REINVENTING GRAVITY: Living Without Dark Matter

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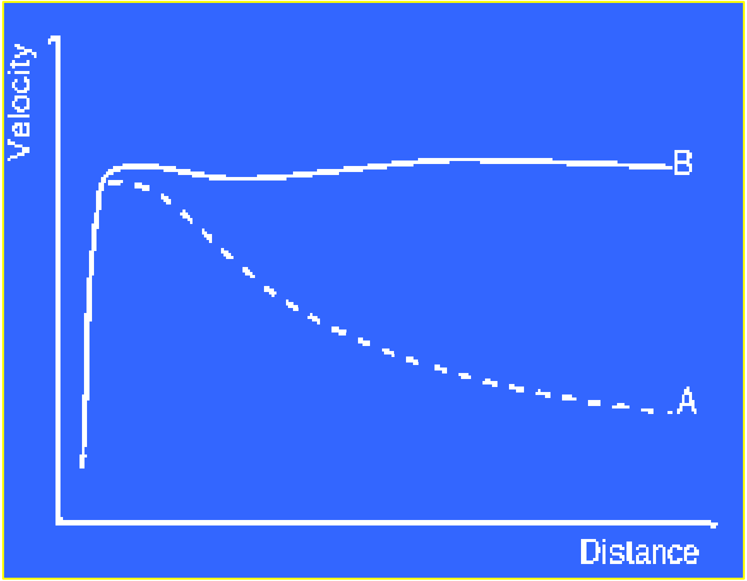
1. Introduction

- In 1916, Einstein published his new theory of gravity called General Relativity. It generalized his Special Theory of Relativity which did not include gravity. In 1919, the theory was validated by the observation of the bending of light during a solar eclipse, as the sun's gravitational pull warped spacetime. Would we want to modify Einstein's outstanding intellectual achievement?

- Most physicists have considered Einstein's General Relativity theory to be in perfect agreement with observational data. However, this is not necessarily true.

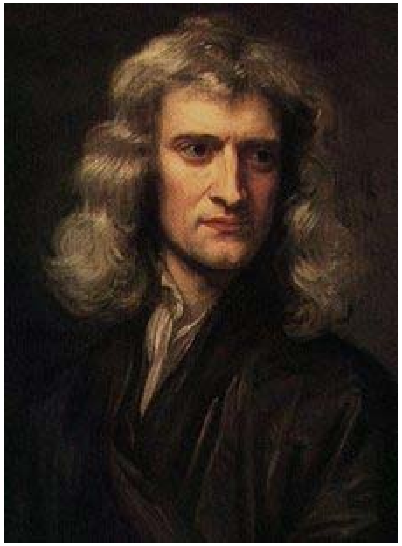
- To explain extensive data in astrophysics, astronomy and cosmology and retain Einstein's and Newton's gravity, we need to postulate large amounts of "Dark Matter" and "Dark Energy" that are invisible and not detected experimentally.

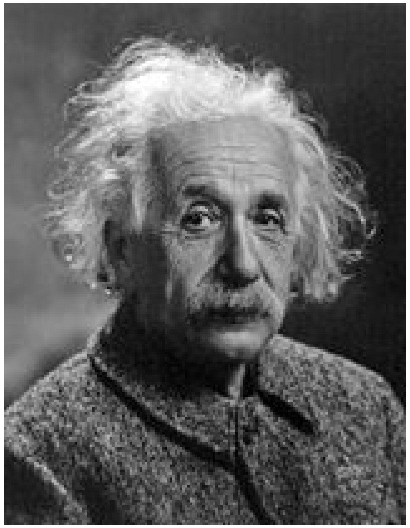
• Since the early 1980s, a growing amount of observational data has been accumulating that shows that Newtonian and Einstein gravity cannot describe the motion of the outermost stars and gas in galaxies correctly, if only their visible mass is accounted for in the gravitational field equations.



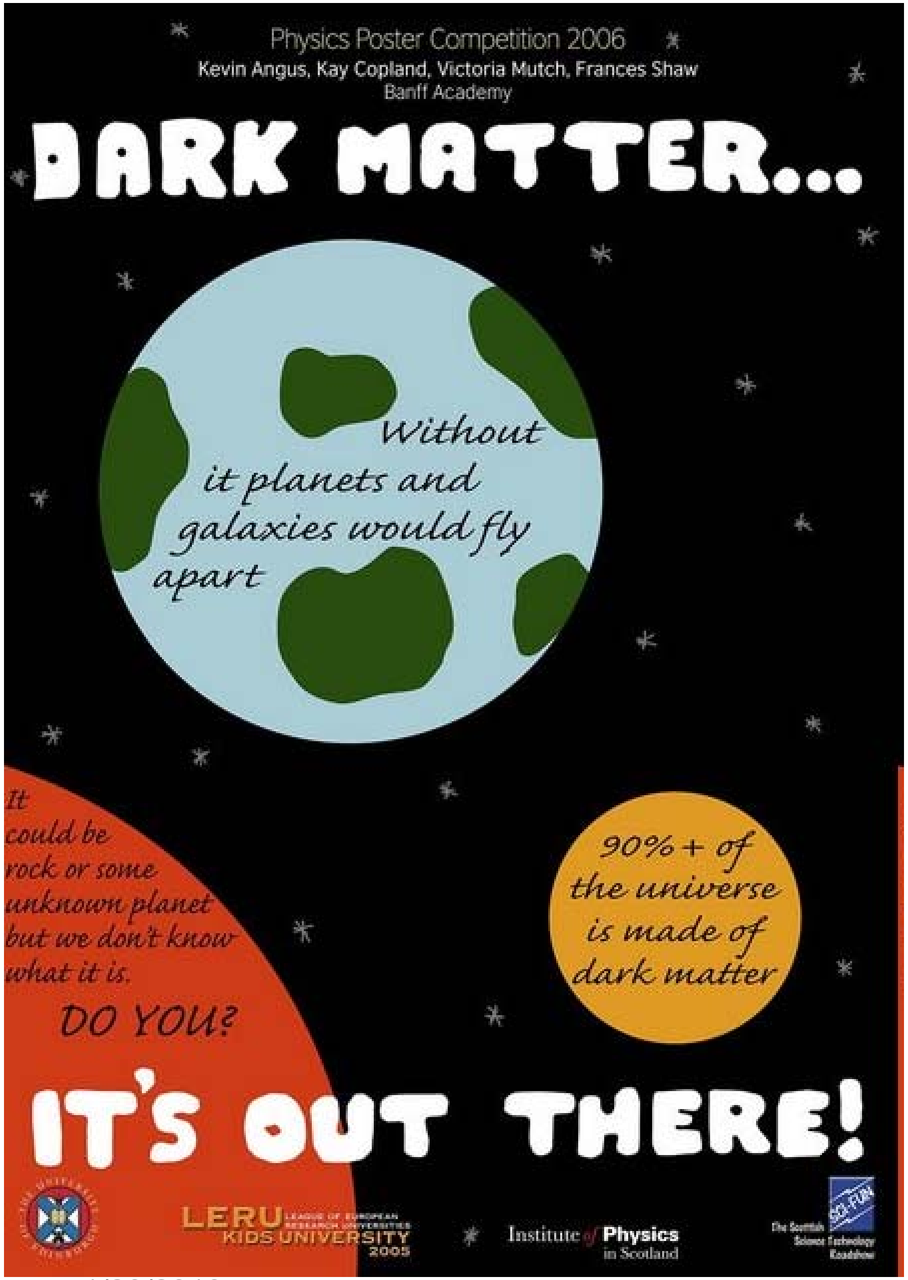
• To save Einstein’s and Newton’s theories, many physicists and astronomers have postulated that there must exist a large amount of “dark matter” in galaxies and also clusters of galaxies that could strengthen the pull of gravity and lead to an agreement of the theories with the data.

• 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.

