Phenomenology of the Accelerating Universe

Federico Piazza

Gubitosi, F. P., Vernizzi, 1210.0201
Gleyzes, Langlois, F.P., Vernizzi, 1304.4840
F. P., F. Vernizzi, 1307.4350
F. P., C. Marinoni, H. Steigerwald 1312.6111
Gleyzes, Langlois, F.P., Vernizzi, 1404.6495
In progress...

Paris Centre for Cosmological Physics

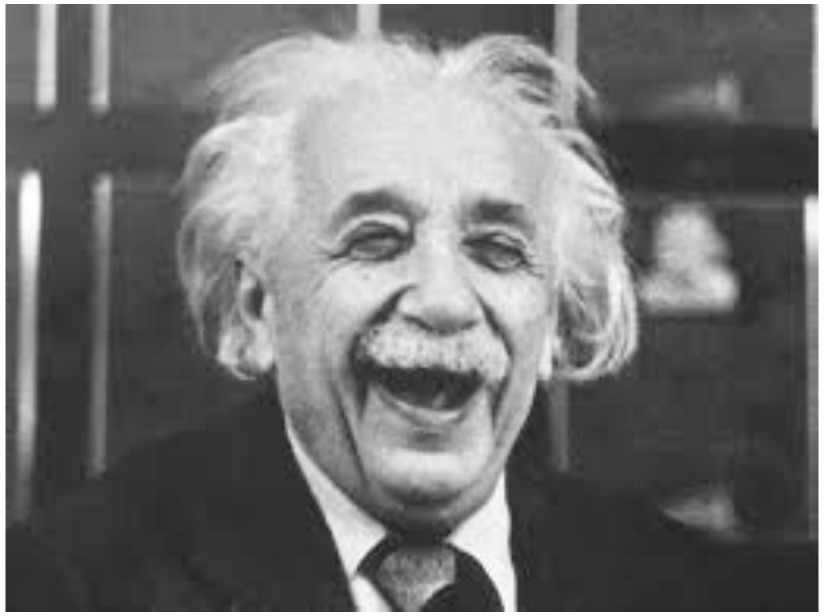
Nobel Prize in Physics 2011

The Universe is accelerating!

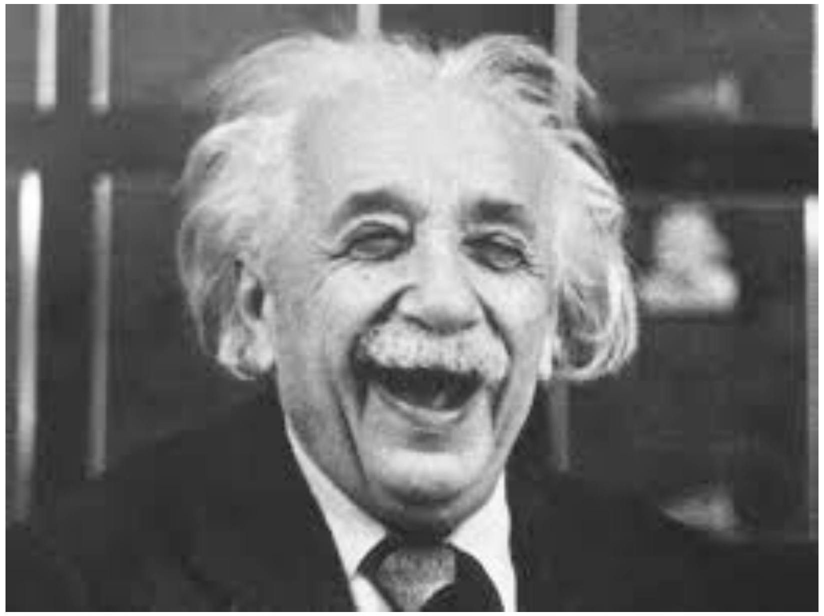
Nobel Prize in Physics 2011

The Universe is accelerating!

...why?!

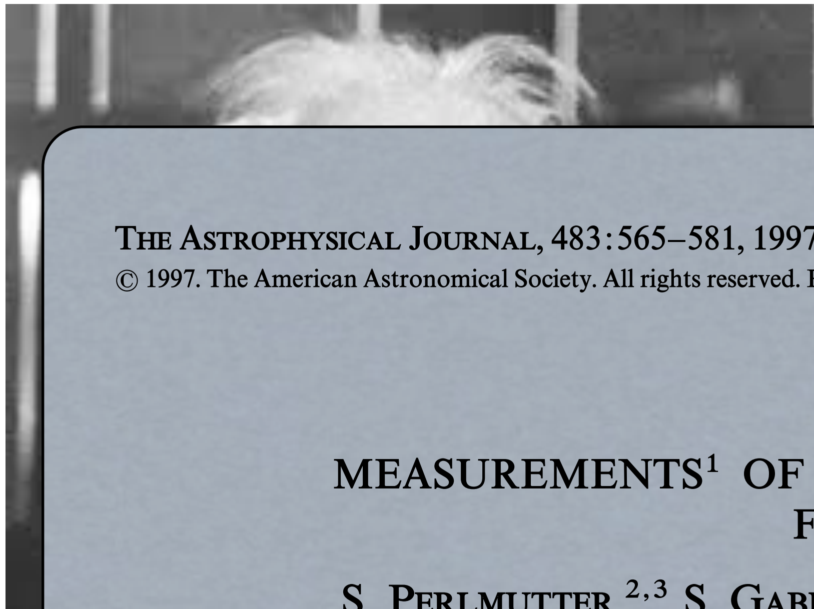


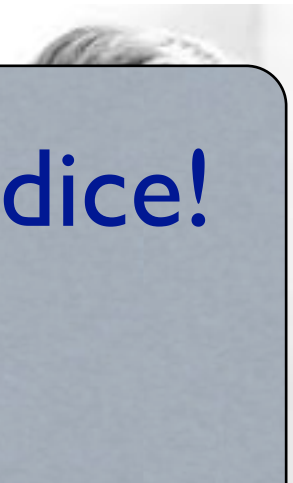
ΛCDM



ΛCDM

The only consistent
low energy theory for
a spin-two field $g_{\mu\nu}$.





THE ASTROPHYSICAL JOURNAL, 483:565–581, 1997 July 10

Beware of theoretical prejudice!

MEASUREMENTS[1] OF THE COSMOLOGICAL PARAMETERS Ω AND Λ FROM THE FIRST SEVEN SUPERNOVAE AT $z \geq 0.35$

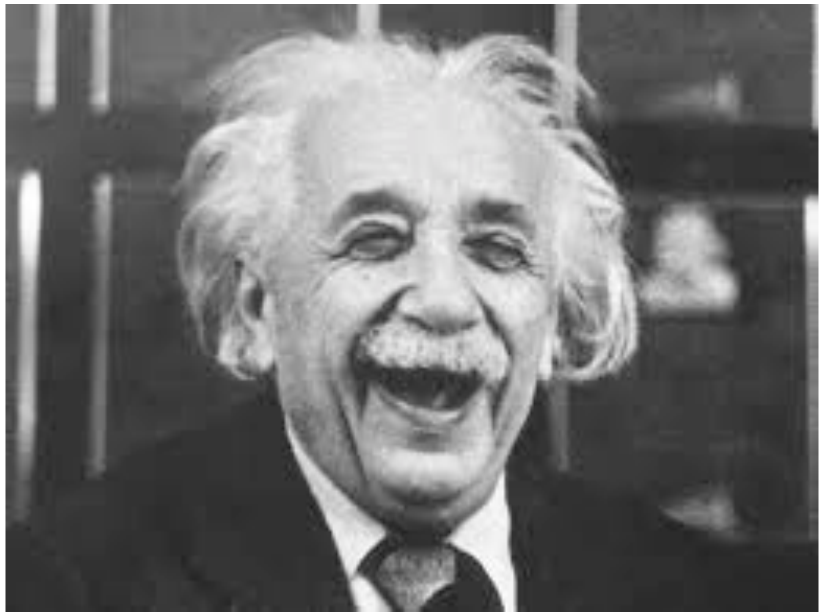
S. PERLMUTTER,[2,3] S. GABI,[2,4] G. GOLDHABER,[2,3] A. GOOBAR,[2,3,5] D. E. GROOM,[2,3] I. M. HOOK,[3,6]
A. G. KIM,[2,3] M. Y. KIM,[2] J. C. LEE,[2] R. PAIN,[2,7] C. R. PENNYPACKER,[2,4] I. A. SMALL,[2,3]
R. S. ELLIS,[8] R. G. MCMAHON,[8] B. J. BOYLE,[9,10] P. S. BUNCLARK,[9] D. CARTER,[9]
M. J. IRWIN,[9] K. GLAZEBROOK,[10] H. J. M. NEWBERG,[11] A. V. FILIPPENKO,[3,6]
T. MATHESON,[6] M. DOPITA,[12] AND W. J. COUCH[13]

(THE SUPERNOVA COSMOLOGY PROJECT)

