Phenomenology of the Accelerating Universe

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Nobel Prize in Physics 2011

The Universe is accelerating!

...why?!

Dark energy: current situation

- Two main classes of observables:

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However: beware of theoretical prejudice!

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

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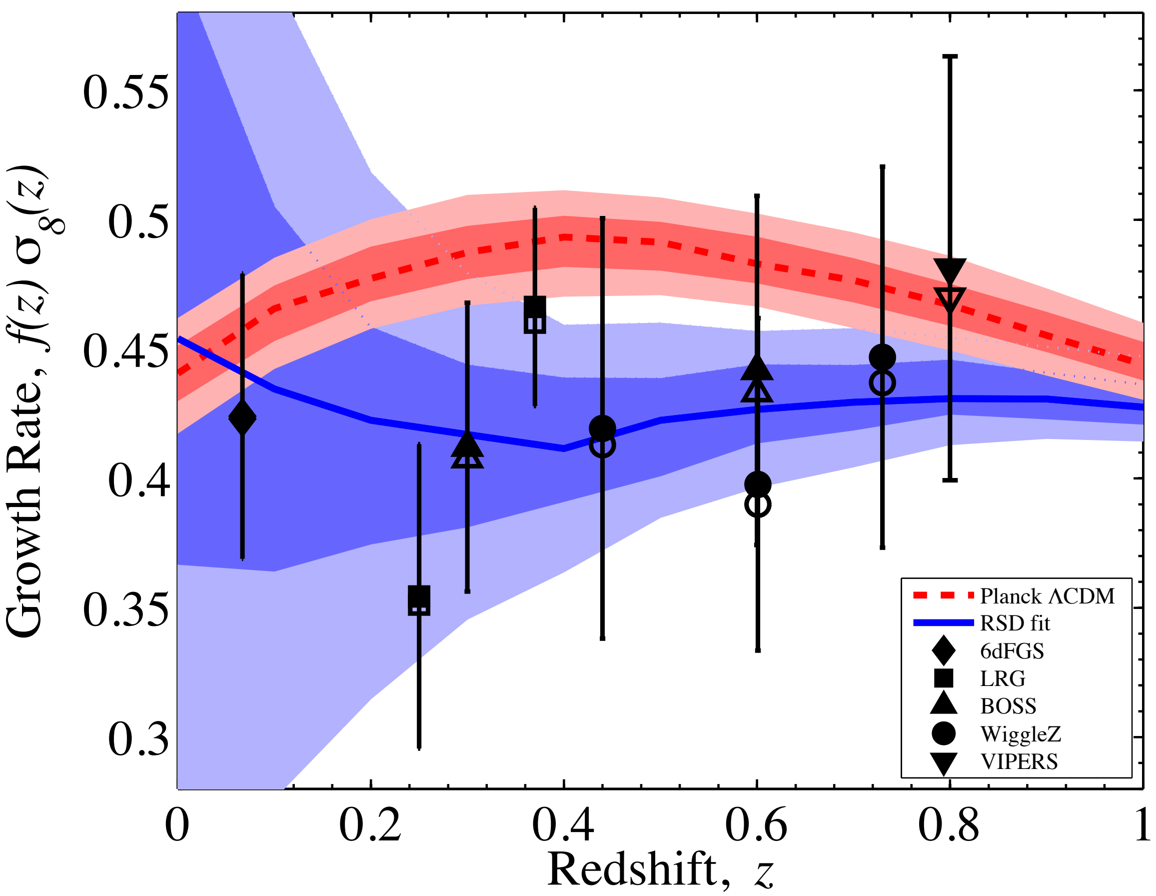
ABSTRACT

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.

Dark energy: current situation

- Two main classes of observables:
    - Background: compatible with w=-1 (LCDM)
    - Perturbations: some interesting tension…

Macaulay et al. '13



Dark energy: current situation

- 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

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

growth rate, lensing potential, etc.

Dark energy: current situation

- 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 Phenomenology

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)

Gubitosi, FP, Vernizzi 2012

The effective field theory (EFT) of dark energy

- Most general description of 1 scalar degree of freedom added to GR
- Cosmological perturbations as the relevant objects of the theory
- Background (0th order) and perturbation (linear and +) sectors
- Unifying framework for DE observables, stability
- Good parameter space to constrain with data (see Planck 2015)

Unitary gauge in Cosmology (technical detour)

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 (technical detour)

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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).

