Constraining Galileon models with recent cosmological data and perspectives

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March 25, 2016

UPSUD – LAL

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

LAL Seminar

UNIVERSITÉ PARIS SUD

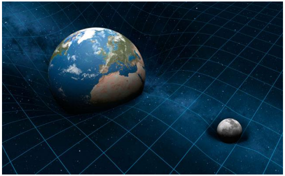
Comprendre le monde, construire l'avenir®

Context

Two theories to describe our Universe

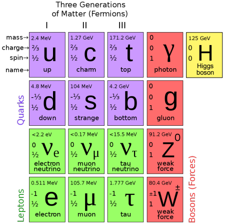
General Relativity

Macroscopic scale



Particle Physics

Microscopic scale

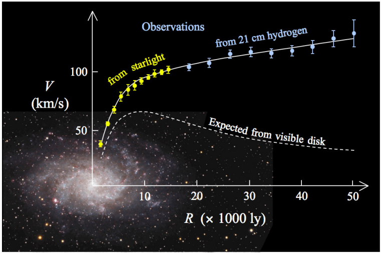


$$\mathcal{S}_{\mathrm{RG}} = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}(\mathbf{R} - \mathbf{\Lambda}) - \mathcal{L}_{\mathrm{SM}}\right]$$

The Dark Side of the Universe

Dark Matter

If galaxies contain only visible matter, then their rotation curve must follow Newton's law...



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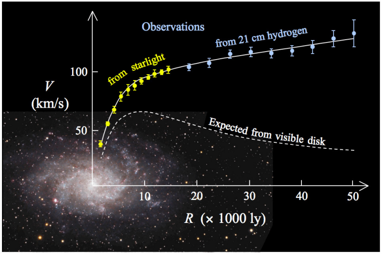

... but it doesn't !
What is the nature of this Dark Matter ?

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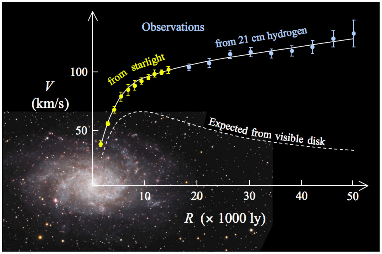

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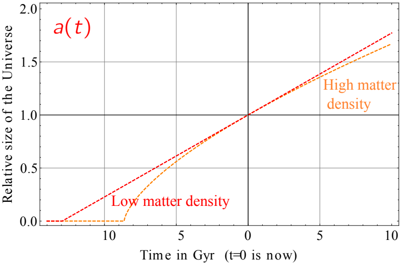
Dark Energy

If Universe contains only matter, then its expansion must slow down...



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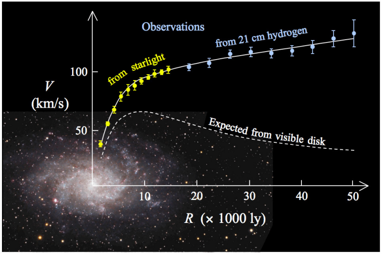

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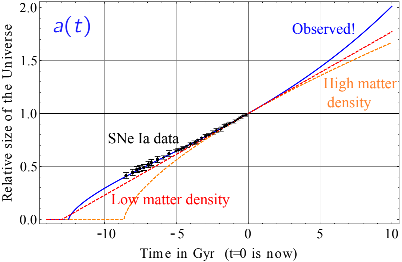
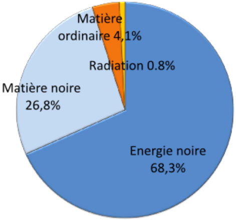


... but it accelerates !
What is the nature of this Dark Energy ?

Going beyond the Standard Models...

Accelerated expansion of the Universe, dynamics of galaxies, etc...

⇒ 95% of the energy content of the Universe is UNKNOWN



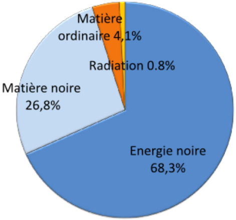
Going beyond the Standard Models...

Accelerated expansion of the Universe, dynamics of galaxies, etc...

$\Rightarrow$ **95% of the energy content of the Universe is UNKNOWN**

Dark Matter

- Supersymmetry
- Axions
- Extra spatial dimensions ? : KK particles, Branon...
- Modified Newton law (MOND) ?



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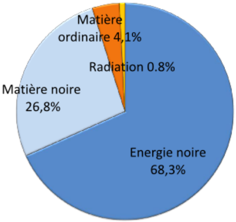

Dark Energy

- Cosmological constant Λ ? Fine tuning problems...
- Quintessence
- Chameleon
- Galileon

Part I : Galileon cosmology

Part II : Cosmological constraints

Part III : Perspectives and summary

Part I

Galileon cosmology

Galileon Lagrangians

The Galileon theory

Modification of the General Relativity :

- to explain the accelerated expansion of the Universe
- without impacting the local gravitation

Principles [Nicolis, Rattazzi & Trincherini, 2009] :

Lagrangians constructed to obtain a second-order equation of motion for π and invariant under a Galilean symmetry $\pi \mapsto \pi + a + b_\mu x^\mu$