Received 1996 August 26; accepted 1997 February 6

ABSTRACT

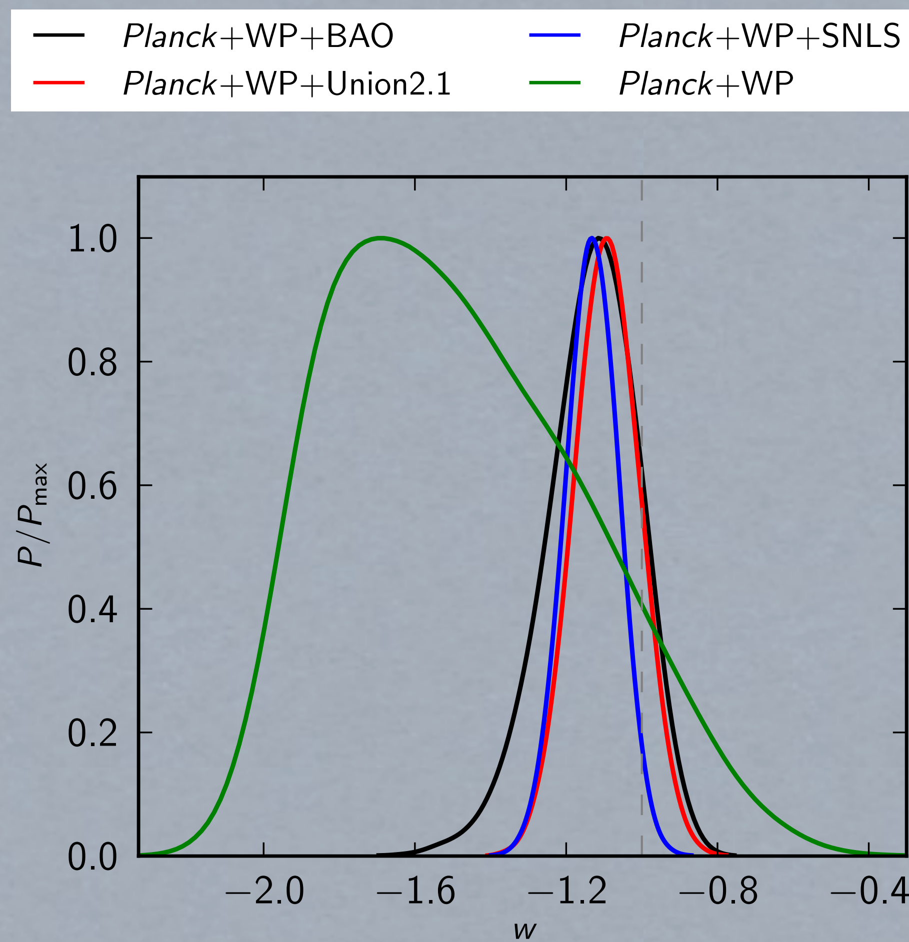
We have developed a technique to systematically discover and study high-redshift supernovae that can be used to measure the cosmological parameters. We report here results based on the initial seven of more than 28 supernovae discovered to date in the high-redshift supernova search of the Supernova Cosmology Project. We find an observational dispersion in peak magnitudes of $\sigma_{M_B} = 0.27$; this dispersion narrows to $\sigma_{M_B,\mathrm{corr}} = 0.19$ after "correcting" the magnitudes using the light-curve "width-luminosity" relation found for nearby ($z \leq 0.1$) Type Ia supernovae from the Calán/Tololo survey (Hamuy et al.). Comparing light-curve width–corrected magnitudes as a function of redshift of our distant ($z = 0.35$–0.46) supernovae to those of nearby Type Ia supernovae yields a global measurement of the mass density, $\Omega_M = 0.88^{+0.69}_{-0.60}$ for a $\Lambda = 0$ cosmology. For a spatially flat universe (i.e., $\Omega_M + \Omega_\Lambda = 1$), we find $\Omega_M = 0.94^{+0.34}_{-0.28}$ or, equivalently, a measurement of the cosmological constant, $\Omega_\Lambda = 0.06^{+0.28}_{-0.34}$ (<0.51 at the 95% confidence level). For the more general Friedmann-Lemaître cosmologies with independent Ω_M and Ω_Λ, the results are presented as a confidence region on the Ω_M-Ω_Λ plane. This region does not correspond to a unique value of the deceleration parameter q_0. We present analyses and checks for statistical and systematic errors and also show that our results do not depend on the specifics of the width-luminosity correction. The results for Ω_Λ-versus-Ω_M are inconsistent with Λ-dominated, low-density, flat cosmologies that have been proposed to reconcile the ages of globular cluster stars with higher Hubble constant values.



ΛCDM

The only consistent low energy theory for a spin-two field $g_{\mu\nu}$.

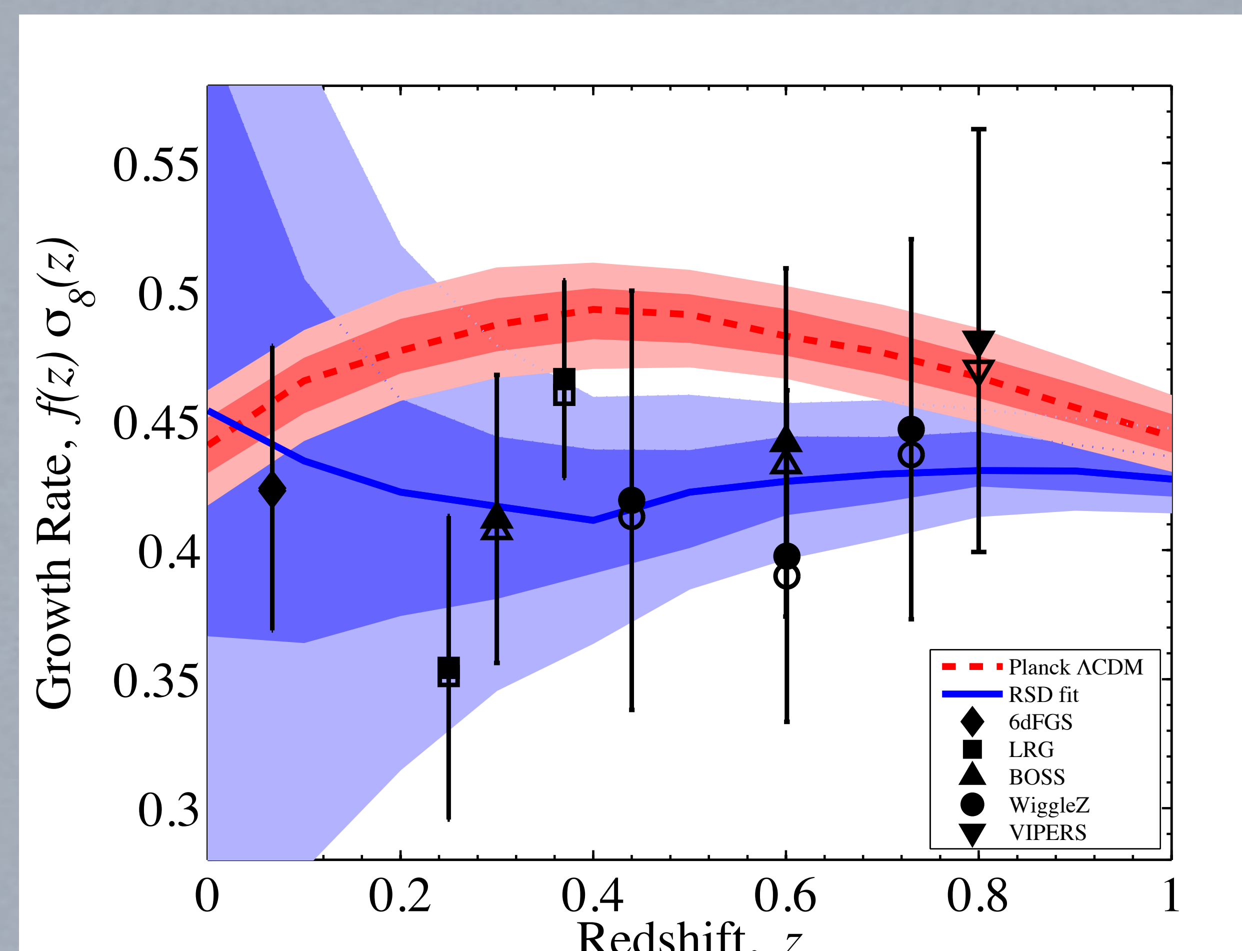
$g_{\mu\nu} + \text{STUFF}$

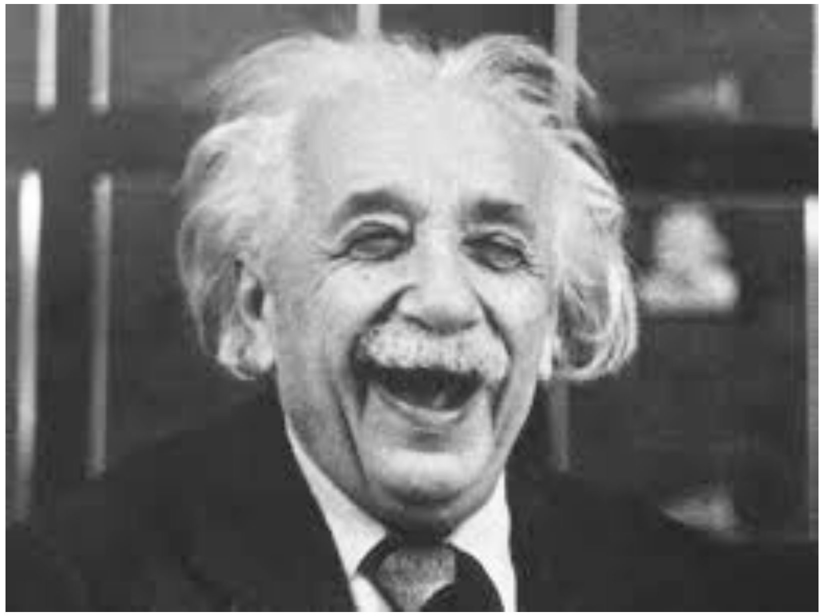


Tensions with LCDM...?

