Status of Bimetric Cosmology


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Why bimetric gravity?

Old CC problem: why isn't Λ huge?
New CC problem: why is Λ nonzero?

$\Rightarrow$ Try modifying GR

$\Rightarrow$ Conceptually simple modification: give the graviton a small mass

This leads naturally to a theory with two metrics

Also: field theory motivation: how to construct interacting spin-2 fields?

Cosmology in bigravity: the situation to date

- Self-accelerating solutions exist, agree with background observations (SNe, BAO, CMB)
  - Akrami, Koivisto, & Sandstad 1209.0457 (JHEP)
- *But*, they are plagued by instabilities!
  - Crisostomi, Comelli, & Pilo 1202.1986 (JHEP)
  - Könnig, Akrami, Amendola, Motta, & ARS 1407.4331 (PRD)
  - Lagos and Ferreira 1410.0207 (JCAP) – see next talk
- Is all lost? (Spoiler alert: Maybe not!)

A new way out? arXiv last Friday: 1503.07521

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Bimetric gravity is cosmologically viable

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Bimetric theory describes gravitational interactions in the presence of an extra spin-2 field. Previous work has suggested that its cosmological solutions are generically plagued by instabilities. We show that by taking the Planck mass for the second metric, M_f, to be small, these instabilities can be pushed back to unobservably early times. In this limit, the theory approaches general relativity with an effective cosmological constant which is, remarkably, determined by the spin-2 interaction scale. This provides a late-time expansion history which is extremely close to ΛCDM, but with a technically-natural value for the cosmological constant. We find M_f should be no larger than the electroweak scale in order for cosmological perturbations to be stable by big-bang nucleosynthesis.

> "The reports of my death have been greatly exaggerated."
>
> —*Metrics Twain*

Introduction.— The Standard Model of particle physics contains fields with spins 0, 1/2, and 1, describing matter and the strong and electroweak forces. General relativity (GR) extends this to the gravitational interactions by introducing a massless spin-2 field. There are theoretical and observational reasons to search for physics beyond these theories. In particular, GR is nonrenormalizable and is associated with the cosmological constant

metric with an additional spin-2 field. It is an extension of an earlier ghost-free theory of massive gravity (a massive spin-2 field on a nondynamical flat background) [6–8] for which the absence of ghost at the nonlinear level was established in Refs. [5, 9–11].

Including spin-2 interactions modifies GR, *inter alia*, at large distances. Bimetric theory is therefore a candidate to explain the accelerated expansion of the Universe [12, 13]. Indeed, bigravity has been shown to possess Friedmann-Lemaître-Robertson-Walker (FLRW) solutions which can match observations of the cosmic expansion history, even in the absence of vacuum energy

Bigravity in a nutshell

The action for bigravity is

$$\mathcal{L} = -\frac{M_{\rm Pl}^2}{2}\sqrt{-g}R(g) - \frac{M_f^2}{2}\sqrt{-f}R(f) + m^2 M_{\rm Pl}^2\sqrt{-g}\,V(\sqrt{g^{-1}f}) + \sqrt{-g}\mathcal{L}_m\,(g,\Phi_i)$$

V: interaction potential built out of the matrix $\sqrt{g^{-1}f}$
m: interaction scale/"graviton mass"
M_{pl}, M_f: Planck masses for $g_{\mu\nu}$ and $f_{\mu\nu}$

$$\mathcal{L} = -\frac{M_{\rm Pl}^2}{2}\sqrt{-g}R(g) - \frac{M_f^2}{2}\sqrt{-f}R(f) + m^2 M_{\rm Pl}^2\sqrt{-g}\,V(\sqrt{g^{-1}f}) + \sqrt{-g}\mathcal{L}_m(g,\Phi_i)$$

