Comments on Taxonomy of Dark Energy Models

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References:

arXiv:1304.4840 Gleyzes, Langlois, Piazza, Vernizzi

arXiv:1211.7054 w/ Bloomfield, Flanagan, and Park

arXiv:1210.0201 Gubitosi, Piazza, Vernizzi

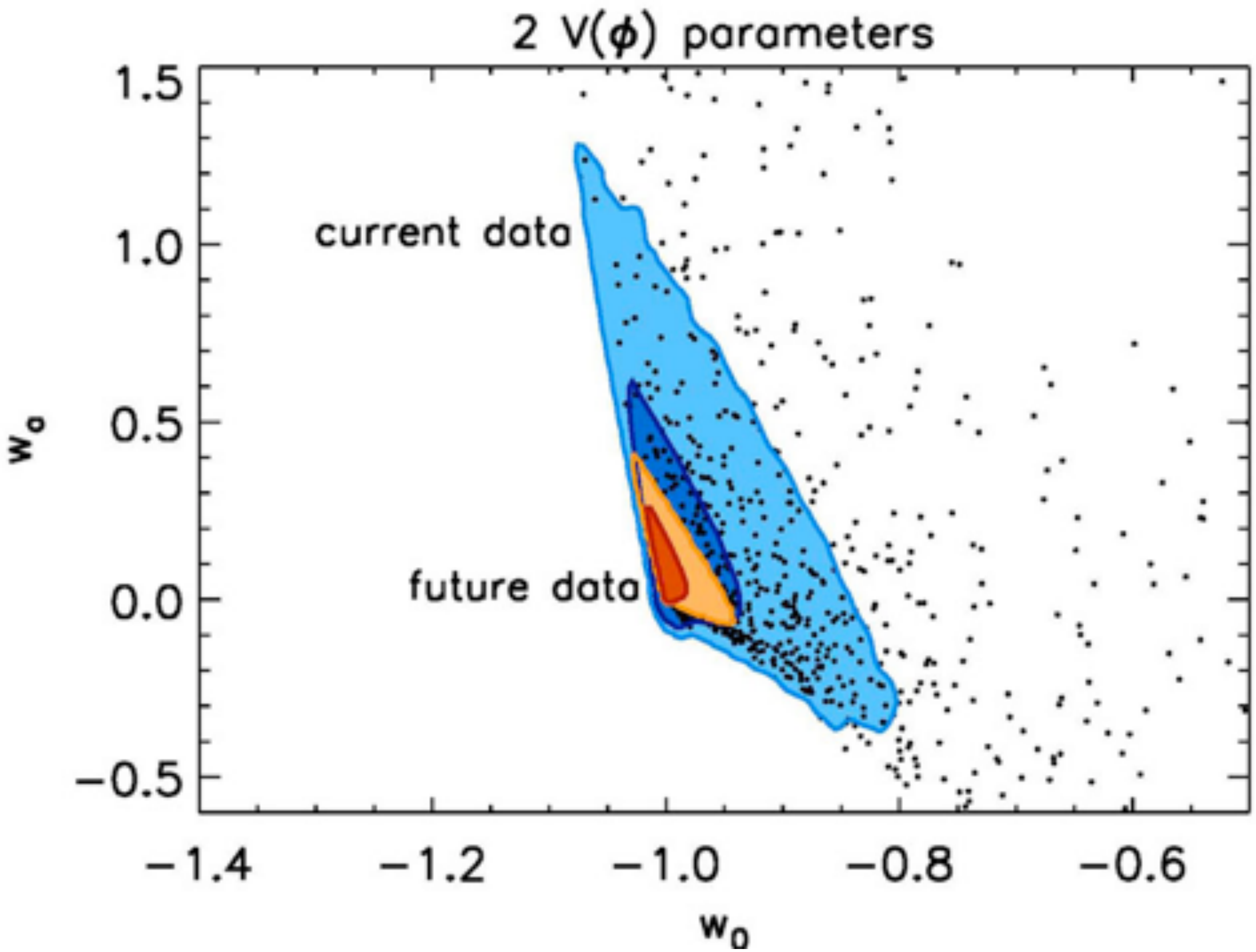
arXiv:1209.2706 w/ Mueller and Bean

arXiv:1112.0303 Bloomfield and Flanagan

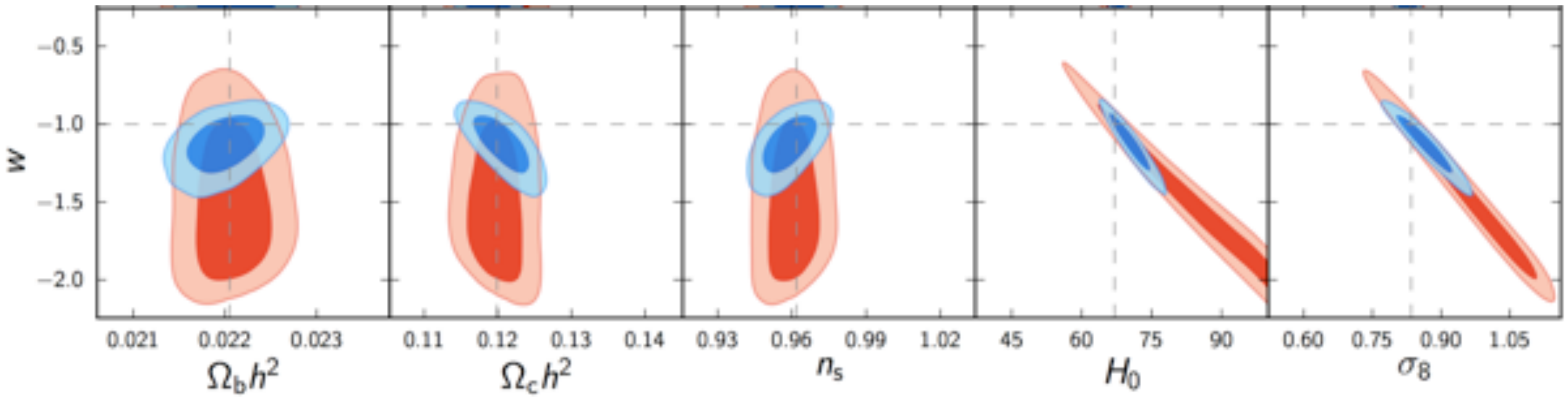
arXiv:1003.1722 w/ Park and Zurek

arXiv:0811.0827 Creminelli, D'Amico, Noreña, Vernizzi

Can we establish a theoretical framework to help guide “realistic” model building?



Nothing wrong with ΛCDM



We want to systematically parametrize all consistent alternatives to a Cosmological Constant in a single framework that can then be compared with observations.

Effective Field Theory and Inflation

Approach One

Weinberg, "Effective Field Theory for Inflation", 0804.4291

Expand background (inflaton and metric) in derivative expansion

Approach Two

Cheung, et. al. "The Effective Field Theory of Inflation", 0709.0293

Expand perturbations about spontaneously broken background
(broken by time dependence)

Advantages of approach two:

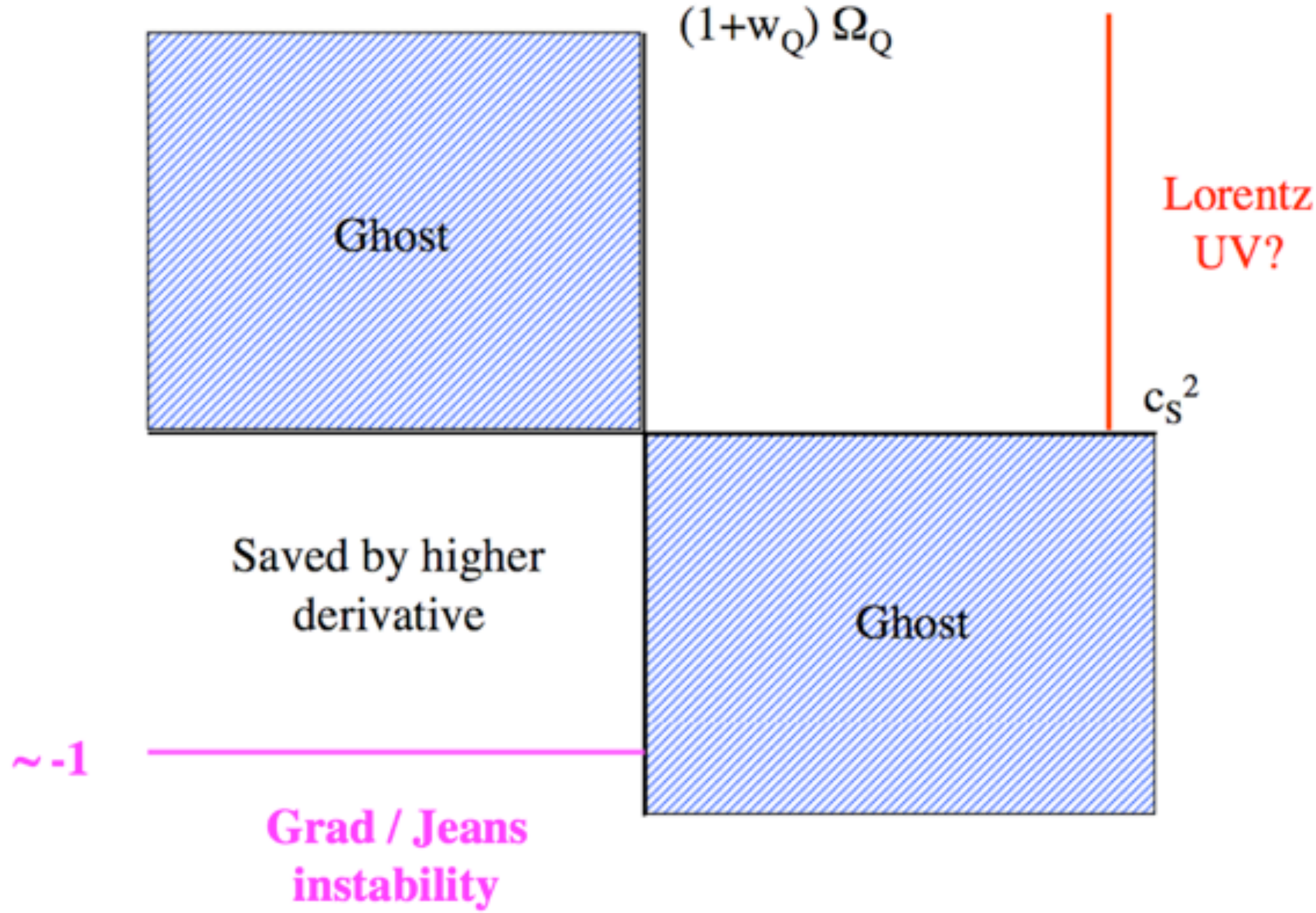
- Inflationary background is not directly observable = focus on perturbations
- Non-linearly realized symmetry establishes relationships between parameters.
- Many inflation models don't admit derivative expansion of background
  (e.g. DBI)

Disadvantage: Background is taken a priori.

EFT of Quintessence

(useful to address stability issues)