$$w = -1.24^{+0.18}_{-0.19} \quad (95\%;\ Planck\text{+WP+}H_0)$$

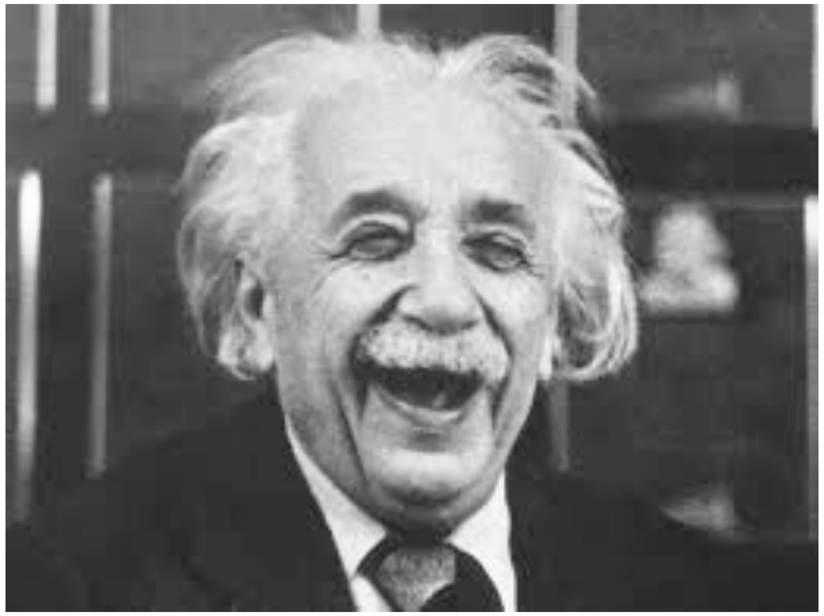
Macaulay et al. '13





ΛCDM

$g_{\mu\nu} + \mathrm{STUFF}$

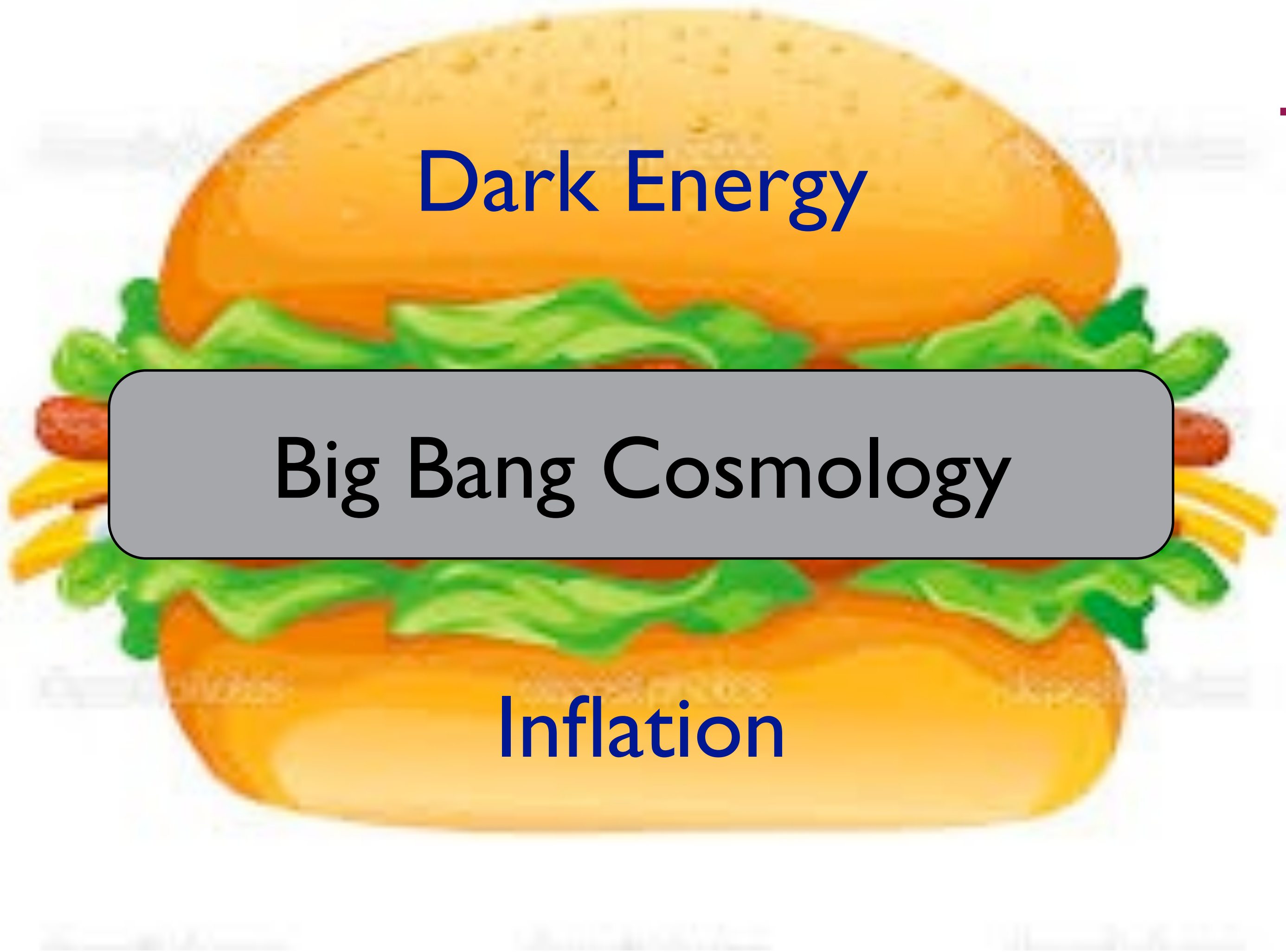


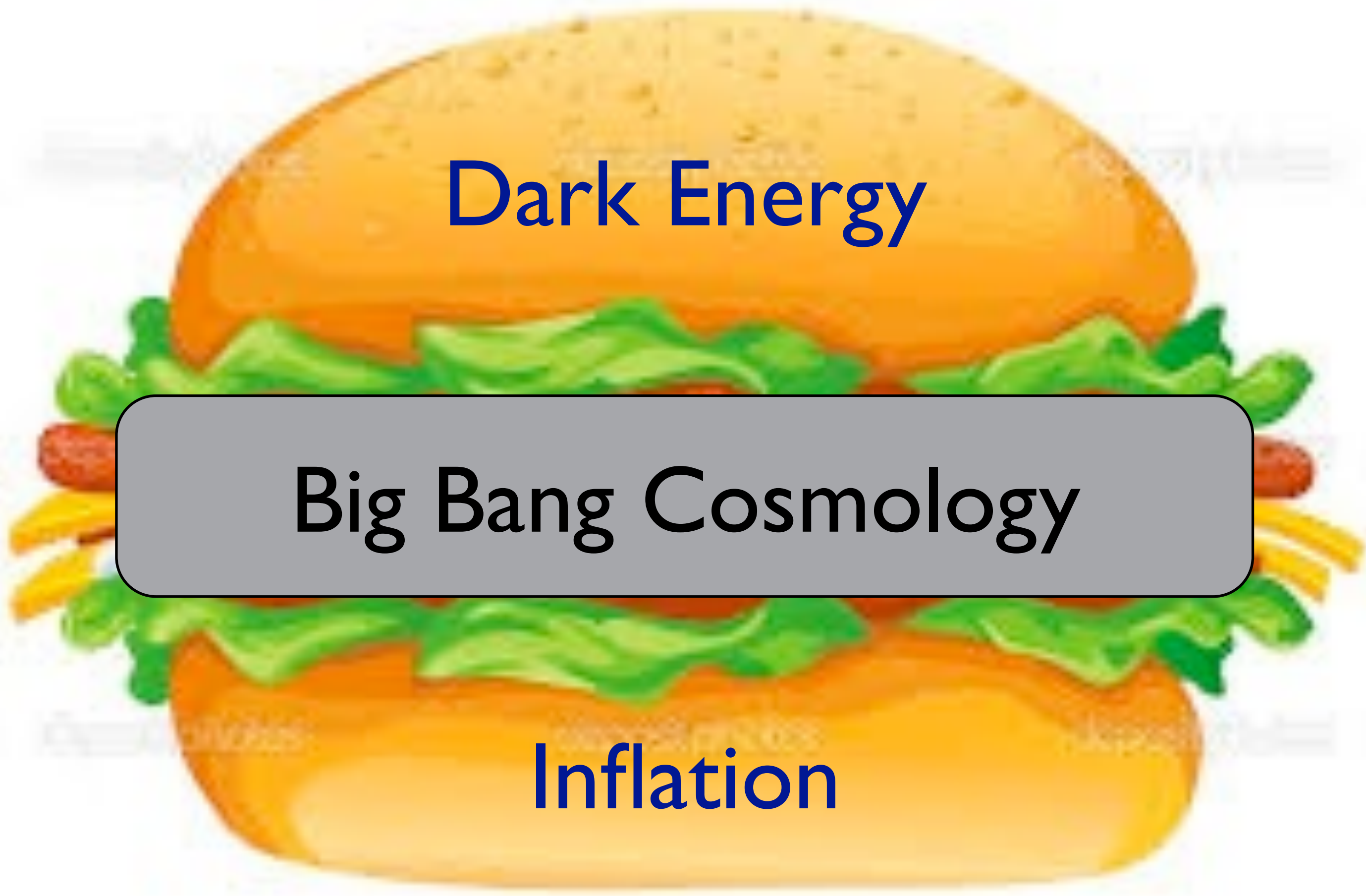
ΛCDM

$g_{\mu\nu}$ + STUFF

Other fundamental ingredients?