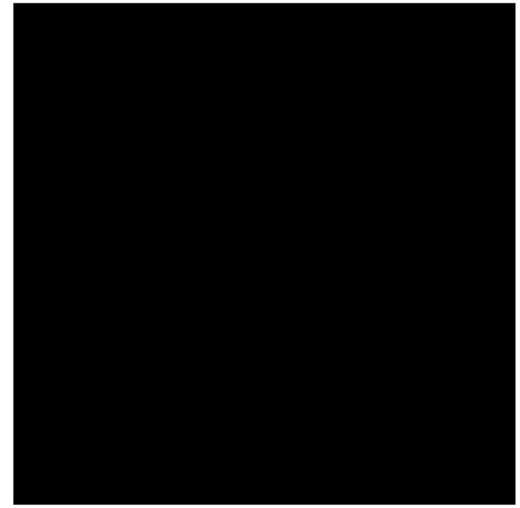


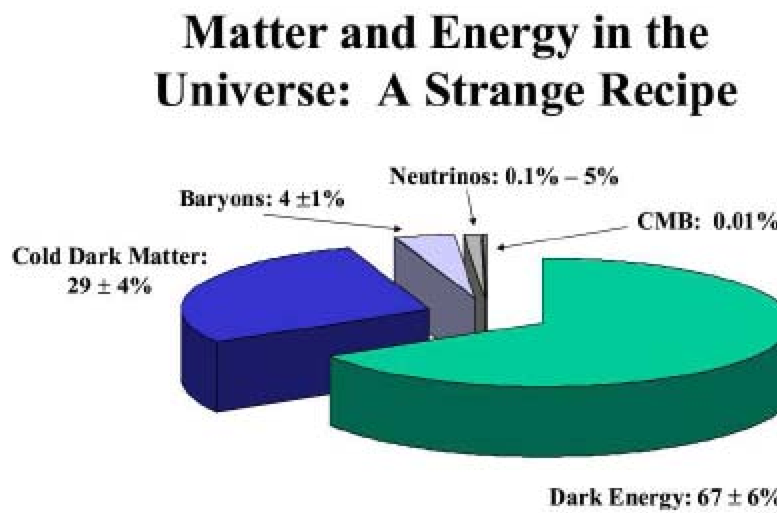


Dark matter



Physics Poster Competition 2006
Kevin Angus, Kay Copland, Victoria Mutch, Frances Shaw
Banff Academy
DARK MATTER...
Without it planets and galaxies would fly apart
It could be rock or some unknown planet but we don't know what it is.
DO YOU?
90% + of the universe is made of dark matter
IT'S OUT THERE!
LERU LEAGUE OF EUROPEAN RESEARCH UNIVERSITIES KIDS UNIVERSITY 2005
Institute of Physics in Scotland
SCI-FUN
The Scottish Science Technology Roadshow





Matter and Energy in the Universe: A Strange Recipe
Neutrinos: 0.1% – 5%
Baryons: 4 ±1%
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

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

- Preferred model of dark matter is WIMPS (weakly interacting massive particles)

- If dark matter is not detected and does not exist, then Einstein’s and Newton’s gravity must be modified.

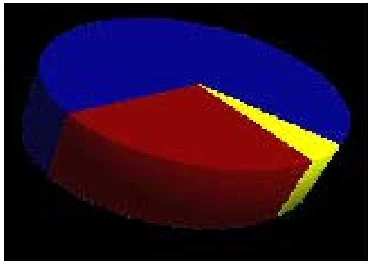
- Can this be done successfully?

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

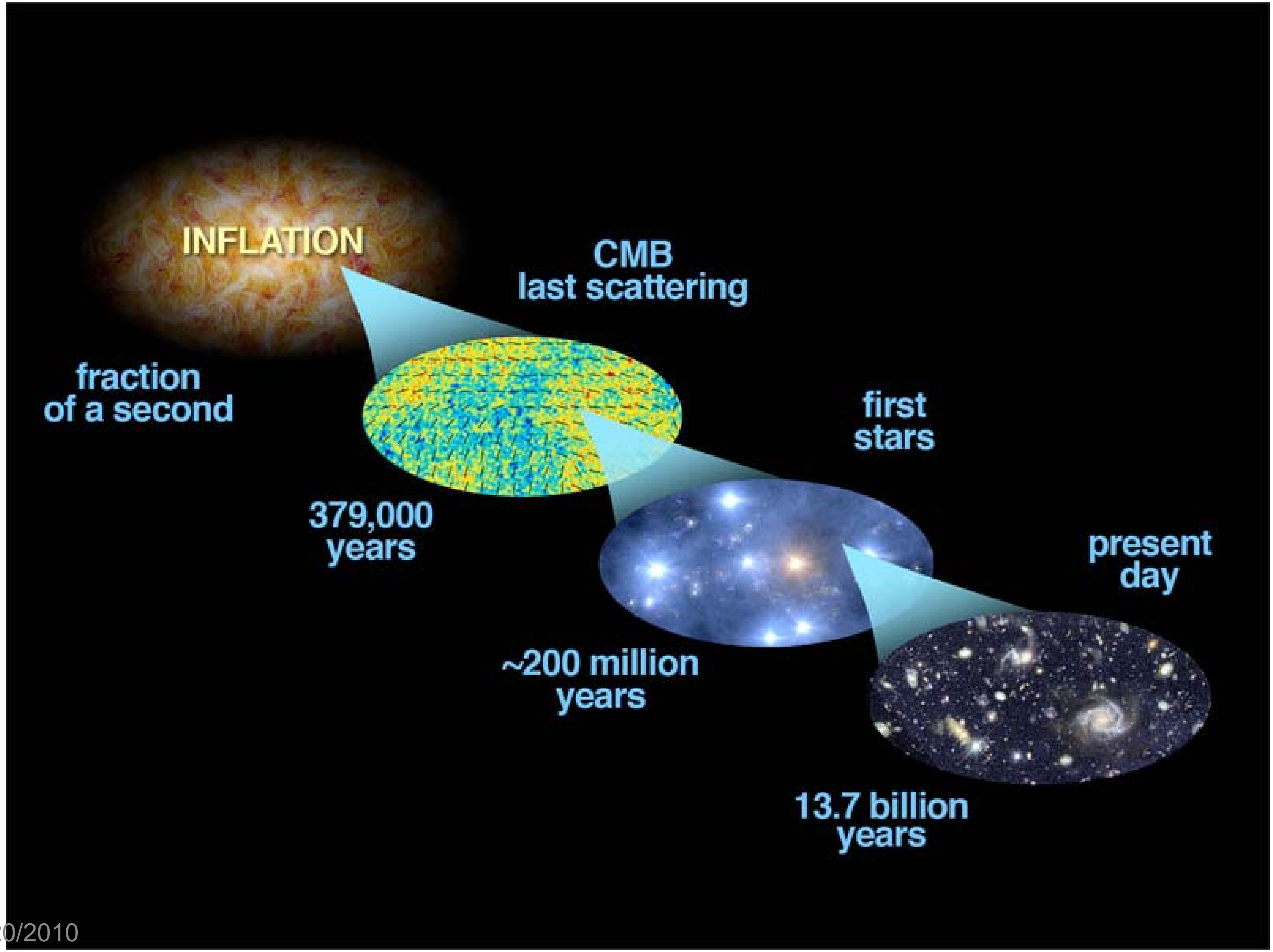
2. Cosmology

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 ~ 2.73 degrees
- Scale-free adiabatic fluctuations $\Delta T/T \sim 10^{-}$



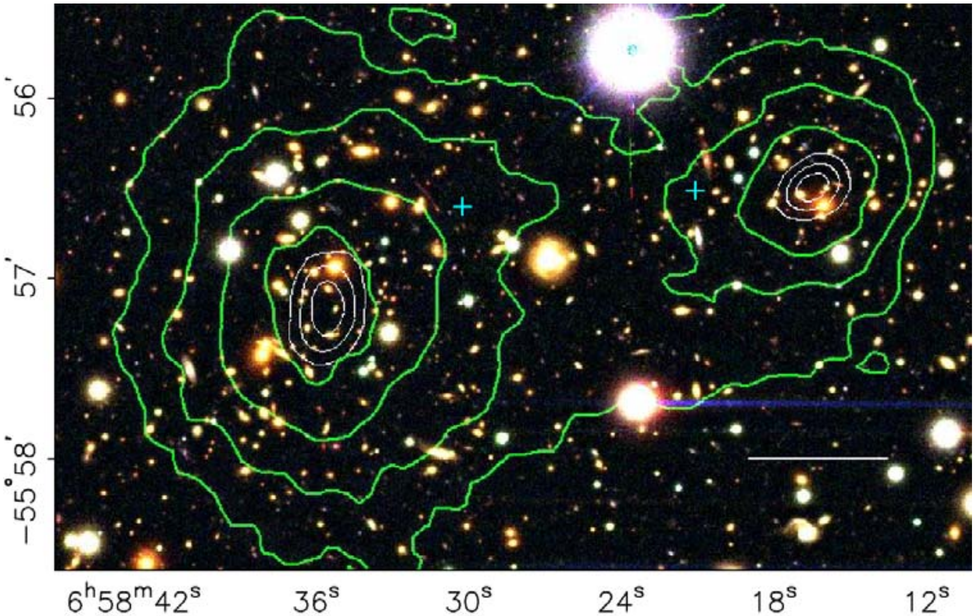
Evolution of the universe in standard cosmology model.

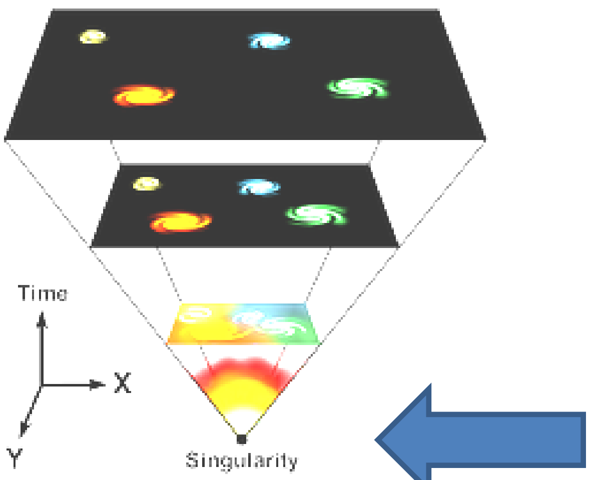


• The dark matter and dark energy are the most puzzling parts of the standard cosmology.

