

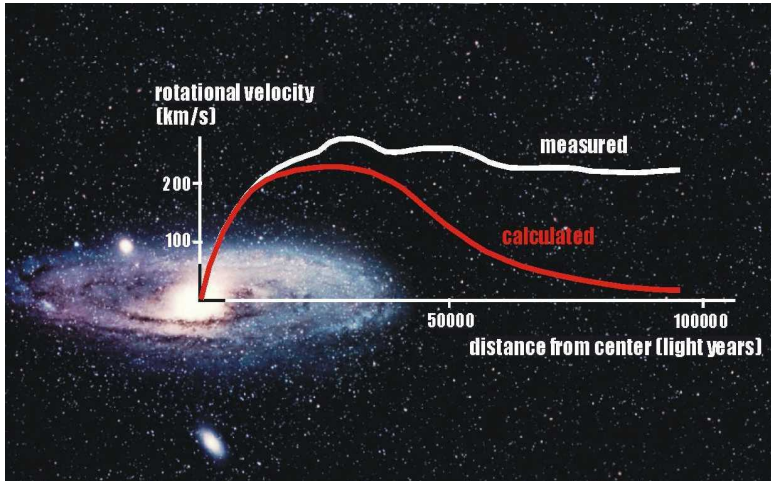
The Axioms of General Relativity And Scalar Field Dark Matter

Alan Parry

Duke University

MSRI Summer Workshop
17 July 2012

Flat Rotation Curves



The Bullet Cluster

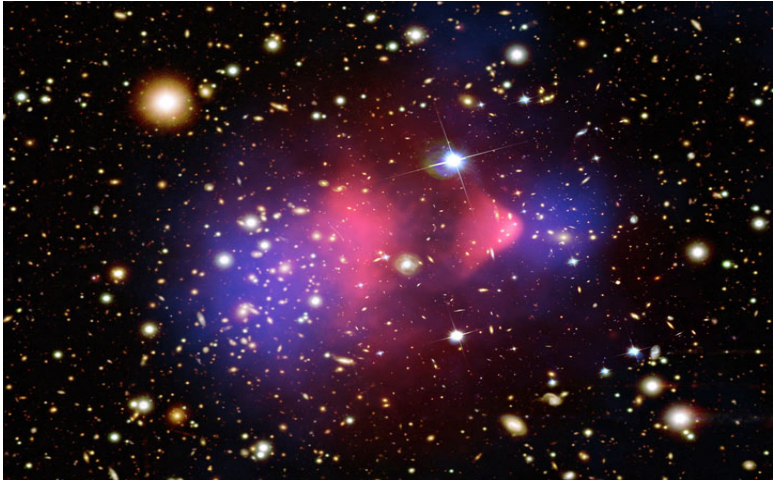


Photo Credit: Chandra X-ray Observatory

Properties of Dark Matter?

- ▶ Dark Matter is matter which interacts only gravitationally with other matter.

Properties of Dark Matter?

- ▶ Dark Matter is matter which interacts only gravitationally with other matter.
- ▶ Dark Matter doesn't emit or reflect light.

Properties of Dark Matter?

- ▶ Dark Matter is matter which interacts only gravitationally with other matter.
- ▶ Dark Matter doesn't emit or reflect light.
- ▶ Dark Matter is collisionless.

Expansion of the Universe

Accelerating or Decelerating?

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

- ▶ 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?

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

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

- ▶ The accelerated expansion of the universe can be accounted for using the Einstein equation with a cosmological constant Λ .

$$G + \Lambda g = 8\pi T$$

Cosmological Constant

- ▶ The accelerated expansion of the universe can be accounted for using the Einstein equation with a cosmological constant Λ .

$$G + \Lambda g = 8\pi T$$

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

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

Cosmological Constant

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

- ▶ The parameter Λ is small but strictly positive in this model.

Cosmological Constant

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

- ▶ 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

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

- ▶ Since $\rho \rightarrow 0$ 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

- We can rewrite the Einstein equation with cosmological constant as

$$G = 8\pi \left(T - \frac{\Lambda}{8\pi} g \right)$$

Dark Energy

- ▶ We can rewrite the Einstein equation with cosmological constant as

$$G = 8\pi \left(T - \frac{\Lambda}{8\pi} g \right)$$

- ▶ This means that we can interpret the cosmological constant as a perfect fluid with stress energy tensor

$$\frac{\Lambda}{8\pi} dt^2 - \frac{\Lambda}{8\pi} a(t)^2 (dx^2 + dy^2 + dz^2)$$

Dark Energy

- ▶ We can rewrite the Einstein equation with cosmological constant as

$$G = 8\pi \left(T - \frac{\Lambda}{8\pi} g \right)$$

- ▶ This means that we can interpret the cosmological constant as a perfect fluid with stress energy tensor

$$\frac{\Lambda}{8\pi} dt^2 - \frac{\Lambda}{8\pi} a(t)^2 (dx^2 + dy^2 + dz^2)$$

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

Dark Energy

- ▶ This negative pressure accounts for the accelerating expansion of the universe.

