Testing O(D, D) string cosmology based on double field theory

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Motivation: cosmology

- General Relativity (GR) is a successful theory of gravity. In GR, the metric $g_{\mu\nu}$ is the only gravitational field.
- However, some observational results cannot be explained by GR + visible matter alone.
- Usually resolve by introducing dark matter, dark energy into the standard cosmological model, ΛCDM.
- Even so, recent tensions within ΛCDM (e.g. H_0 tension) may suggest a need to move beyond standard cosmology.
- Perhaps the above issues can be addressed by modifying the theory of gravity. But how should we modify it?

Motivation: string theory

String theory is a candidate theory of quantum gravity.

In string theory, the closed-string massless sector always includes:

- the metric $g_{\mu\nu}$, a rank-2 symmetric tensor ($g_{\mu\nu} = g_{\nu\mu}$);
- the 'B-field' $B_{\mu\nu}$, a rank-2 antisymmetric potential ($B_{\mu\nu} = -B_{\nu\mu}$);
- the dilaton ϕ, a scalar field.

Furthermore, these fields transform into each other under T-duality.

Natural stringy extension of General Relativity:

Consider $\{g_{\mu\nu}, B_{\mu\nu}, \phi\}$ as the fundamental gravitational multiplet.

The additional degrees of freedom $B_{\mu\nu}$ and ϕ augment gravity beyond GR, allowing new types of solutions.

$\mathbf{O}(D, D)$ cosmology overview: what and why?

What is $\mathbf{O}(D, D)$ cosmology, and why should we care about it?

- The modified gravity implied by string theory has a hidden $\mathbf{O}(D, D)$ symmetry (where D is the spacetime dimension).
- The $\mathbf{O}(D, D)$ covariant formalism of double field theory can prescribe and constrain the allowed interactions with matter in accordance with this symmetry.

Various phenomenological applications, including:

- H-flux, the field strength of $B_{\mu\nu}$, couples differently to fermions depending on chirality. New approach to baryogenesis?
- The extended gravitational sector can induce a dilaton pressure, which can affect clustering. Consequences for dark matter?
- Photons generically couple to the dilaton, which could affect distance measurements. Possible relation to Hubble tension?

O(D, D) symmetry

The generic low-energy limit of various closed string theories is described by the (bosonic) supergravity theory of $\{g_{\mu\nu}, B_{\mu\nu}, \phi\}$,

$$S = \int \mathrm{d}^D x \sqrt{-g} e^{-2\phi} \left(R + 4\partial_\mu \phi \partial^\mu \phi - \frac{1}{12} H_{\lambda\mu\nu} H^{\lambda\mu\nu} \right) ,$$

where $H_{\lambda\mu\nu} = 3\partial_{[\lambda} B_{\mu\nu]}$ ('H-flux') is the field strength of $B_{\mu\nu}$.

Symmetries include diffeomorphisms, $B_{\mu\nu}$ gauge symmetry, T-duality.

E.g. flat background ($g_{\mu\nu} = \eta_{\mu\nu}$, $B_{\mu\nu} = 0 = \partial_\mu \phi$), compact dimension of radius R: T-duality acts as $R \to \alpha'/R$ ($\alpha'^{1/2}$ is the string length).

For arbitrary backgrounds of $\{g_{\mu\nu}, B_{\mu\nu}, \phi\}$, the full implied T-duality group of transformations is **O**(D, D).

Overview of double field theory

We can make the $\mathbf{O}(D, D)$ symmetry manifest using the formalism of double field theory (DFT). (Siegel; 1993) (Hull, Zwiebach; 2009)

- In DFT we describe D-dimensional physics using $D + D$ coordinates, $x^A = (\tilde{x}_\mu, x^\nu)$, $A = 1, \ldots, 2D$.
- Doubled vector indices are raised and lowered using the $\mathbf{O}(D, D)$-invariant $\mathcal{J}$:

$$\mathcal{J}_{AB} = \begin{pmatrix} 0 & \mathbf{1}_D \\ \mathbf{1}_D & 0 \end{pmatrix} = \mathcal{J}^{AB} \,.$$

- DFT also enjoys doubled diffeomorphism symmetry, which unifies ordinary diffeomorphisms and B-field gauge transformations.

Double trouble?

What does it mean to ‘double’ the number of spacetime dimensions?