Dark matter is cold and collisionless, ~ 25 %

Dark energy ~ 70 % is smooth and appears about 9 billion years after the Big Bang (supernovae measurements)





Inflation or Variable Speed of Light (VSL)?

3. Dark Matter and Modified Gravity (MOG)

- Dark matter and dark energy are 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. Is this possible? Yes.

- The Equivalence Principle implies a metric and GR is determined uniquely in a 4-dimensional spacetime. To modify GR we either change the Einstein-Hilbert action, pseudo-Riemannian geometry or add new fields.

- The new fields may be dynamically sourced by ordinary matter (baryonic matter) – "modified gravity" (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 self-consistent, stable 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” (φ_μ) field whose curl is a skew field that couples to matter (“fifth force”). The gravitational field is described by a symmetric Einstein metric tensor. The fifth force charge is proportional to mass $Q_5 = \kappa M$.

- The effective classical theory allows the gravitational coupling “constant” G to vary as a scalar field with space and time.

- The modified Newtonian acceleration law for weak fields can fit a large amount of galaxy rotation curve data without non-baryonic dark matter. It also can fit data for X-ray galaxy clusters without dark matter. The modified acceleration law is consistent with the solar system data (J. R. Brownstein and JWM, 2006; JWM & V. T. Toth, 2007, 2008; J. R. Brownstein, 2008).
- The MOG must also explain the following:
- The CMB data including the power spectrum data;
- The formation of proto-galaxies in the early universe and the growth of galaxies;
- Gravitational lensing data for galaxies and clusters of galaxies;
- The Bullet Cluster 1E0-657-56 and the merging clusters Abell 520 and MACS J0025.4 – 1222;
- N-body simulations of galaxy surveys;
- The accelerating expansion of the universe.

4. Modified Gravity (MOG)

The Scalar-Tensor-Vector-Gravity (STVG) action takes the form:

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

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

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

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

- In addition to the metric $g_{\mu\nu}(x)$, we have a massive vector field $\varphi_\mu(x)$, and 3 scalar fields $G(x)$, $\omega(x)$ and $\mu(x)$. $B_{\mu\nu} = \partial_\mu\varphi_\nu - \partial_\nu\varphi_\mu$ and $V_\varphi(\varphi)$, $V_G(G)$, $V_\omega(\omega)$ and $V_\mu(\mu)$ denote self-interaction potentials.

- Einstein’s gravitational field equations:

Curvature of spacetime | Matter

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu}$$

- MOG gravitational field equations:

Curvature of spacetime | New gravity fields | Matter

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + (\text{vector field } \phi_\mu, \text{varying G}) = 8\pi G_N T_{\mu\nu}$$

Fitting Galaxy Rotation Curves and Clusters

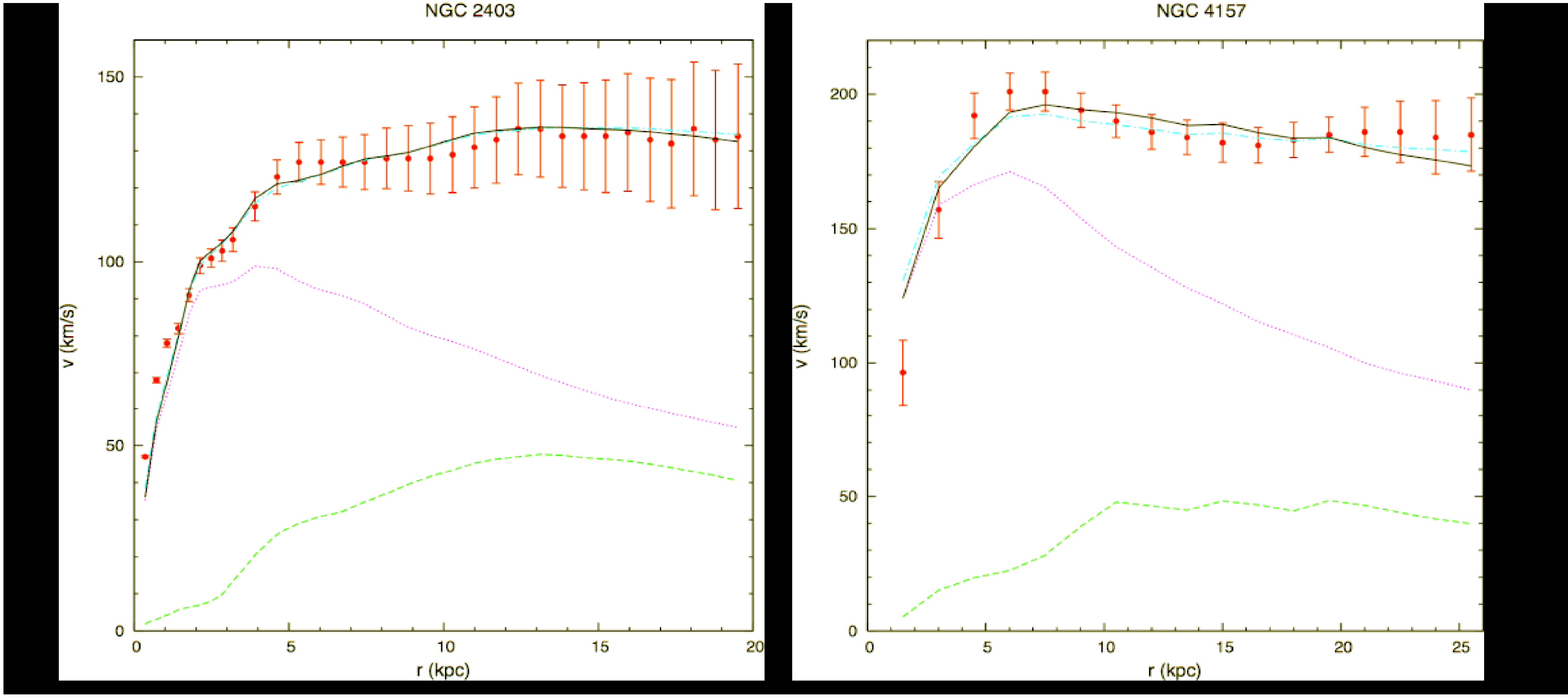
- A fitting routine has been applied to fit a large number of galaxy rotation curves (101 galaxies), using photometric data (58 galaxies) and a core model (43 galaxies) (J. R. Brownstein and JWM, 2005). The fits to the data are remarkably good and for the photometric data only one parameter, the mass-to-light ratio M/L, is used for the fitting once two parameters α and λ are universally fixed for galaxies and dwarf galaxies.

- 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).

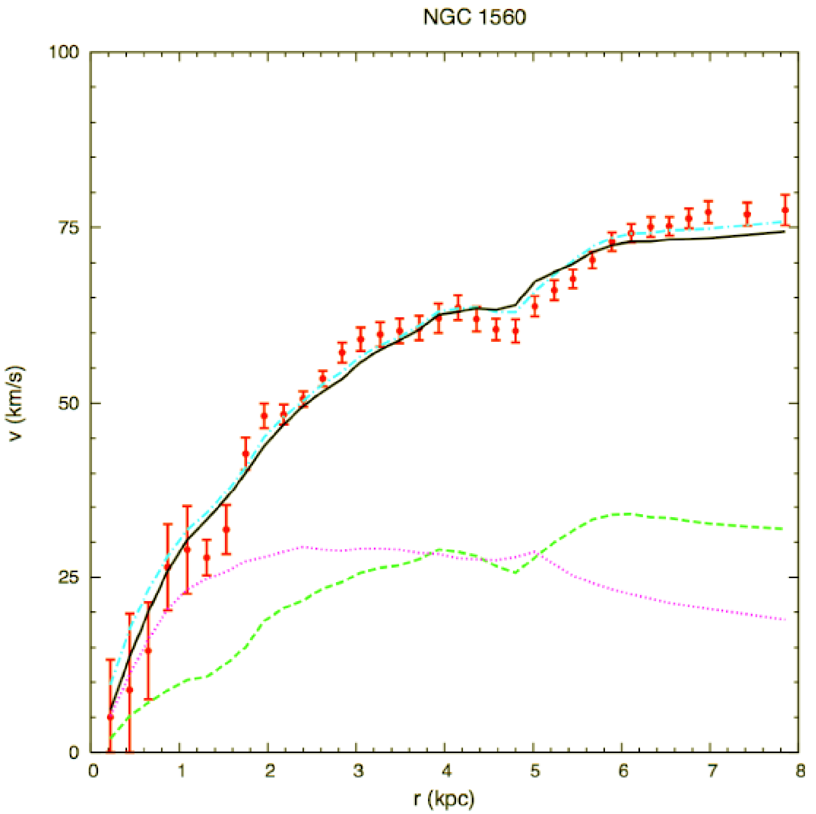
- The rotational velocity curves become the Kepler-Newtonian curves at large distances from the galaxies (satellites).