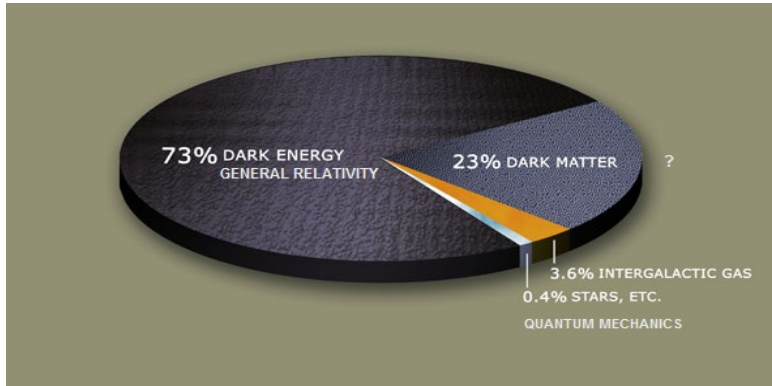
Dark Energy

- ▶ This negative pressure accounts for the accelerating expansion of the universe.
- ▶ The perfect fluid is called Dark Energy.

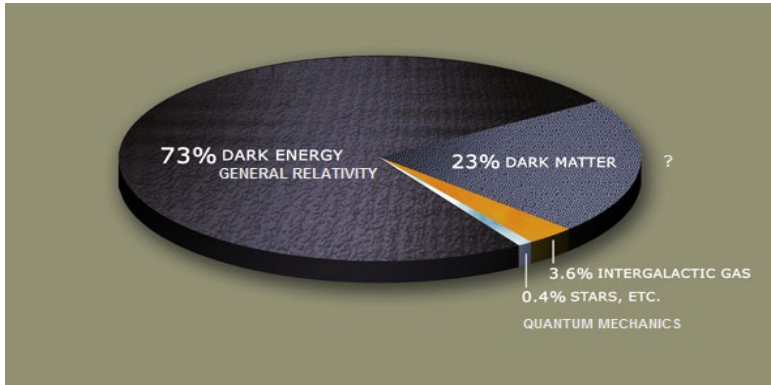
Dark Energy

- ▶ This negative pressure accounts for the accelerating expansion of the universe.
- ▶ 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



Composition Of Matter In The Universe



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

$$\mathcal{F}(g) = \int_M R dV \text{ are}$$

$$G = \text{Ric} - \frac{1}{2}Rg = 0$$

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.

Common Actions



$$G + \Lambda g = 0,$$

modified Einstein equation, but still vacuum (i.e. there's no physical matter).

Common Actions



$$G + \Lambda g = 0,$$

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).

Axiom 0

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

$$\begin{aligned} M &= \{g_{ij}\} & C &= \{\Gamma_{ijk}\} \\ M' &= \{g_{ij,k}\} & C' &= \{\Gamma_{ijk,\ell}\} \end{aligned}$$

Axiom 1

For all coordinate charts $\Phi : \Omega \subset N \rightarrow \mathbb{R}^4$ 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

$$\int_{\Phi(U)} \text{Quad}_M(M') dV_{\mathbb{R}^4} + \textit{boundary term}$$

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

$$\int_{\Phi(U)} \text{Quad}_M(M') dV_{\mathbb{R}^4} + \textit{boundary term}$$

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

Consistency with Current Theory

- 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 .

Consistency with Current Theory

- ▶ 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

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

Consistency with Current Theory

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

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

- ▶ The only action up to constant is

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

which has Euler-Lagrange equation

$$G + \Lambda g = 0$$

Removing Assumptions

- ▶ Newtonian Universe \longrightarrow Special Relativity
Assumption removed: signature of the metric is $(+ + + +)$

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

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?

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

- ▶ Let $\bar{\nabla}$ denote the Levi-Civita connection.

General Connections

- ▶ Let $\bar{\nabla}$ denote the Levi-Civita connection.
- ▶ Then

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

is a tensor, which has components in a coordinate chart,

$$D_{ijk} = \Gamma_{ijk} - \bar{\Gamma}_{ijk}$$

General Connections

- ▶ Let $\bar{\nabla}$ denote the Levi-Civita connection.
- ▶ Then

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

is a tensor, which has components in a coordinate chart,

$$D_{ijk} = \Gamma_{ijk} - \bar{\Gamma}_{ijk}$$

- ▶ Recall that $\bar{\Gamma}_{ijk}$ consists of derivatives of the metric.

General Connections

- ▶ Let $\bar{\nabla}$ denote the Levi-Civita connection.
- ▶ Then

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

is a tensor, which has components in a coordinate chart,

$$D_{ijk} = \Gamma_{ijk} - \bar{\Gamma}_{ijk}$$

- ▶ Recall that $\bar{\Gamma}_{ijk}$ consists of derivatives of the metric.
- ▶ Then

$$\mathcal{F}_{\Phi, U}(g, \nabla) = \int_U R - 2\Lambda - \text{Quad}_g(D) dV$$

is of a form allowed by Axiom 1.

Derivatives of D

- ▶ We can't add in a $\text{Quad}_g(\nabla D)$ term since it would include 2nd derivatives of the metric.