$\Rightarrow$ only 5 Lagrangians possible $\Rightarrow$ 5 free parameters c_i

Other constructions

- Xdim : Galileon π is the position of our 4D brane inside a 5D bulk [Hinterbichler et al. (2010)]
- Massive gravity : Galileon is the fifth polarisation of a massive graviton in dRGT theories [de Rham et al. (2010)]
- Particular case of the Horndeski theories [Horndeski (1974)] describing the most general second order scalar field theories in curved space

- In the Xdim context, the Galilean symmetry appears naturally

Galileon Lagrangians

Galileon Lagrangians

$$\mathcal{L}_1 = \pi, \quad \mathcal{L}_2 = (\nabla_\mu\pi)(\nabla^\mu\pi), \quad \mathcal{L}_3 = (\Box\pi)(\nabla_\mu\pi)(\nabla^\mu\pi),$$

$$\mathcal{L}_4 = (\nabla_\mu\pi)(\nabla^\mu\pi)\left[2(\Box\pi)^2 - 2\pi_{;\mu\nu}\pi^{;\mu\nu} - R\,(\nabla_\mu\pi)(\nabla^\mu\pi)/2\right],$$

$$\mathcal{L}_5 = (\nabla_\mu\pi)(\nabla^\mu\pi)\left[(\Box\pi)^3 - 3(\Box\pi)\pi_{;\mu\nu}\pi^{;\mu\nu} + 2\pi_{;\mu}^{\;;\nu}\pi_{;\nu}^{\;;\rho}\pi_{;\rho}^{\;;\mu} - 6\pi_{;\mu}\pi^{;\mu\nu}\pi^{;\rho}\,G_{\nu\rho}\right]$$

- π field coupled to Ricci scalar and Einstein tensor
  $\Rightarrow$ modified gravity !

Galileon Lagrangians

Galileon action [Appleby & Linder (2011)]

$$\mathcal{S}_{\rm Gal} = \int d^4x\sqrt{-g}\left(\frac{M_P^2 R}{2} - \mathcal{L}_{\rm m} - \frac{1}{2}\sum_{i=1}^{5} \frac{c_i}{M^{3(i-2)}}\mathcal{L}_i - \mathcal{L}_{\rm couplings} \right)$$

- General Relativity
- Matter Lagrangian
- Covariant Galileon Lagrangians [Deffayet et al. 2009]
  - Only five Lagrangian terms possible thanks to a Galilean symmetry $\pi \mapsto \pi + a + b_\mu x^\mu \Rightarrow$ 5 free parameters c_i
  - $M^3 = M_P H_0^2$ and c_i parameters without dimension
- Optional disformal coupling between matter and the Galileon field

Properties

- Only 5 c_i free parameters (beside the couplings to matter).
- Can assume $c_1 = 0$ to avoid an explicit cosmological constant
- No theoretical problems : no ghosts, no instabilities, preserves General Relativity thanks to Vainshtein screening effect.

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Direct couplings to matter

- conformal : $c_0 \pi T^{\mu}_{\mu}/M_P$
- disformal : $c_G \partial_\mu \pi \partial_\nu \pi T^{\mu\nu}/M_P M^3$ (can originate from Xdim, massive gravity)

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Question

How to predict the expansion history of a Galileon Universe ?

Expansion of a Galileon Universe

- FLRW metric : $ds^2 = -dt^2 + a^2(t)\delta_{ij}dx^i dx^j$
- Example with the (00) Einstein equation : $\delta\mathcal{S}/\delta g_{00} = 0$

$$\bar{H}^2(t) = \frac{\Omega_m^0}{a^3(t)} + \frac{\Omega_r^0}{a^4(t)} + \underbrace{\Omega_\Lambda}_{\Omega_{\textbf{Dark Energy}}}$$

$\bar{H} = H/H_0$

Expansion of a Galileon Universe

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$$(1 - 2c_0 y)\bar{H}^2 = \frac{\Omega_m^0}{a^3(t)} + \frac{\Omega_r^0}{a^4(t)}$$

$$+ \underbrace{\frac{c_2}{6}\bar{H}^2 x^2 - 2c_3\bar{H}^4 x^3 + \frac{15}{2}c_4\bar{H}^6 x^4 - 7c_5\bar{H}^8 x^5 - 3c_G\bar{H}^4 x^2 + 2c_0\bar{H}^2 x}_{\Omega_\pi = \text{"new"}\ \Omega_{\text{Dark Energy}}}$$

$y = \pi/M_P$

$x = M_P^{-1} d\pi/d\ln a$

Expansion of a Galileon Universe

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$y = \pi/M_P$

$x = M_P^{-1}d\pi/d\ln a$

$\Omega_\pi =$ **"new"** $\Omega_{\text{Dark Energy}}$

Degeneracy problem !

Equations invariant under a scale transformation γ :

$x \mapsto x/\gamma$, $c_i \mapsto c_i \times \gamma^i$, $c_G \mapsto c_G \times \gamma^2$, $c_0 \mapsto c_0 \times \gamma$!

