Cosmic Acceleration without Dark Energy

Justin Khoury (U. Penn)

with Lasha Berezhiani & Junpu Wang,
1612.00453

The dual roles of acceleration

1. Expansion history (geometry)

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left(\frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\Omega^2\right)$$

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$$\boxed{\frac{\mathrm{d}^2\delta_\mathrm{m}}{\mathrm{d}t^2} + 2H(a)\frac{\mathrm{d}\delta_\mathrm{m}}{\mathrm{d}t} = 4\pi G_\mathrm{N}\rho_\mathrm{m}(a)\delta_\mathrm{m}}$$

$$\delta_\mathrm{m} \equiv \frac{\delta\rho_\mathrm{m}}{\rho_\mathrm{m}}$$

cf. Lam's lecture

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"damping" due to cosmic expansion

Jeans instability

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- Matter-dominated:

$$\delta_\mathrm{m} \sim a$$

- Accelerating universe:

$$\delta_\mathrm{m} \sim a\, g(a)$$

$$g(a) \equiv \exp\left(\int_0^a \mathrm{d}\ln a\left[\Omega_\mathrm{m}(a)^{0.545} - 1\right]\right)$$

Linder (2005)

The Folk Theorem

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Cosmic Acceleration

Dark Energy
(Negative pressure)

Modified Gravity
($\Longrightarrow$ new degrees of freedom)

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JK, Miller & Tolley, 1108.1397; 1305.0822

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- Spatial diffs
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- 2 transverse, traceless gravitons

Focus on unit-determinant 3-metric: $\boxed{\tilde{h}_{ij} \qquad \det \tilde{h} = 1}$

First-class constraints: $\{\tilde{\mathcal{H}}_i, \tilde{\mathcal{H}}_j\} \sim 0$

Preserved under time-evolution: $\dot{\tilde{\mathcal{H}}}_i \sim 0$

$\Longrightarrow$ Only possibility is GR! *

* Technical assumption: dependence on spatial gradients only through $R^{(3)}$.

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Symmetron

The Hubble constant

Planck (somewhat indirect)

Aghanim et al. (2016)

$$H_0^{\Lambda\mathrm{CDM}} = 66.93 \pm 0.62 \ \mathrm{km\ s^{-1}Mpc^{-1}}$$

Local (direct)

Riess et al. (2016)

$$H_0^{\mathrm{direct}} = 73.24 \ \pm \ 1.74 \ \mathrm{km\ s^{-1}Mpc^{-1}}$$

Unified Dark Matter/Dark Energy?

Chaplygin gas

Bilic, Tupper & Viollier (2002);
Bento, Bertolami & Sen (2002)

Dark matter with exotic equation of state:

$$P \sim -\frac{1}{\rho^{\alpha}}$$

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Dark matter with exotic equation of state:

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- Early times/high density: $P \simeq 0$ (non-relativistic fluid)
- Late times/low density: $P < 0$ (cosmic acceleration)

$\therefore$ A single fluid behaves as a dust fluid at early times and as dark energy at late times.

Chaplygin growth of perturbations

$$\ddot{\delta}_k + H\dot{\delta}_k[2 - 3(2w - c_s^2)] - \frac{3}{2}H^2\delta_k\left[1 - 6c_s^2 - 3w^2 + 8w\right] = -\left(\frac{kc_s}{a}\right)^2\delta_k$$

where $c_s^2(a) = \frac{\mathrm{d}P}{\mathrm{d}\rho} = -\alpha w(a)$

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$$\alpha \lesssim 10^{-5}$$

Sandvik, Tegmark,
Zaldarriaga & Waga (2002)

To salvage model, need $c_s^2 \neq \frac{\mathrm{d}P}{\mathrm{d}\rho}$, but this requires new degree of freedom.

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- NO dark energy (or negative pressure)

- NO new degrees of freedom (just baryons and DM)

Agnostic about microphysical nature of DM (e.g. WIMPS, axions, ultra-light scalar DM, superfluid...)

The Basic Idea

Set Up

Easiest to describe theory in `Einstein-frame':

$$\boxed{\mathcal{L} = \frac{\sqrt{-g}R}{16\pi G_{\rm N}} + \mathcal{L}_{\rm DM}[g_{\mu\nu}] + \mathcal{L}_{\rm b}[\tilde{g}_{\mu\nu}]}$$

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The physical metric $\tilde{g}_{\mu\nu}$ will be constructed out of $g_{\mu\nu}$ and DM quantities (energy density, 4-velocity).

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- Interested in large/linear scale evolution, where dissipation is negligible $\Longrightarrow$ perfect fluid
- Ignore vorticity $\Longrightarrow$ superfluid

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Effective Description of Superfluids

Greiter, Wilczek & Witten (1989)

Superfluid phase is defined as:

- Global U(1) symmetry, spontaneously broken

$\Longrightarrow$ Goldstone boson $\theta \to \theta + c$

- State has finite charge density, $\langle J^0 \rangle \sim \langle \dot{\theta} \rangle \neq 0$

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Hence, at lowest order in derivatives the EFT of phonons is

$$\mathcal{L}_{\rm DM} = \sqrt{-g} P(X) \; ; \quad X = -g^{\mu\nu} \partial_\mu \theta \partial_\nu \theta$$

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is perfect fluid form with

- Energy density: $\rho_{\rm DM} = 2P_{,X}(X)X - P(X)$
- Pressure: $P_{\rm DM} = P(X)$
- 4-velocity: $u_\mu = -\frac{1}{\sqrt{X}}\partial_\mu\theta$

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In short: $X \longleftrightarrow \rho_{\rm DM}$