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

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)

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

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

only affect perturbations

Time-dependent couplings

Examples

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

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

Examples

const.

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

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

Quintessence

Examples

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

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

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

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

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

"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

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

"Generalized Galileons" (≡ Horndeski)

(Deffayet et al., 2011)

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

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

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

$$\mathcal{L}_5 = D(\phi, X) G^{\mu\nu} \nabla_\mu \nabla_\nu \phi + \frac{1}{3} D_{,X}(\phi, X) \left[(\Box\phi)^3 - 3(\Box\phi)(\nabla_\mu \nabla_\nu \phi)^2 + 2(\nabla_\mu \nabla_\nu \phi)^3 \right] \,,$$

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

Examples

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

$$+ \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\, \delta K \delta g^{00} + \epsilon_4(t) \Big(\underbrace{\delta K^\mu{}_\nu\, \delta K^\nu{}_\mu - \delta K^2}_{\epsilon_4(t)} + \underbrace{\frac{R^{(3)}\, \delta g^{00}}{2}}_{\tilde{\epsilon}_4(t)} \Big) + \dots \Big]$$

Beyond Horndeski (linear)

(see David's talk before this)

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

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

Complete background separation/redundancies

related by Friedmann eq.

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

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

also participates in perturbations

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Complete background separation/redundancies

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

$$\lambda(t),\ \mathcal{C}(t),\ \mu(t) \equiv \frac{d \ln M^2(t)}{dt} \left\{ \begin{array}{l} \bar{w}(t) \\ \mu(t) \end{array} \right.$$

$\bar{w}(t)$ Expansion History

$\mu(t)$

$\mu_3(t)$

$\epsilon_4(t)$

$\mu_2^2(t)$

Perturbation sector

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Complete background separation/redundancies