Derivatives of D

- ▶ We can't add in a $\text{Quad}_g(\nabla D)$ term since it would include 2nd derivatives of the metric.
- ▶ Considering the torsion part eliminates that problem.

Derivatives of D

- ▶ We can't add in a $\text{Quad}_g(\nabla D)$ term since it would include 2nd derivatives of the metric.
- ▶ Considering the torsion part eliminates that problem.
- ▶ Let T be the torsion tensor of ∇ . Its components are

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

Derivatives of T

- ▶ Need a derivative of T we could square to get the appropriate $\text{Quad}_g(C')$ term.

Derivatives of T

- ▶ Need a derivative of T we could square to get the appropriate $\text{Quad}_g(C')$ term.
- ▶ Covariant derivatives of either connection won't do because in one case, we will get terms like $\bar{\Gamma}\Gamma = g'\Gamma$ or Γ^2 , the square of either is not allowed by the axioms.

Derivatives of T

- ▶ Need a derivative of T we could square to get the appropriate $\text{Quad}_g(C')$ term.
- ▶ Covariant derivatives of either connection won't do because in one case, we will get terms like $\bar{\Gamma}\Gamma = g'\Gamma$ or Γ^2 , the square of either is not allowed by the axioms.
- ▶ Perhaps we need another object to try and differentiate.

Fully Antisymmetrizing D

► Define

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

Fully Antisymmetrizing D

- Define

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

- 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

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

Exterior Derivative of γ

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

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

- ▶ Then functionals of the form

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

satisfies the axioms.

Exterior Derivative of γ

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

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

- ▶ Then functionals of the form

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

satisfies the axioms.

- ▶ Conjecture - Similar uniqueness result for the above functional.

The Scalar Field

- ▶ As a representative case, consider

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

The Scalar Field

- ▶ As a representative case, consider

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

- ▶ Then the action functional reduces to

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

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.

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.
- ▶ Note that

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

The Scalar Field

- This yields the action

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

The Scalar Field

- This yields the action

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

- The Euler-Lagrange equations for this action are

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

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

The Scalar Field

- This yields the action

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

- The Euler-Lagrange equations for this action are

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

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

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

The Scalar Field

- Define the scalar field

$$f = \left(\frac{c_3}{c_4} \right)^{1/2} \nabla \cdot v$$

The Scalar Field

- ▶ Define the scalar field

$$f = \left(\frac{c_3}{c_4} \right)^{1/2} \nabla \cdot v$$

- ▶ Then by the previous Euler-Lagrange equations

$$v = \left(\frac{c_3}{c_4} \right)^{1/2} \nabla f$$

The Scalar Field

- ▶ Define the scalar field

$$f = \left(\frac{c_3}{c_4} \right)^{1/2} \nabla \cdot v$$

- ▶ Then by the previous Euler-Lagrange equations

$$v = \left(\frac{c_3}{c_4} \right)^{1/2} \nabla f$$

- ▶ f is the scalar field we refer to.

The Einstein-Klein-Gordon Equations

- Making the substitution yields

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

The Einstein-Klein-Gordon Equations

- ▶ Making the substitution yields

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

- ▶ This has a solution if and only if the original system does.

The Einstein-Klein-Gordon Equations

- ▶ Making the substitution yields

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

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

- ▶ 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

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

The Connection Recovered

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

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

- ▶ If we had considered a different case, the above formula would be different, but we would still acquire the same Einstein-Klein-Gordon equations.

The Connection Recovered

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

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

- ▶ 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

$$\frac{c_4}{c_3} = \gamma^2$$

$$c_4 = 16\pi\mu_0$$

The Einstein-Klein-Gordon Equations

- Now let

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

- Then the Einstein-Klein-Gordon Equations become

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

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.

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.
- ▶ 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

- ▶ Vacuum $G = 0$

Math Motivations

- ▶ Vacuum $G = 0$
- ▶ Dark Energy $G + \Lambda g = 0$

Math Motivations

- ▶ Vacuum $G = 0$
- ▶ Dark Energy $G + \Lambda g = 0$
- ▶ Dark Matter?

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

$$\square_g f = \Upsilon^2 f$$

Physical Motivations - Consistency

- ▶ SFDM predicts smooth flat densities in galactic centers rather than cuspy ones that are as yet unobserved but predicted by WIMP models.

Physical Motivations - Consistency

- ▶ 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.

Physical Motivations - Consistency

- ▶ 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

- Density waves are thought to cause the spiral structure.

Physical Motivations - Spirals

- ▶ Density waves are thought to cause the spiral structure.
- ▶ 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.

Physical Motivations - Ellipticals

- ▶ Ripples in the luminosity of some elliptical galaxies could indicate a wave-like energy density of the dark matter.
- ▶ Scalar field dark matter has wave-like energy density profiles.

Physical Motivations - Dwarf Spheroidals

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

Physical Motivations - Dwarf Spheroidals

- ▶ Some models predict unexplained waves in the energy density profiles.
- ▶ SFDM has waves in its energy density profiles.

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.