Assume (as usual) that DM is nearly pressureless ($P_{\rm DM} \ll \rho_{\rm DM}$)

e.g. $$P(X) \sim X^{\frac{1}{2w}}\ ; \qquad w \ll 1$$

Baryons

$$\mathcal{L} = \frac{\sqrt{-g}R}{16\pi G_{\rm N}} + \mathcal{L}_{\rm DM}[g_{\mu\nu}] + \mathcal{L}_{\rm b}[\tilde{g}_{\mu\nu}]$$

Effective metric $\tilde{g}_{\mu\nu}$ is constructed from $g_{\mu\nu}$ and DM quantities, namely u_μ and $\rho_{\rm DM}(X)$ (or equivalently X).

$$\tilde{g}_{\mu\nu} = -Q^2(X)u_\mu u_\nu + R^2(X)\left(g_{\mu\nu} + u_\mu u_\nu\right)$$

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Particle Physics Model

Can put theory in more familiar form by `integrating in' massive scalar field ϕ and vector field A_μ. Suppose DM is fermion ψ .

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Integrate out scalar and vector:

$$\boxed{\begin{aligned} \phi &= \frac{m_\psi}{M m_\phi^2}\langle\bar{\psi}\psi\rangle \quad \sim \quad \rho_{\rm DM} \\ A^\mu &= \frac{\alpha}{m_A^2}\langle\bar{\psi}\gamma^\mu\psi\rangle \quad \sim \quad u^\mu \end{aligned}}$$

Substitute back $\Longrightarrow$ recover our model (+ small corrections)

Direct detection

Baryon-DM coupling leads to potentially detectable direct detection signals.

$$\mathcal{L}_{\rm eff} \sim G_{\rm F}^{\varphi} \bar{\psi}\psi\bar{b}b + G_{\rm F}^{a} \bar{\psi}\gamma^i\psi\bar{b}\gamma_i b$$

$$G_{\rm F}^{\varphi} = 2c_{\rm DM}^2 \frac{{\rm d}\ln Q}{{\rm d}\ln X}\frac{m_\psi m_{\rm b}}{\rho_{\rm DM}}\,; \qquad G_{\rm F}^{a} = \frac{Q^2 - R^2}{R^2 Q^2}\frac{m_\psi m_{\rm b}}{\rho_{\rm DM}}$$

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Suppressed by DM density

Signal is model-dependent, but is tied to cosmic evolution at high redshift.

$$\rho_{\rm DM}^{\rm local} \simeq \rho_{\rm DM}^{\rm cosmic}(z \simeq 50)$$

Cosmological Predictions

Acceleration without Dark Energy

Dark matter experiences (decelerating) matter-dominated expansion

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Toy model:

$$\boxed{a(\tilde{a}) = \tilde{a} + \alpha\tilde{a}^2 + \beta\tilde{a}^3}$$

2 parameters

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- Angular-diameter distance to CMB fixes H_0

Consider $67.5 \lesssim H_0 \lesssim 74.1$

agrees with Planck

agrees with HST

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Intuition: The Einstein-frame universe is younger, hence its structures appear (to a baryon observer) underdeveloped.

Structure seen by baryons after 14 billion years.

Structure of pure CDM universe of same age.

Stability

Baryon-DM coupling results in kinetic mixing between $\delta_{\rm b}$ and $\delta_{\rm DM}$.
After diagonalization, find:

$$\boxed{\omega^2 = 0}$$

$P_{\rm b} = 0$

and

$$\boxed{\omega^2 = \frac{P_{,X} - \frac{\Lambda_{\rm b}^4}{2R^2 X}(Q - 2XQ_{,X})(R^2 - Q^2 + 2XQQ_{,X})}{P_{,X} + 2XP_{,XX} - \Lambda_{\rm b}^4\,(Q_{,X} + 2XQ_{,XX})}\,k^2}$$

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- e.g., Conformal coupling: $Q(X) = R(X)$

$$\Longrightarrow \quad c_s^2 \sim \frac{\rho_{\rm b}}{\rho_{\rm DM}} \quad \text{at late times}$$

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Same issue as Chaplygin

- e.g., Pressure coupling: $Q(X) = 1$

$$\Longrightarrow \quad \boxed{c_s^2 \sim \frac{\rho_\gamma}{\rho_{\rm DM}}} \quad \text{at late times}$$

Potentially observable!

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Planck: $\sigma_8 = 0.831 \pm 0.013$

$$H_0^{\Lambda\rm CDM} = 66.93 \pm 0.62$$

HST: $H_0^{\rm direct} = 73.24 \pm 1.74$

Redshift-space distortions

Sensitive to the rate function

$$f \equiv \frac{\mathrm{d}\ln a}{\mathrm{d}\ln \tilde{a}} = 1 - \frac{\mathrm{d}\ln R}{\mathrm{d}\ln \tilde{a}}$$

Integrated Sachs-Wolfe Effect

$$\left(\frac{\delta T}{T}\right)_{\rm ISW} = \int_{\tau_{\rm rec}}^{\tau_0} {\rm d}\tau \frac{\partial}{\partial \tau}(\Phi + \Psi)$$

- During matter-domination, $\Phi + \Psi = \text{const.}$
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$$\therefore \quad (\Phi + \Psi)_{\rm eff} = \Phi + \Psi + \mathcal{O}(1)\frac{\delta\rho_{\rm DM}}{\rho_{\rm DM}}$$

Too much ISW?!?

Scale dependence?!?

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- Sufficiently different $\Longrightarrow$ worth developing predictions

JK, Miranda & Solomon, in progress

- Opens door to unifying the (seemingly incongruous) phenomena of dark matter and cosmic acceleration

- Can generalize to use only fraction of DM, e.g. neutrinos, as agent of cosmic acceleration.

Berezhiani, Dvali, JK & Wang, in progress