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

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

$$\lambda(t),\ \mathcal{C}(t),\ \mu(t) \equiv \frac{d \ln M^2(t)}{dt}$$

$\bar{w}(t)$ Expansion History

$\mu(t)$

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

$\epsilon_4(t)$

$\mu_2^2(t)$ Unconstrained

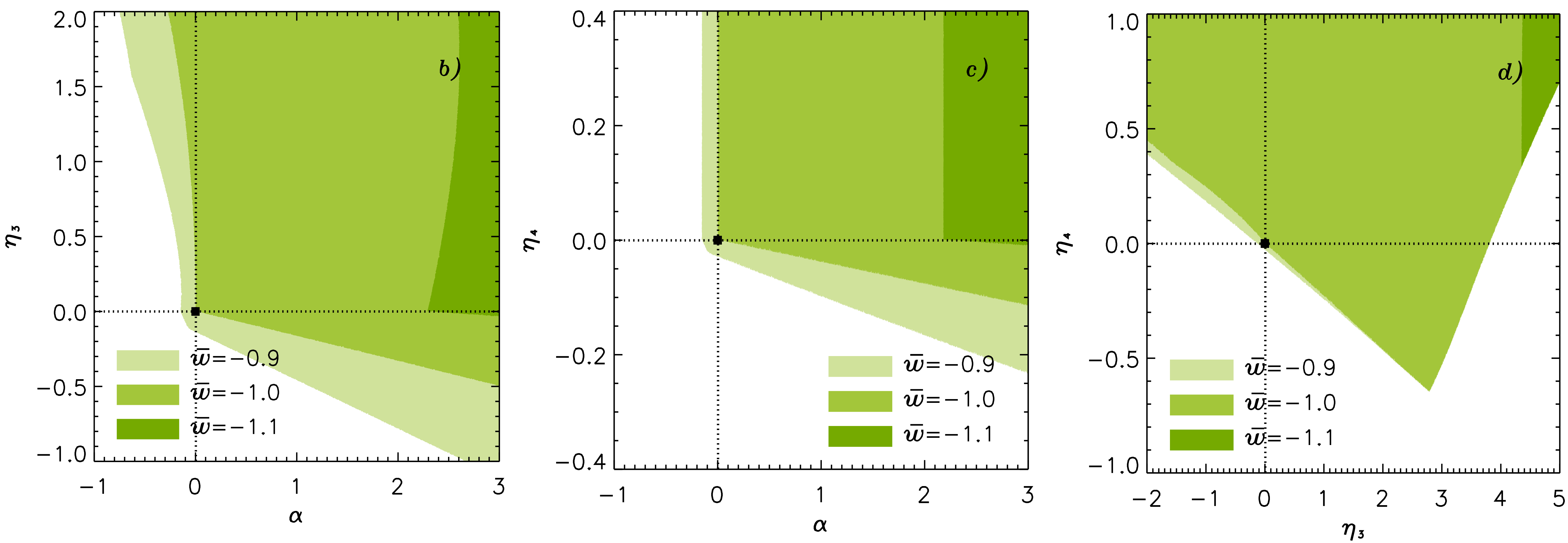
Stability

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

No ghost: A>0

No gradient instabilities: B>0

$\mu_2^2 = 0$



Effective Newton constant

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

``always'' negligible

Notable exception: f(R)

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

If modified gravity is responsible for acceleration $\Rightarrow$ $G_{\rm eff}(z, \cancel{k})$

See also Baker et. al. 1409.8284

Effective Newton constant

If modified gravity is responsible for acceleration $\Longrightarrow$ $G_{\rm eff}(z,\cancel{k})$

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

More than just parameterize $G_{\rm eff}(z)$!

Growth rate

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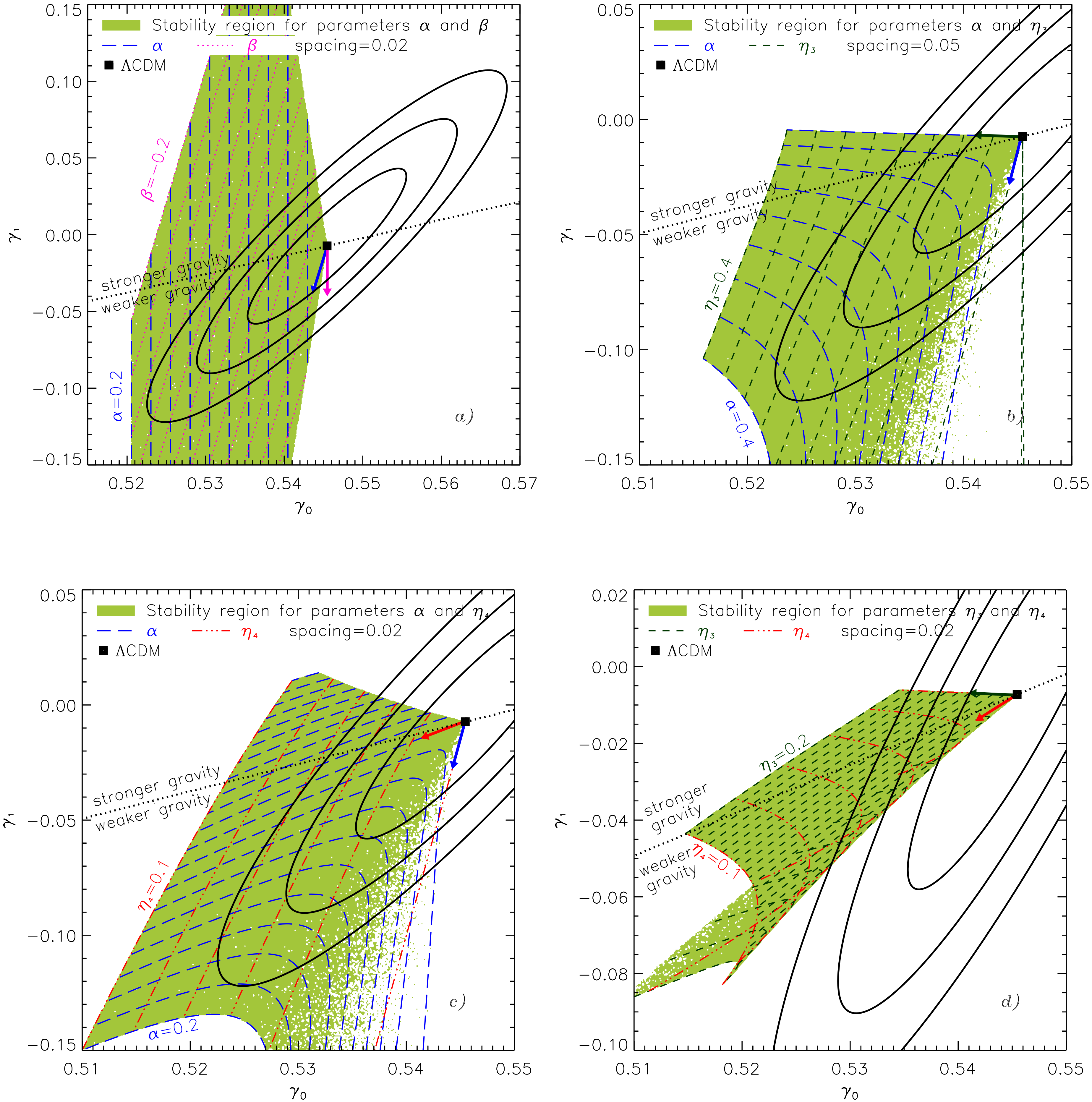
$$f \equiv \frac{d\ln\delta}{d\ln a} = \Omega_m^{\gamma_0+\gamma_1\ln(\Omega_m)}$$

