Testing Gravity on Cosmic scales: A case study of Jordan-Brans-Dicke Gravity

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Why explore modified gravity?

- Test laws of gravity on cosmic scales, up to 15 orders of magnitude larger than the Solar System where GR is well-established
- Universe accelerates ($\Lambda$ has fine-tuning and coincidence problems)
- Cosmic tensions ($S_8$ and $H_0$) and absence of obvious candidates
Requirements on any new model

- Bring about concordance among probes. Ideally, but not necessarily, among all probes (both $H_0$ & $S_8$).
- Be favored in model selection sense (e.g. evidence, goodness of fit, DIC).
- Exhibit greater than 5σ deviation in additional parameters (wrt fiducial model).
- Stay robust when confronted with additional data.
Two approaches to modified gravity

• “Model-independent” modified gravity
  — $G_{\text{matter}} - G_{\text{light}}$ modifying $\Psi$ and $\Psi + \Phi$
  — Index $\gamma_G$ modifying linear growth rate
  — Horndeski $\alpha_i$ encompassing a subset of stable scalar-tensor theories
  — $E_G$ encapsulating $(g \times \kappa) / (g \times v)$ cross-correlations

• Model-specific modified gravity
  — Constrain a distinct model. Examples include: JBD, general $f(R)$, DGP, DHOST, non-local gravity, bigravity
Model-independent vs model specific

- Why take “model-independent” approach?
  - Zeroth-order approach: search for any deviations from GR
  - Simultaneously constrain large classes of models

- Why take model-specific approach?
  - Simulate/model the nonlinear scales (screening mechanism is highly model-dependent) → increase constraining power
  - Changes to both expansion and growth (expansion commonly fixed to $\Lambda$CDM in model-independent approaches)
    → increase ability to resolve multiple tensions (i.e. both $H_0$ & $S_8$)
**“Model-independent” test of gravity**

\[ Q(k, z) \] modifies Poisson equation

\[ \Sigma(k, z) \] modifies light deflection

10-15\% level constraints on \( \Sigma_2 \) in fiducial and LS+Planck cases, \( Q_2 \) bounded from above, \( S_8 \) constraint improves by up to factor of 3.
“Model-independent” test of gravity: full MG subspace

Figure 12. Marginalized posterior distributions of the modified gravity parameters $\{Q_i, \Omega_j\}$ and their correlation for $\Lambda$ with large-scale cuts to the data together with Planck in cyan, and $\{\Lambda, t, P_{0/2}\}$ with large scale cuts to the data together with Planck in brown (simultaneously varying 5 vanilla cosmological parameters, 14 astrophysical WL/RSD parameters, optical depth to reionization, and additional CMB parameters). The indices of the MG parameters indicate transitions at $k_0 = 0.05 h$ Mpc$^{-1}$ and $z = 1$, such that '1' refers to $\{low \ z, low \ k\}$, '2' refers to $\{low \ z, high \ k\}$, '3' refers to $\{high \ z, low \ k\}$, and '4' refers to $\{high \ z, high \ k\}$. The GR prediction is given by the intersection of the horizontal and vertical dashed lines ($Q = \Omega = 1$).
Model-specific approach: A case study of Jordan-Brans-Dicke (JBD) Gravity

\[ S_{\text{BD}} = \int d^4 x \sqrt{-g} \left[ \frac{M_{\text{Pl}}^2}{2} \left( \frac{\phi R - \omega_{\text{BD}}}{\phi} g^{\mu \nu} \partial_\mu \phi \partial_\nu \phi - 2V \right) + L_m \right] \]

- \( S_{\text{BD}} = \) JBD action, \( R = \) Ricci scalar, \( L_m = \) matter Lagrangian
- \( \phi = \) real scalar field, \( V = \) potential (taken to be constant)
- \( g^{\mu \nu} = \) metric (with determinant \( g \))
- \( M_{\text{Pl}} = (8\pi G)^{-1/2} = \) reduced Planck mass (\( G \) is bare grav. constant)
- \( \omega_{\text{BD}} = \) JBD coupling constant