$\Rightarrow$ *The same $\bar{H}(z)$ evolution can be obtained with small x and high c_is or high x and small c_is*

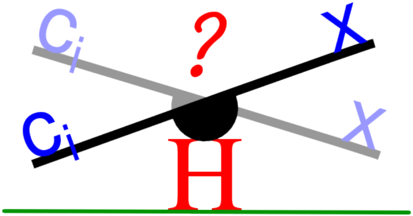
Expansion of a Galileon Universe

Two solutions :

- a value of x is known at some instant of the Universe history

or

- break the degeneracy with a new parametrisation



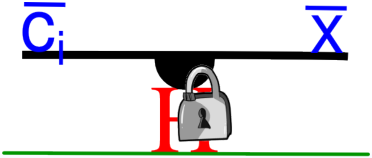
Expansion of a Galileon Universe

New parametrisation

New parametrisation

We set $x_0 = x(z=0)$ the x initial condition :

$$\boxed{\bar{c}_i = c_i x_0^i,\ \ \bar{c}_G = c_G x_0^2,\ \ \bar{c}_0 = c_0 x_0,\ \ \bar{x} = x/x_0,\ \ \bar{y} = y/x_0}$$



[Neveu et al., A&A 555, A53 (2013)]

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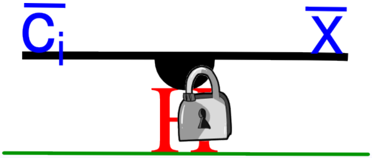
$$\begin{aligned}\bar{H}^2 &= \frac{\Omega_m^0}{a^3} + \frac{\Omega_r^0}{a^4} + \frac{c_2}{6}\bar{H}^2 x^2 - 2c_3\bar{H}^4 x^3 + \frac{15}{2}c_4\bar{H}^6 x^4 - 7c_5\bar{H}^8 x^5 - 3c_G\bar{H}^4 x^2 \\ &= \frac{\Omega_m^0}{a^3} + \frac{\Omega_r^0}{a^4} + \frac{\bar{c}_2}{6}\bar{H}^2 \bar{x}^2 - 2\bar{c}_3\bar{H}^4 \bar{x}^3 + \frac{15}{2}\bar{c}_4\bar{H}^6 \bar{x}^4 - 7\bar{c}_5\bar{H}^8 \bar{x}^5 - 3\bar{c}_G\bar{H}^4 \bar{x}^2\end{aligned}$$

Bonus : $\bar{x}(z=0) = 1 \Rightarrow \bar{x}$ is known at $z = 0$!



[Neveu et al., A&A 555, A53 (2013)]

Expansion of a Galileon Universe

Solving the Galileon equations

4 differential equations with 3 unknown functions $\bar{H}(z)$, $\bar{x}(z)$,$\bar{y}(z)$

By definition : $\bar{y}' = \bar{x}$

Einstein equation (00) : $\dfrac{\delta \mathcal{S}_{\rm Gal}}{\delta g_{00}} = 0$

$$(1-2\bar{c}_0\bar{y})\bar{H}^2 = \frac{\Omega_m^0}{a^3} + \frac{\Omega_r^0}{a^4} + \frac{\bar{c}_2}{6}\bar{H}^2\bar{x}^2 - 2\bar{c}_3\bar{H}^4\bar{x}^3 + \frac{15}{2}\bar{c}_4\bar{H}^6\bar{x}^4 - 7\bar{c}_5\bar{H}^8\bar{x}^5 - 3c_G\bar{H}^4\bar{x}^2 + 2\bar{c}_0\bar{H}^2\bar{x}$$

Einstein equation (ij) : $\dfrac{\delta \mathcal{S}_{\rm Gal}}{\delta g_{ij}} = 0$

Equation of motion π : $\dfrac{\delta \mathcal{S}_{\rm Gal}}{\delta \pi} = 0$

$$\Rightarrow \begin{cases} \dfrac{d\bar{H}}{d\ln a} = f(\bar{c}_i, \bar{x}, \bar{H}, \Omega_r^0) \\ \dfrac{d\bar{x}}{d\ln a} = g(\bar{c}_i, \bar{x}, \bar{H}, \Omega_r^0) \end{cases}$$

then numerical integration with RK4 method

Expansion of a Galileon Universe

Solving the Galileon equations

- Two trivial initial conditions at $z = 0$:

$$\boxed{\bar{x}(z=0) = 1, \quad \bar{H}(z=0) = 1}$$

- 1 assumption in the $\bar{c}_0 \neq 0$ case : $\bar{y}_0 = 0$ to get $G_N(z) = G_N$ today

$$(1 - 2\bar{c}_0\bar{y})\bar{H}^2 = \ldots \Rightarrow G_N(z) \equiv G_N/(1 - 2\bar{c}_0\bar{y})$$

- 1 constraint equation : used to fix $\bar{c}_5$ given Ω_m^0, Ω_r^0 and the other $\bar{c}_i$s :

$$\bar{c}_5 = \frac{1}{7}\left(-1 + \Omega_m^0 + \Omega_r^0 + \frac{\bar{c}_2}{6} - 2\bar{c}_3 + \frac{15}{2}\bar{c}_4 - 3\bar{c}_G + 2\bar{c}_0\right)$$