- For a consistent theory (closure of doubled diffeomorphisms), all fields should satisfy the section condition,

$$\partial_A \partial^A = 2\, \partial_\mu \tilde{\partial}^\mu = 0\,.$$

- A natural choice is $\tilde{\partial}^\mu = 0$, i.e. choosing all fields to be independent of the $\tilde{x}_\mu$ coordinates. The theory is not truly ‘doubled’: it is just a repackaging of D-dimensional physics.
- Interpretation: the level-matching condition (constraint equation of motion) for massless modes of the closed string is $p_\mu \tilde{p}^\mu = 0$, where $\tilde{p}^\mu$ is the T-dual momentum (for string winding modes).

Ingredients of double field theory

The basic fields of double field theory are:

- the DFT dilaton d, providing a volume element e^{-2d};
- an $\mathbf{O}(D,D)$, symmetric DFT metric $\mathcal{H}_{AB}$, satisfying

$$\mathcal{H}_{AB} = \mathcal{H}_{BA}\,, \qquad \mathcal{H}_A{}^C \mathcal{H}_B{}^D \mathcal{J}_{CD} = \mathcal{J}_{AB}\,.$$

Doubled geometry: can construct a 'semi-covariant' derivative, as well as a (fully-covariant) DFT Ricci tensor $\mathcal{R}_{AB}$ and scalar $\mathcal{R}$.

On Riemannian backgrounds (i.e. usual spacetime), with the section choice $\tilde{\partial}^\mu = 0$: $\{d, \mathcal{H}_{AB}\} \to \{g_{\mu\nu}, B_{\mu\nu}, \phi\}$, such that

$$e^{-2d} = e^{-2\phi}\sqrt{-g}\,; \qquad \mathcal{H}_{AB} = \begin{pmatrix} g^{\mu\nu} & -g^{\mu\sigma}B_{\sigma\nu} \\ B_{\mu\rho}g^{\rho\nu} & g_{\mu\nu} - B_{\mu\rho}g^{\rho\sigma}B_{\sigma\nu} \end{pmatrix}.$$

T-duality transformations are simply linear $\mathbf{O}(D,D)$ rotations of $\mathcal{H}$.

DFT coupled to matter

The DFT Ricci scalar $\mathcal{R}$ gives the 'stringy' gravitational Lagrangian,
(Jeon, Lee, Park; 2011)

$$\mathcal{R} = R + 4\Box\phi - 4\partial_\mu\phi\partial^\mu\phi - \tfrac{1}{12}H_{\lambda\mu\nu}H^{\lambda\mu\nu} \,.$$

We can extend $\mathbf{O}(D, D)$ covariance to interactions with matter $\{\Upsilon_a\}$,

$$S = \int_\Sigma e^{-2d}\left[\tfrac{1}{16\pi G}\mathcal{R} + L_{\mathrm{m}}(\Upsilon_a)\right] \,,$$

where L_{m} is an $\mathbf{O}(D, D)$-covariant Lagrangian for the additional matter.

Varying this action yields a DFT generalization of Einstein's equations, or 'Einstein double field equations', (SA, Cho, Park; 2018)

$$G_{AB} = 8\pi G T_{AB} \,,$$

where the DFT energy-momentum tensor T_{AB} is conserved on-shell.

Note: $\mathbf{O}(D, D)$ covariance $\Rightarrow$ volume element must always be e^{-2d}.

Riemannian spacetime backgrounds

On Riemannian spacetime backgrounds, the EDFEs reduce to the usual closed-string equations of motion plus source terms,

$$\begin{aligned} R_{\mu\nu} + 2\nabla_\mu(\partial_\nu\phi) - \tfrac{1}{4}H_{\mu\rho\sigma}H_\nu{}^{\rho\sigma} &= 8\pi G K_{(\mu\nu)}\ ; \\ \nabla^\rho\left(e^{-2\phi}H_{\rho\mu\nu}\right) &= 16\pi G e^{-2\phi}K_{[\mu\nu]}\ ; \\ R + 4\Box\phi - 4\partial_\mu\phi\partial^\mu\phi - \tfrac{1}{12}H_{\lambda\mu\nu}H^{\lambda\mu\nu} &= 8\pi G T_{(0)}\ , \end{aligned}$$

Many common fields, particles, etc. admit a DFT embedding, from which we can derive their DFT energy-momentum tensors explicitly. Generally, $K_{\mu\nu}$ gives the kinetic part and $T_{(0)}$ the trace contribution.

