Observables and Unobservables in Dark Energy Cosmologies

Kosmologietag

Bielefeld, 25 April 2013

Mariele Motta

Universität Heidelberg ITP

Unicamp IFGW

[ArXiv:1210.0439], (PRD 87, 023501 (2013))
[in preparation]

In collaboration with
L. Amendola, M. Kunz, I. Sawicki, I. Saltas

Dark Energy Cosmology

Dark Energy Cosmology

Relaxes assumptions behind ΛCDM

[$G_N = 1$
1 potential Ψ]

Dark Energy Cosmology

Relaxes assumptions behind ΛCDM

[$G_N = 1$
1 potential Ψ]

Changes background evolution

Dark Energy Cosmology

Relaxes assumptions behind ΛCDM [$G_N = 1$; 1 potential Ψ]

Changes background evolution

Introduces DE perturbations

Dark Energy Cosmology

Relaxes assumptions behind ΛCDM [$G_N = 1$ 1 potential Ψ]

Changes background evolution

Introduces DE perturbations

(we talk only about perturbation theory)

Dark Energy Cosmology

Relaxes assumptions behind ΛCDM [$G_N = 1$, 1 potential Ψ]

Changes background evolution

Introduces DE perturbations

(we talk only about perturbation theory)

Dark Energy configuration:

$$Y(k,a) \equiv -\frac{2k^2\Psi}{3\Omega_m\delta_m} = 1$$

Effective Newton's Constant

$$\eta(k,a) \equiv -\frac{\Phi}{\Psi} = 1$$

Slip parameter

Dark Energy Cosmology

Relaxes assumptions behind ΛCDM

[$G_N = 1$
1 potential Ψ]

Changes background evolution

Introduces DE perturbations

(we talk only about perturbation theory)

Dark Energy configuration:

$$Y(k,a) \equiv -\frac{2k^2\Psi}{3\Omega_\mathrm{m}\delta_\mathrm{m}} = 1$$

Effective Newton's Constant

$$\eta(k,a) \equiv -\frac{\Phi}{\Psi} = 1$$

Slip parameter

time- and scale-dependent
Gravitational coupling

2 potentials

to test for Dark Energy...

to test for deviations of

$$Y(k,a) \equiv -\frac{2k^2\Psi}{3\Omega_\mathrm{m}\delta_\mathrm{m}} = 1, \quad \eta(k,a) \equiv -\frac{\Phi}{\Psi} = 1$$

to test for Dark Energy...

to test for deviations of

$$Y(k,a) \equiv -\frac{2k^2\Psi}{3\Omega_{\mathrm{m}}\delta_{\mathrm{m}}} = 1, \quad \eta(k,a) \equiv -\frac{\Phi}{\Psi} = 1$$

Normal approach:

to test for Dark Energy...

to test for deviations of

$$Y(k,a) \equiv -\frac{2k^2\Psi}{3\Omega_\mathrm{m}\delta_\mathrm{m}} = 1, \quad \eta(k,a) \equiv -\frac{\Phi}{\Psi} = 1$$

Normal approach:

- assume a parameterization for free functions

to test for Dark Energy...

to test for deviations of

$$Y(k,a) \equiv -\frac{2k^2\Psi}{3\Omega_{\rm m}\delta_{\rm m}} = 1, \quad \eta(k,a) \equiv -\frac{\Phi}{\Psi} = 1$$

Normal approach:

- assume a parameterization for free functions
- evolve it in a modified code while fitting the data in a model- (paramaterization-) dependent way

a step back

What is observable without assuming a DE model?

a step back

Minimal of assumptions:

FLRW universe

$$\mathrm{d}s^2 = -(1+2\Psi)\mathrm{d}t^2 + a^2(t)(1+2\Phi)\mathrm{d}\boldsymbol{x}^2$$

Linear bias

$$\delta_{\mathrm{gal}} = b(k,a)\delta_m$$

Matter follow geodesics
and is pressureless

Equivalence principle holds:
no velocity bias

$$\theta_{gal} \simeq \theta_m$$

a step back

What can we observe?

Linear perturbations

Weak lensing

$$\kappa = \frac{1}{2}\int_0^{\chi_s} k^2(\Psi - \Phi)W(\chi, \chi_s)d\chi$$

Redshift-space distortions

$$\delta^z_{\rm gal}(k, z, \mu) = \delta_{\rm gal}(k, z) - \mu^2 \frac{\theta_{\rm gal}(k, z)}{a^2 H}$$

a step back

What can we observe?