arXiv:0811.0827 Creminelli, D'Amico, Noreña, Vernizzi



Simple First Step towards EFT of Dark Energy

Adapt approach of Weinberg

arXiv:1003.1722 w/ Park and Zurek

arXiv:1112.0303 Bloomfield and Flanagan

Approach One

Weinberg, “Effective Field Theory for Inflation”, 0804.4291

Expand background (inflaton and metric) in derivative expansion

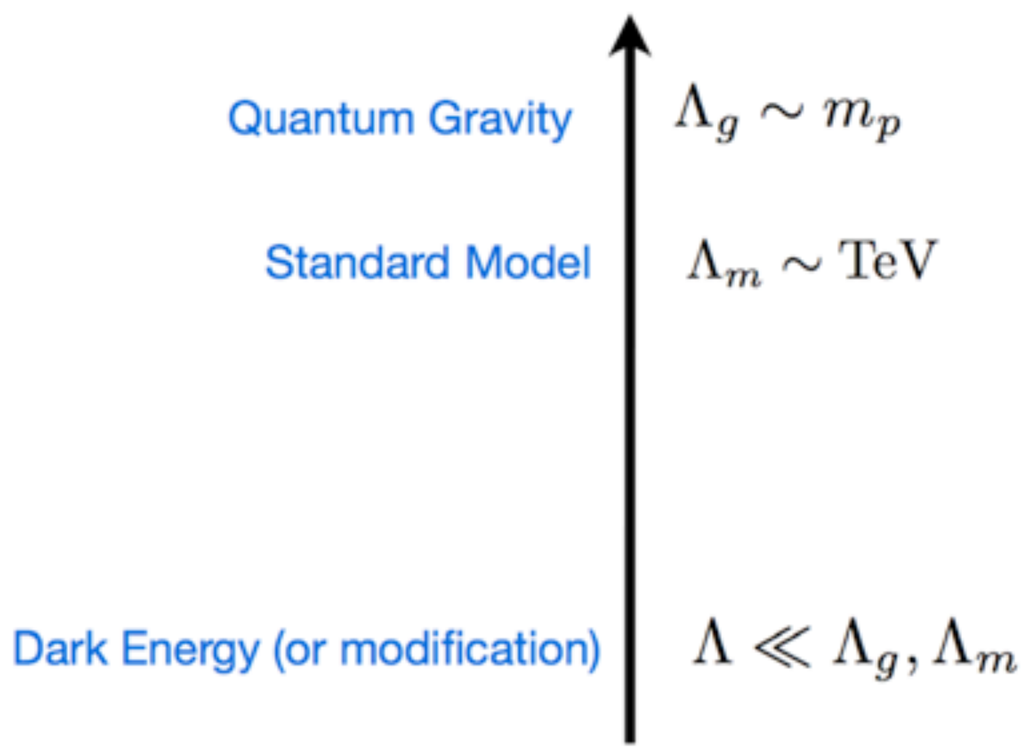
$$
\begin{aligned}
\Delta S = \int d^4x\sqrt{-g}\Big\{ & \frac{\alpha_1}{\Lambda^4}(g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi)^2 + \frac{\alpha_2}{\Lambda^3}\Box\varphi g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi + \frac{\alpha_3}{\Lambda^2}(\Box\varphi)^2 \\
& + \frac{b_1}{\Lambda^2\Lambda_m^2}T^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi + \frac{b_2}{\Lambda^2\Lambda_m^2}Tg^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi + \frac{b_3}{\Lambda\Lambda_m^2}T\Box\varphi \\
& + \frac{c_1}{\Lambda^2}R^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi + \frac{c_2}{\Lambda^2}Rg^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi + \frac{c_3}{\Lambda}R\Box\varphi \\
& + d_1 W^{\mu\nu\lambda\rho}W_{\mu\nu\lambda\rho} + d_2\epsilon^{\mu\nu\lambda\rho}W_{\mu\nu}{}^{\alpha\beta}W_{\lambda\rho\alpha\beta} + d_3R^{\mu\nu}R_{\mu\nu} + d_4R^2 \\
& + \frac{e_1}{\Lambda_m^4}T^{\mu\nu}T_{\mu\nu} + \frac{e_2}{\Lambda_m^4}T^2 + \frac{e_3}{\Lambda_m^2}R_{\mu\nu}T^{\mu\nu} + \frac{e_4}{\Lambda_m^2}RT\Big\},
\end{aligned}
$$

Already many subtleties...