Varying the action with respect to the metric and scalar field:

\[
3H^2 = \frac{\rho}{M_{\text{Pl}}^2 \phi} - \frac{3H}{\phi} \frac{\dot{\phi}}{\phi} + \frac{\omega_{\text{BD}}}{2} \frac{\dot{\phi}^2}{\phi^2} + \frac{V}{\phi}
\]

\[
2\dot{H} + 3H^2 = -\frac{P}{M_{\text{Pl}}^2 \phi} - \frac{\omega_{\text{BD}}}{2} \frac{\dot{\phi}^2}{\phi^2} - 2H \frac{\ddot{\phi}}{\phi} - \frac{\dot{\phi}}{\phi} \frac{\ddot{\phi}}{\phi} + \frac{V}{\phi}
\]

RD: \( \phi = \) constant \( \rightarrow \) \( a \sim (t/\phi)^{1/2} \)

MD: \( \phi = \phi_0 a^{1/(1 + \omega_{\text{BD}})} \rightarrow a = (t/t_0)^{(2 + 2\omega_{\text{BD}})/(4 + 3\omega_{\text{BD}})} \)

VD: \( \phi \sim a^{4/(1 + 2\omega_{\text{BD}})} \rightarrow \) acceleration expansion driven by \( V \)

Scalar field has effect throughout full evolution of Universe
Linear perturbations in JBD gravity

Modified Poisson equation:
\[ \frac{k^2}{a^2} \psi \simeq -4\pi G_{\text{matter}} \rho_m \delta_m \]

Effective gravitational constant:
\[ \frac{G_{\text{matter}}}{G} \simeq \frac{1}{\phi} \frac{4 + 2\omega_{BD}}{3 + 2\omega_{BD}} \]

Two types of JBD gravity

- **restricted**: vary \( \omega_{BD} \), fix \( G_{\text{matter}}/G|_{a=1} = 1 \)
- **unrestricted**: vary both \( \omega_{BD} \) and \( G_{\text{matter}}/G|_{a=1} \)

On subhorizon scales:
\[ \delta_m'' + \left[ 1 + \frac{\mathcal{H}'}{\mathcal{H}} \right] \delta_m' - \frac{3}{2} \frac{G_{\text{matter}}}{G} \Omega_m(a) \delta_m \simeq 0 \]

Gravitational slip (both JBD types):
\[ 2 \frac{\Psi}{\Psi + \Phi} = \frac{2\gamma}{1 + \gamma} \simeq \frac{4 + 2\omega_{BD}}{3 + 2\omega_{BD}} \]
Why explore JBD gravity?

1. **Testbed for cosmological analyses of modified gravity** (and extended cosmologies more broadly), given its rich history and the role it plays in some of the fundamentally motivated extensions to SM of particle physics (particularly in string theory, extra-dimensional theories, and the decoupling limit of theories with higher spin fields).

2. **Simplest modified gravity theory.** Approximates a wider range of scalar-tensor theories (within Horndeski) on cosmological scales where gradients are suppressed.

3. **One of remaining viable theories** after LIGO-VIRGO measurement of the speed of gravitational waves ($\alpha_T = 0$).

4. Use model-specific approach to simultaneously constrain and explore degeneracies between modified gravity, neutrino mass, and baryonic feedback.

5. Explore whether the theory can help to **alleviate cosmic tensions** ($H_0$ & $S_8$) whilst being favored in model selection sense.
Earlier constraints on JBD gravity

- Shapiro time delay by Cassini: $\omega_{BD} > 4.0 \times 10^4$ (95% CL)  
  \cite{Bertotti2003}

- Pulsar-white dwarf binary: $\omega_{BD} > 1.2 \times 10^4$ (95% CL)  
  \cite{Freire2012}

- Cosmology (early & late): $\omega_{BD} \gtrsim 10^2 - 10^3$ (95% CL)  
  \textit{Not competitive, but probing different redshifts and scales.}  
  \cite{Avilez2014, SolàPeracaula2019, SolàPeracaula2020, Ballardini2016, Ballardini2020}

- Big Bang Nucleosynthesis:  
  \{ $\omega_{BD} > 300$, $G_{BBN}/G = 0.98 \pm 0.06$ \} (95% CL)  
  \cite{Clifton2005, Alvey2020}

