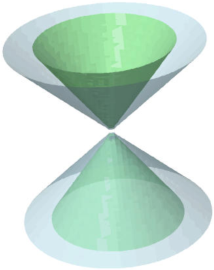

Constraints on Bi-Metric Gravity

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WHY MODIFY GENERAL RELATIVITY (GR)?

- Dark Energy, Dark Matter effects on cosmological scales
- But sub-solar system tests verify GR
- GR seems wrong, but not *that* wrong
- Also, testing new physics theories require us to go beyond GR (Braneworlds e.t.c)

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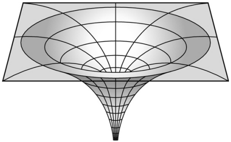
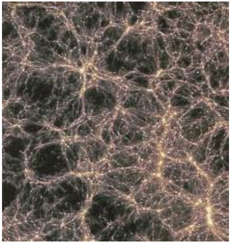
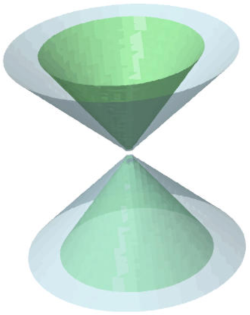
A PHENOMENOLOGICAL APPROACH: SCALAR-TENSOR THEORIES

- Already have useful solutions in GR:
  - for black holes, stars. . . (e.g. Schwarzschild)
  - for cosmology (FRW)
- Useful to construct 2^{nd} metric for matter to propagate through
- Then relate to GR metric through some specified transformation
- How general can this transformation then be?





Bi-Metric Gravity & the Disformal Coupling



Considering 1 added DOF, ϕ, the most general matter geometry is:

Disformal Metric

$$\tilde{g}_{\mu\nu} = C(\phi, X)g_{\mu\nu} + D(\phi, X)\partial_\mu\phi\partial_\nu\phi,$$

where $X = -\frac{1}{2}(\nabla\phi)^2$,
to 1st order derivatives of ϕ.
(Bekenstein, 1993)

OUR SIMPLE CASE

- We consider a disformal metric in the context of Dark Energy
- ϕ is Dark Energy field that drives inflation
- Einstein metric is an isotropic expanding universe:

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = -dt^2 + a(t)^2\delta_{ij}dx^i dx^j$$

- Only Radiation feels the disformal metric. The action is:

$$\mathcal{S} = \int \sqrt{-g}d^4x \left[\frac{\mathcal{R}}{16\pi G} - \frac{1}{2}g^{\mu\nu}(\partial_\mu\phi)(\partial_\nu\phi) - V(\phi)\right] + S_\gamma(\tilde{g}_{\mu\nu}) + S_{\text{mat}}(g_{\mu\nu}),$$

OUR SIMPLE CASE

- $\tilde{g}_{\mu\nu}$ is a simplified disformal metric:

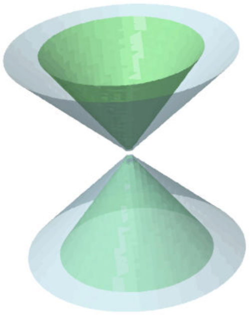
$$\tilde{g}_{\mu\nu} = g_{\mu\nu} + \frac{1}{M^4}\partial_\mu\phi\partial_\nu\phi\ .$$

- And the potential is: $V = V_0 e^{-\phi}$.
- Our universe is spatially isotropic, so $\partial_i\phi = 0_i$, and so the disformal line element becomes:

$$d\tilde{s}^2 = \tilde{g}_{\mu\nu}dx^\mu dx^\nu = -(1 - \frac{\dot{\phi}^2}{M^4})dt^2 + a(t)^2\delta_{ij}dx^i dx^j\ .$$

where 'dot' derivative is w.r.t. cosmic time, t
Note, disformal geometry becomes ill defined as $\dot{\phi}^2 \to M^4$.

MODIFIED REDSHIFT



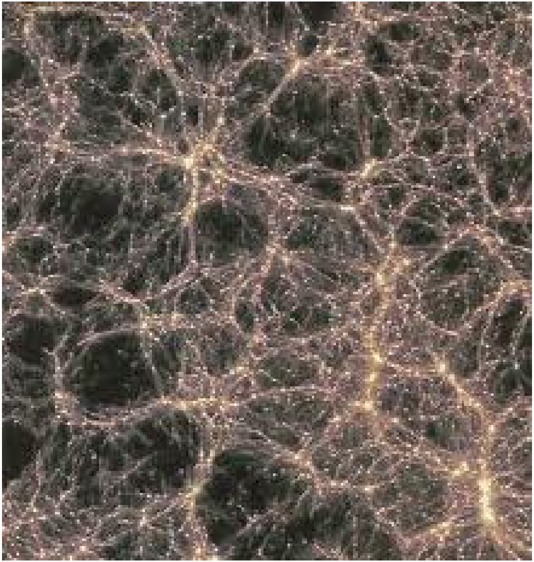
Light now follows disformal geodesics:

$$d\tilde{s}^2 = 0$$

$$1 + z := \frac{\omega_{emitted}}{\omega_{recived}} = \frac{a_0}{a}\sqrt{\frac{M^4 - \dot{\phi}^2}{M^4 - \dot{\phi}_0^2}},$$

As $\dot{\phi}^2 \to M^4$, light becomes infinitely redshifted

Perfect Fluid & Blackbody Assumptions



$$\dot{\rho}_\gamma + 4H\rho_\gamma = -\Gamma \rho_\gamma \dot{\phi}$$

Where:

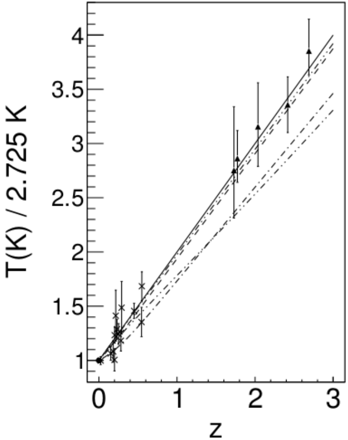
$$\Gamma = \frac{4H\dot{\phi} + V'}{M^4 + \rho_\gamma - \dot{\phi}^2}$$

And we expect the CMB blackbody keeps its shape in our disformal geometry:

$$\rho_\gamma \propto T_\gamma^4$$

CMB TEMPERATURE EVOLUTION: DISFORMAL MODELS *vs* DATA

MEASUREMENTS: (NOTERDAEME *et al.* 2010), (LUZZI *et al.* 2009), (MATHER *et al.* 1999),



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THE CONSTRAINTS ON M

Range of M for which disformal geometry becomes singular:

$$4.33 \times 10^{-5}\ \text{eV} \lesssim M \lesssim 1.37 \times 10^{-3}\ \text{eV}$$

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Range of M excluded at 68% confidence from T_{CMB} evolution:

$$1.53 \times 10^{-5}\ \mathrm{eV} \leq M \leq 3.07 \times 10^{-3}\ \mathrm{eV}$$

What Next?

- Investigate all matter forms in disformal metric
- What is going on on a quantum level?
  - Specifically, does our blackbody relation really hold?
- What can Planck tell us?
- How do cosmic perturbations evolve in this theory?

CONCLUSIONS

- Radiation can be affected by a disformal metric in an observable way
- Geometry unstable for certain energy scales (certain values of M)
- Disformal effects could provide a means to constrain exotic gravity theories

Questions