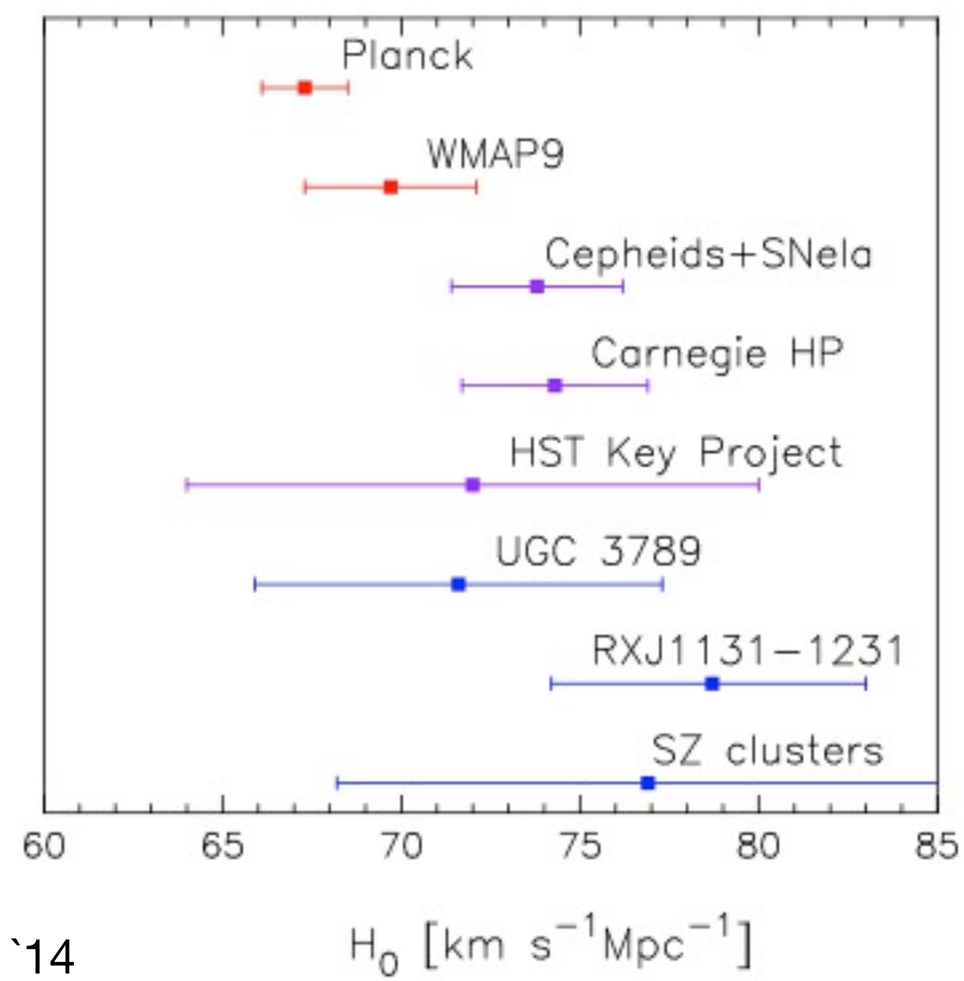
The history of the Universe

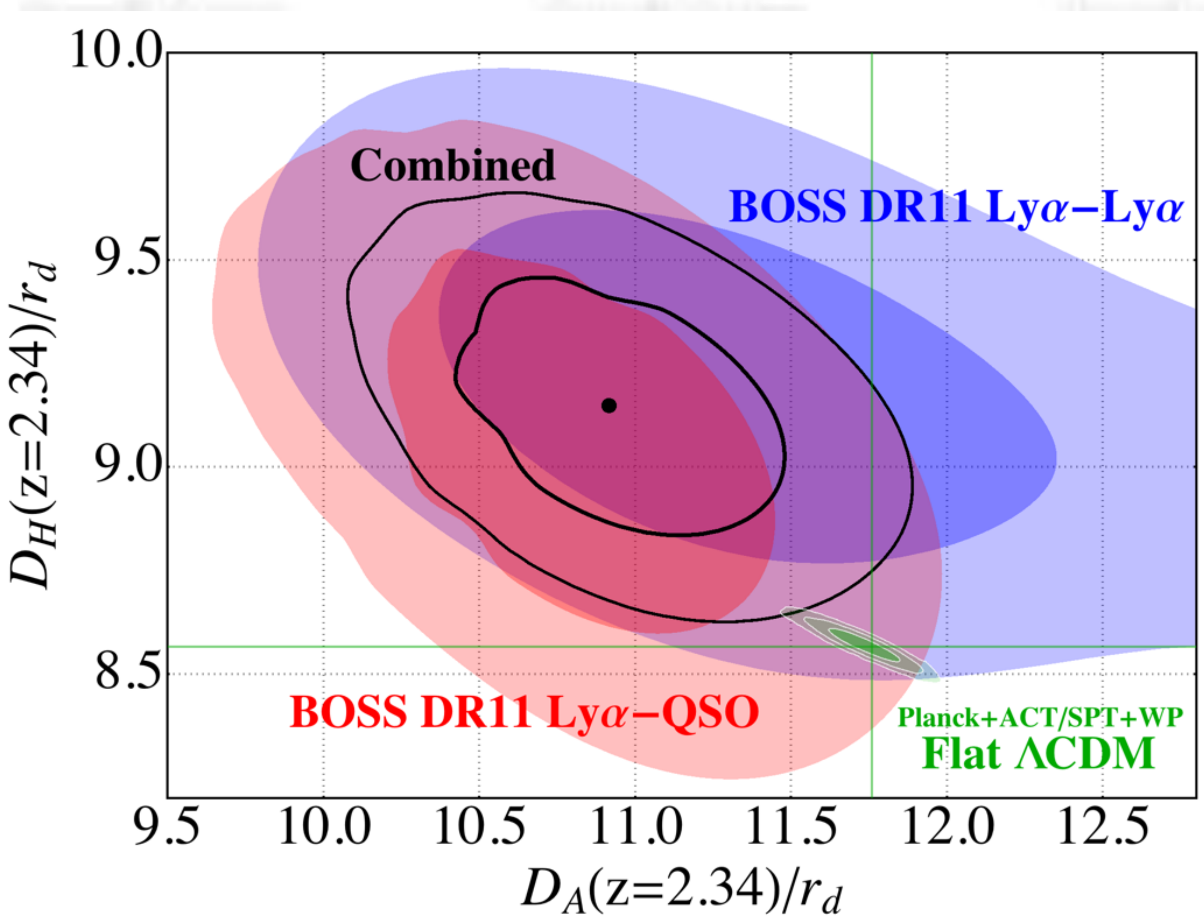




The history of the Universe

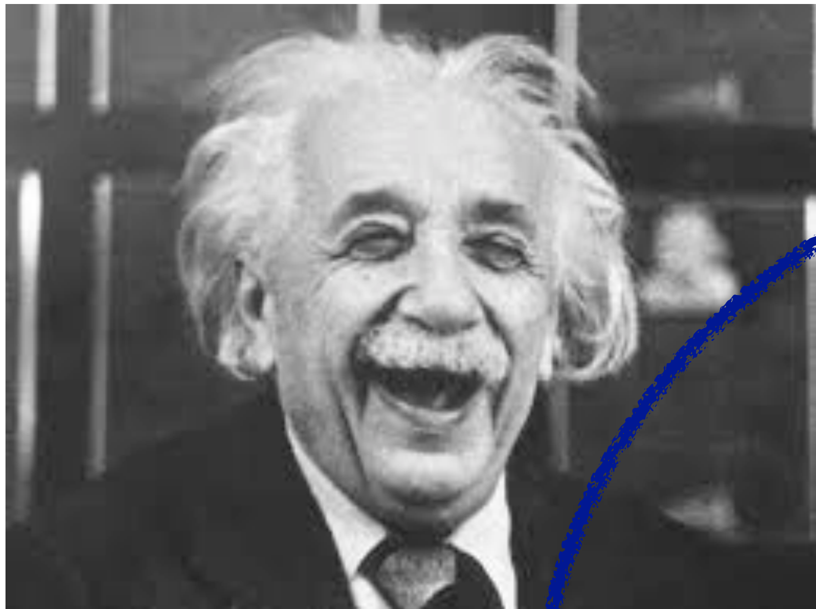
Planck paper





Delubac et al. `14

Geometrical anomalies?
However: “small” effects...



ΛCDM

This Talk

$g_{\mu\nu}$ + STUFF

Other fundamental ingredients?

Phenomenology of dark energy

- Two main classes of observables

Phenomenology of dark energy

- Two main classes of observables

$$S[\phi, g_{\mu\nu}, \Psi_m]$$

Background

$$\phi = \phi_0(t)$$

$$ds^2 = -dt^2 + a^2(t)dx^2$$

$$\rho_m = \rho_m(t)$$

equation of state $w(z)$

Perturbations

$$\delta\rho_m(t, \vec{x}) \Leftrightarrow \delta\phi(t, \vec{x})$$

growth rate, lensing potential, etc.

Phenomenology of dark energy

- Two main classes of observables

- EUCLID, DESI etc... are specifically designed to target perturbation sector

- `No shortage' of dark energy models (>5000 papers on Spires)
  Need for a Unifying and Effective description

Ideally...

- A limited number of effective operators, each one responsible for an observable dynamical feature (e.g. flavor-changing neutral currents in physics beyond Standard Model)

What are the relevant degrees of freedom?

QCD → nucleons and pions

EW theory → 3 massive vector bosons, 1 ``Higgs”...

Cosmology → Cosmological Perturbations!

They (re-)enter the horizon

1) Small in amplitude   (expansion in number of cosmological perturbations)

2) Large in size (expansion in number of derivatives)

What are the relevant degrees of freedom?

QCD → nucleons and pions

EW theo

Cosmo

They (re-

As opposed to: Expansion in number of “fields” (Weinberg `08)

$$V = V_1\phi + V_2\phi^2 + V_3\phi^3 + V_4\phi^4$$
$$= V_2\delta\phi^2 + V_3\phi_0(t)\delta\phi^2 + 6V_4\phi_0^2(t)\delta\phi^2$$

All terms potentially important in cosmological perturbation theory!

1) Small in amplitude (expansion in number of cosmological perturbations)

2) Large in size (expansion in number of derivatives)

Unitary Gauge in Cosmology

The Effective Field Theory of Inflation (Creminelli et al. `06, Cheung et al. `07)

Main idea: scalar degrees of freedom are `eaten' by the metric. Ex:

$$\phi(t,\vec{x}) \to \phi_0(t) \quad (\delta\phi = 0) \qquad -\frac{1}{2}\partial\phi^2 \to -\frac{1}{2}\dot{\phi}_0^2(t)\ g^{00}$$

Unitary Gauge in Cosmology

The Effective Field Theory of Inflation (Creminelli et al. `06, Cheung et al. `07)

Main idea: scalar degrees of freedom are `eaten' by the metric. Ex:

$$\phi(t,\vec{x}) \to \phi_0(t) \quad (\delta\phi = 0) \qquad -\frac{1}{2}\partial\phi^2 \to -\frac{1}{2}\dot{\phi}_0^2(t)\ g^{00}$$

Effective Field Theory of Dark Energy: (Gubitosi, F.P., Vernizzi 2012)

1) Assume WEP (universally coupled metric $S_m[g_{\mu\nu}, \Psi_i]$)

2) Write the most generic action for $g_{\mu\nu}$ compatible with the residual un-broken symmetries (3-diff).

The Action

$$S = \int d^4x \, \sqrt{-g} \, \frac{M^2(t)}{2} \, \left[R \, - \, 2\lambda(t) \, - \, 2\mathcal{C}(t) g^{00} \right.$$

The most generic action written in terms of $g_{\mu\nu}$ compatible with the residual symmetry of spatial diffeomorphisms

The Action

$$S = \int d^4x \sqrt{-g} \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$

The most generic action written in terms of $g_{\mu\nu}$ compatible with the residual symmetry of spatial diffeomorphisms

Genuine 4-dim covariant terms are still allowed, but will in general be multiplied by functions of time cause time translations are broken

The Action

$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00}\right.$$

The most generic action written in terms of $g_{\mu\nu}$ compatible with the residual symmetry of spatial diffeomorphisms

General functions of time are allowed

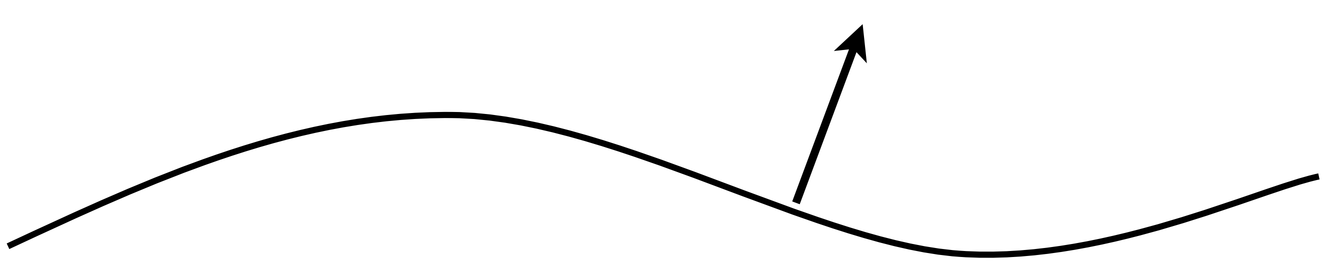
The Action

$$S = \int d^4x \, \sqrt{-g} \, \frac{M^2(t)}{2} \, \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$

The most generic action written in terms of $g_{\mu\nu}$ compatible with the residual symmetry of spatial diffeomorphisms

...as well as tensors with free `0' indices

Essentially: contractions with $$n_\mu = -\frac{\partial_\mu \phi}{\sqrt{-(\partial\phi^2)}}$$



The Action

$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2} \, \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$

Any arbitrarily complicate action with one scalar d.o.f. will reduce to this in Unitary gauge, plus terms that start explicitly quadratic in the perturbations

Gubitosi, F. P., Vernizzi, 12

The Action

$$S = \int d^4x \sqrt{-g}\,\frac{M^2(t)}{2}\,\Big[R - 2\lambda(t) - 2\mathcal{C}(t)g^{00}$$

$$+ \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\,\delta K \delta g^{00} + \epsilon_4(t)\left(\delta K^{\mu}{}_{\nu}\,\delta K^{\nu}{}_{\mu} - \delta K^2 + \frac{R^{(3)}\,\delta g^{00}}{2}\right) + \ldots\Big]$$

The Action

Background (expansion history)

$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$

$$\left. + \mu_2^2(t) (\delta g^{00})^2 - \mu_3(t)\, \delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^\mu{}_\nu\, \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) + \ldots \right]$$

(linear) perturbations

Time-dependent couplings

The Power of the EFT of DE

$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2} \, \Big[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00}$$

$$+ \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\, \delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^\mu{}_\nu \, \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) + \dots \Big]$$

- Clear separation: background v.s. perturbed sector
- Expansion in number of cosmological perturbations
- Expansion in number of derivatives
- Observables, stability etc.

