The Axioms of General Relativity And Scalar Field Dark Matter

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MSRI Summer Workshop
17 July 2012

Flat Rotation Curves

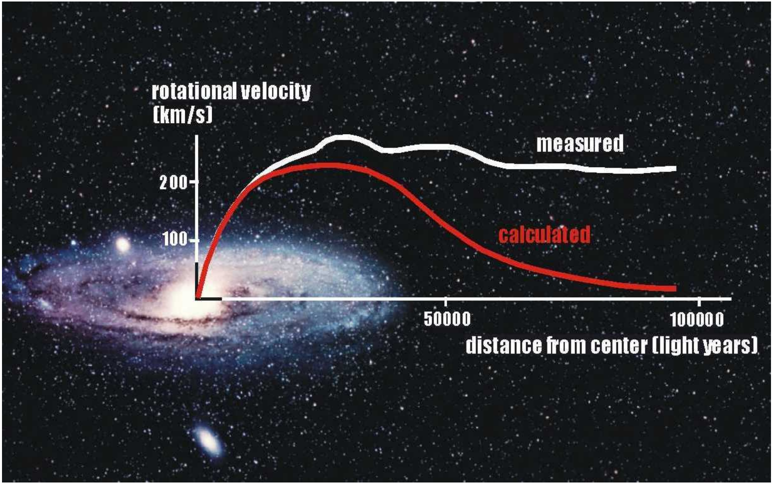

Photo Credit: Queens University

The Bullet Cluster

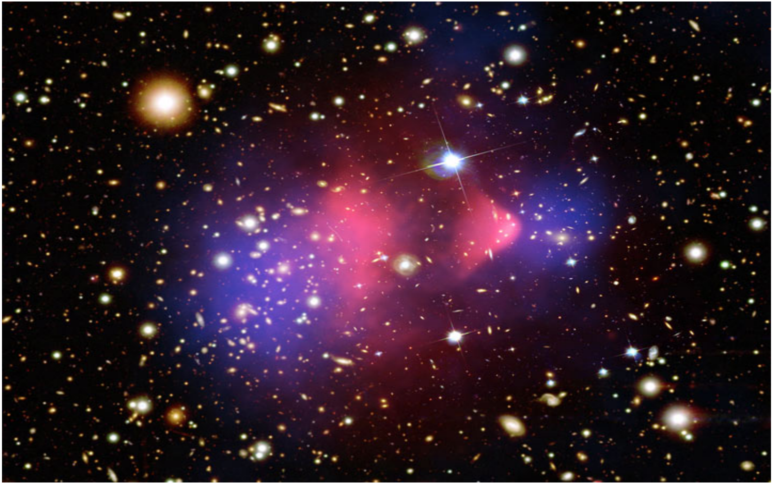

Photo Credit: Chandra X-ray Observatory

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- Dark Matter doesn't emit or reflect light.
- Dark Matter is collisionless.

Expansion of the Universe
Accelerating or Decelerating?

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$$\frac{\ddot{a}}{a} = -\frac{4}{3}\pi(\rho + 3P)$$

- A currently expanding dust dominated perfect fluid, like our current universe, would cause the expansion to decelerate asymptotically to 0.

Expansion of the Universe Accelerating or Decelerating?

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- A currently expanding dust dominated perfect fluid, like our current universe, would cause the expansion to decelerate asymptotically to 0.
- However, a recent Nobel Prize winning observation, by Perlmutter, Schmidt, and Riess, has shown that the expansion of the universe is actually accelerating.

Cosmological Constant

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- Under the same assumptions on the perfect fluid nature of the regular matter in the universe, the ODE's from before become

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8}{3}\pi\rho + \frac{\Lambda}{3}$$
$$\frac{\ddot{a}}{a} = \frac{\Lambda}{3} - \frac{4}{3}\pi(\rho + 3P)$$

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- The parameter Λ is small but strictly positive in this model.
- So after some rapid decelerating expansion when the energy density of the universe is high, eventually the $\rho + P$ term will become smaller than the Λ term and the expansion will accelerate forever thereafter.

Cosmological Constant

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$$\frac{\ddot{a}}{a} = \frac{\Lambda}{3} - \frac{4}{3}\pi(\rho + 3P)$$

- Since $\rho \to 0$ as the universe expands, the Hubble constant, $\frac{\dot{a}}{a}$ will continue to decrease asymptotically to $\left(\frac{\Lambda}{3}\right)^{1/2}$

Dark Energy

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- Then this fluid has positive energy density and *negative* pressure!