$\Rightarrow$ 5 (+1 or 2) free parameters to constrain :
$\Omega_m^0, \Omega_r^0, \bar{c}_2, \bar{c}_3, \bar{c}_4, (\bar{c}_G, \bar{c}_0)$

Linear perturbations

Growth of structures in a Galileon theory

- Linear perturbations of the Galileon field $\delta\pi$
- Scalar perturbations of the metric ψ, ϕ :

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

- Tensorial perturbations of the metric $\delta g_{ij} = a^2 \begin{pmatrix} 0 & 0 & 0 \\ 0 & h_\oplus & h_\otimes \\ 0 & h_\otimes & h_\oplus \end{pmatrix}$

After computation, we obtain a new Poisson equation for gravity, with an **effective gravitational coupling** :

$$\nabla^2\psi = 4\pi a^2 G_{\text{eff}}^{(\psi)}(z)\rho_m\delta_m, \quad G_{\text{eff}}^{(\psi)}(z) = \bar{G}\left(z, \bar{c}_i, \bar{x}, \bar{H}, \frac{d\bar{x}}{d\ln a}, \frac{d\bar{H}}{d\ln a}\right) G_N$$

and other quantities such as :

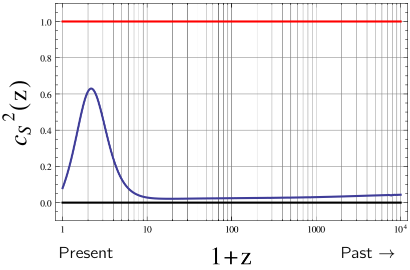
- normalisation factor of the kinetic terms of $\delta\pi$ and h_{ij}
- squared sound speed of scalar and tensorial perturbations $c_s^2(z)$ and $c_T^2(z)$

Linear perturbations

Theoretical constraints

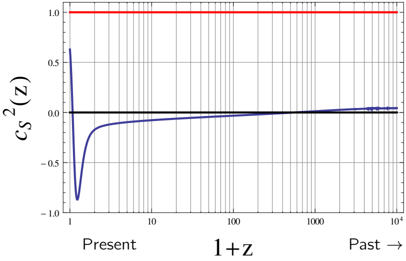
Reducing the Galileon phase space

1. no-ghost conditions (eg. positive normalisation of $\delta\pi$ kinetic term)
2. stability conditions (eg. $c_s^2 > 0$)



$\forall z > 0,\ c_s^2(z) > 0 \Rightarrow$ allowed scenario !

$\Rightarrow$ to be compared to data



$\exists z > 0,\ c_s^2(z) < 0 \Rightarrow$ forbidden scenario !

$\Rightarrow$ rejected

Part II

Cosmological constraints

Cosmological data

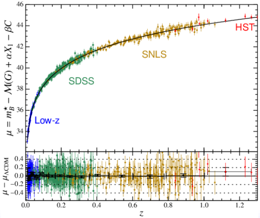
Type Ia supernovæ

- Use of most recent data : **740 SNe Ia precisely measured by a joint SNLS-SDSS analysis** [Betoule et al. 2014]
  - Each SNIa is characterised by : z, magnitude $m^*_{B,mes}$, color $\mathcal{C}$, stretch X_1
- B-band peak magnitude prediction for each SNIa at a given redshift z :

$$m^*_B(z) = 5\log_{10}\left[(1+z)\int_0^z \frac{dz}{\bar{H}(z,\mathrm{cosmo})}\right] - \alpha X_1 + \beta\mathcal{C} + \mathcal{M}_\mathcal{B}$$

compared with data by a χ^2 method $\Rightarrow \chi^2(\Omega_m^0, \bar{c}_2, \bar{c}_3, \bar{c}_4, \bar{c}_G)$

- Technical details :
  - α, β and $\mathcal{M}_\mathcal{B}$: nuisance parameters fitted on data jointly with the cosmological parameters as recommended by [Conley et al. 2011] : way to make SNe Ia better standard candles
  - Rigorous use of α, β et $\mathcal{M}_\mathcal{B}$
  - We assume $\Omega_r^0 = 0$ because here $z < 1.4$



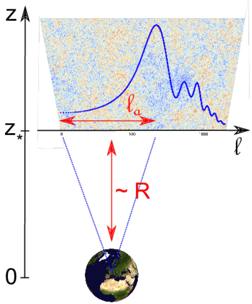
Cosmological data

Cosmological Microwave Background

- Full power spectrum prediction not available in Galileon theory
  $\Rightarrow$ **use of simplified set of observables : l_a, R, z_***, linked to the power spectrum first peak only

$$D_A(z) = \frac{c}{H_0}\frac{1}{1+z}\int_0^z \frac{dz'}{\bar{H}(z')}, \quad r_s(z) = \frac{c}{H_0}\int_0^{\frac{1}{1+z}} da\frac{\bar{c}_{s,m}(a)}{a^2\bar{H}(a)}$$

$$l_a = (1+z_*)\frac{\pi D_A(z_*)}{r_s(z_*)}, \quad R = \frac{\sqrt{\Omega_m^0 H_0^2}}{c}(1+z_*)D_A(z_*)$$