Note: asymmetric $K_{\mu\nu}$ possible (e.g. fermions, strings) $\rightarrow$ source for H, which gives a topological obstruction to dualizing H to an axion.

Interpretation of $K_{\mu\nu}$ and $T_{(0)}$

Can arrange the DFT energy-momentum tensor into terms sourcing

$$\begin{aligned}
\delta g_{\mu\nu} : \qquad & T_{\mu\nu} \equiv e^{-2\phi}\left(K_{(\mu\nu)} - \frac{1}{2} g_{\mu\nu} T_{(0)}\right) , \\
\delta B_{\mu\nu} : \qquad & \Theta_{\mu\nu} \equiv e^{-2\phi} K_{[\mu\nu]} , \\
\delta \phi : \qquad & \sigma \equiv e^{-2\phi} T_{(0)} .
\end{aligned}$$

Here $T_{\mu\nu}$ is the canonically normalized energy-momentum tensor in GR, while $\Theta_{\mu\nu}$ and σ represent sources for $B_{\mu\nu}$ and ϕ, respectively.
Note: gravitational mass may not be simply $-T_0{}^0$. (Cho, Morand, Park; 2019)

On-shell conservation of the DFT energy-momentum tensor gives

$$\nabla^\mu T_{\mu\nu} + \frac{1}{2} H_\nu{}^{\mu\lambda}\Theta_{\mu\lambda} - \nabla_\nu \phi\, \sigma = 0 , \qquad \nabla^\mu \Theta_{\mu\nu} = 0 .$$

If we convert to Einstein frame via $g_{\mu\nu} \equiv e^{2\phi}\tilde{g}_{\mu\nu}$, we have

$$\widetilde{T}_{\mu\nu} \equiv e^{2\phi} T_{\mu\nu} , \qquad \widetilde{\Theta}_{\mu\nu} \equiv \Theta_{\mu\nu} , \qquad \widetilde{\sigma} \equiv e^{4\phi}(\sigma + T^\mu{}_\mu) .$$

Cosmology in DFT

Now consider $D = 4$ homogeneous and isotropic solutions in DFT,

$$\mathrm{d}s^2 = -N(t)^2\mathrm{d}t^2 + a(t)^2\left[\frac{\mathrm{d}r^2}{1-Kr^2} + r^2\mathrm{d}\Omega^2\right] ,$$

$$B_{(2)} = \frac{hr^2}{\sqrt{1-Kr^2}}\cos\vartheta\,\mathrm{d}r\wedge\mathrm{d}\varphi , \quad \phi = \phi(t) .$$

This gives $H_{(3)} = \mathrm{d}B_{(2)} = h\,\mathrm{Vol}_3$ which is homogeneous and isotropic.

For matter, the DFT energy-momentum tensor is constrained as

$$K^{\mu}{}_{\nu} = \mathrm{diag}(K^t{}_t(t), K^r{}_r(t), \ldots, K^r{}_r(t)) , \quad T_{(0)} = T_{(0)}(t) ,$$

giving the energy density, pressure and anisotropic strain

$$\rho = \left(-K^t{}_t + \frac{1}{2}T_{(0)}\right)e^{-2\phi} , \quad p = \left(K^r{}_r - \frac{1}{2}T_{(0)}\right)e^{-2\phi} , \quad \pi^{\mu}{}_{\nu} = 0 .$$

O(D, D)-complete Friedmann equations

Choosing e.g. cosmic gauge, $N(t) = 1$ and defining $H \equiv \dot{a}/a$, EDFEs $\Rightarrow$ **O**(D, D)-complete Friedmann equations (OFEs),
(SA, Cho, Franzmann, Mukohyama, Park; 2019)

$$\begin{aligned}
\frac{8\pi G}{3}\rho e^{2\phi} + \frac{h^2}{12a^6} &= H^2 - 2\dot{\phi}H + \frac{2}{3}\dot{\phi}^2 + \frac{K}{a^2}\,, \\
\frac{4\pi G}{3}(\rho + 3p)e^{2\phi} + \frac{h^2}{6a^6} &= -H^2 - \dot{H} + \dot{\phi}H - \frac{2}{3}\dot{\phi}^2 + \ddot{\phi}\,, \\
\frac{4\pi G}{3}(2\rho - \sigma)\, e^{2\phi} &= -H^2 - \dot{H} + \frac{2}{3}\ddot{\phi}\,.
\end{aligned}$$

Furthermore, DFT energy-momentum conservation leads to one non-trivial conservation law (can also be derived from the OFEs),

$$\dot{\rho} + 3H(\rho + p) + \dot{\phi}\sigma = 0\,.$$

Properties of the OFEs

The OFEs have various interesting properties.