Astrophysical constraints much more powerful. However, expect nonlinear corrections (screening) in \textit{generalized} JBD gravity, which may completely shield astrophysical systems.
End-to-end approach

- Analytical and numerical description of the background expansion and linear perturbations.
- Nonlinear regime captured with hybrid suite of \( N \)-body simulations \( \rightarrow \) modified fitting function for matter power spectrum
- Cosmological constraints from existing probes of the expansion history, large-scale structure, and CMB. *Simultaneous constraints on modified gravity, massive neutrinos, and baryonic feedback for the first time.*

- Accurately account for observational systematics (e.g. baryonic feedback, intrinsic alignments, photo-z and shear calibration uncertainties, galaxy bias).
- Accurately account for theoretical systematics from modeling new physics such as neutrino mass, dark matter, DE/MG.
- Understand the role of degeneracies between different parameters (cosmological, astrophysical, gravitational, instrumental).
JBD impact on the expansion, growth, CMB

\[ H^2_{\text{JBD}} / H^2_{\text{GR}} \simeq 1 / \phi = \left( \frac{3 + 2 \omega_{\text{BD}}}{4 + 2 \omega_{\text{BD}}} \right) \frac{G_{\text{matter}}}{G} \]

1-sided \( \omega_{\text{BD}} \), 2-sided \( G_{\text{matter}}/G \)

\[ G_{\text{light}} / G = 1 / \phi \]

\( \omega_{\text{BD}} \), \( G_{\text{matter}}/G \)
CMB degeneracies

\[ H^2 \propto \phi^{-1} \propto f(\omega_{BD}) \frac{G_{\text{matter}}}{G} \]

\[ \theta_d/\theta_s \propto \sqrt{H(a)/n_e} \propto (G_{\text{matter}}/G)^{1/4}(1 + C N_{\text{eff}})^{1/4}/\sqrt{1 - Y_P} \]

Partly break degeneracy between \( N_{\text{eff}} \) and \( Y_P \) (and between \( N_{\text{eff}} \) and \( G_{\text{matter}}/G \)) via early ISW, potential high baryon fraction as \( N_{\text{eff}} \) increases, phase shift in acoustic oscillations due to neutrino perturbations.
1) Modify geodesic and poisson equations. Generate initial conditions using 2LPT.

2) Run a hybrid suite of Ramses and COLA simulations.

3) Modify HMCODE to match simulations (MG, neutrino mass, baryonic feedback).
CMB constraints on restricted JBD gravity

**Restricted JBD:**
- Vary $\omega_{BD}$ (GR-limit as $\omega_{BD} \rightarrow -\infty$)
- Fix $G_{\text{matter}}/G|_{a=1} = 1$

**Planck18:** $\omega_{BD} > 1150$ (95% CL)
**ACT DR4:** $\omega_{BD} > 330$ (95% CL)
**Planck + ACT:** $\omega_{BD} > 1380$ (95% CL)

Small impact on $H_0$ tension (more substantial for ACT).
Negligible impact on $S_8$ tension.

*SJ et al (2020)*
3×2pt constraints on JBD gravity

In all slides: all other cosmological and systematics parameters simultaneously varied. (systematics include e.g. intrinsic alignments, photo-z uncertainties, galaxy bias, velocity dispersion)

Unrestricted JBD:

• $T(S_8) = 1.6$ (down by nearly 1σ)
• $ΔDIC = -1$

$ω_{BD} ≳ 100$ (95% CL)

Fix $m_ν$: $G_{matter}/G = 1.07^{+0.12}_{-0.15}$

Vary $m_ν$: $G_{matter}/G = 1.03^{+0.11}_{-0.15}$
Joint CMB/LSS/SN constraints on JBD gravity

S8 and H0 tensions alleviated, less so when CMB polarization data is included.

\[ T(S_8) < 1\sigma \text{ (wrt KiDS × 2dFLenS)} \]
\[ T(H_0) \sim 3\sigma \text{ with polarization} \]
\[ T(H_0) \sim 2\sigma \text{ without polarization} \]
Assessing concordance as a requirement for combining datasets

Use the log $\mathcal{I}$ statistic to assess concordance.

