Nonlocal Cosmology

arXiv:1401.0254

arXiv:0705.0153 & 1307.6693 (Deser)

arXiv:0904.0961 (Deffayet)

Problem: What is making the universe accelerate?

- FLRW: $ds^2 = -dt^2 + a^2(t)\, d\boldsymbol{x} \cdot d\boldsymbol{x}$
  - ❖ $H(t) \equiv \frac{\dot{a}}{a}$ ➔ $H_0 \sim 68\ \frac{\text{km}}{\text{s-Mpc}}$
  - ❖ $q(t) \equiv -1 - \frac{\dot{H}}{H^2}$ ➔ $q_0 \sim -.54$
- General Relativity with $\frac{a_0}{a(t)} \equiv 1 + z$
  - ❖ $3H^2 = 3H_0^2\, [\Omega_r\, (1+z)^4 + \Omega_m\, (1+z)^3 + \Omega_\Lambda]$
  - ❖ $-2\dot{H} - 3H^2 = 3H_0^2\, [⅓\Omega_r\, (1+z)^4 + 0 - \Omega_\Lambda]$
- ΛCDM works
  - ❖ But why is $G\Lambda$ so small and why dominant NOW?
- Scalar quintessence works, but also unnatural
- $f(R)$ models don't really work (arXiv:1005.2205)

Modifications of Gravity

- $f(R)$ only local, invariant, stable & $g_{\mu\nu}$-based
- Retain locality and sacrifice invariance
  - ❖ Horava gravity
  - ❖ Massive gravitons
- Retain invariance and sacrifice locality for:
  - ❖ Summing QIR effects from primordial inflation
  - ❖ Explaining late time acceleration w/o Dark Energy
  - ❖ Explaining galactic structure w/o Dark Matter

Newton was against nonlocality

- I agree
  - Fundamental theory is local
  - But quantum effective field equations are not
  - $M = 0$ loops could give big IR corrections
- Primordial Inflation ➔ IR gravitons
  - $N(t,k) = \left[\frac{Ha(t)}{2ck}\right]^2$ for EVERY wave vector
  - Perhaps their attraction stops inflation
  - Late time modifications from vacuum polarization
  - Would affect large scales most
- But for now, just model-building

Late-Time Acceleration (arXiv:0705.0153 with Deser)

- Nonlocality via $\frac{1}{\Box}$ for $\Box \equiv \frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}\,g^{\mu\nu}\partial_\nu\right)$
  - ❖ Retarded BC ➔ both $\frac{1}{\Box}$ and $\partial_t \frac{1}{\Box}$ vanish at $t = 0$
- Act it on R ➔ $X \equiv \frac{1}{\Box} R$ is dimensionless
- $\mathcal{L} = \frac{R[1+f(X)]\sqrt{-g}}{16\pi G}$
  - ❖ $f(X)$ the "nonlocal distortion function"
- Field equations: $G_{\mu\nu} + \Delta G_{\mu\nu} = 8\pi G T_{\mu\nu}$

$$\Delta G_{\mu\nu} = \left[G_{\mu\nu} + g_{\mu\nu}\Box - D_\mu D_\nu\right]\left(f(X) + \frac{1}{\Box}[Rf'(X)]\right)$$

$$+ \left[\delta_\mu^{(\rho}\delta_\nu^{\sigma)} - \tfrac{1}{2} g_{\mu\nu} g^{\rho\sigma}\right]\partial_\rho X\, \partial_\sigma\left(\frac{1}{\Box}[Rf'(X)]\right)$$