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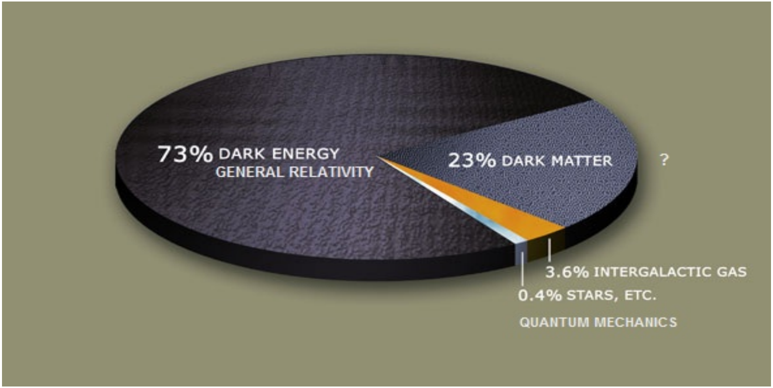
- The perfect fluid is called Dark Energy.
- To get a high enough energy density of Dark Energy to account for the current level of expansion and acceleration effects, Dark Energy must account for about 73% of the matter-energy in the universe.

Composition Of Matter In The Universe



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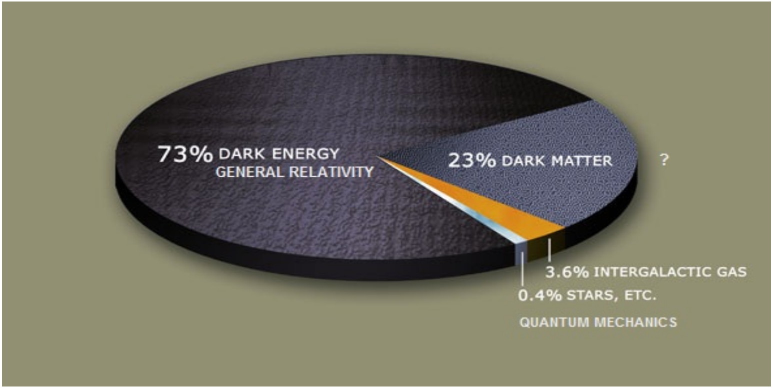

Is Dark Matter described by Quantum Mechanics or General Relativity?

On Spiral Galaxies, Dark Matter, and the Axioms of General Relativity

This presentation discusses some aspects of the paper by Hubert L. Bray entitled,

"On Spiral Galaxies, Dark Matter,
and the Axioms of General Relativity"[1]

[1] [arXiv:submit/0028100 [astro-ph.GA]], 2010

Common Actions

The Euler-Lagrange equations of the action given by $\mathcal{F}(g) = \int_M R\, dV$ are

$$G = \mathrm{Ric} - \frac{1}{2} R g = 0$$

That is, vacuum general relativity.

Common Actions

For the action $\mathcal{F}(g) = \int_M R - 2\Lambda \, dV$, they are

$$G + \Lambda g = 0$$

That is, vacuum general relativity with a cosmological constant.

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- $$G + \Lambda g = 0,$$
  modified Einstein equation, but still vacuum (i.e. there's no physical matter).
- $$G = -\Lambda g,$$
  the cosmological constant interpreted as a matter field in usual GR, specifically a perfect fluid with positive energy density, but negative pressure.

Common Actions

Formulating general relativity in this way provides a possible method to define a set of Axioms that motivate general relativity.

Axiom 0

- (N, g, ∇) is a spacetime manifold with Lorentzian (i.e. signature $(-+++)$) metric g and a connection ∇ (not necessarily the Levi-Civita connection).

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- N is a smooth manifold, which is Haussdorff and second countable.

Axiom 1 (Preliminaries)

In coordinates, let

$$g_{ij} = g(\partial_i, \partial_j)$$
$$\Gamma_{ijk} = g(\nabla_{\partial_i}\partial_j, \partial_k) = g_{\ell k}\Gamma_{ij}{}^{\ell}$$

and define

$$M = \{g_{ij}\} \qquad C = \{\Gamma_{ijk}\}$$
$$M' = \{g_{ij,k}\} \qquad C' = \{\Gamma_{ijk,\ell}\}$$

Axiom 1

For all coordinate charts $\Phi : \Omega \subset N \to \mathbb{R}^4$ and open sets U whose closure is compact and interior of Ω, (g, ∇) is a critical point of the functional

$$\mathcal{F}_{\Phi,U}(g, \nabla) = \int_{\Phi(U)} \text{Quad}_M(M' \cup M \cup C' \cup C) \, dV_{\mathbb{R}^4}$$

with respect to smooth variations of the metric and connection compactly supported in U, for some fixed quadratic functional Quad_M with coefficients in M.