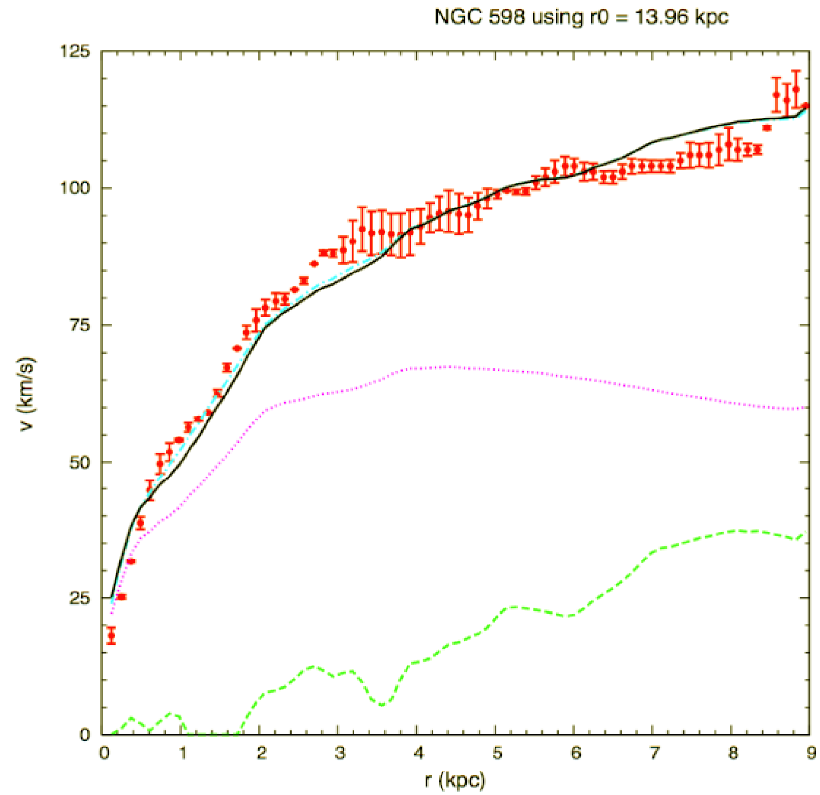
- The Tully-Fisher law is satisfied by MOG: $v_c^2 \propto \frac{M}{\sqrt{M}} = \sqrt{M}.$

- For every feature in the surface brightness distribution, MOG produces a corresponding feature in the predicted rotation curve (matching the observed rotation curve).

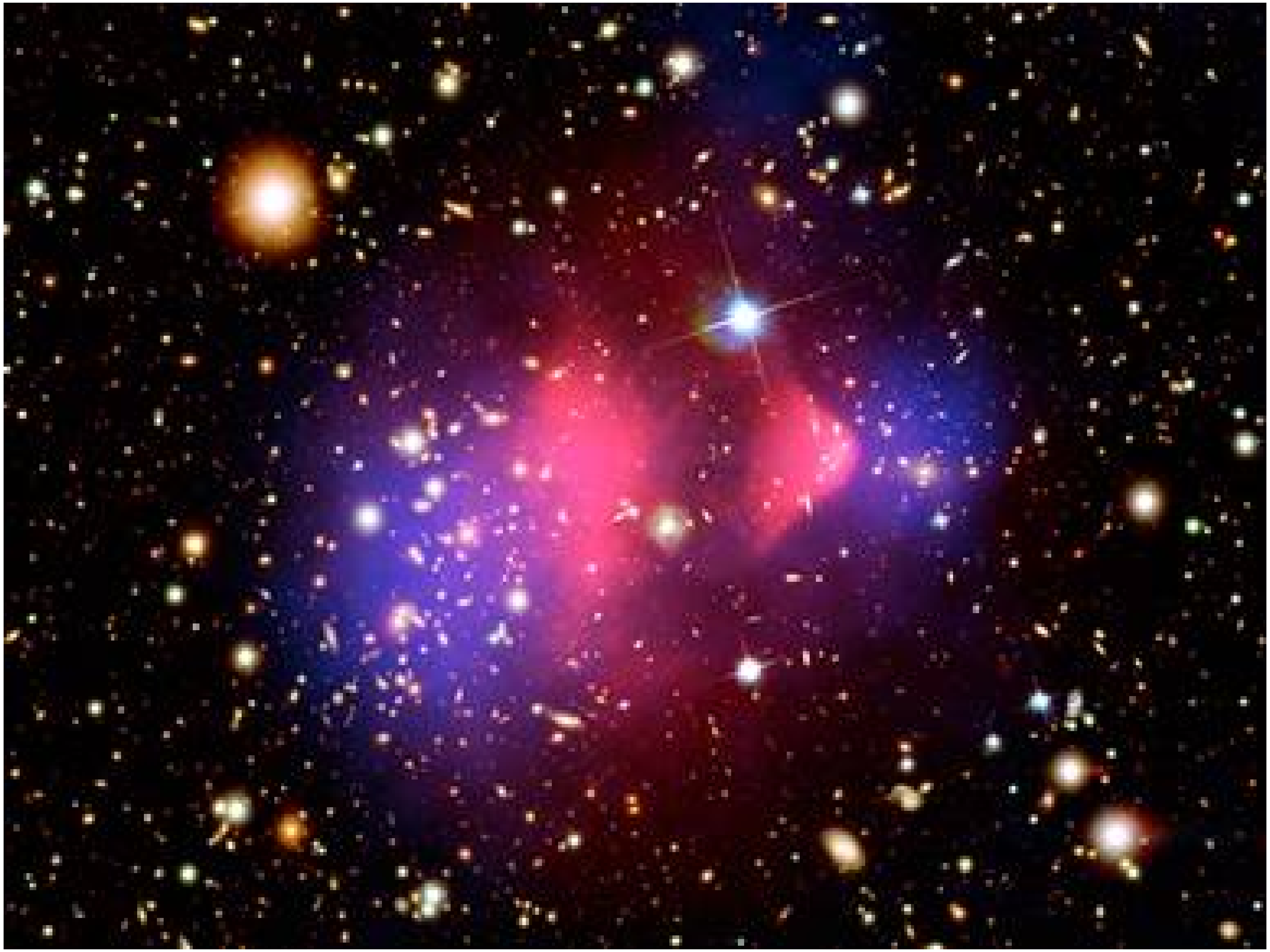


Photometric fits to galaxy rotation curves. There are 4 benchmark galaxies presented here; each is a best fit via the single parameter $(M/L)_{stars}$ based on the photometric data of the gaseous (HI plus He) and luminous stellar disks. The radial coordinate (horizontal axis) is given in kpc and the 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.

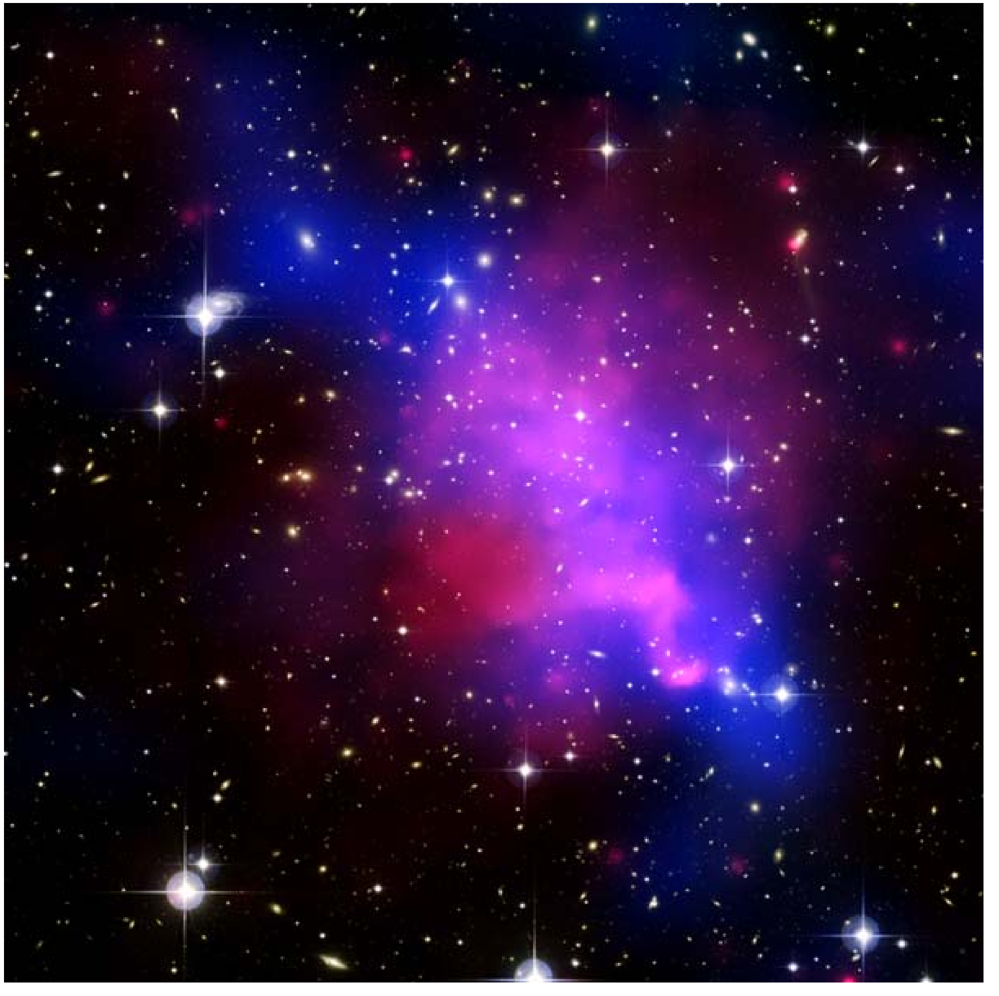

NGC 1560
v (km/s)
r (kpc)
0
25
50
75
100
0
1
2
3
4
5
6
7
8


NGC 598 using r0 = 13.96 kpc
v (km/s)
r (kpc)
0
25
50
75
100
125
0
1
2
3
4
5
6
7
8
9

Merging clusters: “Bullet Cluster” 1E 0657-56. D. Clowe et al. Astrophys. J. Lett. 648, L109 (2006). J. R. Brownstein and J. W. Moffat, Mon.Not.Roy.Astron.Soc.382:29-47, 2007.