- Preliminary results using Planck 2015 TT,TE,EE data
- Only $\bar{H}(z)$ needed to compute the observables
- Technical details :
  - z_* evaluated using Hu & Sugiyama 1996 fitting formula
  - Minimisation on h and $\Omega_b^0 h^2$ together with CMB predictions (following Komatsu et al. 2009 prescriptions)

Cosmological data

Baryonic Acoustic oscillations

- 6 BAO $D_V(z)$ and 3 BAO/Lyman-α measurements
- Only $\bar{H}(z)$ needed to compute the observables

z	$D_V\left(\frac{r_d^{\text{fid}}}{r_d}\right)$ (Mpc)	$H\left(\frac{r_d}{r_d^{\text{fid}}}\right)$ (km/s/Mpc)	$D_A\left(\frac{r_d^{\text{fid}}}{r_d}\right)$ (Mpc)	r	Survey
0.106	456 ± 20	-	-	-	6dFGS
0.15	664 ± 25	-	-	-	SDSS MGS
0.32	1264 ± 25	-	-	-	BOSS LOWZ
0.44	1716 ± 83	-	-	-	WiggleZ
0.57	-	96.8 ± 3.4	1421 ± 20	0.539	BOSS CMASS
0.6	2221 ± 101	-	-	-	WiggleZ
0.73	2516 ± 86	-	-	-	WiggleZ
2.34	-	222 ± 7	1662 ± 96	0.43	BOSS DR11
2.36	-	223 ± 7	1616 ± 60	0.39	BOSS DR11

- Technical details :
  - CMB and BAO data fitted simultaneously (same sonic horizon $r_s(z)$)

Cosmological data

Growth of structures

- **8 growth rate measurements** $f\sigma_8(z)$ [6dFGRS, WiggleZ, VIPERS, SDSS, et BOSS]
- Measurements **independent** from any fiducial cosmology hypothesis or GR requirement
- **4 Alcock-Paczynski parameter** $F(z)$ **measurements**
  (replace the fiducial cosmology hypothesis by a geometrical hypothesis on data)
- Only $\bar{H}(z)$ and $\delta_m(z)$ needed to compute the observables

$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G_{\text{eff}}^{(\psi)}(t,\pi)\rho_m\delta_m = 0$$

- Technical details :
  - Hypothesis : same value of σ_8 at z_* in ΛCDM and Galileon models :

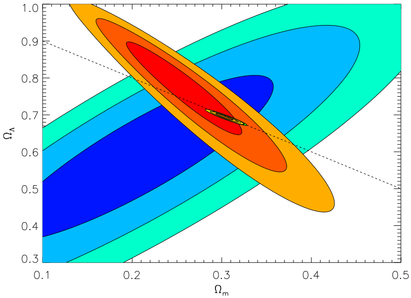
$$\sigma_8(a) = \sigma_8(a_{\text{initial}})\frac{D(a)}{D(a_{\text{initial}})}, \quad \sigma_8(a_{\text{initial}}) = \sigma_8^{\text{Planck}}(1)\frac{D^{\Lambda\text{CDM}}(a_*)}{D^{\Lambda\text{CDM}}(1)}$$

Constraining the Galileon parameters

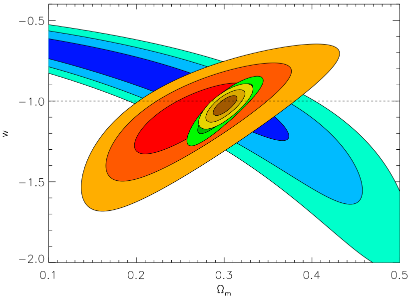
Analyse $\chi^2(\Omega_m^0, \bar{c}_2, \bar{c}_3, \bar{c}_4, \bar{c}_G) = \chi^2_{SN} + \chi^2_{CMB+BAO} + \chi^2_{Struct}$

ΛCDM and FWCDM constraints

ΛCDM and FWCDM constraints



ΛCDM constraints



FWCDM constraints

Blue : SNe Ia, Red : Growth, Green : CMB+BAO+Lyα, Yellow : combination
[Preliminary – Neveu et al. (2016)]