Hierarchy of Scales,
Additional matter sector complicates picture

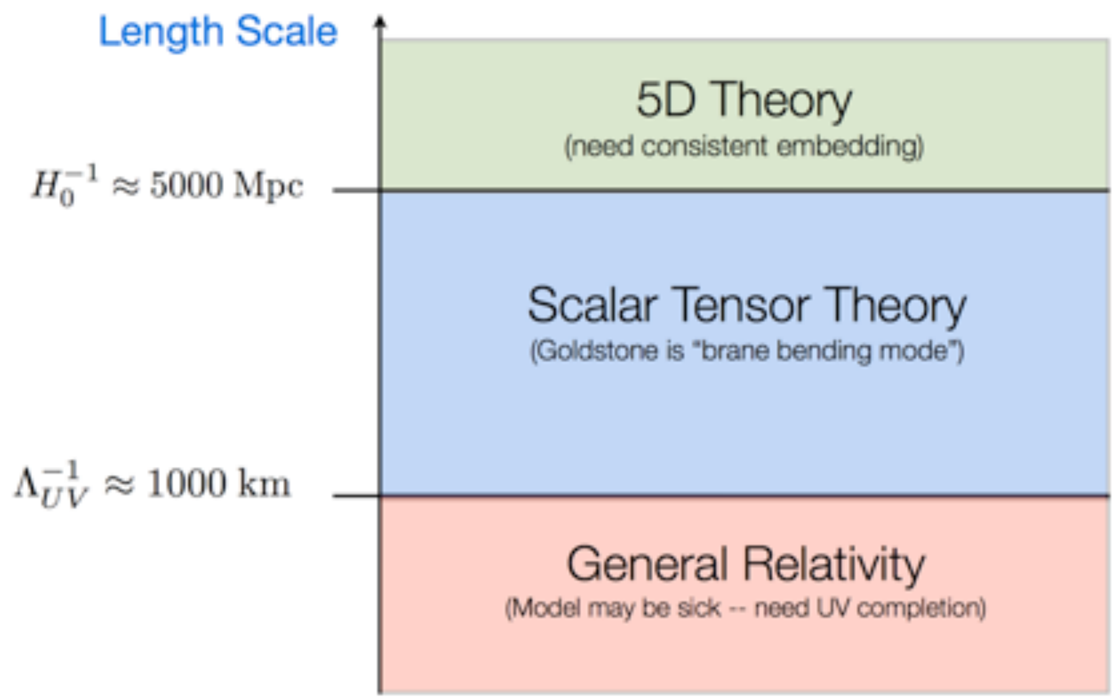
Examples at the Four Derivative level

$$\frac{1}{\Lambda^2} f_1(\varphi)\,(\Box\varphi)^2 \qquad \frac{1}{\Lambda_m^4} f_2(\varphi) T^2 \qquad f_3(\varphi)\frac{T}{\Lambda_m^2}\frac{\Box\varphi}{\Lambda^2} \qquad \frac{1}{\Lambda^4} f_4(\varphi)\,(\partial\varphi)^4$$



Already many subtleties...

How to capture modified gravity models?



Scalar-tensor theory

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{16\pi G_N}\Omega^2(\varphi)R + \mathcal{L}_\varphi + \mathcal{L}_m\right]$$

Non-canonical scalar with "K-essence" type correction

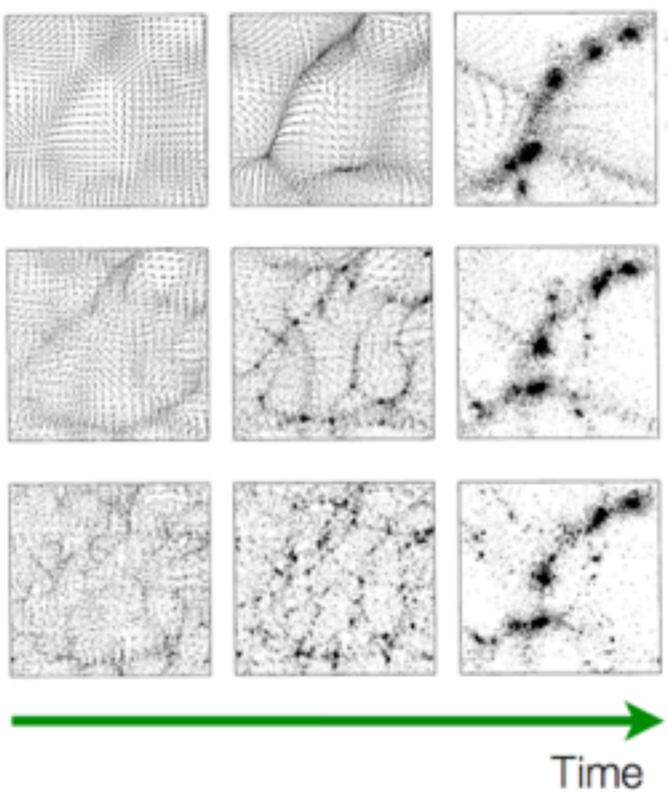
$$\mathcal{L}_\varphi = -\frac{1}{2}Z(\varphi)\partial_\mu\varphi\partial^\mu\varphi - U(\varphi) + \frac{1}{\Lambda^4}\alpha(\varphi)(\partial\varphi)^4$$

Already many subtleties...