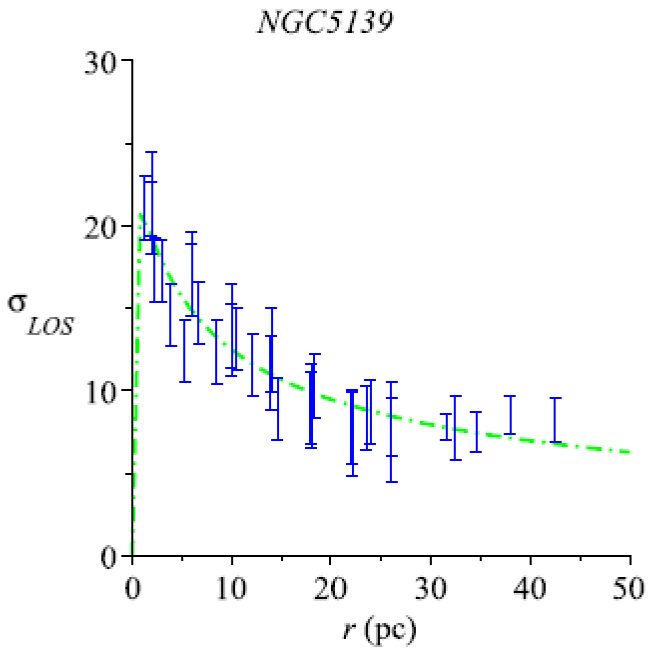


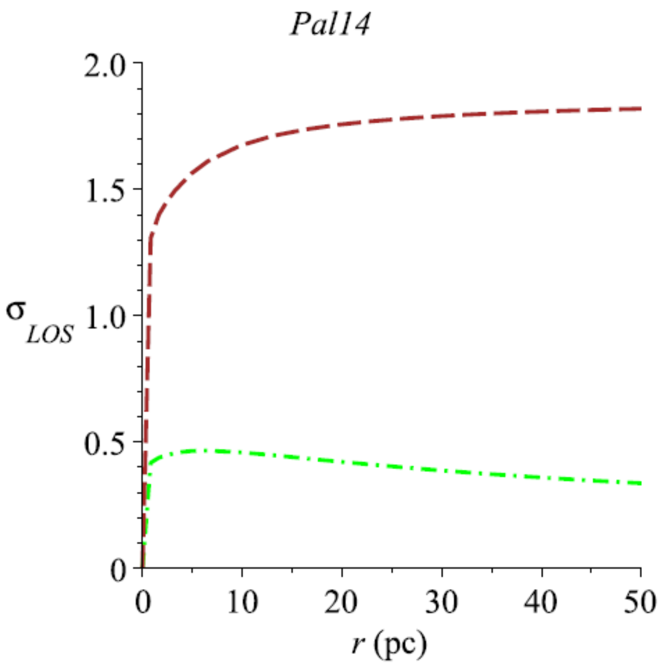
Merging clusters: Abell 520. “Cosmic train wreck”. It does not show separation of dark matter! Constellation of Orion about 2.4 billion light years away. “A dark matter core was found, which also contained hot gas but no bright galaxies. “ Hendrick Hoekstra . A. Mahdavi et al. Astrophys. J. 668, 806 (2007).



GLOBULAR CLUSTERS AS ASTRONOMICAL TEST OF MOG

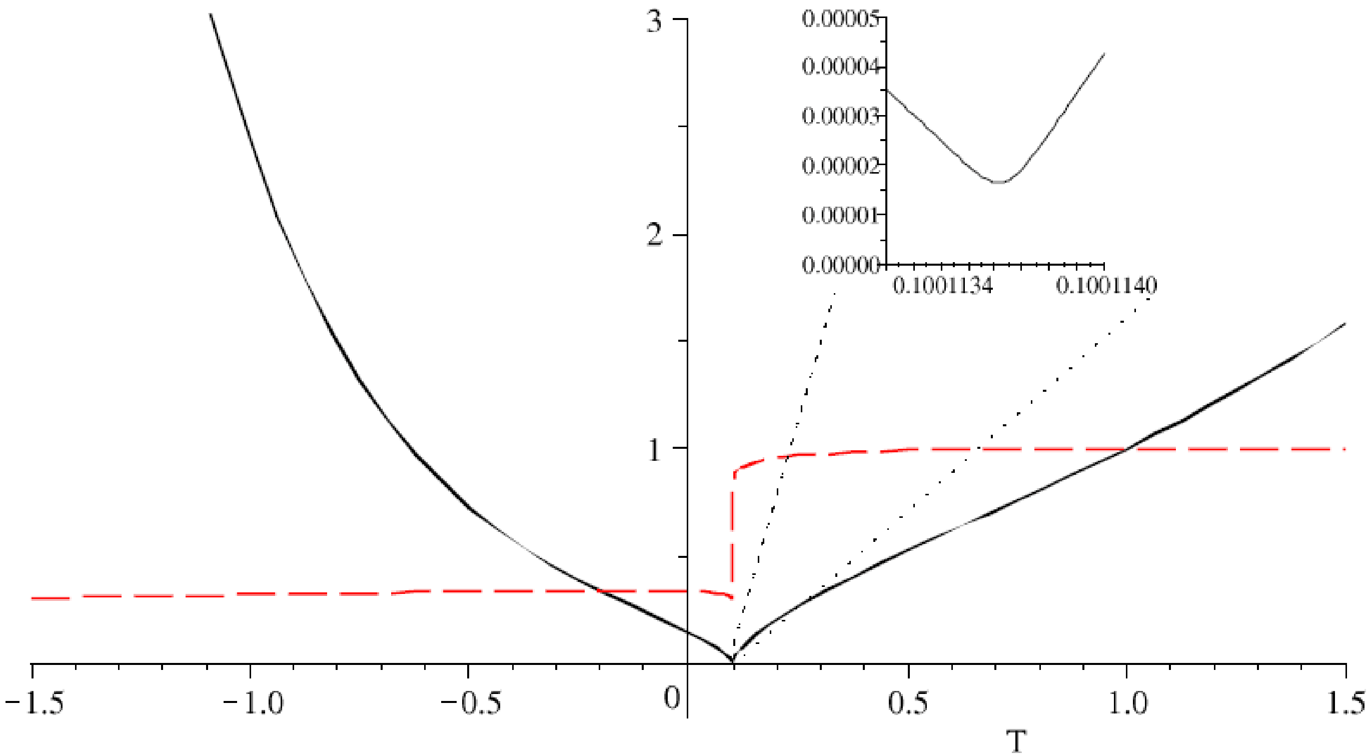
• Globular clusters near the edge of our MILKY WAY galaxy are an excellent astronomical testing laboratory for MOG. (JWM and V. T. Toth, The Astrophysical Journal, 680:1158-1161, 2008 June 20.)