- Causal and conserved

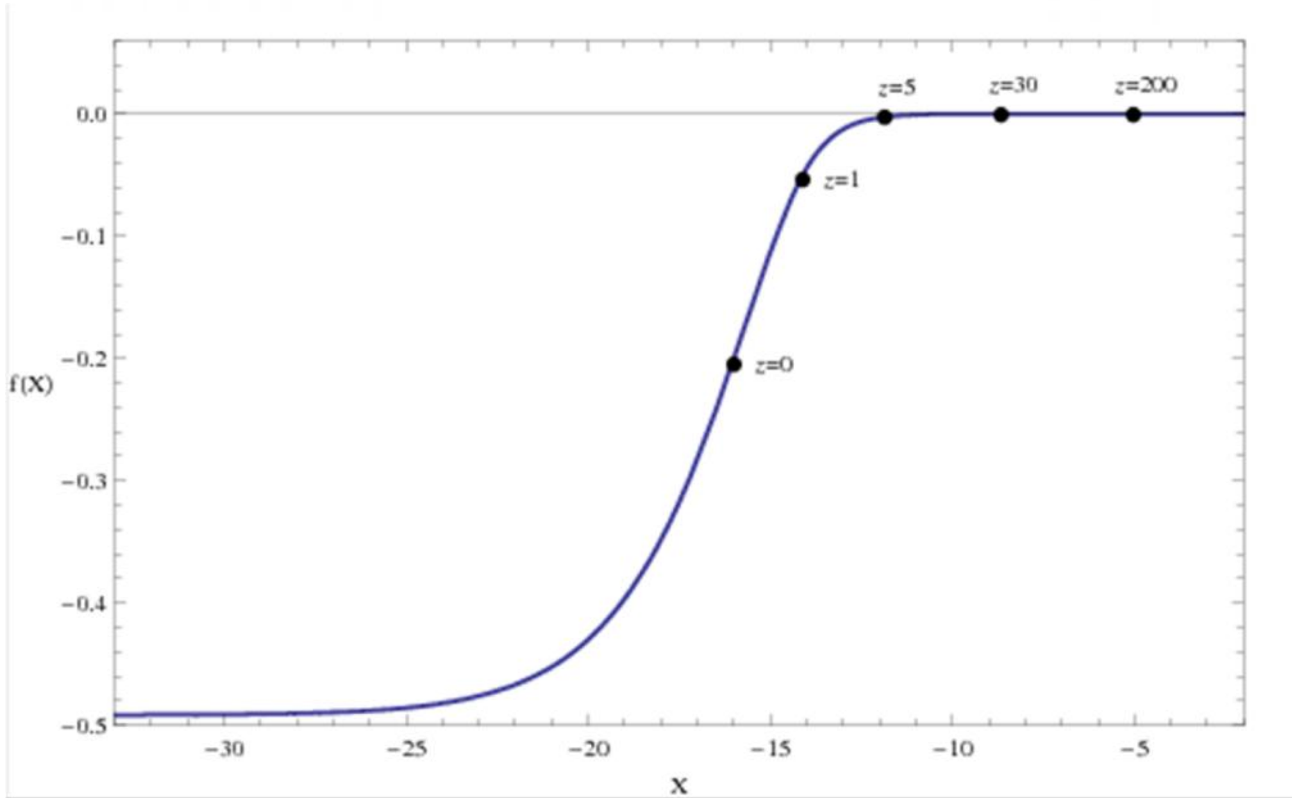
Specialization to FLRW:

$$ds^2 = -dt^2 + a^2(t)d\boldsymbol{x} \cdot d\boldsymbol{x}$$

- $R = 6\dot{H} + 12H^2$
- $\left[\frac{1}{\Box} f\right](t) = -\int_0^t \frac{dt'}{a^3(t')} \int_0^{t'} dt''\, a^3(t'') f(t'')$
- Two Built-In Delays:
  - ❖ $R = 0$ during Radiation domination $\left(H = \frac{1}{2t}\right)$
    - ➔ No modification until $t_{eq} \sim 10^5$ years
  - ❖ $X = \frac{1}{\Box} R \sim -\frac{4}{3} \ln\left(\frac{t}{t_{eq}}\right)$ during Matter domination
    - ➔ $X \sim -15$ at $t \sim 10^{10}$ years