Steigerwald, Bel Marinoni 1403.0898



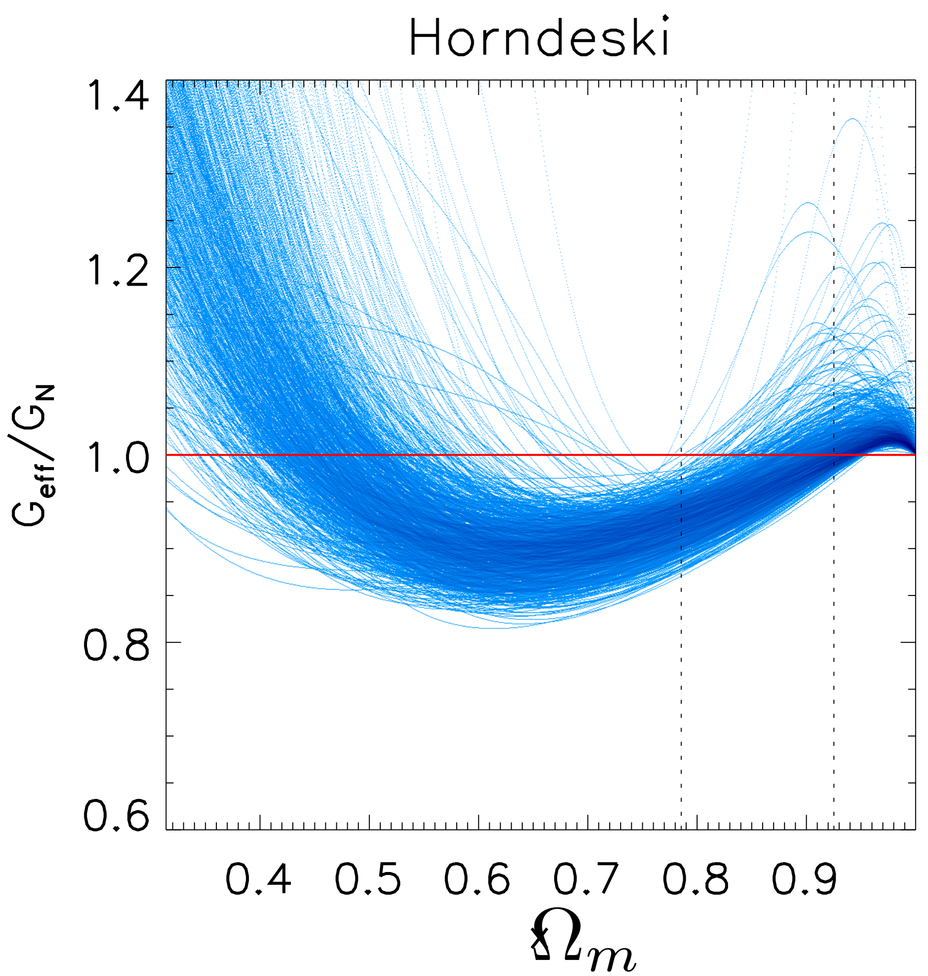
Non trivial result:

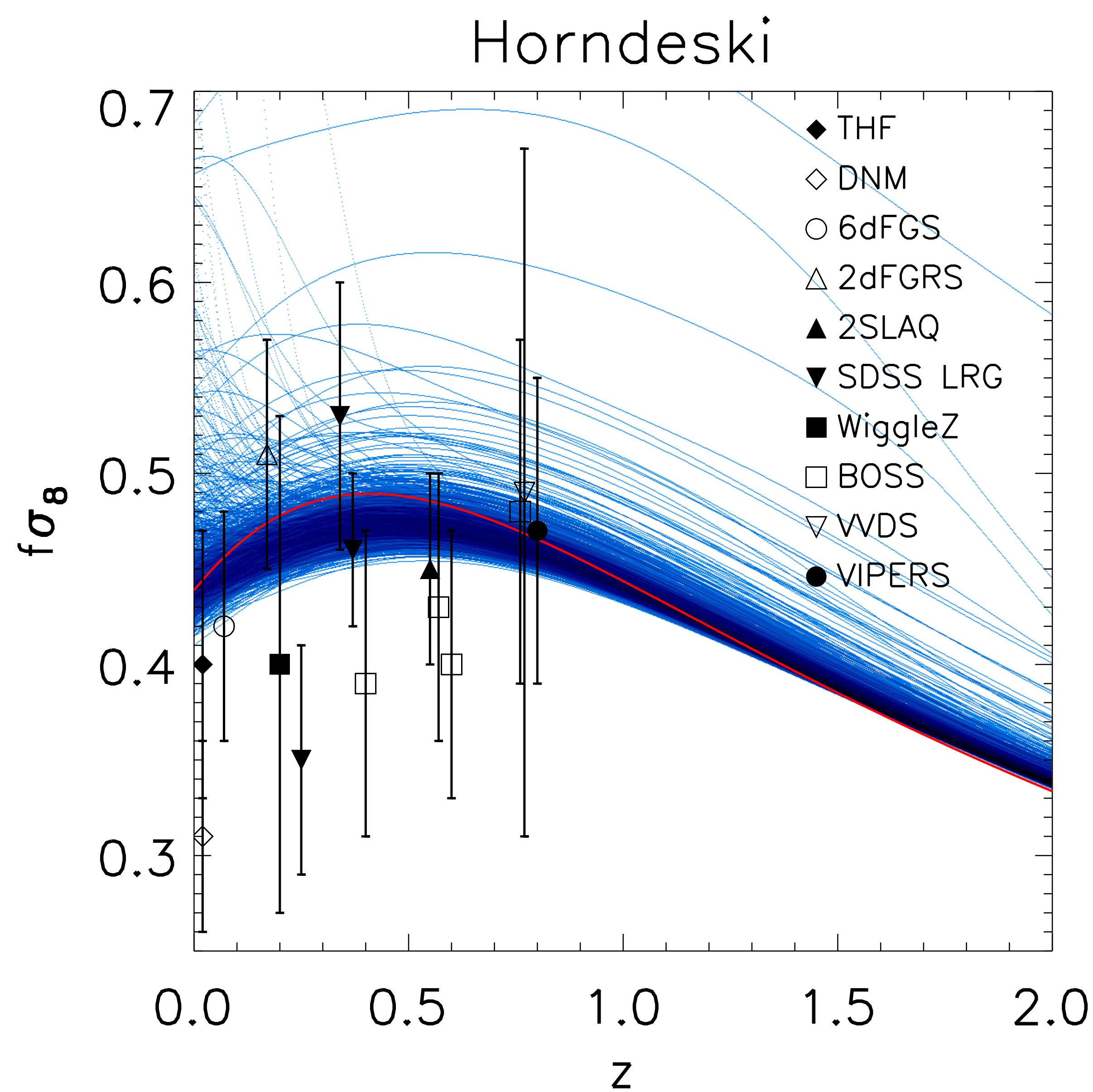
$$\gamma_0 < \gamma_0(\Lambda CDM)$$

Perenon, Marinoni, F. P. in preparation

Growth rate (preliminary)