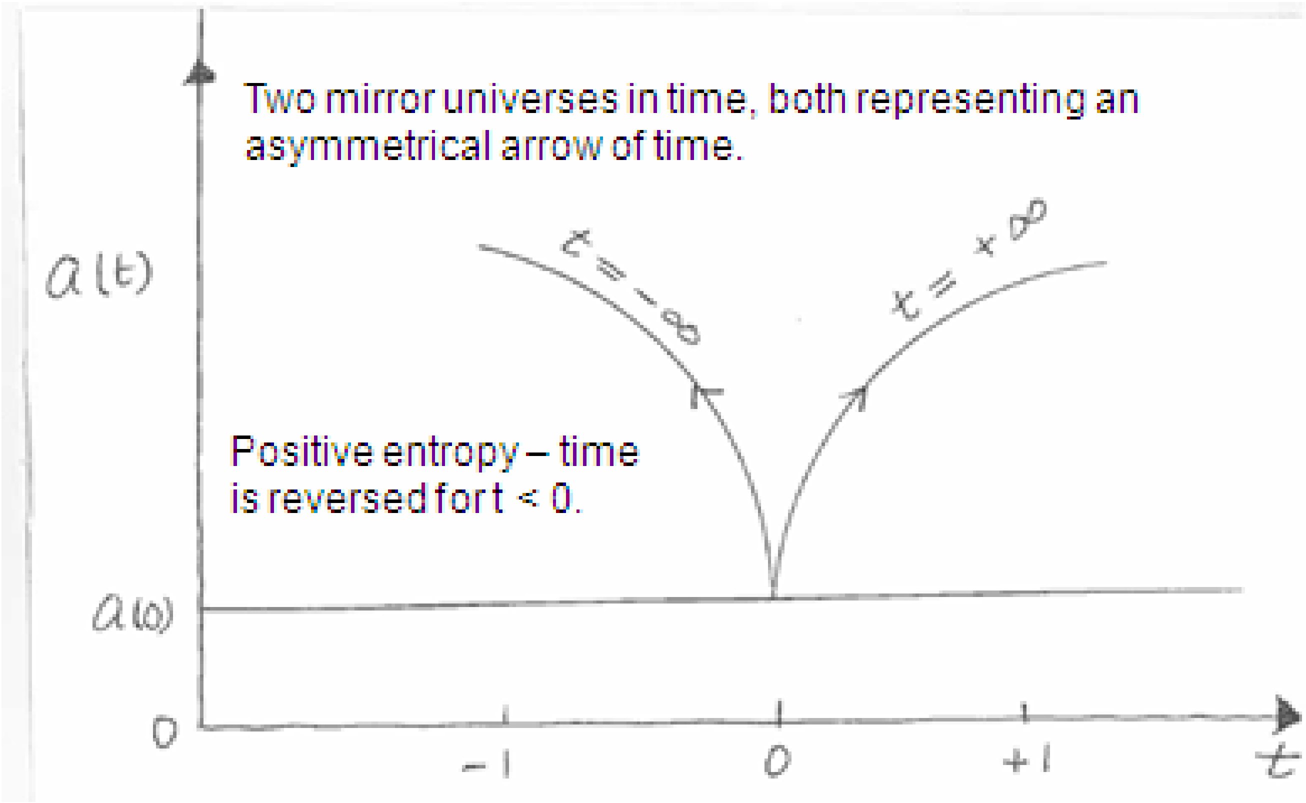
5. MOG COSMOLOGY

• The MOG cosmology equations possess an exact numerical solution, given initial conditions.



The MOG "bouncing" cosmology. The horizontal axis represents time, measured in Hubble units of H_0^{-1}. The solid (black) line is a/a_0, the scale factor normalized to the present epoch. The dashed (red) line is G/G_0. The inset shows details of the bounce, demonstrating that a smooth bounce occurs even as the matter density of the universe is more than 10^{14} times its present value.

Evolution of Endless Universe – no Big-Bang singularity at t=0!



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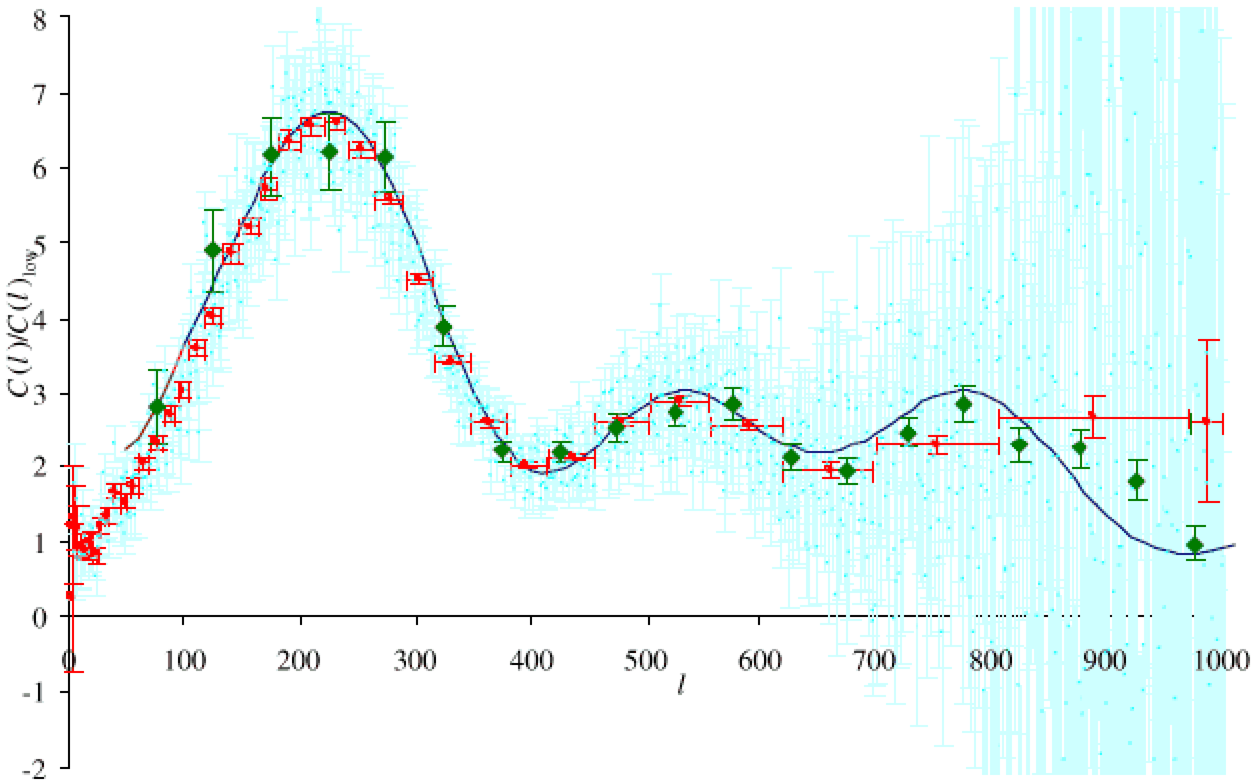
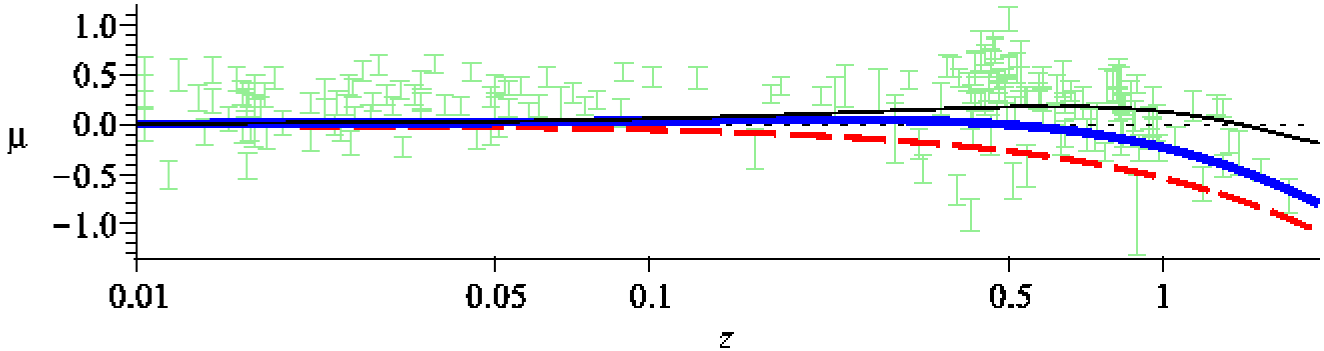
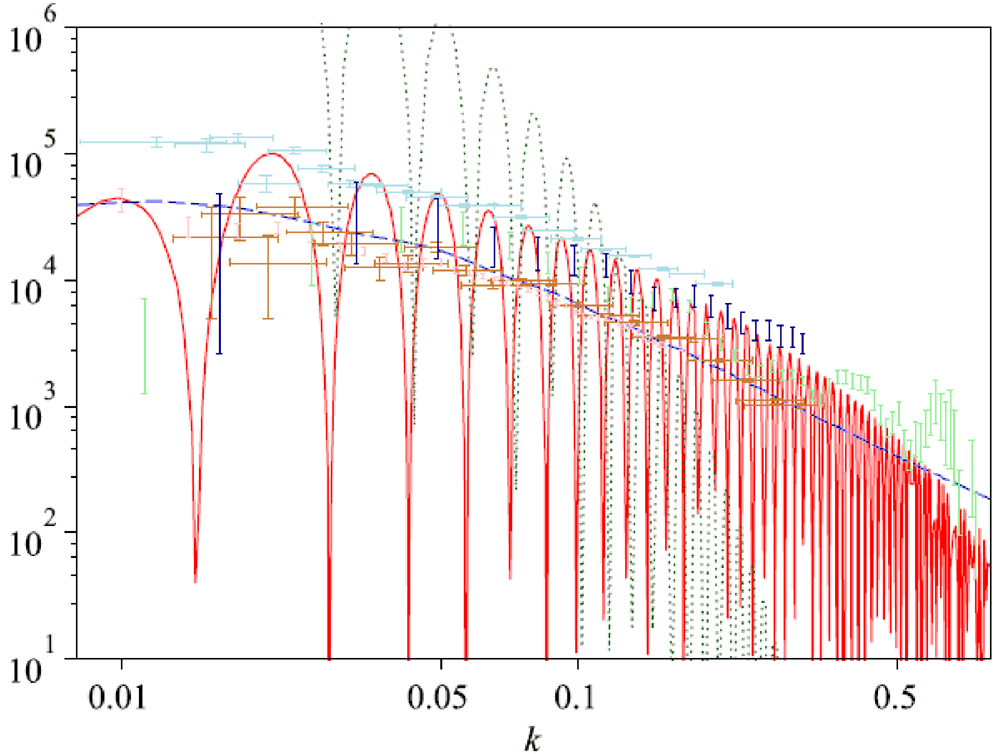


MOG and the acoustic power spectrum. Calculated using $\Omega_M = 0.3$, Ω_b=0.035, $H_0 = 71$ km/s/Mpc. Also shown are the raw WMAP 3-year data set (light blue), binned averages with horizontal and vertical error bars provided by the WMAP project (red), and data from the Boomerang experiment (green).