Examples

$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2} \, \Big[R \,-\, 2\lambda(t) \,-\, 2\mathcal{C}(t) g^{00}$$

$$+\, \mu_2^2(t)(\delta g^{00})^2 \,-\, \mu_3(t)\, \delta K \delta g^{00} +\, \epsilon_4(t) \left(\delta K^{\mu}{}_{\nu}\, \delta K^{\nu}{}_{\mu} - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) \,+ \ldots \Big]$$

Examples

const.

$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2} \Big[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00}$$

$$+ \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\, \delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^\mu{}_\nu \, \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) + \dots \Big]$$

Quintessence

Examples

$$S = \int d^4x \sqrt{-g} \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$

$$\left. + \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\, \delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^\mu{}_\nu \, \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) + \ldots \right]$$

Non-minimally coupled scalar field
(Brans-Dicke, f(R) etc.)

Examples

const.

$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$

$$\left. + \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\,\delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^\mu{}_\nu \, \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) + \dots \right]$$

K-essence

(Amendariz-Picon et al., 2000)

$$S = \int d^4x \sqrt{-g} P(\phi, X) \qquad X \equiv g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi$$

Examples

$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$

$$\left. + \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\, \delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^\mu{}_\nu\, \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) + \ldots \right]$$

"Galilean Cosmology" (Chow and Khoury, 2009)

$$S = \int d^4x \sqrt{-g} \left[\frac{M^2}{2} e^{-2\phi/M} R - \frac{r_c^2}{M} (\partial\phi)^2 \Box\phi \right]$$

Gleyzes, Langlois, F.P., Vernizzi, 1304.4840

Examples

$$S = \int d^4x \sqrt{-g} \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$
$$\left. + \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\, \delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^\mu{}_\nu \, \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) + \dots \right]$$

"Generalized Galileons" (≡ Horndeski)

(Deffayet et al., 2011)

$$\mathcal{L}_2 = A(\phi, X) \,,$$
$$\mathcal{L}_3 = B(\phi, X) \Box\phi \,,$$
$$\mathcal{L}_4 = C(\phi, X) R - 2C_{,X}(\phi, X) \left[(\Box\phi)^2 - (\nabla_\mu \nabla_\nu \phi)^2 \right] \,,$$
$$\mathcal{L}_5 = D(\phi, X) G^{\mu\nu} \nabla_\mu \nabla_\nu \phi + \frac{1}{3} D_{,X}(\phi, X) \left[(\Box\phi)^3 - 3(\Box\phi)(\nabla_\mu \nabla_\nu \phi)^2 + 2(\nabla_\mu \nabla_\nu \phi)^3 \right] \,,$$

Examples

Gleyzes, Langlois, F.P., Vernizzi, 1304.4840

$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} + \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\,\delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^\mu{}_\nu \, \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) + \dots \right]$$

$\epsilon_4(t)$ $\tilde{\epsilon}_4(t)$

Beyond Horndeski (linear)

The most general (linear) theory without higher derivatives on the propagating degree of freedom

Beyond Horndeski (full, non-linear)

Gleyzes, Langlois, F.P., Vernizzi, 1404.6495

Standard Lore:
higher (time) derivatives: disaster!
New degrees of freedom AND ghost-like

Equations of motion with higher derivatives BUT

- Not on the propagating degree of freedom once you solve the constraints
- Not if taken in appropriate combinations
- Not in some specific gauge (ex. the 3+1 ADM formalism)

Beyond Horndeski (full, non-linear)

Gleyzes, Langlois, F.P., Vernizzi, 1404.6495

“Generalized Galileons” (≡ Horndeski)

(Deffayet et al., 2011)

$$\mathcal{L}_2 = A(\phi, X) \ ,$$
$$\mathcal{L}_3 = B(\phi, X)\Box\phi \ ,$$
$$\mathcal{L}_4 = C(\phi, X)R - 2C_{,X}(\phi, X)\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right] \ ,$$
$$\mathcal{L}_5 = D(\phi, X)G^{\mu\nu}\nabla_\mu\nabla_\nu\phi + \frac{1}{3}D_{,X}(\phi, X)\left[(\Box\phi)^3 - 3(\Box\phi)(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3\right] \ ,$$

Beyond Horndeski (full, non-linear)

Gleyzes, Langlois, F.P., Vernizzi, 1404.6495

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

Beyond Horndeski (full, non-linear)

Gleyzes, Langlois, F.P., Vernizzi, 1404.6495

$$\mathcal{L}_4 = (2XC_X - C)(K^2 - K_{ij}K^{ij}) + C\ {}^{(3)}R\ + \dots$$

3+1 decomposition

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

Beyond Horndeski (full, non-linear)

Gleyzes, Langlois, F.P., Vernizzi, 1404.6495

$$\mathcal{L}_4^{\rm new} = A(N,t)(K^2 - K_{ij}K^{ij}) + B(N,t)\ {}^{(3)}\!R$$

see also X. Gao 1406.0822

Generalization!

$$\mathcal{L}_4 = (2XC_X - C)(K^2 - K_{ij}K^{ij}) + C\ {}^{(3)}\!R\ + \ldots$$

3+1 decomposition

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

Beyond Horndeski (full, non-linear)

Gleyzes, Langlois, F.P., Vernizzi, 1404.6495

$$\mathcal{L}_4^{\rm new} = A(N,t)(K^2 - K_{ij}K^{ij}) + B(N,t)\ {}^{(3)}R$$

$$H_4^{\rm new} = \int d^3x \left[N\,\mathcal{H}_0(N, h_{ij}, \pi^{ij}) + N^i\,\mathcal{H}_i(h_{ij}, \pi^{ij})\right]$$

$\frac{\delta}{\delta N^i}$ → same as GR: 3 “first class” constraints

$\frac{\delta}{\delta N}$ → fixes N in terms of the other variables

6 - 3 = 3 d.o.f. As any healthy scalar tensor theory should have

Beyond Horndeski (full, non-linear)

Gleyzes, Langlois, F.P., Vernizzi, 1404.6495

- Equations of motion with higher derivatives
- Only two derivatives on the true propagating degree of freedom
- No ghosts
- Interesting phenomenology (modified Jeans phenomenon)

Beyond Horndeski (full, non-linear)

Gleyzes, Langlois, F.P., Vernizzi, 1404.6495

- Equations of motion with higher derivatives
- Only two derivatives on the true propagating degree of freedom
- No ghosts
- Interesting phenomenology (modified Jeans phenomenon)

usually, at small distances

$$(\partial_t^2 + c_m^2 k^2)\delta\rho_m \approx 0$$

Beyond Horndeski (full, non-linear)

Gleyzes, Langlois, F.P., Vernizzi, 1404.6495

- Equations of motion with higher derivatives
- Only two derivatives on the true propagating degree of freedom
- No ghosts
- Interesting phenomenology (modified Jeans phenomenon)

usually, at small distances

$$(\partial_t^2 + c_m^2 k^2)\delta\rho_m \approx 0$$

$$(\partial_t^2 + c_s^2 k^2)\delta\phi - C_\phi \dot{\phi}\, \partial_t \delta\rho_m \approx 0 \,,$$
$$(\partial_t^2 + c_m^2 k^2)\delta\rho_m - C_m k^2\, \partial_t (\delta\phi/\dot{\phi}) \approx 0$$

Stability and Observables

F. P., C. Marinoni, H. Steigerwald 1312.6111
and in progress...

$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$

$$\left. + \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\, \delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^{\mu}{}_{\nu}\, \delta K^{\nu}{}_{\mu} - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) + \dots \right]$$

$$\lambda(t), \quad \mathcal{C}(t), \quad \mu(t) \equiv \frac{dM^2(t)}{dt}$$

$\bar{w}(t)$ — Expansion History

$\mu(t)$

$\mu(t)$, $\mu_3(t)$, $\epsilon_4(t)$ — Growth rate, lensing etc.

$\mu_2^2(t)$ — Unconstrained

Stability

$$S_\pi = \int a^3(t) M^2(t) \left[A\left(\mu, \mu_2^2, \mu_3, \epsilon_4\right) \dot{\pi}^2 + B\left(\mu, \mu_3, \epsilon_4\right) \frac{(\vec{\nabla}\pi)^2}{a^2} \right] + \text{lower order in derivatives.}$$

No ghost: A>0

No gradient instabilities: B>0

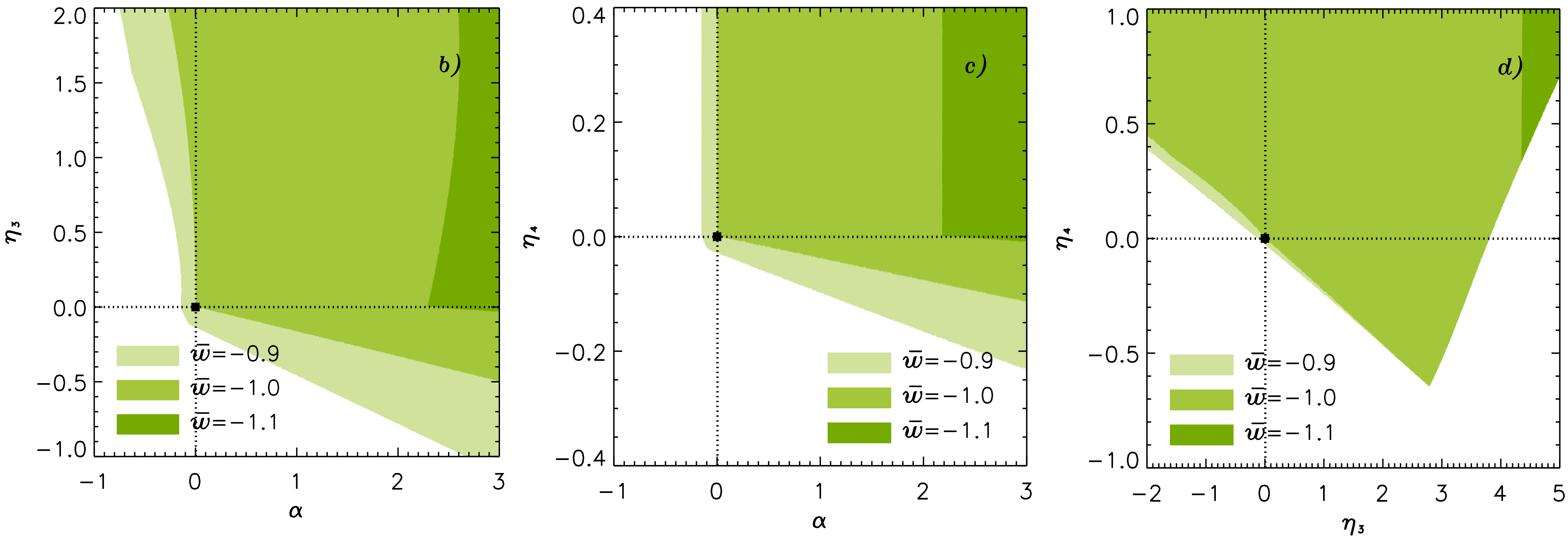
Stability

$$S_\pi = \int a^3(t) M^2(t) \left[A\left(\mu, \mu_2^2, \mu_3, \epsilon_4\right) \dot{\pi}^2 + B\left(\mu, \mu_3, \epsilon_4\right) \frac{(\vec{\nabla}\pi)^2}{a^2} \right] + \text{lower order in derivatives.}$$