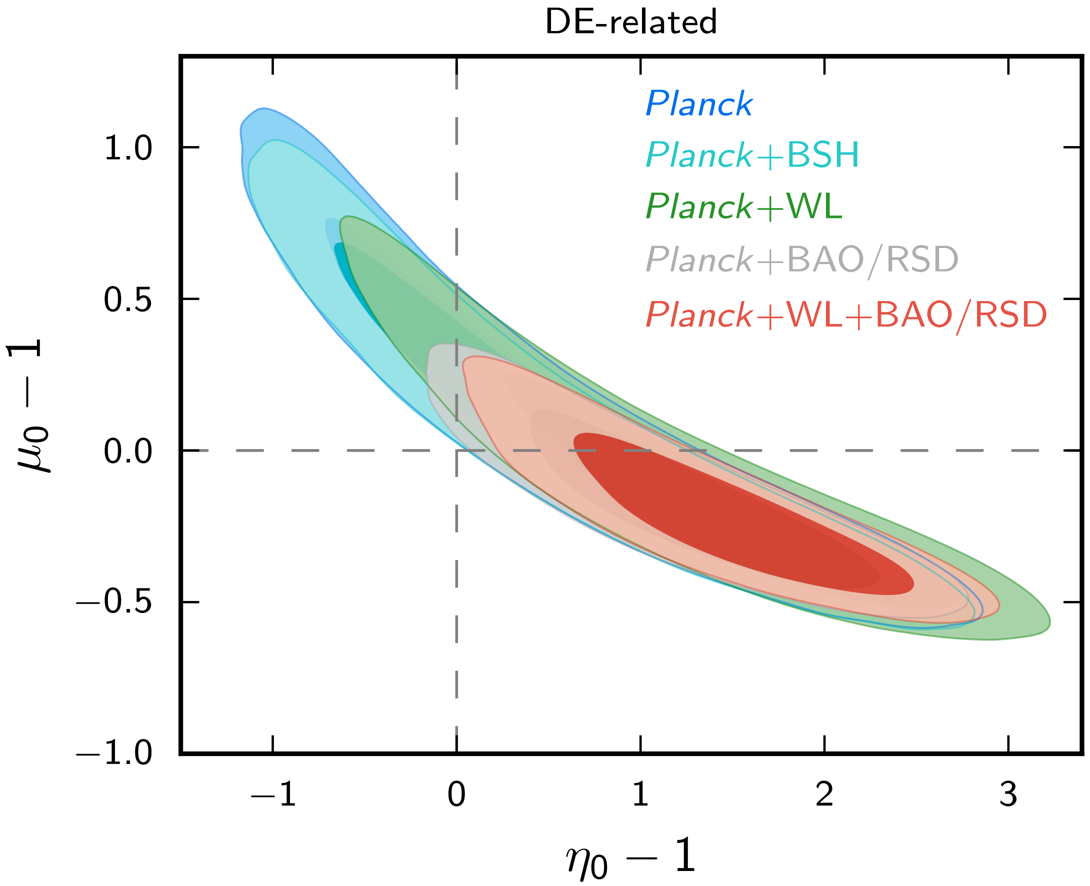
Modified gravity: less growth than LCDM?