Type Ia supernova luminosity-redshift data and the MOG/ΛCDM predictions. No astrophysical dimming was applied. 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.

MOG Verifiable Predictions



The matter power spectrum. Three models are compared against five data sets (see text): ΛCDM (dashed blue line, $\Omega_b = 0.035$, $\Omega_c = 0.245$, $\Omega_\Lambda = 0.72$, $\mathrm{H} = 71$ km/s/Mpc), a baryon-only model (dotted green line, $\Omega_b = 0.035$, $\mathrm{H} = 71$ km/s/Mpc), and MOG (solid red line, $\alpha = 19$, $\mu = 5h$ Mpc^{-1}, $\Omega_b = 0.035$, $\mathrm{H} = 71$ km/s/Mpc.) Data points are colored light blue (SDSS 2006), gold (SDSS 2004), pink (2dF), light green (UKST), and dark blue (CfA).

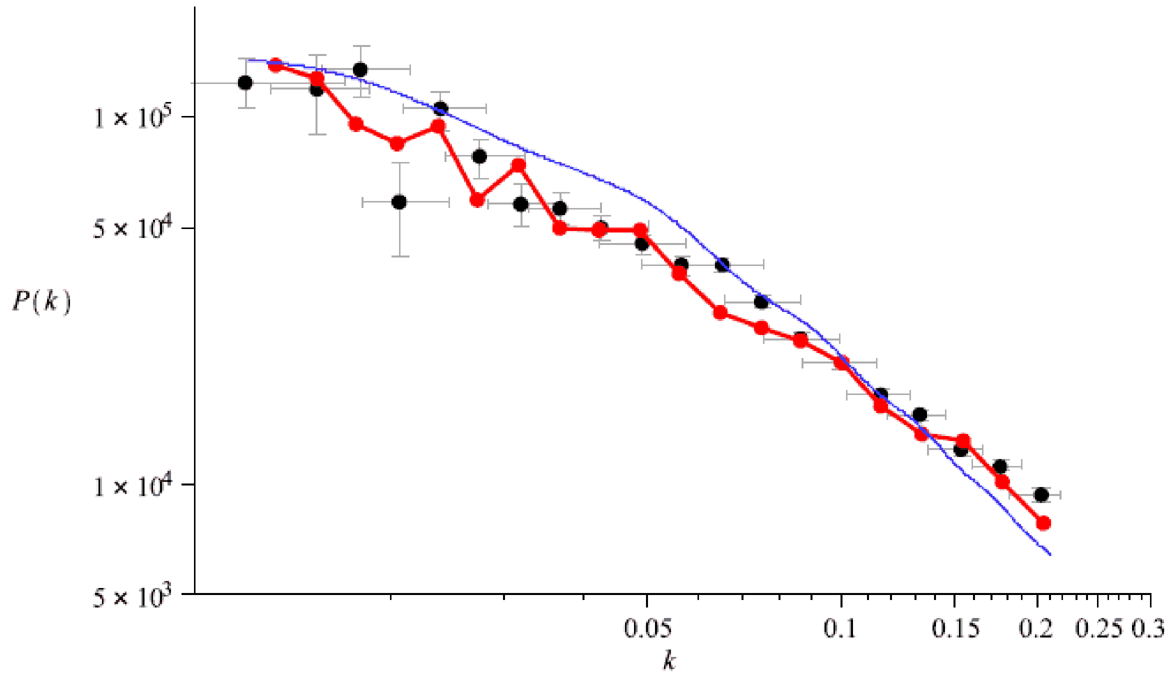
$$T(k) = \frac{\Omega_b}{\Omega_m} T_b(k) + \frac{\Omega_c}{\Omega_m} T_c(k),$$

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

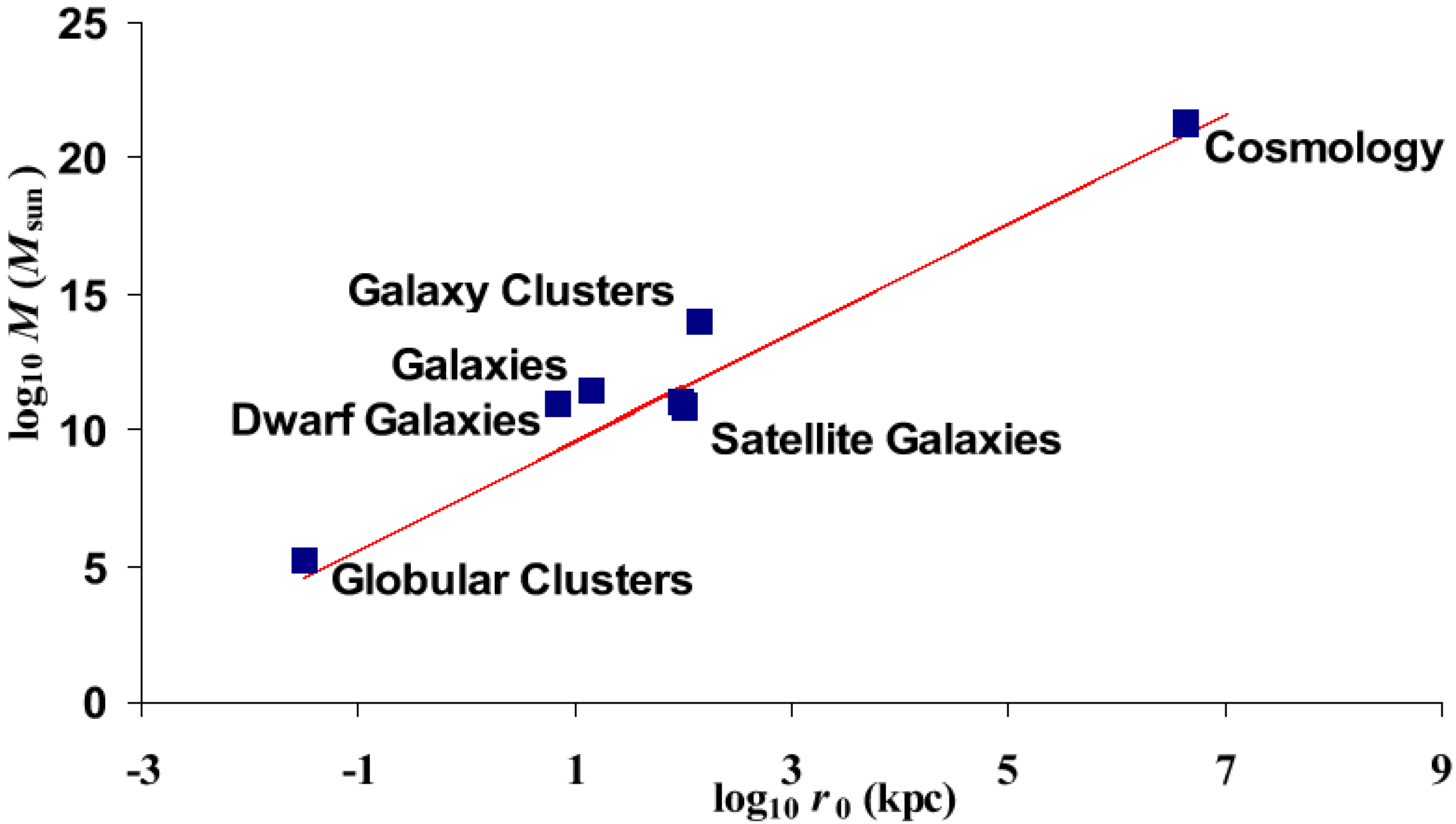
$$\ddot{\delta}_{\mathbf{k}} + 2H\dot{\delta}_{\mathbf{k}} + \left(\frac{c_s^2 k^2}{a^2} - 4\pi G_{\mathrm{eff}}\rho\right)\delta_{\mathbf{k}} = 0,$$

$$G_{\mathrm{eff}} = G_N \left\{1 + \alpha\left[1 - \left(1 + \frac{\mu a}{k}\right) e^{-\mu a/k}\right]\right\}.$$

• Verifiable prediction of matter power spectrum that distinguishes cold dark matter from MOG without exotic dark matter.



The effect of window functions on the power spectrum is demonstrated by applying the SDSS luminous red galaxy survey window functions to the MOG prediction. Baryonic oscillations are greatly dampened in the resulting curve (solid red line), yielding excellent agreement with the data after normalization. A normalized linear ΛCDM estimate is also shown (thin blue line) for comparison.