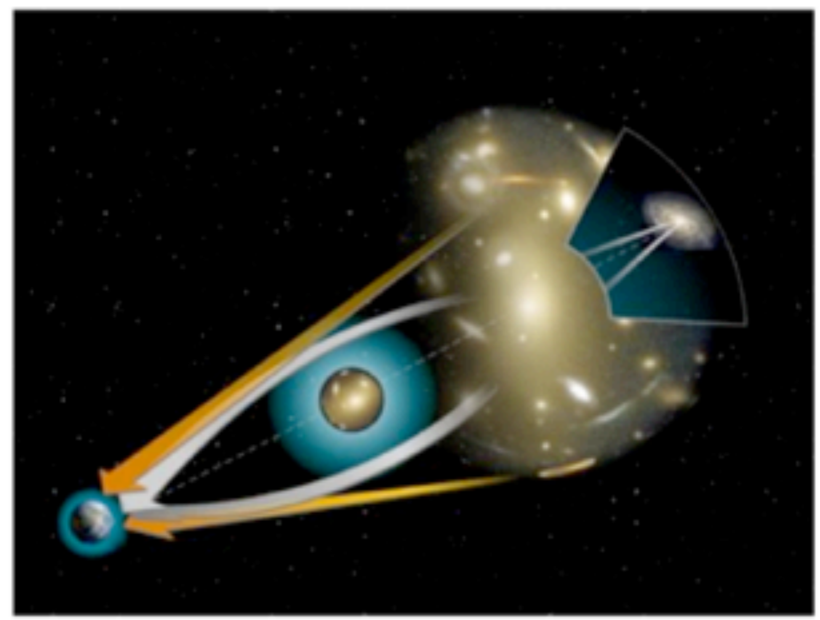
How to capture modified gravity models?

$$ds^2 = -\left(1+2\Phi\right)dt^2 + a^2\left(1-2\Psi\right)d\vec{x}^2$$

Φ Growth of Structure



$\Phi + \Psi$ Gravitational Lensing



Already many subtleties...

How to capture modified gravity models?

Scalar - Tensor / Modified Gravity leads to shear

$$\Psi - \Phi = 2\frac{\Omega'}{\Omega}\delta\varphi$$

Growth modified by change of effective coupling

$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G_{eff}\bar{\rho}\delta_m \approx 0$$

$$\delta_m \sim \frac{\delta\rho}{\rho}$$

$$G_{\rm eff} = G_N \Omega_0^{-2} \frac{Z_0 + 8m_p^2 {\Omega_0'}^2}{Z_0 + 6m_p^2 {\Omega_0'}^2}$$

Approach One: EFT of Background

arXiv:1003.1722 w/ Park and Zurek

- What observational properties might the most general action predict?

$$S = \int d^4x\sqrt{-g}\left\{\frac{M_p^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi)\right.$$

Canonical scalar field

$$+f_{quartic}(\phi)(\nabla\phi)^4$$

Quartic kinetic

$$+f_{curv}(\phi)G^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi$$

Coupling to curvature

$$\left.+f_{GB}(\phi)\left(R^2 - 4R^{\mu\nu}R_{\mu\nu} + R_{\mu\nu\sigma\rho}R^{\mu\nu\sigma\rho}\right)\right\}$$

Gauss-Bonnet (GB) term

$$+S_{\rm m}\left[e^{\alpha(\phi)}g_{\mu\nu}\left(1 + f_{kin}(\phi)(\nabla\phi)^2\right), \psi_{\rm m}\right]$$

