis corresponds to the $q = 0$ empty universe. The MOG result is represented by a thick (blue) line. Dashed (red) line is a matter-dominated Einstein de-Sitter universe with $\Omega_M = 1$, $q = 0.5$. Thin (black) line is the ΛCDM prediction.

This graph depicts the dimming of light from the exploding supernova stars, telling us that the expansion of the universe is apparently accelerating.
The matter power spectrum. Three models are compared against five data sets (see text): ΛCDM (dashed blue line, $\Omega_b = 0.035$, $\Omega_c = 0.245$, $\Omega_\Lambda = 0.72$, $H = 71$ km/s/Mpc), a baryon-only model (dotted green line, $\Omega_b = 0.035$, $H = 71$ km/s/Mpc), and MOG (solid red line, $\alpha = 19$, $\mu = 5h$ Mpc$^{-1}$, $\Omega_b = 0.035$, $H = 71$ km/s/Mpc.) Data points are colored light blue (SDSS 2006), gold (SDSS 2004), pink (2dF), light green (UKST), and dark blue (CfA).

$$T(k) = \frac{\Omega_b}{\Omega_m} T_b(k) + \frac{\Omega_c}{\Omega_m} T_c(k),$$

$$P(k) = T^2(k) P_0(k),$$

$$\ddot{\delta}_k + 2H \dot{\delta}_k + \left( \frac{c_s^2 k^2}{a^2} - 4\pi G_{\text{eff}} \rho \right) \delta_k = 0,$$

$$G_{\text{eff}} = G_N \left\{ 1 + \alpha \left[ 1 - \left( 1 + \frac{\mu a}{k} \right) e^{-\mu a/k} \right] \right\}.$$
• Verifiable prediction of matter power spectrum that distinguishes cold dark matter from MOG without exotic dark matter.

The blue curve is the standard cosmology $\Lambda$CDM (CDM cold dark matter) fit to matter power spectrum data. The red jagged curve is the MOG fit after a window function has smoothed out the unit oscillations with no collisionless dark matter particles.

2/4/2013
7. DOES DARK ENERGY EXIST?


The void model says that there is a huge void embedded in an Einstein de-Sitter universe. Such voids have been observed since the 80s. They have large walls of galaxies surrounding them. We may be situated near the center of the void avoiding any deviation from isotropy. The CMB observed ~ 400,000 years after t=0 is isotropic with a uniform temperature at 2.7 degrees Kelvin.

The void expands faster than the surrounding over-dense environment, causing light from distant supernovae and galaxies to appear dimmer. The expansion of the void and the outside universe are decelerating not accelerating. Dark energy does not exist in this model! Einstein’s cosmological constant $\Lambda=0$. 
8. MODIFICATION OF STELLAR COLLAPSE AND BLACK HOLES

- We anticipate that MOG will modify how stars collapse and the nature of black holes.

- An exact numerical solution in MOG yields a collapsed object with a singularity at \( r=0 \), which cannot be reached by a test particle, because of an infinitely repulsive force. Two event horizons are formed for the collapsed star.

- We know that a supermassive object with mass \( \sim 3 \times 10^6 M_{\odot} \) is at the center of our Galaxy (MILKY WAY). We are not able to determine yet whether the object is a GR black hole with a horizon. Perhaps future telescopes and space missions will be able to get close enough to the supermassive object to tell whether it is a black hole in spacetime or some other kind of object. However, as distant observers, we can never see a black hole event horizon form! The formation of the event horizon occurs in the infinite future, so we cannot actually ever see a black hole event horizon form as a star collapses.