Consistency with Current Theory

- In the appendix of Bray's paper, Bray shows that the action

$$\int_U R \, dV$$

can be written in any coordinate chart in the form

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- The boundary term vanishes since we only consider compactly supported variations in U.

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- In fact, it has been shown that, up to a constant, this is the only expression whose integral over $\Phi(U)$ is invariant under compactly supported variations of the coordinate chart Φ.

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- In fact, it has been shown that, up to a constant, this is the only expression whose integral over $\Phi(U)$ is invariant under compactly supported variations of the coordinate chart Φ.
- So for any nontrivial $\text{Quad}_M(M')$ expression over all coordinate charts, the Euler-Lagrange equations are the same, namely,

$$G = 0.$$

Consistency with Current Theory

- Similar results, including uniqueness in the same sense, holds for actions of the type

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$$\int_{\Phi(U)} \mathrm{Quad}_M(M' \cup M)\, dV_{\mathbb{R}^4}$$

- The only action up to constant is

$$\int_U R - 2\Lambda\, dV$$

which has Euler-Lagrange equation

$$G + \Lambda g = 0$$

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Removing Assumptions

- Newtonian Universe $\longrightarrow$ Special Relativity
  Assumption removed: signature of the metric is $(++++)$
- Special Relativity $\longrightarrow$ General Relativity
  Assumption removed: metric is the flat one
- What assumption could be removed next?
- Perhaps that the connection ∇ is the Levi-Civita one. But what do you get if you do?

General Connections

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$$D(X, Y, Z) = g(\nabla_X Y, Z) - g(\bar{\nabla}_X Y, Z)$$

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- Recall that $\bar{\Gamma}_{ijk}$ consists of derivatives of the metric.
- Then
$$\mathcal{F}_{\Phi,U}(g, \nabla) = \int_U R - 2\Lambda - \mathrm{Quad}_g(D)\, dV$$
is of a form allowed by Axiom 1.

Derivatives of D

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- Let T be the torsion tensor of ∇. Its components are

$$\begin{aligned} T_{ijk} &= \Gamma_{ijk} - \Gamma_{jik} \\ &= (\Gamma_{ijk} - \bar{\Gamma}_{ijk}) - (\Gamma_{jik} - \bar{\Gamma}_{jik}) \\ &= D_{ijk} - D_{jik} \end{aligned}$$

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- Perhaps we need another object to try and differentiate.

Fully Antisymmetrizing D

- Define

$$
\begin{aligned}
\gamma_{ijk} &= \frac{1}{6}\left(T_{ijk} + T_{jki} + T_{kij}\right) \\
&= \frac{1}{6}\left(D_{ijk} - D_{jik} + D_{jki} - D_{kji} + D_{kij} - D_{ikj}\right) \\
&= \frac{1}{6}\left(\Gamma_{ijk} - \Gamma_{jik} + \Gamma_{jki} - \Gamma_{kji} + \Gamma_{kij} - \Gamma_{ikj}\right)
\end{aligned}
$$

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- This is the fully antisymmetric part of D, which makes γ a 3-form.

Exterior Derivative of γ

- We can take the exterior derivative of a k-form. Thus

$$d\gamma_{ijk\ell} = -\gamma_{ijk,\ell} + \gamma_{ij\ell,k} - \gamma_{ik\ell,j} + \gamma_{jk\ell,i}.$$

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- Then functionals of the form

$$\mathcal{F}_{\Phi,U}(g,\nabla) = \int_U \left(R - 2\Lambda - \frac{c_3}{24}\,|d\gamma|^2 - \mathrm{Quad}_g(D)\right) dV$$

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- Conjecture - Similar uniqueness result for the above functional.

The Scalar Field

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$$D_{ijk} = \gamma_{ijk}$$

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- Then the action functional reduces to

$$\begin{aligned}\mathcal{F}_{\Phi,U}(g,\nabla) &= \int_U R - 2\Lambda - \frac{c_3}{24}\left|d\gamma\right|^2 - \frac{c_4}{6}\left|\gamma\right|^2 \, dV \\ &= \int_U R - 2\Lambda - c_3\left|d\gamma\right|^2_{4-form} - c_4\left|\gamma\right|^2_{3-form} \, dV\end{aligned}$$

The Scalar Field

- Let $\gamma = \star(v^*)$ where v is a vector field, v^* is its dual 1-form, and $\star$ is the Hodge-star.