$S =$ suspiciousness metric

$Q_{\text{DMAP}} =$ goodness of fit metric

Unrestricted JBD:

$\Delta \log \mathcal{I} = 0.93$ (fix $m_\nu$)

$\Delta \log \mathcal{I} = 0.37$ (vary $m_\nu$)

Swapping order changes by $\Delta \log \mathcal{I}$ by $\sim 1$.

$$\log \mathcal{I} = \left[2 \ln(10)\right]^{-1} \left[ Q_{\text{DMAP}} + 4 \ln S \right]$$
Full constraints on JBD gravity

Fix $m_\nu$:
$\omega_{BD} > 1540$ (95% CL)
$G_{\text{matter}}/G = 0.996 +/- 0.029$
$T(H_0) = 3.0$
$\Delta\text{DIC} = 2.0$

Vary $m_\nu$:
$\omega_{BD} > 2230$ (95% CL)
$G_{\text{matter}}/G = 0.997 +/- 0.029$
$T(H_0) = 3.1$
$\Sigma m_\nu < 0.12$ eV (95% CL)
$\Delta\text{DIC} = 4.6$

Translating above to BBN:
$G_{\text{BBN}}/G = 0.99 +/- 0.03$

Fixing $m_\nu$ and varying $m_\nu$.

SJ et al (2020)
JBD parameterization

$$\omega_{\text{BD}} \geq \{1540, 160, 160, 350\} \text{ (95\% CL)}$$

Fiducial: $$G_{\text{matter}}/G = 0.996 \pm 0.029$$

$$\rightarrow G_{\text{matter}}/G = 0.970 \pm 0.033$$

Fiducial: $$B > 2.8 \text{ (95\% CL)}$$

$$\rightarrow B > 3.1 \text{ (95\% CL)}$$

Fiducial: $$\sum m_\nu < 0.12 \text{ eV (95\% CL)}$$

$$\rightarrow \Sigma m_\nu < 0.32 \text{ eV (95\% CL)}$$
Summary

• End-to-end exploration of a distinct modified gravity theory (analytic description, numerical simulations, cosmological constraints from existing probes).

• Simultaneous constraints on modified gravity, massive neutrinos, and baryonic feedback for the first time. Neutrino mass bound can degrade by up to factor of 3 in JBD gravity.

• Cosmic tensions partly alleviated (S8 fully, H0 down to 3σ), due to increased uncertainty rather than deviations in new parameters. Extended model not found favored in model selection sense.

• A positive shift in the effective gravitational constant suppresses the CMB damping tail, which might complicate future inferences of small-scale physics.

• Expect order of magnitude improvements in JBD constraints with Stage-IV surveys. Will allow for comparable constraints from cosmology and astrophysics.
Extra slides
Constraints on JBD gravity

![Graph showing probability density against ln(ω⁻¹ BD) and Gmatter/G for different combinations of datasets including KiDS, 2dFLenS, All-BOSS, Pantheon, and Planck15 and Planck18.]
**S₈ and H₀ tensions**

- KiDS×2dFLenS + All-BOSS + Planck† + Pantheon (JBD+Gₘₐτₐₜₐr+∑mₙ)
- KiDS×2dFLenS + All-BOSS + Pantheon (JBD+Gₘₐτₐₜₐr+∑mₙ)
- Planck* + All-BOSS + Pantheon (JBD+Gₘₐτₐₜₐr+∑mₙ)
- KiDS×2dFLenS + All-BOSS + Pantheon (ΛCDM)
- Planck* + All-BOSS + Pantheon (ΛCDM)

![Graph showing S₈ and H₀ tensions](image-url)
Degeneracies and systematics

KiDS×2dFLenS + All-BOSS + All-Planck18 + Pantheon

KiDS×2dFLenS + All-BOSS + All-Planck15 + Pantheon

$\Omega_m$ vs $H_0$

$S_8$ vs $G_{\text{matter}}/G$

$P/P_{\text{max}}$ vs $\Sigma m_\nu$ [eV]

$B$ vs $A_{IA}$