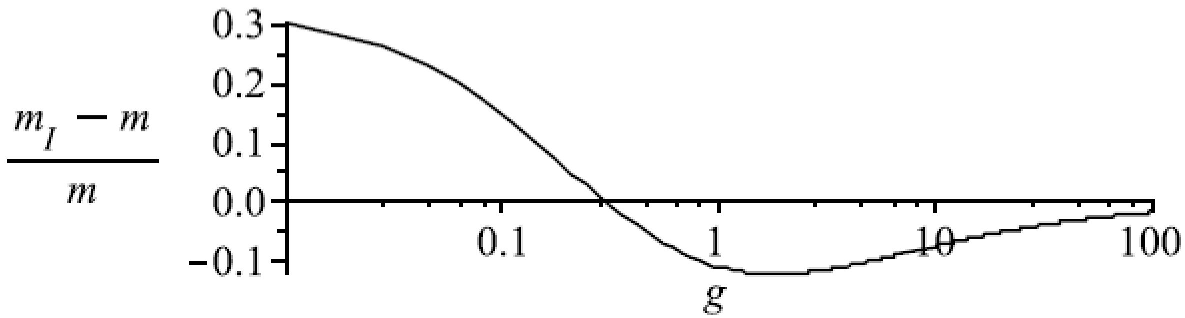


The relationship $\mu^2 M = \text{const.}$ between mass M and the Yukawa-parameter $r_0 = \mu^{-1}$ across many orders of magnitude remains valid. The solid red line represents our theoretical prediction.

6. ORIGIN OF INERTIA AND SPACE EXPERIMENT TEST OF MOG (LISA PATHFINDER SPACE PROBE)

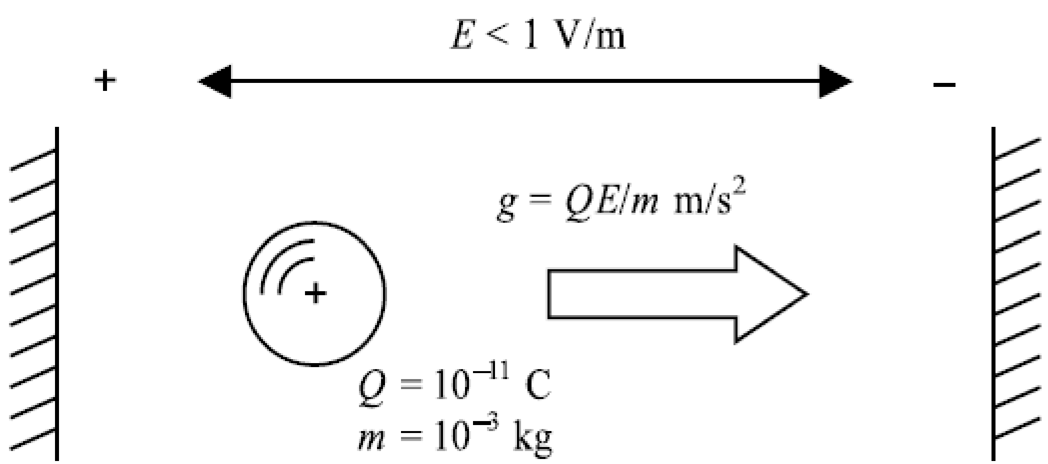
- MOG does not satisfy Birkhoff's theorem. It can realize Mach's principle and explain the origin of inertia (JWM & V. T. Toth, 2009 (Mon. Not. Roy. Astr. Soc. 395 (2009) L25). The inertial force arises as the influence of distant matter in the universe.

$$F = mg \qquad F_I = F(g),$$
$$F(g) \sim -mg, \qquad F_I + F(g) = 0.$$



Does MOG violate the weak equivalence principle for very small accelerations? The horizontal axis in this plot is acceleration, measured in units of the "cosmic acceleration" $cH_0 \sim 7 \times 10^{-10}$ m/s^2. The vertical axis shows the predicted difference between inertial mass $m_I = -F(g)/g$ and passive gravitational mass m.

• Observational test in space of violation of equivalence principle at very small accelerations:



Schematic of a simple experiment that can be used to verify the validity of the force law $F = mg$ for very small accelerations. With the values presented here, a measurement of a deflection of ~1.8 mm over the course of ten minutes with an accuracy better than 10% is required, in order to measure the deficit in inertial mass. A smaller acceleration (corresponding to $E \sim 0.01$ V/m) could be used to measure an excess in inertial mass of up to ~30%.

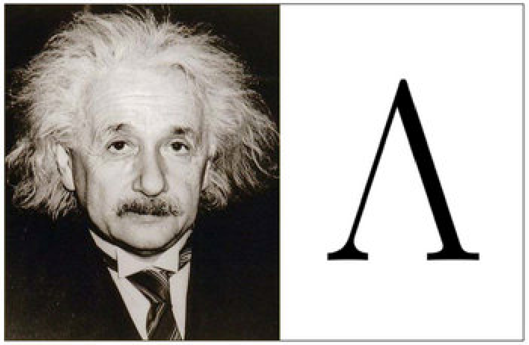
7. DOES DARK ENERGY EXIST?

• The dark energy problem has currently many possible explanations. However, two models proposed are: 1) The "void" model 2) The standard LambdaCDM cosmology.

• 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 overdense 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 and Λ=0.

• Both the void and the ΛCDM models violate the cosmological Copernican Principle!



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. There may or may not be an event horizon for the collapsed star.

- We know that a supermassive object with mass 3 X 10^6 M_{SUN} is at the center of our MILKY WAY galaxy. 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.

9. Conclusions

• A stable and self-consistent modified gravity (MOG) is constructed from a pseudo-Riemannian geometry and a massive skew field obtained from the curl of a massive vector field (phion field) (STVG). The static spherically symmetric solution of the field equations yields a modified Newtonian acceleration law with a distance scale dependence. The gravitational "constant" G, the effective mass and the coupling strength of the skew field run with distance scale r.

• A fit to ~ 100 galaxy rotations curves is obtained and mass profiles of X-ray galaxy clusters are also successfully fitted for those clusters that are isothermal.

• A fit to the Bullet Cluster 1E0657-56 data can be achieved with the "running" of the gravitational "constant" G without non-baryonic dark matter. The lensing of galaxies and clusters can be explained without dark matter.

• The CMB power spectrum acoustical peaks data including the third peak can be fitted with the density parameters:

• The power spectrum for growth of fluctuations and the formation of galaxies and clusters can be incorporated in MOG without dark matter. The acceleration of the universe can be explained in MOG. The universe undergoes a bounce at $t \sim 0$ and the cosmology is singularity-free. The thermodynamic arrow of time is reversed for $t \to -\infty$ and the second law of thermodynamics is not violated as the universe expands away from the bounce towards $t = -\infty$ and $t = +\infty$.

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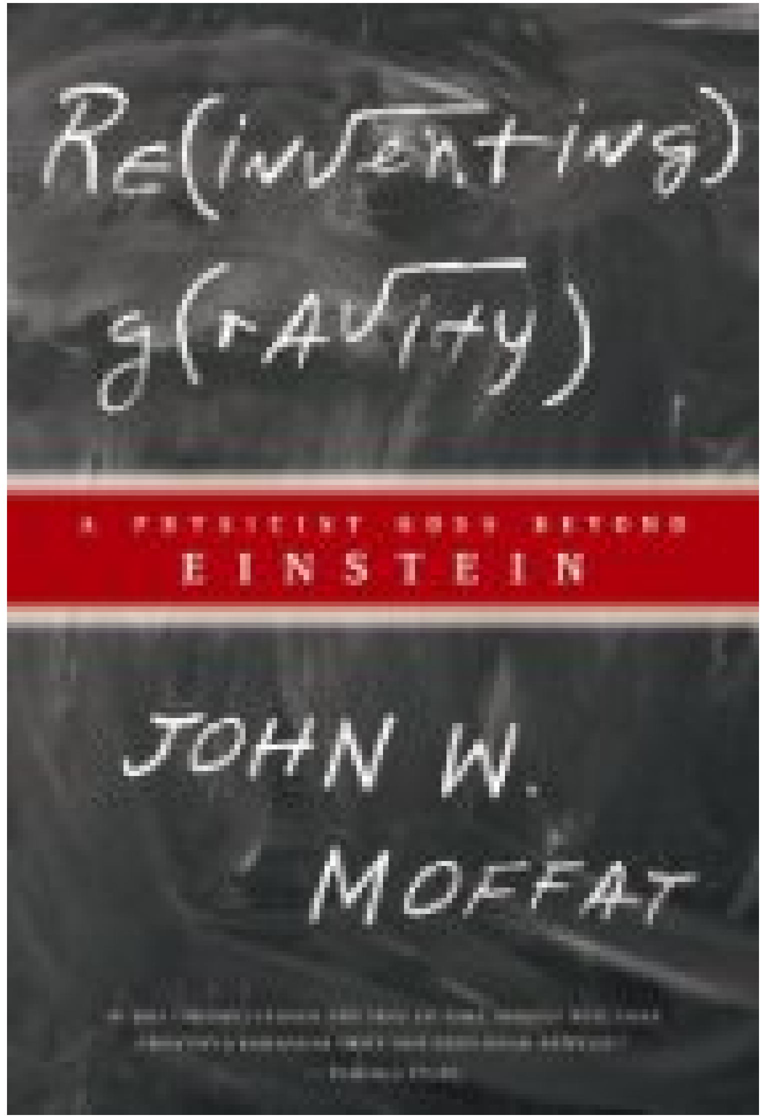

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