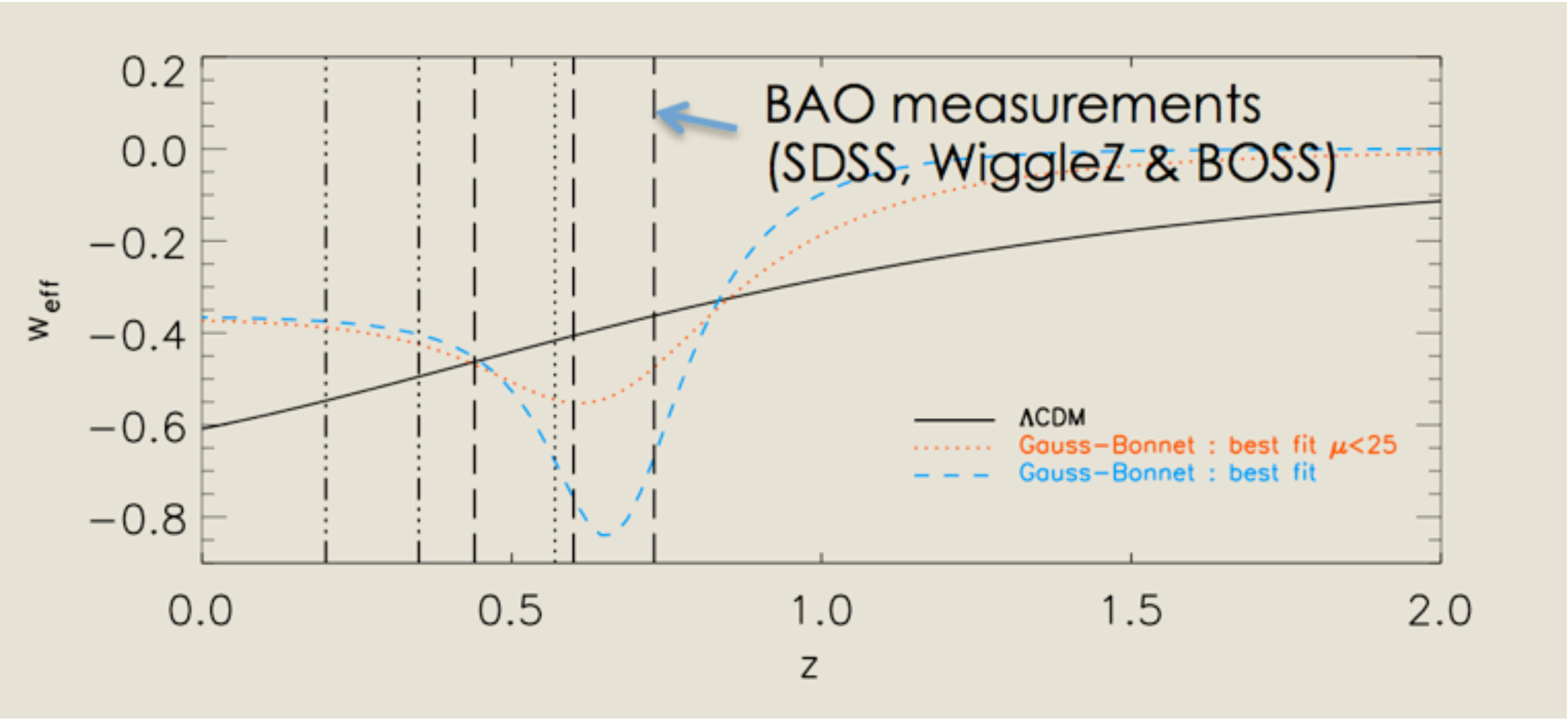
Non-minimally coupling to matter

Weak Equivalence principle

Approach One Application:

Requiring attractor behavior leads to constraints on coefficients of the EFT

arXiv:1209.2706 w/ Mueller and Bean



Can establish constraints on the background, but we miss a large class of non-linear models

Approach Two:

Assume ΛCDM Background,
construct most general theory of perturbations

arXiv:1304.4840 Gleyzes, Langlois, PIazza, Vernizzi
arXiv:1211.7054 w/ Bloomfield, Flanagan, and Park
arXiv:1210.0201 Gubitosi, Piazza, Vernizzi

$$
\begin{aligned}
S = \int d^4x\sqrt{-g}\Big[& \frac{m_0^2}{2}\Omega(t)R + \Lambda(t) - c(t)\delta g^{00} \\
& + \frac{M_2^4(t)}{2}(\delta g^{00})^2 + \frac{M_3^4(t)}{3!}(\delta g^{00})^3 + \dots \\
& - \frac{\bar{M}_1^3(t)}{2}\delta g^{00}\delta K^{\mu}{}_{\mu} - \frac{\bar{M}_2^2(t)}{2}(\delta K^{\mu}{}_{\mu})^2 - \frac{\bar{M}_3^2(t)}{2}\delta K^{\mu}{}_{\nu}\delta K^{\nu}{}_{\mu} + \dots \\
& + \lambda_1(t)(\delta R)^2 + \lambda_2(t)\delta R_{\mu\nu}\delta R^{\mu\nu} + \gamma_1(t)C_{\mu\nu\sigma\lambda}C^{\mu\nu\sigma\lambda} + \gamma_2(t)\epsilon^{\mu\nu\sigma\lambda}C_{\mu\nu}{}^{\rho\theta}C_{\sigma\lambda\rho\theta} + \dots \\
& + m_1^2(t)n^{\mu}n^{\nu}\partial_\mu g^{00}\partial_\nu g^{00} + m_2^2(t)(g^{\mu\nu} + n^{\mu}n^{\nu})\partial_\mu g^{00}\partial_\nu g^{00} + \dots\Big] + S_m[g_{\mu\nu}]. \quad (2.1)
\end{aligned}
$$