- 3 OFEs + 1 conservation law $\Rightarrow$ 3 independent equations (c.f. GR cosmology, which has 2 Friedmann eq.s + 1 conservation law).
- If $\dot{\phi} = \ddot{\phi} = 0$, $h = 0 \Rightarrow$ GR cosmology; $\sigma \equiv \rho - 3p$ ('critical line').
  But converse not true! Non-trivial dilaton solutions also exist there.
- It is useful to define two equation-of-state parameters,

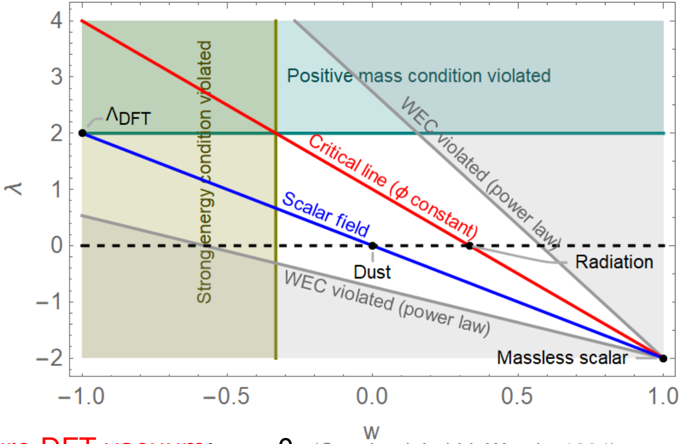
$$w := \frac{p}{\rho}\,; \qquad \lambda := \frac{\sigma}{\rho}\,.$$

- w is the usual parameter corresponding to pressure, while λ is the ratio of the dilaton pressure to the energy density.
- For constant w and λ ("generalized perfect fluid"), we can solve:

$$\rho = \rho_0 \frac{e^{-\lambda\phi}}{a^{3(1+w)}}\,.$$

Cosmological solutions

Identify various regions and types of matter in the (w, λ)-plane.



Also, pure DFT vacuum: $\rho = 0$. (Copeland, Lahiri, Wands; 1994)

DFT vacuum with negative spatial curvature can reduce H_0 tension.

(Lee, Park, Velasco-Sevilla, Yin; 2023)

Solution: radiation with H-flux and freezing dilaton

There are also analytic solutions to the OFEs beyond power law, e.g. there is a radiation solution ($w = 1/3$, $\lambda = 0$), with non-vanishing H-flux and frozen dilaton at late times. (SA, Cho, Franzmann, Mukohyama, Park; 2019)

- Einstein-frame scale factor w.r.t. conformal time η ($\mathrm{d}\eta \equiv \mathrm{d}t/a$),

$$\tilde{a}^2 = \frac{\tau(C_1 + \Omega_{\rm rad} H_0^2 \tau)}{1 + K\tau^2}\,; \qquad \tau = \begin{cases} \tan(\eta - \eta_0) & \text{for} \quad K = 1\,, \\ \eta - \eta_0 & \text{for} \quad K = 0\,, \\ \tanh(\eta - \eta_0) & \text{for} \quad K = -1\,. \end{cases}$$

- The dilaton profile is (c.f. $h = 0$: Copeland, Lahiri, Wands; 1994)

$$e^{2\phi} = \left(\frac{C_1 \tau}{\tau_* \left(C_1 + \Omega_{\rm rad} H_0^2 \tau\right)}\right)^{\pm\sqrt{3}} + \frac{1}{12}\frac{h^2}{C_1^2}\left(\frac{C_1 \tau}{\tau_* \left(C_1 + \Omega_{\rm rad} H_0^2 \tau\right)}\right)^{\mp\sqrt{3}}\,,$$

  which converges to a constant as $\eta \to \infty$ (for $K \in \{0, -1\}$).
- For nonzero h, the string-frame scale factor $a = \tilde{a}e^{\phi}$ has a minimum $\Rightarrow$ purely classical bouncing cosmology.