Reconstructing ΛCDM (arXiv:0904.0961 with Deffayet)

$$f(X) \approx ¼\left[tanh\left(\frac{X}{3} + \frac{11}{2}\right) - 1\right]$$



Screening

- Solar system a problem for $f(R)$ models
  - $R > 0$ for cosmology AND solar system
  - Need "screening mechanism" to suppress deviations inside solar system
- $f\left(\frac{1}{\square}R\right)$ models avoid this problem
  - $\square \sim -\partial_t^2 + \nabla^2$ ➔ $\frac{1}{\square}$ provides a ± sign
    - $\frac{1}{\square}R < 0$ for cosmology
    - $\frac{1}{\square}R > 0$ for gravitationally bound systems
  - $f(X) = 0$ for $X > 0$ means NO solar system changes

Local Version Is Haunted (Nojiri & Odintsov, arXiv:0708.0924)

- $R\left[1 + f\left(\frac{1}{\Box}R\right)\right]$ ➔ $R[1 + f(\phi)] + \xi[\Box\phi - R]$
  - ❖ Varying with respect to ξ enforces $\phi = R$
  - ❖ NB both scalars have 2 pieces of initial value data
- $\xi\Box\phi \rightarrow -\partial_\mu\xi\partial_\nu\phi g^{\mu\nu}$
  $= -\frac{1}{4}\partial_\mu(\xi + \phi)\partial_\nu(\xi + \phi)g^{\mu\nu} + \frac{1}{4}\partial_\mu(\xi - \phi)\partial_\nu(\xi - \phi)g^{\mu\nu}$
- $\xi - \phi$ has negative kinetic energy
- Mixing with gravity doesn't help

No new initial value data for the original nonlocal version

- Synchronous gauge: $ds^2 = -dt^2 + h_{ij}(t, \boldsymbol{x}) d\boldsymbol{x}^i d\boldsymbol{x}^j$
- GR initial value data: $h_{ij}(0, \boldsymbol{x})$ & $\dot{h}_{ij}(0, \boldsymbol{x}) = 6 + 6$
  - ❖ 4+4 constrained fields
  - ❖ 2+2 dynamical gravitons
- NC initial value data ➔ count the ∂_t's
  - ❖ $R \sim \partial_t^2$ & $\frac{1}{\square} \sim \frac{1}{\partial_t^2}$ ➔ $\frac{1}{\square} R \sim (\partial_t)^0$
  - ❖ $\Delta G_{\mu\nu}$ has up to $\partial_t^2 \frac{1}{\square}$ ➔ only $h_{ij}(0, \boldsymbol{x})$ and $\dot{h}_{ij}(0, \boldsymbol{x})$
- Same initial value constraints as GR
- No graviton ever becomes a ghost

A problem with how the model reproduces ΛCDM without Λ

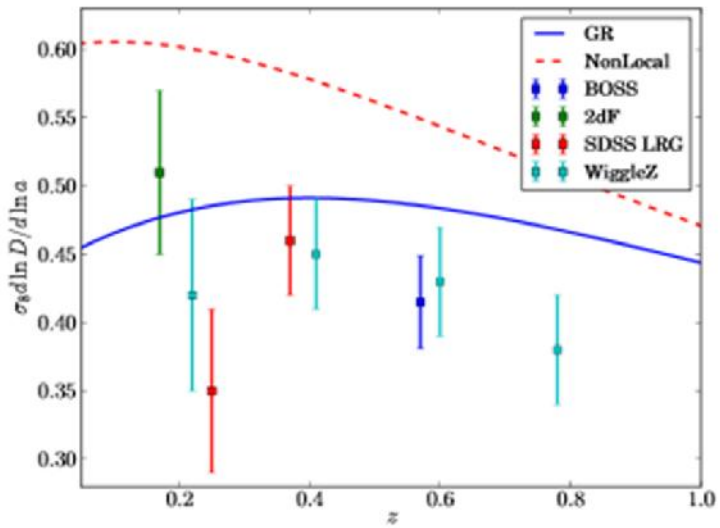
- For FLRW with slowly varying $H(t)$
  - ❖ $G_{\mu\nu} + \Delta G_{\mu\nu} \approx \left\{1 + f(X) + \frac{1}{\Box}[Rf'(X)]\right\} G_{\mu\nu} = 8\pi G T_{\mu\nu}$
- This is effectively a time-varying Newton constant
  - ❖ $G_{eff}(t) = \frac{G}{1+f(X)+\frac{1}{\Box}[Rf'(X)]}$
  - ❖ Balances the Friedmann Eqn: $3H^2 \approx 8 \;\; G_{eff}(t) \times \frac{\rho_m}{a^3(t)}$
- But $G_{eff}(t)$ also strengthens the force of gravity
  - ❖ Not relevant for solar system
  - ❖ Should increase structure formation
  - ❖ Dodelson & Park have confirmed this, & it's bad