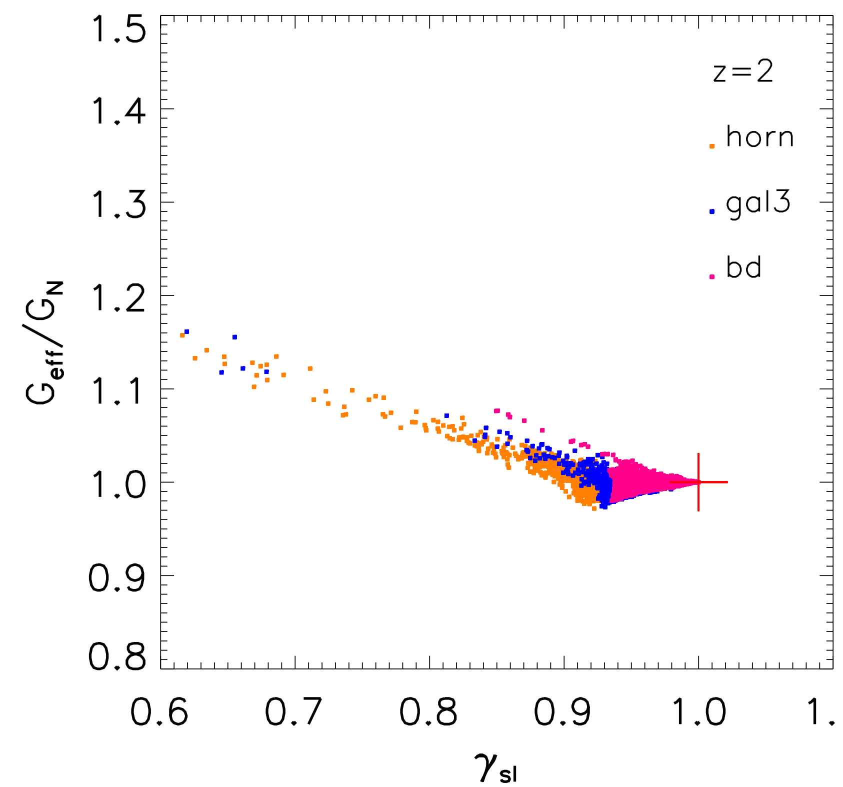


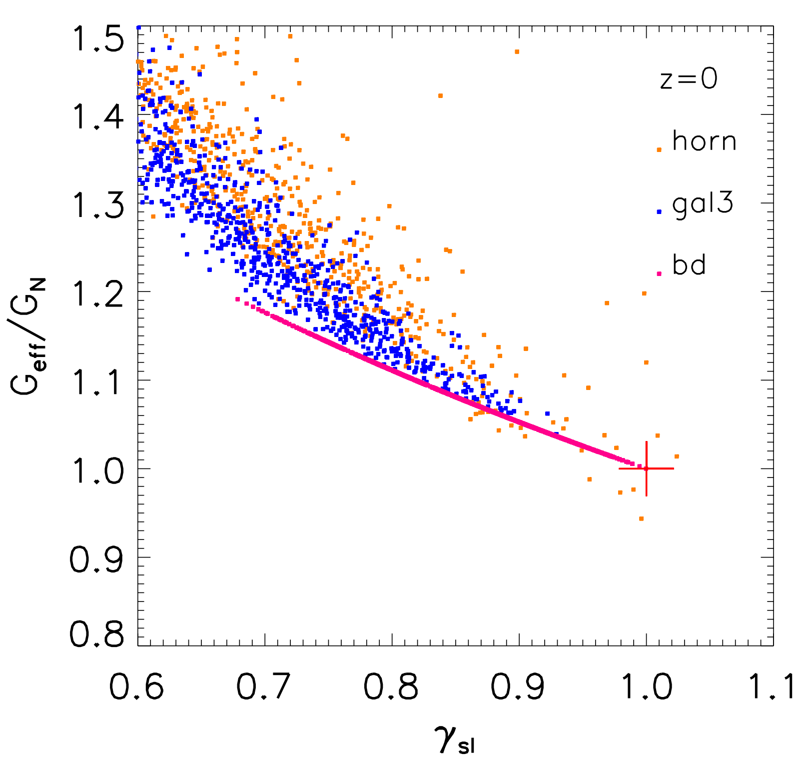
Perenon, Marinoni, F. P. in preparation

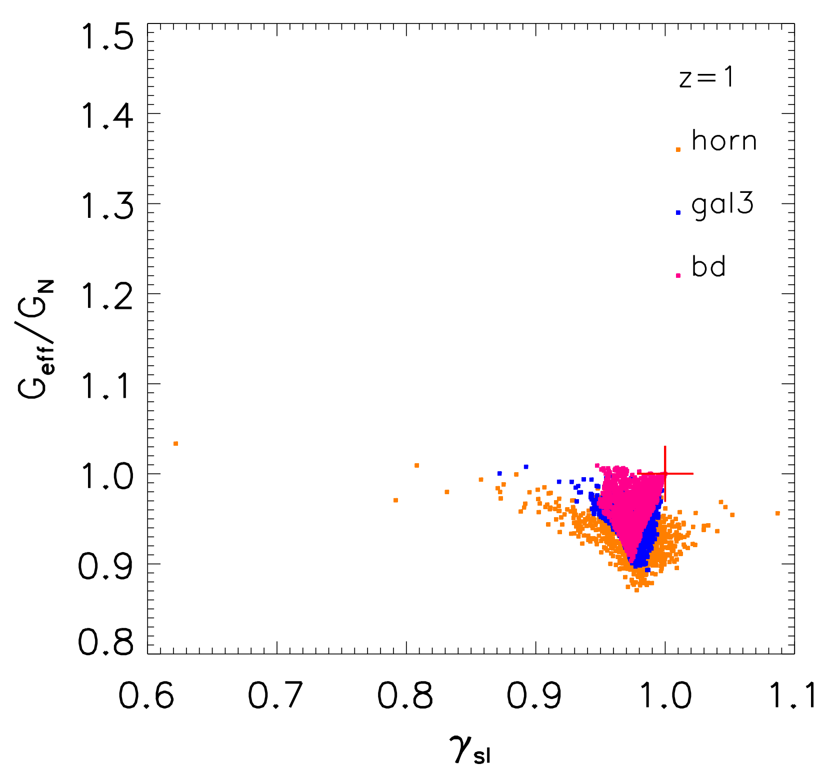
Other observables (preliminary)