Linear perturbations

Weak lensing

$$\kappa = \frac{1}{2}\int_0^{\chi_s} k^2(\Psi - \Phi) W(\chi, \chi_s) d\chi$$

Redshift-space distortions

$$\delta^z_{\rm gal}(k, z, \mu) = \delta_{\rm gal}(k, z) - \mu^2 \frac{\theta_{\rm gal}(k, z)}{a^2 H}$$

Galaxies follow geodesics

$$\left(a^2\theta_{\rm gal}\right)' = a^2 H k^2 \Psi$$

a step back

What can we observe?

Linear perturbations

Weak lensing

$$\kappa = \frac{1}{2}\int_0^{\chi_s} k^2(\Psi - \Phi) W(\chi, \chi_s) d\chi$$

Redshift-space distortions

$$\delta^z_{\rm gal}(k,z,\mu) = \delta_{\rm gal}(k,z) - \mu^2 \frac{\theta_{\rm gal}(k,z)}{a^2 H}$$

Galaxies follow geodesics

$$\left(a^2\theta_{\rm gal}\right)' = a^2 H k^2 \Psi$$

a step back

What can we observe?

Linear perturbations

Weak lensing

$$\kappa = \frac{1}{2}\int_0^{\chi_s} k^2(\Psi - \Phi)W(\chi,\chi_s)d\chi$$

Map out the metric!

Redshift-space distortions

$$\delta^z_{\rm gal}(k,z,\mu) = \delta_{\rm gal}(k,z) - \mu^2\frac{\theta_{\rm gal}(k,z)}{a^2H}$$

Galaxies follow geodesics

$$\left(a^2\theta_{\rm gal}\right)' = a^2Hk^2\Psi$$

What can we observe?

Redshift-space distortions

$$\delta^z_{\rm gal}(k,z,\mu) = \delta_{\rm gal}(k,z) - \mu^2 \frac{\theta_{\rm gal}(k,z)}{a^2 H}$$

a step back

What can we observe?

Redshift-space distortions

$$\delta^z_{\rm gal}(k,z,\mu) = \delta_{\rm gal}(k,z) - \mu^2 \frac{\theta_{\rm gal}(k,z)}{a^2 H}$$

+ Equivalence Principle

$$\theta_{gal} \simeq \theta_m$$

a step back

What can we observe?

Redshift-space distortions

$$\delta^z_{\rm gal}(k,z,\mu) = \delta_{\rm gal}(k,z) - \mu^2 \frac{\theta_{\rm gal}(k,z)}{a^2 H}$$

+ Equivalence Principle

$$\theta_{gal} \simeq \theta_m$$

+ Continuity Equation

$$\theta_m = -\delta'_m - 3\Phi'$$

a step back

What can we observe?

Redshift-space distortions

$$\delta^z_{\rm gal}(k,z,\mu) = \delta_{\rm gal}(k,z) - \mu^2\frac{\theta_{\rm gal}(k,z)}{a^2H}$$

+ Equivalence Principle

$$\theta_{gal} \simeq \theta_m$$

+ Continuity Equation

$$\left[\theta_m = -\delta'_m\right] - 3\Phi'$$

a step back

What can we observe?

Redshift-space distortions

$$\delta^z_{\rm gal}(k,z,\mu) = \delta_{\rm gal}(k,z) - \mu^2 \frac{\theta_{\rm gal}(k,z)}{a^2 H}$$

+ Equivalence Principle

$$\theta_{gal} \simeq \theta_m$$

+ Continuity Equation

$$\left[\theta_m = -\delta'_m\right] - 3\Phi'$$

Observation of $\delta'_{\rm m}$

Prezi

Observables:

$$\Psi \qquad \Phi \qquad \delta'_m$$

Prezi

Observables:

$$\Psi \qquad \Phi \qquad \delta'_m$$

ratios

Dark Energy Configuration:

$$Y(k,a) \equiv -\frac{2k^2\Psi}{3\Omega_{\mathrm{m}}\delta_{\mathrm{m}}}$$

$$\eta(k,a) \equiv -\frac{\Phi}{\Psi}$$

$$f \equiv \frac{\delta'_m}{\delta_m}$$

Observables:

$$\Psi \quad \Phi \quad \delta'_m$$

ratios

Dark Energy Configuration:

$$Y(k,a) \equiv -\frac{2k^2\Psi}{3\Omega_m \delta_m}$$

$$\eta(k,a) \equiv -\frac{\Phi}{\Psi}$$

$$f \equiv \frac{\delta'_m}{\delta_m}$$

Observables:

$$\Psi \quad \Phi \quad \delta'_m$$

ratios

Dark Energy Configuration:

$$Y(k,a) \equiv -\frac{2k^2\Psi}{3\Omega_m\delta_m}$$

$$\eta(k,a) \equiv -\frac{\Phi}{\Psi}$$

$$f \equiv \frac{\delta'_m}{\delta_m}$$

Anisotropic-stress is observable!