ΛCDM and FWCDM constraints

ΛCDM and FWCDM constraints

ΛCDM best fit values from different data samples

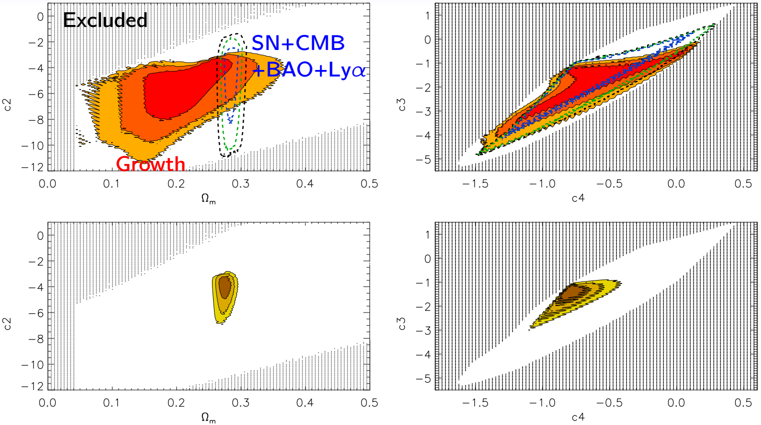
Probe	Ω_m^0	Ω_Λ^0	h	$\Omega_b^0 h^2$	χ^2	N_{data}
SNe Ia	$0.214^{+0.109}_{-0.103}$	$0.588^{+0.158}_{-0.157}$	-	-	691.0	740
Growth	$0.265^{+0.048}_{-0.039}$	$0.759^{+0.078}_{-0.091}$	-	-	2.9	12
Planck+BAO+Lyα	$0.305^{+0.007}_{-0.006}$	$0.693^{+0.006}_{-0.006}$	0.695	0.0240	14.5	15
All	$0.303^{+0.007}_{-0.006}$	$0.695^{+0.006}_{-0.006}$	0.697	0.0241	710.6	767

FWCDM best fit values from different data samples

Probe	Ω_m^0	w	h	$\Omega_b^0 h^2$	χ^2	N_{data}
SNe Ia	$0.231^{+0.112}_{-0.132}$	$-0.92^{+0.20}_{-0.23}$	-	-	691.7	740
Growth	$0.261^{+0.048}_{-0.039}$	$-1.11^{+0.14}_{-0.15}$	-	-	3.0	12
Planck+BAO+Lyα	$0.301^{+0.013}_{-0.012}$	$-1.04^{+0.06}_{-0.06}$	0.698	0.0241	15.5	15
All	$0.301^{+0.010}_{-0.008}$	$-1.03^{+0.04}_{-0.04}$	0.697	0.0241	711.7	767

Uncoupled Galileon model

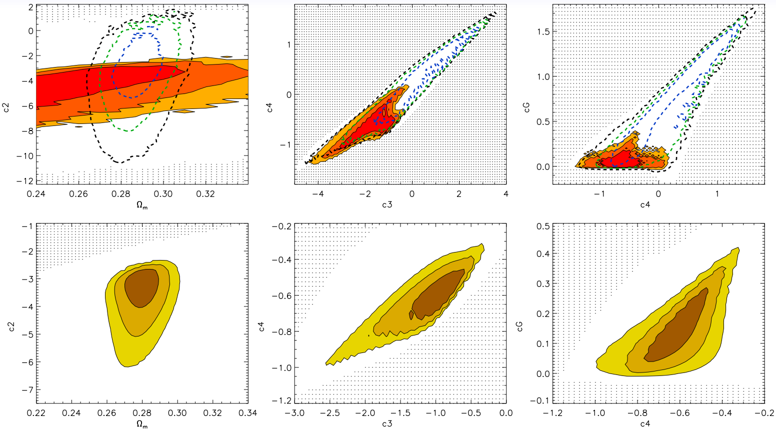
small tension but $\approx 1\sigma$ compatibility



[Preliminary – Neveu et al. (2016)]

Probe	Ω_m^0	$\bar{c}_2$	$\bar{c}_3$	$\bar{c}_4$	h	$\Omega_b^0 h^2$	χ^2	$N_{\rm data}$
JPBL	$0.284^{+0.008}_{-0.007}$	$-5.146^{+1.733}_{-2.841}$	$-1.782^{+0.858}_{-1.430}$	$-0.631^{+0.449}_{-0.280}$	0.719	0.0241	720.7	755
All	$0.275^{+0.006}_{-0.006}$	$-4.145^{+0.491}_{-0.857}$	$-1.545^{+0.217}_{-0.423}$	$-0.776^{+0.128}_{-0.061}$	0.736	0.0240	731.9	767

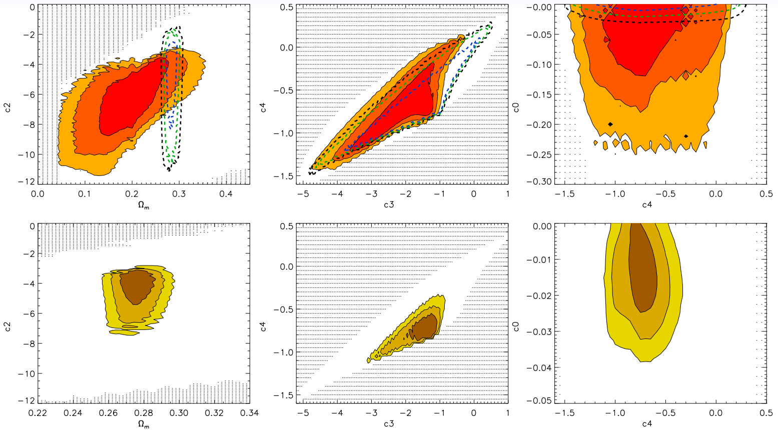
Disformal coupling $\bar{c}_G$



[Preliminary – Neveu et al. (2016)]