Framework now compatible with Vainshtein mechanism

Adapt EFT of Inflation (Cheung, et. al. 0709.0293) to dark energy

arXiv:1304.4840 Gleyzes, Langlois, PIazza, Vernizzi
arXiv:1211.7054 w/ Bloomfield, Flanagan, and Park
arXiv:1210.0201 Gubitosi, Piazza, Vernizzi

Must include Dark Matter Sector

Background taken a priori as Lambda-CDM

Messy!

$$
\begin{aligned}
S_\pi = \int d^4x a^3 \sqrt{\tilde{g}} \Big[& c\left(\dot{\pi}^2 - \frac{\tilde{g}^{ij}}{a^2}\tilde{\nabla}_i\pi\tilde{\nabla}_j\pi\right) + \left(3\dot{H}c - \frac{m_0^2}{4}\dot{\Omega}\dot{R}^{(0)}\right)\pi^2 - c\dot{h}\pi + \frac{m_0^2}{2}\dot{\Omega}\pi\delta R \\
& + 2M_2^4\dot{\pi}^2 + \bar{M}_1^3\dot{\pi}\left(-\frac{\dot{h}}{2} + 3\dot{H}\pi + \frac{\tilde{\nabla}^2\pi}{a^2}\right) - \frac{\bar{M}_2^2}{2}\left(-\frac{\dot{h}}{2} + 3\dot{H}\pi + \frac{\tilde{\nabla}^2\pi}{a^2}\right)^2 \\
& - \frac{\bar{M}_3^2}{2}\left(-\frac{\dot{h}^i{}_j}{2} + \dot{H}\pi\delta^i_j + \frac{\tilde{g}^{ik}}{a^2}\tilde{\nabla}_k\tilde{\nabla}_j\pi\right)\left(-\frac{\dot{h}^j{}_i}{2} + \dot{H}\pi\delta^j_i + \frac{\tilde{g}^{jl}}{a^2}\tilde{\nabla}_l\tilde{\nabla}_i\pi\right) \\
& + \bar{M}_3^2(t)H^2\frac{\tilde{g}^{ij}}{a^2}\tilde{\nabla}_i\pi\tilde{\nabla}_j\pi - \hat{M}^2\dot{\pi}\delta R^{(3)} + \dots \Big],
\end{aligned}
$$

However, adequately reproduces existing models...

Operator	Ω	Λ	c	M_2^4	$\bar{M}_1^3$	$\bar{M}_2^2$	$\bar{M}_3^2$	$\hat{M}^2$
Model	R		δg^{00}	$(\delta g^{00})^2$	$\delta g^{00}\delta K^\mu{}_\mu$	$(\delta K^\mu{}_\mu)^2$	$\delta K^\mu{}_\nu K^\nu{}_\mu$	$\delta g^{00}\delta R^{(3)}$
ΛCDM	1	✓	0	-	-	-	-	-
Quintessence	1/✓	✓	✓	-	-	-	-	-
$F(R)$	✓	✓	0	-	-	-	-	-
k-essence	1/✓	✓	✓	✓	-	-	-	-
Galileon Kinetic Braiding	1/✓	✓	✓	✓	✓	-	-	-
DGP	✓	✓†	✓†	✓†	✓	-	-	-
Ghost Condensate	1/✓	✓	0	-	-	✓	✓	-
Horndeski	✓	✓	✓	✓	✓	✓†	✓†	✓†

Is such an approach worth exploring further?

Many experimentalists / observers seem to think yes.

Some Challenges:

- Hierarchy of many scales
- Non-locality at equal matter/DE?
- Complicated equations (Just a Numerical challenge?)
- Can we measure these coefficients well?
- Is there really a good model of modified gravity?
- ... ?

Should we all just accept w= -1 and move on?

“Don’t modify gravity, understand it.” -- Nima

https://webcast.stsci.edu/webcast/detail.xhtml?talkid=3398