Three things to keep in mind…

1. V has restricted form to avoid ghosts
   de Rham, Gabadadze, and Tolley
   Hassan and Rosen

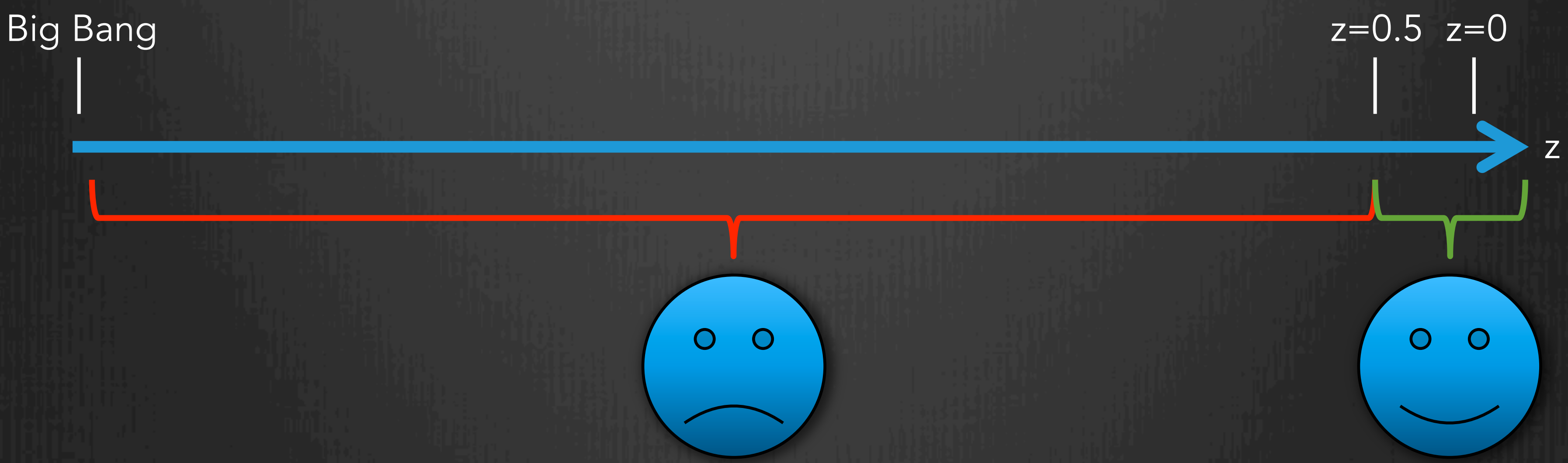
2. Self-acceleration requires m ~ H_0 ~ 10^{-33} eV

3. Diffeomorphism invariance broken by $g^{-1}f$
   Recovered when m=0
   Expect small m to be protected from quantum corrections
   (Contrast this with Λ!)

There is nothing stable in the world; uproar's your only music.
John Keats

- Most FLRW solutions have gradient instability
- Subhorizon scalar perturbations grow exponentially from t=0 until recently

  Until z~0.5 in the simplest model



Our goal: push back instability without losing acceleration

The GR limit of bigravity

The field equations are

$$G_{\mu\nu}(g) + m^2 V^g_{\mu\nu} = \frac{1}{M^2_{\rm Pl}} T_{\mu\nu},$$

$$\frac{M_f^2}{M^2_{\rm Pl}} G_{\mu\nu}(f) + m^2 V^f_{\mu\nu} = 0,$$

Limit M_f → 0: bigravity becomes GR

- f equation: $V^f_{\mu\nu} = 0$ fixes f in terms of g algebraically
- This implies $V^g_{\mu\nu} = V g_{\mu\nu}$
- The metric interactions leave behind an effective cosmological constant!

Exorcising the instability

- *Question*: what happens to the instability in the GR limit?
- *Answer*: it never vanishes, but ends at earlier and earlier times
- By making f-metric Planck mass very small, instability can be unobservable or beyond cutoff of the EFT
- Perturbations stable after $H = H_\star$, with

$$H_\star \sim \frac{M_{\rm Pl}}{M_f} H_0$$

- Ex: instability absent after BBN requires $M_f \sim 100$ GeV

Doesn't the GR limit make the theory boring?
Don't we lose self-acceleration?

No!

Consider (example) the interaction potential

$$V = \mathrm{Tr}(\sqrt{g^{-1}f}) - \left(\mathrm{Tr}(\sqrt{g^{-1}f})^2 - \mathrm{Tr}(g^{-1}f)\right)$$

The effective cosmological constant is

$$\Lambda_{\mathrm{eff}} = \frac{1}{3}m^2 + \mathcal{O}\left(\frac{M_f^2}{M_{\mathrm{Pl}}^2}\right)$$

We still have self-acceleration and automatic consistency with observations!

Taking M_f / M_{pl} small ($<\sim 10^{-17}$) we find

$$\text{Bigravity} = \Lambda\text{CDM} + O(M_f^2 / M_{pl}^2)$$

Bad news: difficult to distinguish from GR

Good news: small CC is technically natural
HUGE improvement over standard ΛCDM

(More good news: agrees with observations as well as GR does)

In summary…

- By taking second-metric Planck mass to be small, bigravity cosmologies become stable
  - Instability still exists, but at unobservably early times
- Cosmologies become exactly ΛCDM at late times
- GR limit only valid when

$$M_f^2 G_{\mu\nu}(f) \ll m^2 M_{\rm Pl}^2 V_{\mu\nu}^f$$

$$\implies H \ll \frac{M_{\rm Pl}}{M_f} H_0$$

This is also the condition for absence of instability! (Nontrivial)

→ Possible early-time tests

How was this missed?

M_f is usually seen as a redundant parameter. The rescaling

$$f_{\mu\nu} \to (M_{\rm Pl}/M_f)^2 f_{\mu\nu}, \qquad \beta_n \to (M_f/M_{\rm Pl})^n \beta_n, \qquad M_f \to M_{\rm Pl}$$

leaves the action unchanged.

Common practice in bigravity: set $M_f = M_{pl}$ from the start!

In this language, the GR limit is

$$\beta_1 \sim 10^{17}$$
$$\beta_2 \sim 10^{34}$$
etc.

which looks *weird* and highly unnatural!

Also: need more than one β_n nonzero

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