Probe	Ω_m^0	$\bar{c}_2$	$\bar{c}_3$	$\bar{c}_4$	$\bar{c}_G$	h	$\Omega_b^0 h^2$	χ^2
JPBL	$0.288^{+0.009}_{-0.007}$	$-3.106^{+1.832}_{-1.583}$	$0.057^{+1.562}_{-1.181}$	$0.197^{+0.650}_{-0.625}$	$0.692^{+0.552}_{-0.463}$	0.710	0.0244	721.1
All	$0.280^{+0.007}_{-0.005}$	$-3.434^{+0.392}_{-0.729}$	$-1.062^{+0.216}_{-0.334}$	$-0.610^{+0.094}_{-0.088}$	$0.146^{+0.089}_{-0.064}$	0.727	0.0240	724.7

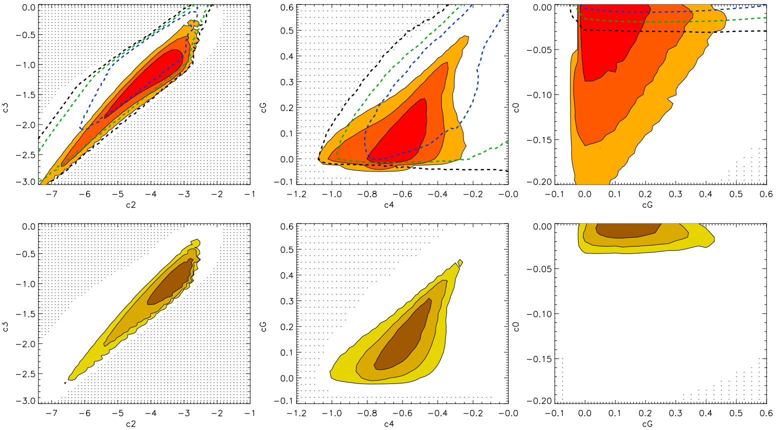
Conformal coupling $\bar{c}_0$



[Preliminary – Neveu et al. (2016)]

Probe	Ω_m^0	$\bar{c}_2$	$\bar{c}_3$	$\bar{c}_4$	$\bar{c}_0 < 0$	h	$\Omega_b^0 h^2$
JPBL	$0.284^{+0.008}_{-0.006}$	$-5.147^{+1.734}_{-2.812}$	$-1.783^{+0.855}_{-1.416}$	$-0.631^{+0.468}_{-0.277}$	-0.017 (95% CL)	0.719	0.0241
All	$0.276^{+0.007}_{-0.005}$	$-4.359^{+0.631}_{-1.352}$	$-1.567^{+0.259}_{-0.694}$	$-0.737^{+0.162}_{-0.078}$	$-0.013^{+0.008}_{-0.008}$	0.747	0.0244

Conformal $\bar{c}_0$ and disformal $\bar{c}_G$ couplings ($\Omega_m^0 = 0.28$ fixed)

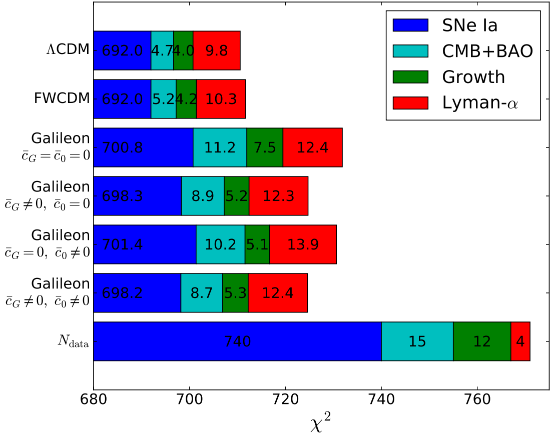


[Preliminary – Neveu et al. (2016)]

Probe	$\bar{c}_2$	$\bar{c}_3$	$\bar{c}_4$	$\bar{c}_G$	$\bar{c}_0$	h	$\Omega_b^0 h^2$
All	$-3.400^{+0.385}_{-0.697}$	$-1.049^{+0.204}_{-0.327}$	$-0.609^{+0.096}_{-0.064}$	$0.148^{+0.096}_{-0.064}$	-0.027 (95% CL)	0.727	0.0240