Cosmological perturbation variables

Scalar perturbations (and their origins):

Gravitational perturbations

- A (δg_{00}),
- B (δg_{i0}),
- C (δg_{ij}, traceful),
- E (δg_{ij}, traceless),
- f (B_{i0}),
- $\widehat{m}$ (B_{ij}),
- $\delta\phi$ (ϕ).

Matter perturbations

- $\delta\rho$ (δT_{00}),
- v (δT_{i0}),
- δp (δT_{ij}, traceful),
- π_{T} (δT_{ij}, traceless),
- $\mathcal{J}$ (Θ_{i0}),
- $\mathcal{I}$ (Θ_{ij}),
- $\delta\sigma$ (σ).

Vector perturbations: $\hat{B}_i$, $\hat{E}_i$, $\hat{f}_i$, $\hat{m}_i$; $\hat{v}^i$, $\hat{\pi}_i$, $\hat{\mathcal{J}}_i$, $\hat{\mathcal{I}}^i$.

Tensor perturbations: $\hat{E}_{ij}$; $\hat{\pi}_{ij}$.

Extra h- and $\widehat{m}$-dependent terms mix perturbation equations.

(SA, Mukohyama; 2024)

Perturbed conservation equations

There are also two non-trivial perturbed conservation equations, corresponding to the continuity equation and the Euler equation:

$$
\begin{aligned}
0 &= \delta\rho' + 3\mathcal{H}\,(\delta\rho + \delta p) + \bar{\phi}'\delta\sigma + \delta\phi'\bar{\sigma} - k^2\,(\bar{\rho} + \bar{p})\,v\,,\\
0 &= [(\bar{\rho} + \bar{p})\,(v + B)]' + 4\mathcal{H}\,[(\bar{\rho} + \bar{p})\,(v + B)]\\
&\quad + \delta p + (\bar{\rho} + \bar{p})\,A - \frac{2}{3}k^2\bar{p}\pi_{\mathrm{T}} + \frac{h}{a^4}\mathcal{I} - \bar{\sigma}\delta\phi\,.
\end{aligned}
$$

When $\bar{\sigma} = 0 = \delta\sigma$ and for $k \to 0$ (superhorizon limit), the former implies that adiabatic superhorizon perturbations are conserved.

However, when $\bar{\sigma}$ or $\delta\sigma$ are nonzero, this is no longer true in general. Nevertheless, under certain conditions (e.g. constant w and λ), a new conserved variable may be identified. (SA, Mukohyama; 2024)

Clustering in double field theory

Convenient to work in Einstein frame: conservation equations take the same form even though the variables are different, e.g. $\tilde{C} = C - \delta\phi$.

Use conformal time ($\tilde{N} = \tilde{a}$), Newtonian gauge ($B = 0$, $E = 0$). If anisotropic strain vanishes ($\pi_{\mathrm{T}} = 0$), trace-free EDFE implies $\tilde{A} = -\tilde{C}$ (c.f. in Bardeen variables: $\Psi = \Phi$).

Combining the continuity and Euler equations gives (subhorizon limit):

$$\tilde{\delta}'' + \left[(1 - 3\tilde{w})\,\tilde{\mathcal{H}} - \tilde{\lambda}\bar{\phi}'\right]\tilde{\delta}' + \tilde{c}_{\mathrm{s}}^2 k^2 \tilde{\delta} - \frac{h}{\tilde{a}^4} k^2 \left(\frac{\mathcal{I}}{\bar{\tilde{\rho}}}\right) = k^2 \left[(1 + \tilde{w})\,\tilde{C} + \tilde{\lambda}\delta\phi\right] ,$$

where the sound speed and equation-of-state parameters satisfy

$$\delta\tilde{p} = \tilde{c}_{\mathrm{s}}^2 \delta\tilde{\rho} \,, \qquad \tilde{w} = w \,, \qquad \tilde{\lambda} = \lambda - 1 + 3w \,.$$

If dilaton fluctuations are suppressed, $\tilde{\delta} = \delta + 4\delta\phi \simeq \delta$ (string frame).