No ghost: A>0

No gradient instabilities: B>0

$\mu_2^2 = 0$



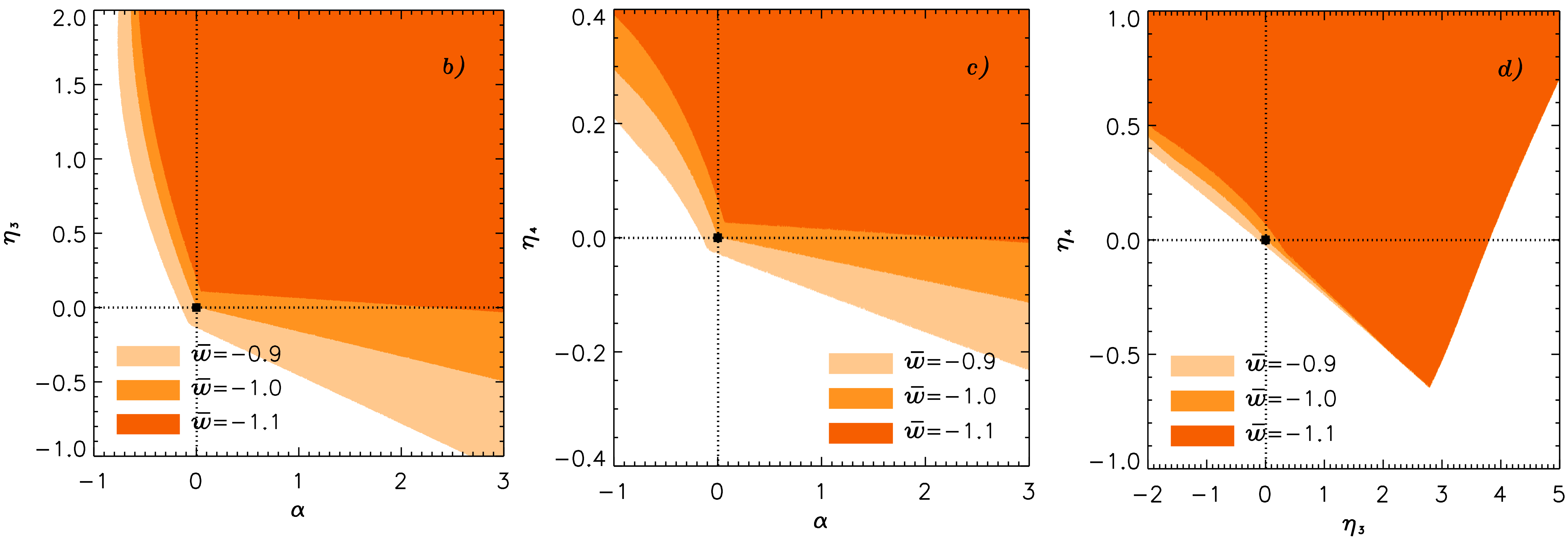
Stability

$$S_\pi = \int a^3(t) M^2(t) \left[A\left(\mu, \mu_2^2, \mu_3, \epsilon_4\right) \dot{\pi}^2 + B\left(\mu, \mu_3, \epsilon_4\right) \frac{(\vec{\nabla}\pi)^2}{a^2} \right] + \text{lower order in derivatives.}$$

No ghost: A>0

No gradient instabilities: B>0

$\mu_2^2 \gg H^2$



F. P., C. Marinoni, H. Steigerwald 1312.6111

Growth rate

$$G_{\text{eff}}(t) = G_{\text{eff}}(\mu, \mu_3, \epsilon_4)$$

$$f \equiv \frac{d\ln\delta}{d\ln a} = \Omega_m^{\gamma_0+\gamma_1 \ln(\Omega_m)}$$

Steigerwald, Bel Marinoni 1403.0898

F. P., C. Marinoni, H. Steigerwald 1312.6111

Growth rate

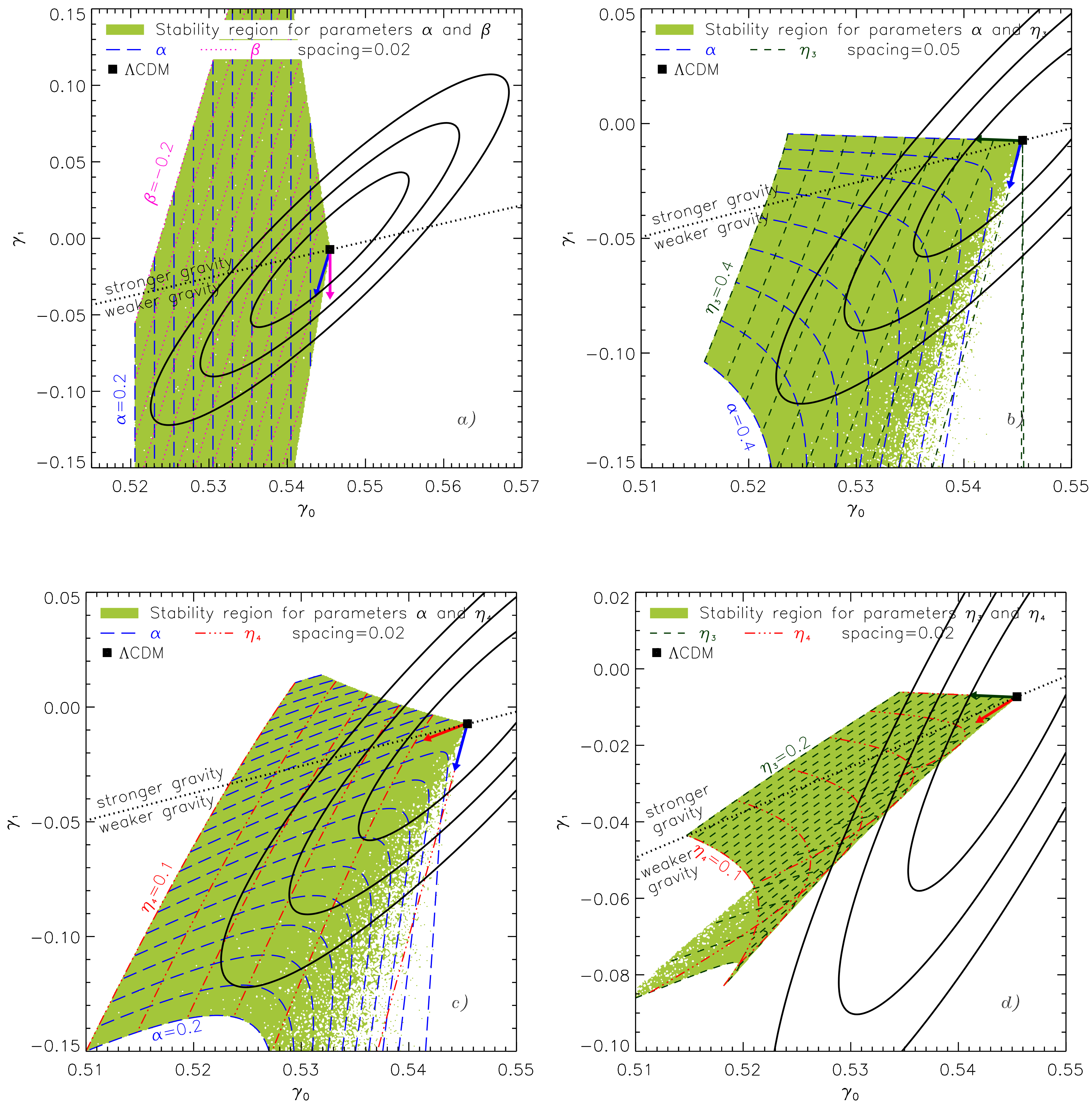
$$G_{\text{eff}}(t) = G_{\text{eff}}(\mu, \mu_3, \epsilon_4)$$

$$f \equiv \frac{d\ln\delta}{d\ln a} = \Omega_m^{\gamma_0+\gamma_1 \ln(\Omega_m)}$$

Steigerwald, Bel Marinoni 1403.0898

Non trivial result:

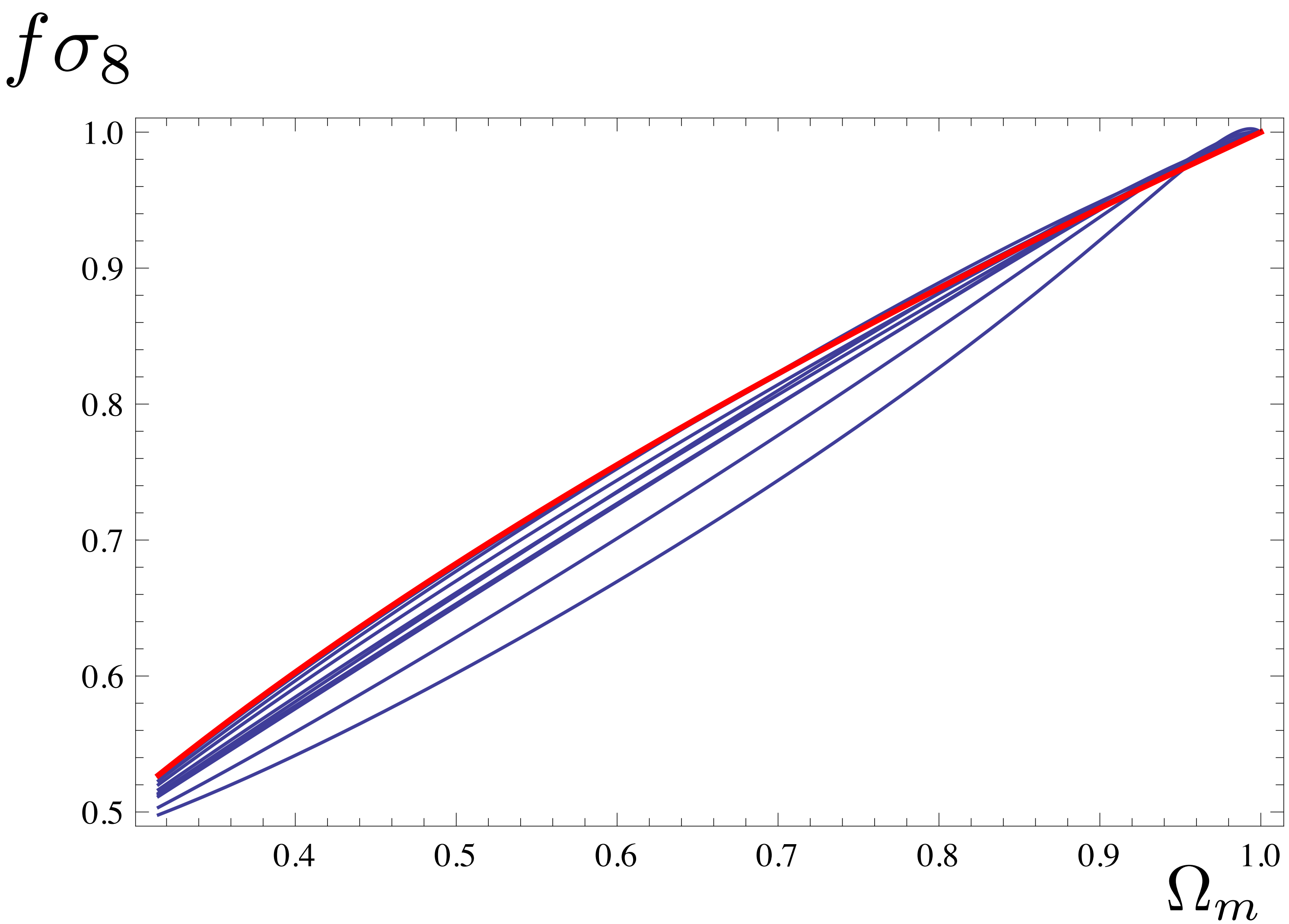
$$\gamma_0 < \gamma_0(\Lambda CDM)$$

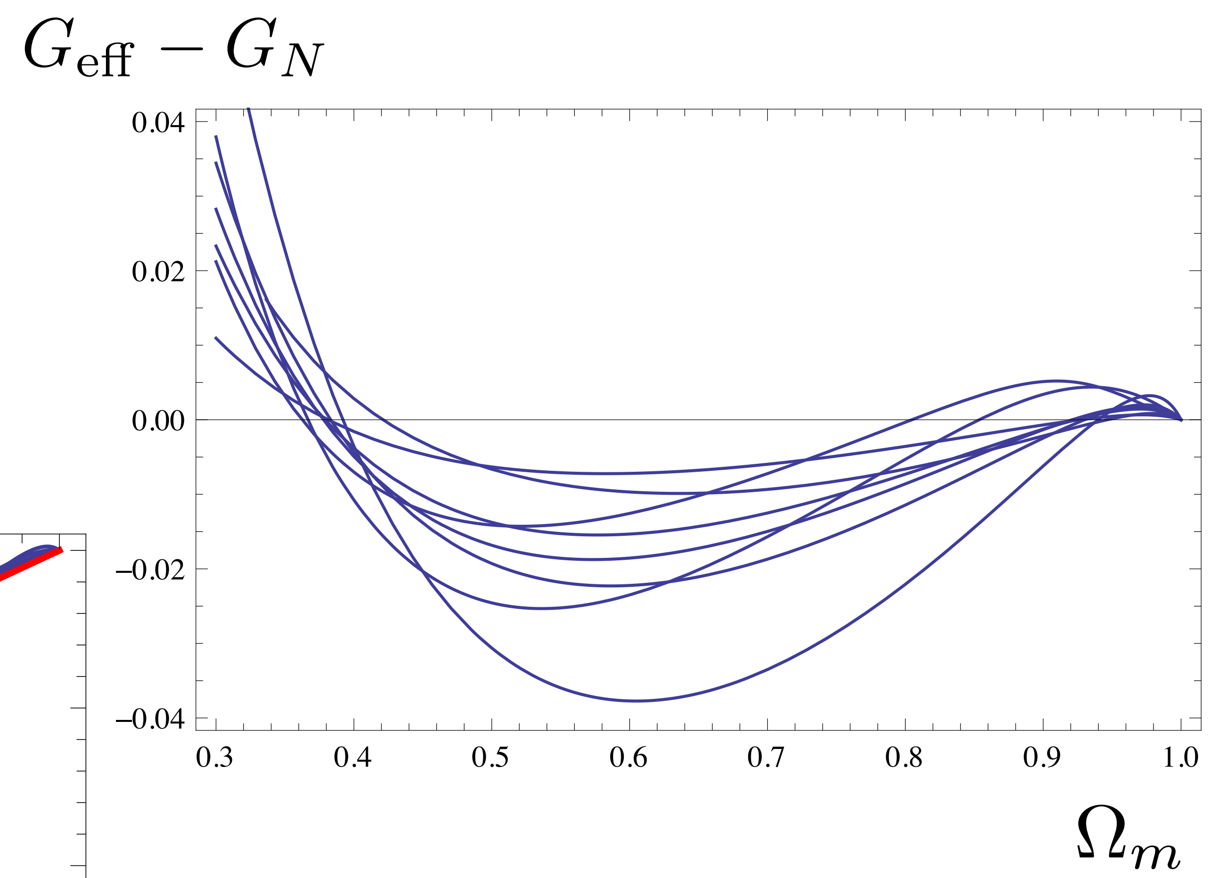


H. Steigerwald, C. Marinoni, F. P. in preparation

Growth rate (preliminary)

Modified gravity: less growth than LCDM?





Conclusions

- Unifying framework for dark energy/modified gravity
- Effective language: cosmological perturbations as the relevant d.o.f.
- Systematic way to address stability (e.g. stable violations of NEC)
- Observational constraints and forecasts: much work in progress

$$S_\pi = \int a^3 M^2 \Bigg\{ \Bigg[(\mathcal{C} + 2\mu_2^2)(1+\epsilon_4) + \frac{3}{4}(\mu - \mu_3)^2 \Bigg] \dot{\pi}^2$$

$$- \Bigg[(\mathcal{C} + \frac{\mathring{\mu}_3}{2} - \dot{H}\epsilon_4 + H\mathring{\epsilon}_4)(1+\epsilon_4) - (\mu - \mu_3)\left(\frac{\mu - \mu_3}{4(1+\epsilon_4)} - \mu - \mathring{\epsilon}_4 \right) \Bigg] \frac{(\vec{\nabla}\pi)^2}{a^2} \Bigg\}$$

$$4\pi G_{\rm eff} = \frac{1}{2M^2} \frac{2\mathcal{C} + 2(\mu + \mathring{\epsilon}_4)^2 + \mathring{\mu}_3 - 2\dot{H}\epsilon_4 + 2H\mathring{\epsilon}_4 + 3(a/k)^2\mathcal{A}}{(1+\epsilon_4)^2[2\mathcal{C} + \mathring{\mu}_3 - 2\dot{H}\epsilon_4 + 2H\mathring{\epsilon}_4] + 2(1+\epsilon_4)(\mu + \mathring{\epsilon}_4)(\mu - \mu_3) - (\mu - \mu_3)^2/2 + 3(a/k)^2\mathcal{A}'}$$

$$\mathring{\mu}_3 \;\equiv\; \dot{\mu}_3 + \mu\mu_3 + H\mu_3, \qquad \mathring{\epsilon}_4 \;\equiv\; \dot{\epsilon}_4 + \mu\epsilon_4 + H\epsilon_4$$

$$\mathcal{A} \;\equiv\; 2\dot{H}\mathcal{C} - \dot{H}\mathring{\mu}_3 + \ddot{H}(\mu - \mu_3) - 2H\dot{H}\mu_3 - 2H^2(\mu^2 + \dot{\mu}), \qquad \mathcal{A}' \;\equiv\; (1+\epsilon_4)^2\mathcal{A}$$

The Action

$$S = \int d^4x \sqrt{-g} \left[\frac{M^2}{2} f(t) R - \Lambda(t) - c(t) g^{00} \right] + S_{DE}^{(2)}$$

Enough for background equations:

$$\begin{aligned} c &= \frac{1}{2}(-\ddot{f} + H\dot{f})M^2 + \frac{1}{2}(\rho_D + p_D) \\ \Lambda &= \frac{1}{2}(\ddot{f} + 5H\dot{f})M^2 + \frac{1}{2}(\rho_D - p_D) \end{aligned}$$

The Action

$$S = \int d^4x\sqrt{-g}\left[\frac{M^2}{2}f(t)R - \Lambda(t) - c(t)g^{00}\right] + S_{DE}^{(2)}$$

Enough for background equations:

$$\begin{aligned} c &= \frac{1}{2}(-\ddot{f} + H\dot{f})M^2 + \frac{1}{2}(\rho_D + p_D) \\ \Lambda &= \frac{1}{2}(\ddot{f} + 5H\dot{f})M^2 + \frac{1}{2}(\rho_D - p_D) \end{aligned}$$

Generally Related to post-newtonian parameters

The Action

$$S = \int d^4x\sqrt{-g}\left[\frac{M^2}{2}f(t)R - \Lambda(t) - c(t)g^{00}\right] + S_{DE}^{(2)}$$

Enough for background equations:

$$\begin{aligned} c &= \frac{1}{2}(-\ddot{f} + H\dot{f})M^2 + \frac{1}{2}(\rho_D + p_D) \\ \Lambda &= \frac{1}{2}(\ddot{f} + 5H\dot{f})M^2 + \frac{1}{2}(\rho_D - p_D) \end{aligned}$$

Generally Related to post-newtonian parameters

"Bare" Planck Mass

The Action

$$S = \int d^4x\sqrt{-g}\left[\frac{M^2}{2}f(t)R - \Lambda(t) - c(t)g^{00}\right] + S_{DE}^{(2)}$$