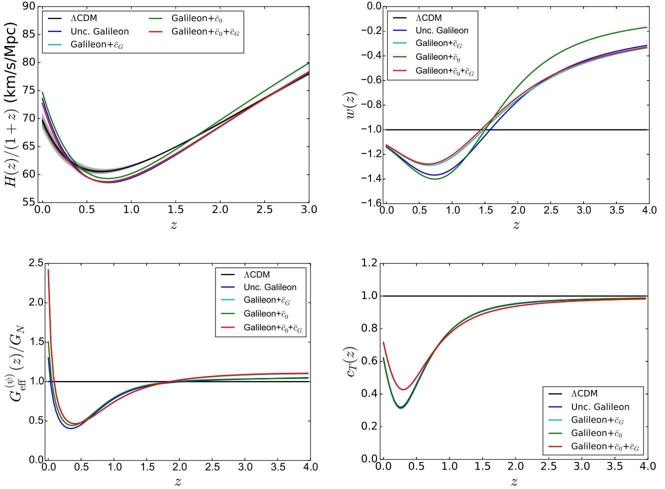
Galileon constraints

Comparing the models



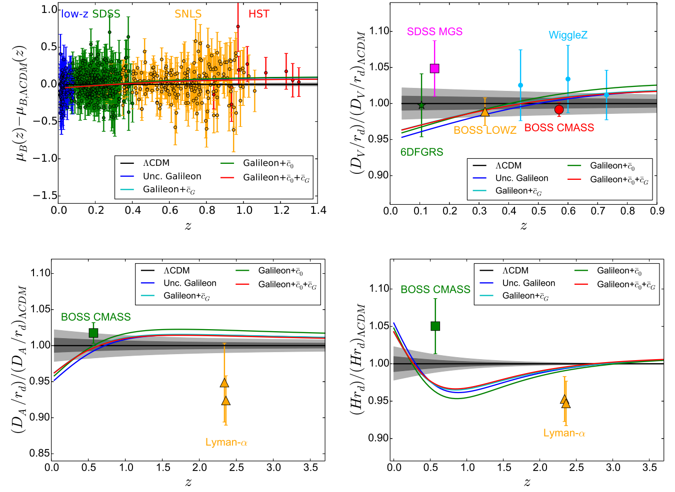
Galileon constraints

Comparing the models



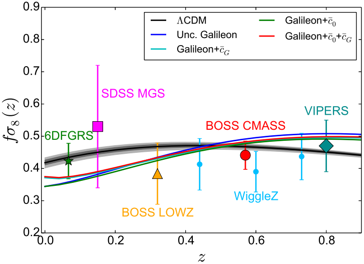
Galileon constraints

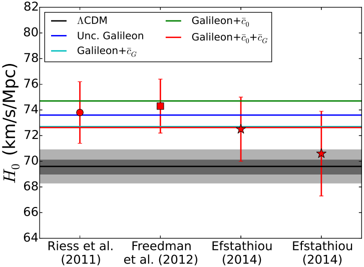
Comparing the models



Galileon constraints

Comparing the models



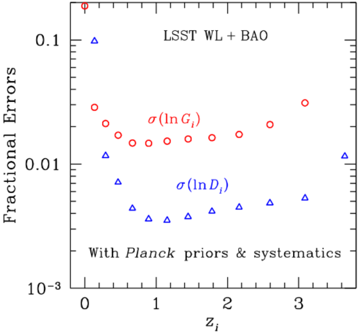


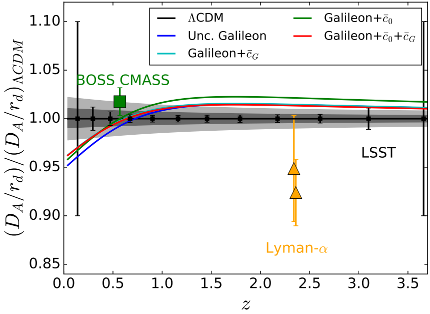
Part III

Perspectives and summary

Future dark energy experiments : Galileon forecasts

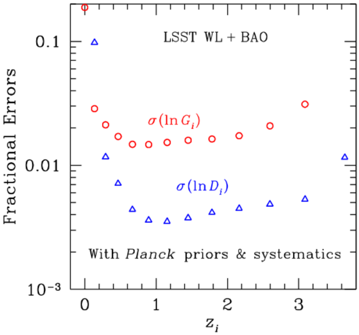
LSST

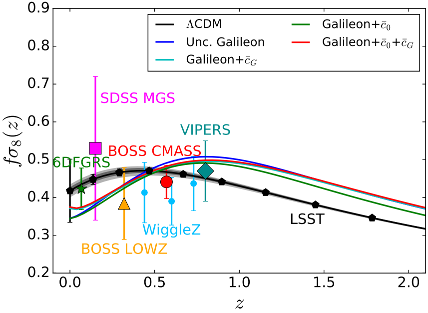




Future dark energy experiments : Galileon forecasts

LSST





Discussions and summary

Summary

- Galileon theory : a good candidate to model dark energy :
  - good theoretical properties
  - weak modification of local gravity
- **Accelerated expansion prediction in agreement with recent cosmological data** [Neveu et al., A&A 555, A53 (2013), 569, A90 (2014), in prep. (2016)]
- **Equivalent χ^2s obtained for both Galileon and ΛCDM models**
- SN+CMB+BAO constraints confirmed in the uncoupled case by [Barreira et al., Phys.Rev.D. 87,103511 (2013)] using a full power spectrum CMB prediction [Neveu et al., 569, A90 (2014)]
- In Neveu et al. (2016), use of non-cosmological data as $\dot{G}_N$, GW, CMS results... and constraints on the tracker solution of the Galileon model
- Future dark energy experiments like LSST are precise enough to distinguish ΛCDM from Galileon theory with distance measurements and growth data