Clustering in double field theory: examples

We can consider fluctuation evolution on different matter backgrounds. Assume a generalized perfect fluid ($\tilde{c}_{\mathrm{s}}^2 = \tilde{w}$, $\tilde{\lambda}$ constant) and $\mathcal{I} = 0$.

- 'Critical' (GR-like) matter: $\tilde{w} = \tilde{c}_{\mathrm{s}}^2 = 0$, $\tilde{\lambda} = 0$ ($\lambda = 1$): the DFT Poisson equation in the subhorizon limit gives standard growth,

$$\tilde{\delta}''_{\mathrm{m}} + \tilde{\mathcal{H}}\tilde{\delta}'_{\mathrm{m}} = -D^2\tilde{C} \simeq 4\pi G\tilde{a}^2\bar{\tilde{\rho}}_{\mathrm{m}}\tilde{\delta}_{\mathrm{m}}\,.$$

- Scalar-type matter: $\tilde{w} = \tilde{c}_{\mathrm{s}}^2 = 0$, $\tilde{\lambda} = -1$ ($\lambda = 0$):

$$\tilde{\delta}''_{\mathrm{s}} + \left(\tilde{\mathcal{H}} + \bar{\phi}'\right)\tilde{\delta}'_{\mathrm{s}} = -D^2\tilde{C} + D^2\delta\phi \simeq 8\pi G\tilde{a}^2\bar{\tilde{\rho}}_{\mathrm{s}}\tilde{\delta}_{\mathrm{s}}\,.$$

Thus we see that clustering may be enhanced depending on the dilaton pressure σ of the matter in question.
(SA, Cho, Jang, Park, Pookkillath; in progress)

Maxwell theory in DFT

$\mathbf{O}(D, D)$-covariant Maxwell theory couples to the dilaton, e.g. in $D = 4$:

$$S_\gamma = \int \mathrm{d}^4 x \sqrt{-g} \left[-\frac{1}{4} e^{-2\phi} F^{\mu\nu} F_{\mu\nu} \right] .$$

Note: Maxwell Lagrangian is Weyl-invariant in $D = 4$, so the same coupling is present both in string frame and Einstein frame.

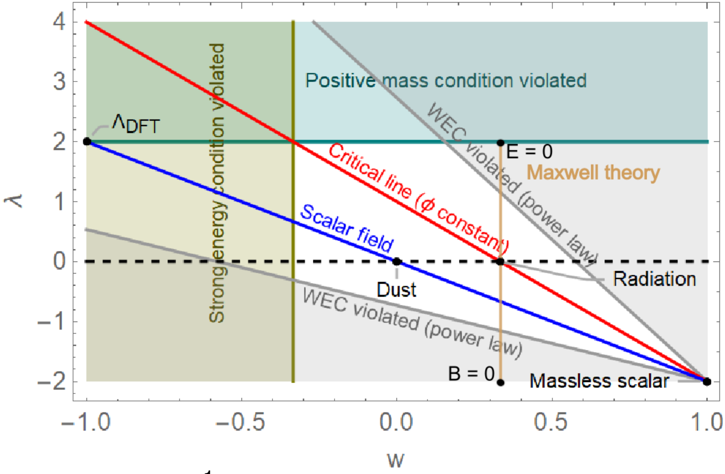
On cosmological backgrounds, the dilaton stress-energy is

$$\sigma_\gamma = \frac{1}{2} e^{-2\phi} F^{\mu\nu} F_{\mu\nu} = \frac{1}{N^2 a^2} B_k B^k - \frac{1}{a^4} E^k E_k ,$$

where $F_{i0} \equiv E_i$ and $F_{ij} \equiv \sqrt{g_{(3)}} \epsilon_{ijk} B^k$ are the electric/magnetic fields.

$\sigma_\gamma = 0$ when $E_i = B_i \Rightarrow$ radiation solution on critical line.

Maxwell theory in DFT



Maxwell theory: $w = \frac{1}{3}$ and $-2 \leq \lambda \leq -2$; if $E = B$, $\lambda = 0$ (radiation).

Luminosity distance

Consider isotropic radiation emission in an expanding universe.