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- Let $\gamma = \star(v^*)$ where v is a vector field, v^* is its dual 1-form, and $\star$ is the Hodge-star.
- Note that

$$|\gamma|^2_{3-form} = -|v|^2 \qquad |d\gamma|^2_{4-form} = -(\nabla \cdot v)^2$$

The Scalar Field

- This yields the action

$$\mathcal{F}_{\Phi,U}(g,\nabla) = \int_U R - 2\Lambda + c_3(\nabla \cdot v)^2 + c_4 \left|v\right|^2 \, dV$$

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- The Euler-Lagrange equations for this action are

$$G + \Lambda g = c_4(v^* \otimes v^*) - \frac{1}{2}(c_3(\nabla \cdot v)^2 + c_4 \left|v\right|^2)g$$

$$\nabla(\nabla \cdot v) = \frac{c_4}{c_3} v$$

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- To satisfy the dominant energy condition, acquire a nontrivial solution, and a deterministic equation, we must have that $c_3, c_4 > 0$.

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- f is the scalar field we refer to.

The Einstein-Klein-Gordon Equations

- Making the substitution yields

$$G + \Lambda g = c_3 \left(df \otimes df - \frac{1}{2} \left(|df|^2 + \frac{c_4}{c_3} |f|^2 \right) g \right)$$

$$\Box_g f = \frac{c_4}{c_3} f$$

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- This has a solution if and only if the original system does.
- It also has an action all its own

$$\bar{\mathcal{F}}_{\Phi,U}(g, \nabla) = \int_U R - 2\Lambda - c_3 |df|^2 - c_4 f^2 \, dV$$

The Connection Recovered

- In the case we worked out, we can recover the connection as follows

$$\Gamma_{ijk} = \left(\frac{c_3}{c_4}\right)^{1/2} (\star df)_{ijk} + \frac{1}{2}\left(g_{ik,j} + g_{jk,i} - g_{ij,k}\right)$$

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- If we had considered a different case, the above formula would be different, but we would still acquire the same Einstein-Klein-Gordon equations.
- It's unclear how the connection on its own manifests itself physically.

The Einstein-Klein-Gordon Equations

- Now let

$$\frac{c_4}{c_3} = \Upsilon^2 \qquad\qquad c_4 = 16\pi\mu_0$$

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- Then the Einstein-Klein-Gordon Equations become

$$G + \Lambda g = 8\pi\mu_0 \left\{ \frac{2}{\Upsilon^2} df \otimes df - \left(\frac{|df|^2}{\Upsilon^2} + f^2 \right) g \right\}$$
$$\Box_g f = \Upsilon^2 f$$

The Einstein-Klein-Gordon Equations

- The parameter Υ actually has an important role. It determines a minimum length scale for the scalar field and is vital to the solution of these equations. Hence it should be constant throughout the universe if this theory is to hold.

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- The parameter Υ actually has an important role. It determines a minimum length scale for the scalar field and is vital to the solution of these equations. Hence it should be constant throughout the universe if this theory is to hold.
- As such, determining the appropriate value of this new fundamental constant Υ is an important problem to solve in this theory as well.

Math Motivations

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- Vacuum $G = 0$
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- Dark Matter?

$$G + \Lambda g = 8\pi\mu_0 \left\{ \frac{2}{\Upsilon^2} df \otimes df - \left(\frac{|df|^2}{\Upsilon^2} + f^2 \right) g \right\}$$

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Physical Motivations - Consistency

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- SFDM predicts smooth flat densities in galactic centers rather than cuspy ones that are as yet unobserved but predicted by WIMP models.
- WIMP models also predict smaller galaxies than those observed whereas there is a minimum length scale of scalar fields.
- SFDM is also consistent with cold dark matter models of the early universe and unlike WIMP models has not “hot” version. A hot dark matter model is inconsistent with observables.

Physical Motivations - Spirals

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- This paper shows that under some simplifications to the problem readily tractable, SF can cause elliptical potentials which in turn cause density waves.

Physical Motivations - Ellipticals

- Ripples in the luminosity of some elliptical galaxies could indicate a wave-like energy density of the dark matter.

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- Scalar field dark matter has wave-like energy density profiles.

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- Some models predict unexplained waves in the energy density profiles.

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Physical Motivations - Dwarf Spheroidals

- Some models predict unexplained waves in the energy density profiles.
- SFDM has waves in its energy density profiles.
- My work is in this vein.