Observables:

$$\Psi \qquad \Phi \qquad \delta'_m$$

ratios

Dark Energy Configuration:

$$Y(k,a) \equiv -\frac{2k^2\Psi}{3\Omega_{\rm m}\delta_{\rm m}} \qquad \eta(k,a) \equiv -\frac{\Phi}{\Psi} \qquad f \equiv \frac{\delta'_m}{\delta_m}$$

Anisotropic-stress is observable!

Growth rate and Effective G, not!

Let's see what this can do for us...

Horndeski

$$\mathcal{L}_2 = K(\phi, X)\,,$$

$$\mathcal{L}_3 = -\,G_3(\phi, X)\Box\phi\,,$$

$$\mathcal{L}_4 = G_4(\phi, X)R + G_{4,X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right]\,,$$

$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{G_{5,X}}{6}\Big[(\Box\phi)^3 - \\ - 3\,(\Box\phi)\,(\nabla_\mu\nabla_\nu\phi)^2 + 2\,(\nabla_\mu\nabla_\nu\phi)^3\Big]\,.$$

Horndeski

$$\mathcal{L}_2 = K(\phi, X)\,,$$
$$\mathcal{L}_3 = -G_3(\phi, X)\Box\phi\,,$$
$$\mathcal{L}_4 = G_4(\phi, X)R + G_{4,X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right]\,,$$
$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{G_{5,X}}{6}\Big[(\Box\phi)^3 - 3\,(\Box\phi)\,(\nabla_\mu\nabla_\nu\phi)^2 + 2\,(\nabla_\mu\nabla_\nu\phi)^3\Big]\,.$$

the most general DE theory described by a single degree of freedom

Horndeski

equation of motion + constraints=

$$\eta\left(\frac{\Psi'}{\Psi}\right)' + \eta'' + \frac{\Psi'}{\Psi}\left(\eta\frac{\Psi'}{\Psi} + 2\eta' + \alpha_1\eta - \alpha_2\right) +$$

$$+ \alpha_1\eta' + \alpha_3\eta - \alpha_5 + k^2\left(\alpha_4\eta - \alpha_6\right) = \alpha_7\frac{3(1+z)^3\theta_{\rm m}}{2H^3k^2\Psi}\,.$$

Horndeski

equation of motion + constraints=

$$\eta\left(\frac{\Psi'}{\Psi}\right)' + \eta'' + \frac{\Psi'}{\Psi}\left(\eta\frac{\Psi'}{\Psi} + 2\eta' + \alpha_1\eta - \alpha_2\right) + \\ + \alpha_1\eta' + \alpha_3\eta - \alpha_5 + k^2\left(\alpha_4\eta - \alpha_6\right) = \alpha_7\frac{3(1+z)^3\theta_{\rm m}}{2H^3k^2\Psi}\,.$$

only 7 unknwon parameters

Horndeski

equation of motion + constraints=

$$\eta\left(\frac{\Psi'}{\Psi}\right)' + \eta'' + \frac{\Psi'}{\Psi}\left(\eta\frac{\Psi'}{\Psi} + 2\eta' + \alpha_1\eta - \alpha_2\right) + \\ + \alpha_1\eta' + \alpha_3\eta - \alpha_5 + k^2\left(\alpha_4\eta - \alpha_6\right) = \alpha_7\frac{3(1+z)^3\theta_{\rm m}}{2H^3k^2\Psi}\,.$$

only 7 unknwon parameters

By measuring potentials at different scales and redshift slices we can fully constrain this relation without assuming any parameterization

Summary

Summary

- minimal of assumptions

Summary

- **minimal of assumptions**
- **identify observable quantities**

$\Psi \quad \Phi \quad \delta'_m$

Summary

- minimal of assumptions
- identify observable quantities
- reconstruct the metric

$\Psi \quad \Phi \quad \delta'_m$

Prezi

Summary

- minimal of assumptions
- identify observable quantities $\Psi \quad \Phi \quad \delta'_m$
- reconstruct the metric

(δ_m is not observable)

Summary

- minimal of assumptions
- identify observable quantities $\Psi \quad \Phi \quad \delta'_m$
- reconstruct the metric

(δ_m is not observable)

- it is possible to constrain the most general theory for Dark Energy without parameterizing by measurements in different redshifts and scales

Summary

- minimal of assumptions
- identify observable quantities $\Psi \quad \Phi \quad \delta'_m$
- reconstruct the metric

(δ_m is not observable)

- it is possible to constrain the most general theory for Dark Energy without parameterizing by measurements in different redshifts and scales

thank you!