Planck 2015







Conclusions

- Unifying framework for dark energy/modified gravity

- Perturbations “know” about the background (stability)

- $G_{\rm eff}$: more information than just a “blind fit”

- Observational constraints and forecasts: much work in progress

Perturbations "know" about the background

stability conditions

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

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

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

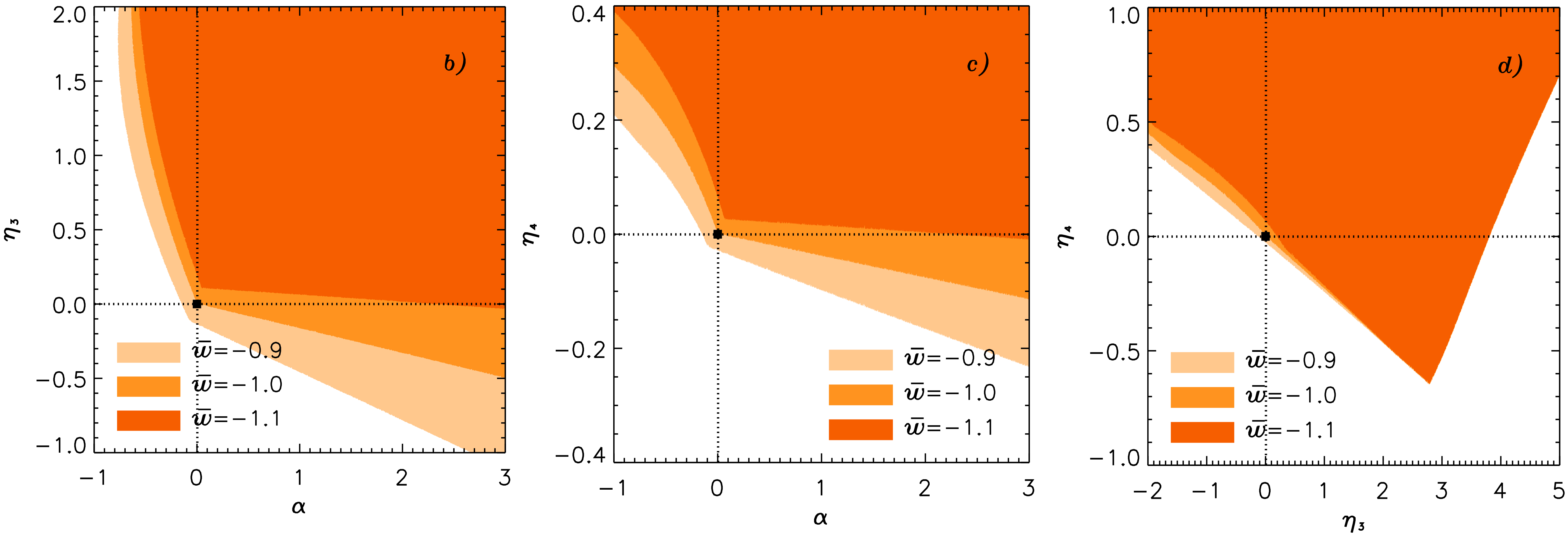
Stability

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

No ghost: A>0

No gradient instabilities: B>0

$\mu_2^2 \gg H^2$



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

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

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

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

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

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:

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

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

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

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

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

Generally Related to post-newtonian parameters

“Bare” Planck Mass

Defined by the modified Friedman equations

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

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

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

Newtonian limit →

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

anisotropic stress

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

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

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

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

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

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 $\longrightarrow$

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

dressed Newton constant