In the case of GR, energy-momentum conservation ($0 = \nabla_\mu T^\mu{}_\nu$) can be used to relate the emitted luminosity to the observed Poynting flux:

$$S^r_{\rm obs} = \frac{a^2_{\rm em} L_{\rm em}}{4\pi a^4_{\rm obs} r^2_{\rm obs}} = \frac{L_{\rm em}}{4\pi d^2_{\rm L}}\,, \qquad d_{\rm L} \equiv \frac{a^2_{\rm obs}}{a_{\rm em}} r_{\rm obs}\,,$$

where $d_{\rm L}$ is the luminosity distance.

However, in DFT the photon evolution is modified by a varying dilaton, which couples differently to the electric and magnetic energy densities.
$\rightarrow$ Possible implications for cosmological distance measurements?
(SA, Cho, Jang, Park; in progress)

Riemannian vs. non-Riemannian

DFT turns out to be more general than just a theory of $\{g_{\mu\nu}, B_{\mu\nu}, \phi\}$.

- DFT also has non-Riemannian solutions. (Morand, Park; 2018)
- In such cases the usual inverse spacetime metric becomes degenerate, and hence the corresponding metric would be singular. However there is no singularity in the DFT metric $\mathcal{H}$.
- Maximally non-Riemannian solutions, $\mathcal{H}_{AB} = \pm\mathcal{J}_{AB}$, are fully $\mathbf{O}(D, D)$-symmetric (their moduli space is trivial).

Factoring out the B-field, a generic non-Riemannian solution is

$$\mathcal{H}_{AB} = \begin{pmatrix} \delta^{\mu}{}_{\rho} & 0 \\ B_{\mu\rho} & \delta_{\mu}{}^{\rho} \end{pmatrix} \begin{pmatrix} H^{\rho\sigma} & Z^{\rho}{}_{\sigma} \\ Z_{\rho}{}^{\sigma} & M_{\rho\sigma} \end{pmatrix} \begin{pmatrix} \delta_{\sigma}{}^{\nu} & -B_{\sigma\nu} \\ 0 & \delta^{\sigma}{}_{\nu} \end{pmatrix},$$

where $H^{\mu\nu}$ and $M_{\mu\nu}$ are degenerate, with $n + \bar{n}$ null eigenvectors $\{X^i, \bar{X}^{\bar{\imath}}\}$ and $\{Y_i, \bar{Y}_{\bar{\imath}}\}$, respectively, and $Z_{\mu}{}^{\nu} \equiv X^i_{\mu} Y^{\nu}_i - \bar{X}^{\bar{\imath}}_{\mu} \bar{Y}^{\nu}_{\bar{\imath}}$.

A different initial singularity

It turns out that certain Riemannian singularities can be identified as fully regular non-Riemannian geometries. (Morand, Park, Park; 2021)

For bouncing cosmological solutions, e.g. the DFT vacuum with negative spatial curvature ($K = -1$), the scale factor in string frame is

$$a^2 = \frac{C_1 \tau}{1 - \tau^2} \left[\left(\frac{\tau}{\tau_*} \right)^{\sqrt{3}} + \frac{h^2}{12 C_1^2} \left(\frac{\tau}{\tau_*} \right)^{-\sqrt{3}} \right], \qquad \tau \equiv \tanh(\eta - \eta_0) \,.$$

Tracing the solution backwards in conformal time η, we see that due to the h-dependent term, the scale factor diverges at a finite time in the past ($\eta = \eta_0$), in a time-reversed 'Big Rip' scenario (a 'Big Stitch-Up'?).

The inverse metric becomes degenerate at the initial singularity
$\Rightarrow$ non-Riemannian geometry? (SA, Jang, Park; in progress)

Summary

- Double field theory coupled to matter gives a 'stringy' modified gravity; **O**(D, D) symmetry constrains the allowed interactions, and the energy-momentum tensor includes sources for $B_{\mu\nu}$ and ϕ.
- DFT cosmology gives the **O**(D, D) completion of the Friedmann equations. Bouncing universe solutions can include radiation, non-vanishing H-flux, and frozen dilaton at late times.
- Clustering of matter may be enhanced depending on the dilaton pressure σ of the matter (arising from its coupling to the dilaton).
- Photons in DFT generically couple to the dilaton, which may have implications for luminosity distance measurements.
- DFT also encompasses non-Riemannian geometries, in which the usual spacetime metric diverges but DFT remains regular. This may include initial singularities of bouncing universes in DFT.