Enough for background equations:

$$c = \frac{1}{2}(-\ddot{f} + H\dot{f})M^2 + \frac{1}{2}(\rho_D + p_D)$$

$$\Lambda = \frac{1}{2}(\ddot{f} + 5H\dot{f})M^2 + \frac{1}{2}(\rho_D - p_D)$$

$$H^2 = \frac{1}{3fM^2}(\rho_m + \rho_D)$$

$$\dot{H} = -\frac{1}{2fM^2}(\rho_m + \rho_D + p_m + p_D)$$

Generally Related to post-newtonian parameters

“Bare” Planck Mass

Defined by the modified Friedman equations

The Action

$$S = \int d^4x\sqrt{-g}\left[\frac{M^2}{2}f(t)R - \Lambda(t) - c(t)g^{00}\right] + S^{(2)}_{DE}$$

Enough for background equations:

$$c \;=\; \frac{1}{2}(-\ddot{f} + H\dot{f})M^2 + \frac{1}{2}(\rho_D + p_D)$$

$$\Lambda \;=\; \frac{1}{2}(\ddot{f} + 5H\dot{f})M^2 + \frac{1}{2}(\rho_D - p_D)$$

Generally Related to post-newtonian parameters

"Bare" Planck Mass

Defined by the modified Friedman equations

Matter + Dark matter (in practice $\rho_m \propto a^{-3}$)

$$H^2 = \frac{1}{3fM^2}(\rho_m + \rho_D)$$

$$\dot{H} = -\frac{1}{2fM^2}(\rho_m + \rho_D + p_m + p_D)$$

Mixing with gravity 1: Brans-Dicke

$$S = \int \sqrt{-g}\left(\frac{M^2}{2} f R - \Lambda - c g^{00} + \frac{M_2^4}{2}(\delta g^{00})^2 - \frac{\bar{m}_1^3}{2}\delta g^{00}\delta K + \frac{1}{2}T^{\mu\nu}\delta g_{\mu\nu}\right)$$

Apply Stueckelberg and go to Newtonian Gauge

$$ds^2 = -(1+2\Phi)dt^2 + a^2(1-2\Psi)\delta_{ij}dx^i dx^j$$

$$S \overset{\text{kinetic}}{=} \int M^2 f\left[-3\dot{\Psi}^2 - 2\vec{\nabla}\Phi\vec{\nabla}\Psi + (\vec{\nabla}\Psi)^2 + c\,\dot{\pi}^2 - c(\vec{\nabla}\pi)^2 + 3(\dot{f}/f)\dot{\Psi}\dot{\pi} + (\dot{f}/f)\vec{\nabla}\pi(\vec{\nabla}\Phi - 2\vec{\nabla}\Psi)\right]$$

Mixing

Mixing with gravity 1: Brans-Dicke

$$S = \int \sqrt{-g}\left(\frac{M^2}{2} f R - \Lambda - c g^{00} + \frac{M_2^4}{2}(\delta g^{00})^2 - \frac{\bar{m}_1^3}{2}\delta g^{00}\delta K + \frac{1}{2}T^{\mu\nu}\delta g_{\mu\nu}\right)$$

Apply Stueckelberg and go to Newtonian Gauge

$$ds^2 = -(1+2\Phi)dt^2 + a^2(1-2\Psi)\delta_{ij}dx^i dx^j$$

$$S \overset{\text{kinetic}}{=} \int M^2 f\left[-3\dot{\Psi}^2 - 2\vec{\nabla}\Phi\vec{\nabla}\Psi + (\vec{\nabla}\Psi)^2 + c\,\dot{\pi}^2 - c(\vec{\nabla}\pi)^2 + 3(\dot{f}/f)\dot{\Psi}\dot{\pi} + (\dot{f}/f)\vec{\nabla}\pi(\vec{\nabla}\Phi - 2\vec{\nabla}\Psi)\right]$$

Mixing

De-mixing = conformal transformation

$$\Phi_E = \Phi + \frac{1}{2}(\dot{f}/f)\pi$$

$$\Psi_E = \Psi - \frac{1}{2}(\dot{f}/f)\pi$$

Mixing with gravity 1: Brans-Dicke

$$S = \int \sqrt{-g}\left(\frac{M^2}{2} f R - \Lambda - c g^{00} + \frac{M_2^4}{2}(\delta g^{00})^2 - \frac{\bar{m}_1^3}{2}\delta g^{00}\delta K + \frac{1}{2}T^{\mu\nu}\delta g_{\mu\nu}\right)$$

Apply Stueckelberg and go to Newtonian Gauge

$$ds^2 = -(1+2\Phi)dt^2 + a^2(1-2\Psi)\delta_{ij}dx^i dx^j$$

$$S \overset{\text{kinetic}}{=} \int M^2 f\left[-3\dot{\Psi}^2 - 2\vec{\nabla}\Phi\vec{\nabla}\Psi + (\vec{\nabla}\Psi)^2 + c\,\dot{\pi}^2 - c(\vec{\nabla}\pi)^2 + 3(\dot{f}/f)\dot{\Psi}\dot{\pi} + (\dot{f}/f)\vec{\nabla}\pi(\vec{\nabla}\Phi - 2\vec{\nabla}\Psi)\right]$$

$$1-\gamma \equiv \frac{\Phi-\Psi}{\Phi} = \frac{M^2\dot{f}^2/f}{2(c+M^2\dot{f}^2/f)}$$

anisotropic stress

Newtonian limit →

$$G_{\text{eff}} = \frac{1}{8\pi M^2 f}\,\frac{c+M^2\dot{f}^2/f}{c+\frac{3}{4}M^2\dot{f}^2/f}$$

dressed Newton constant

Mixing with gravity 2:

(Cf. braiding: Deffayet et al., 2010)

$$f(t) = 1$$

$$S = \int \sqrt{-g}\left(\frac{M^2}{2} f R - \Lambda - c g^{00} + \frac{M_2^4}{2}(\delta g^{00})^2 - \frac{\bar{m}_1^3}{2}\delta g^{00}\delta K + \frac{1}{2}T^{\mu\nu}\delta g_{\mu\nu}\right)$$

Apply Stueckelberg and go to Newtonian Gauge

$$ds^2 = -(1+2\Phi)dt^2 + a^2(1-2\Psi)\delta_{ij}dx^i dx^j$$

$$S \overset{\text{kinetic}}{=} \int M^2\left[-3\dot{\Psi}^2 - 2\vec{\nabla}\Phi\vec{\nabla}\Psi + (\vec{\nabla}\Psi)^2\right] + c\dot{\pi}^2 - c(\vec{\nabla}\pi)^2 - 3\bar{m}_1^3\dot{\Psi}\dot{\pi} - \bar{m}_1^3\vec{\nabla}\Phi\vec{\nabla}\pi$$

Mixing

De-mixing ≠ conformal transformation

$$\Phi_E = \Phi + \frac{\bar{m}_1^3}{2M^2}\pi$$

$$\Psi_E = \Psi + \frac{\bar{m}_1^3}{2M^2}\pi$$

Mixing with gravity 2:

(Cf. braiding: Deffayet et al., 2010)

$$f(t)=1$$

$$S=\int\sqrt{-g}\left(\frac{M^2}{2}fR-\Lambda-cg^{00}+\frac{M_2^4}{2}(\delta g^{00})^2-\frac{\bar{m}_1^3}{2}\delta g^{00}\delta K+\frac{1}{2}T^{\mu\nu}\delta g_{\mu\nu}\right)$$

Apply Stueckelberg and go to Newtonian Gauge

$$ds^2=-(1+2\Phi)dt^2+a^2(1-2\Psi)\delta_{ij}dx^i dx^j$$

$$S\overset{\text{kinetic}}{=}\int M^2\left[-3\dot{\Psi}^2-2\vec{\nabla}\Phi\vec{\nabla}\Psi+(\vec{\nabla}\Psi)^2\right]+c\dot{\pi}^2-c(\vec{\nabla}\pi)^2-3\bar{m}_1^3\dot{\Psi}\dot{\pi}-\bar{m}_1^3\vec{\nabla}\Phi\vec{\nabla}\pi$$

Mixing

Mixing with gravity 2:

(Cf. braiding: Deffayet et al., 2010)

$$f(t) = 1$$

$$S = \int \sqrt{-g} \left(\frac{M^2}{2} f R - \Lambda - c g^{00} + \frac{M_2^4}{2} (\delta g^{00})^2 - \frac{\bar{m}_1^3}{2} \delta g^{00} \delta K + \frac{1}{2} T^{\mu\nu} \delta g_{\mu\nu} \right)$$

Apply Stueckelberg and go to Newtonian Gauge

$$ds^2 = -(1+2\Phi)dt^2 + a^2(1-2\Psi)\delta_{ij}dx^i dx^j$$

$$S \overset{\text{kinetic}}{=} \int M^2 \left[-3\dot{\Psi}^2 - 2\vec{\nabla}\Phi\vec{\nabla}\Psi + (\vec{\nabla}\Psi)^2 \right] + c\dot{\pi}^2 - c(\vec{\nabla}\pi)^2 - 3\bar{m}_1^3 \dot{\Psi}\dot{\pi} - \bar{m}_1^3 \vec{\nabla}\Phi\vec{\nabla}\pi$$

Mixing

Speed of Sound of DE

$$c_s^2 = \frac{c + \frac{1}{2}(H\bar{m}_1^3 + \dot{\bar{m}}_1^3) - \frac{1}{4}\bar{m}_1^6/M^2}{c + \frac{3}{4}\bar{m}_1^6/M^2}$$

Mixing with gravity 2:

(Cf. braiding: Deffayet et al., 2010)

$$f(t) = 1$$

$$S = \int \sqrt{-g}\left(\frac{M^2}{2} f R - \Lambda - c g^{00} + \frac{M_2^4}{2}(\delta g^{00})^2 - \frac{\bar{m}_1^3}{2}\delta g^{00}\delta K + \frac{1}{2}T^{\mu\nu}\delta g_{\mu\nu}\right)$$

Apply Stueckelberg and go to Newtonian Gauge

$$ds^2 = -(1+2\Phi)dt^2 + a^2(1-2\Psi)\delta_{ij}dx^i dx^j$$

$$S \overset{\text{kinetic}}{=} \int M^2\left[-3\dot{\Psi}^2 - 2\vec{\nabla}\Phi\vec{\nabla}\Psi + (\vec{\nabla}\Psi)^2\right] + c\dot{\pi}^2 - c(\vec{\nabla}\pi)^2 - 3\bar{m}_1^3\dot{\Psi}\dot{\pi} - \bar{m}_1^3\vec{\nabla}\Phi\vec{\nabla}\pi$$

$$1 - \gamma = \frac{\Phi - \Psi}{\Phi} = 0$$

NO anisotropic stress

Newtonian limit →

$$G_{\text{eff}} = \frac{1}{8\pi M^2 f}\left(1 - \frac{\bar{m}_1^3}{4cM^2}\right)^{-1}$$

dressed Newton constant