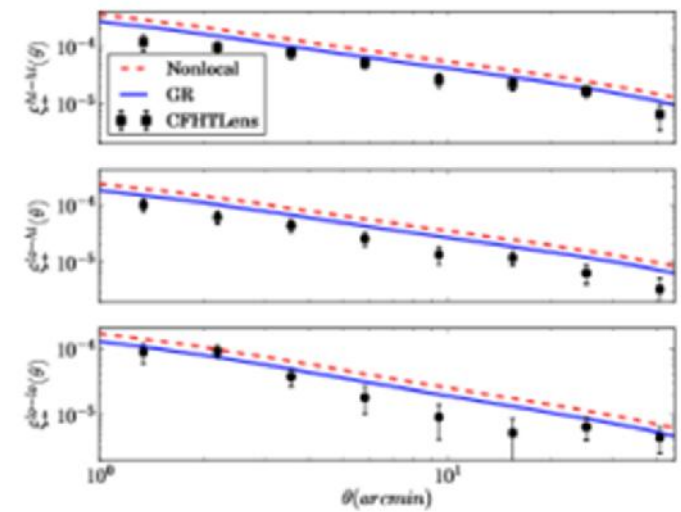
What Dodelson and Park Found

$$ds^2 = -\left[1 + 2\Psi(t)e^{i\mathbf{k}\cdot\boldsymbol{x}}\right]dt^2 + a^2(t)\left[1 + 2\Phi(t)e^{i\mathbf{k}\cdot\boldsymbol{x}}\right]d\boldsymbol{x}\cdot d\boldsymbol{x}$$

- Nonlocal Cosmology predicts:
  - ❖ $\Phi(t) \sim \Phi_{GR}$ throughout
  - ❖ $\Psi(t) \neq \Psi_{GR}$ by $z{\sim}1.5$ and $\Psi(t_0){\sim}2 \times \Psi_{GR}$
- Relevant data sets:
  - ❖ WiggleZ, 2dF, BOSS, SDSS LRG's (redshift space dist.)
  - ❖ CFHTLens (weak lensing)
- Preference of GR over Nonlocal Cosmology:
  - ❖ Redshift space distortions → 7.8σ
  - ❖ Weak lensing → 5.9σ
- Data favors a less highly evolved universe

Most data below BOTH Nonlocal Cosmology & General Relativity





Conclusions

- Nonlocal gravity not fundamental
  - ❖ Infrared QG corrections from primordial inflation
  - ❖ Purely phenomenological for now
- Simplest model based on $Rf\left(\frac{1}{\Box}R\right)$
  - ❖ Built-in delays explain cosmic coincidence
  - ❖ Simple $f(X)$ reproduces ΛCDM without Λ
  - ❖ But structure formation heavily favors GR
- Probably BETTER than GR with 2nd invariant
- Desirable properties
  - ❖ Perfect screening for gravitationally bound systems
  - ❖ No new degrees of freedom
  - ❖ Initial value constraints identical to GR
  - ❖ No kinetic energy instabilities