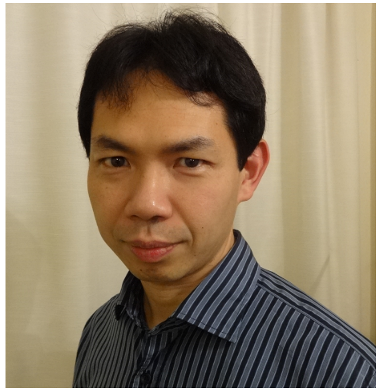
What can Cosmology tell us about Gravity?

Levon Pogosian
Simon Fraser University

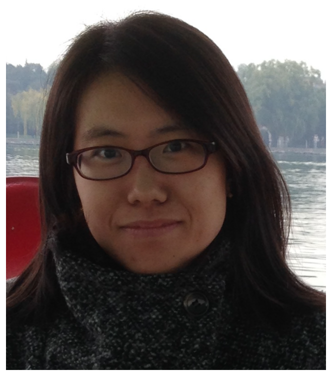

Rob Crittenden
ICG, Portsmouth


Kazuya Koyama
ICG, Portsmouth

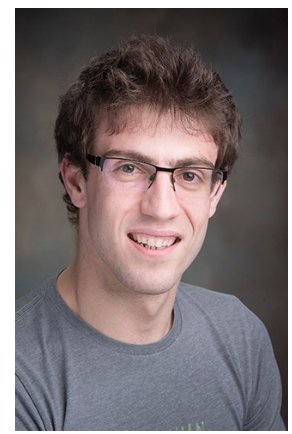

Simone Peirone
U. Leiden


Alessandra Silvestri
U. Leiden


Marco Raveri
U. Chicago

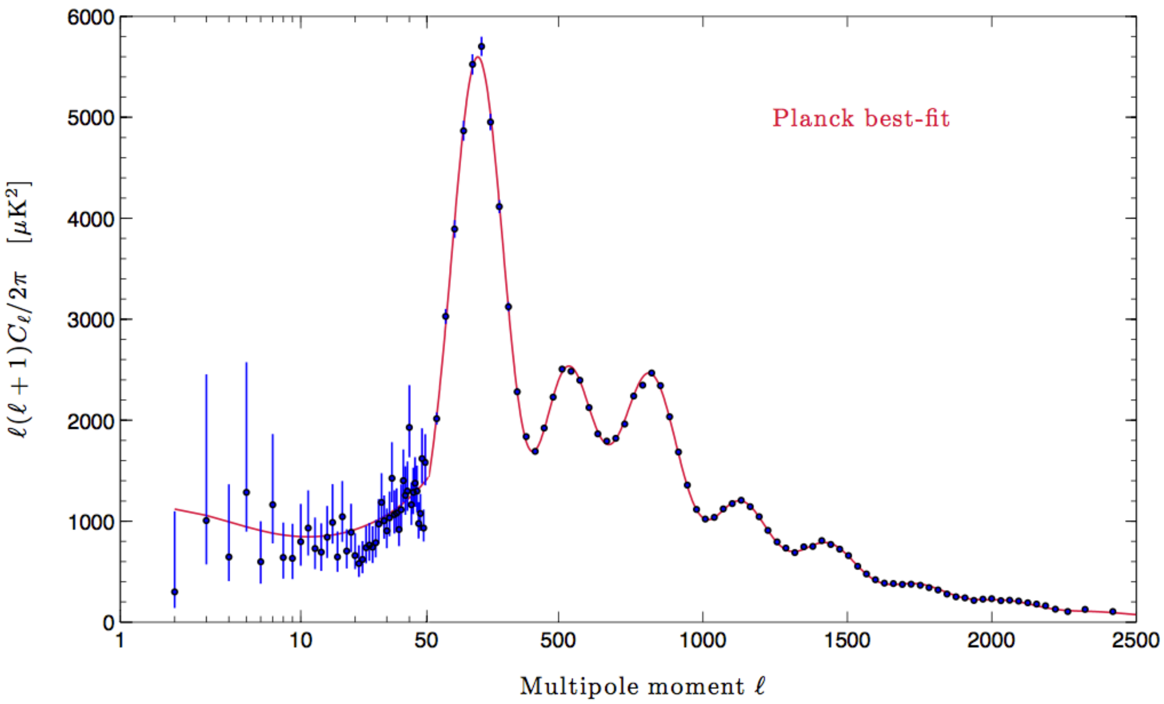

Yuting Wang
NAOC, Beijing


Gong-Bo Zhao
ICG/NAOC


Alex Zucca
SFU

and many others over the years

We have a successful working model of the universe …



<u>Beyond reasonable doubt</u>

practically no spatial curvature
nearly scale-invariant initial spectrum
practically adiabatic initial conditions
Dark Energy and CDM

… but the universe had surprised us before …

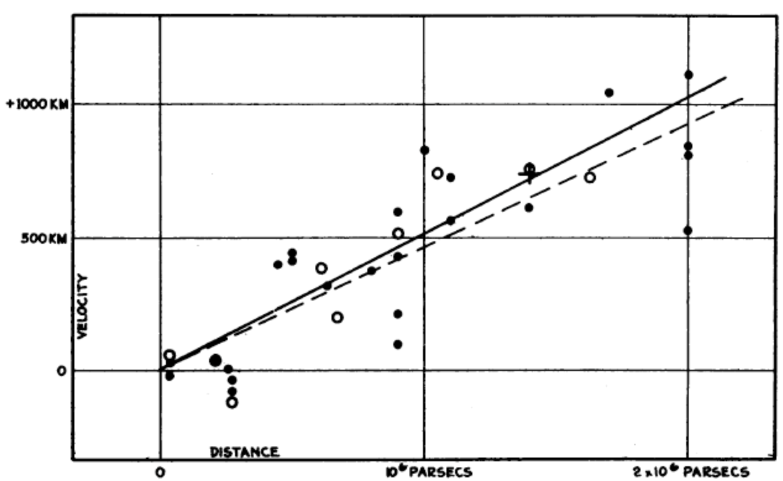
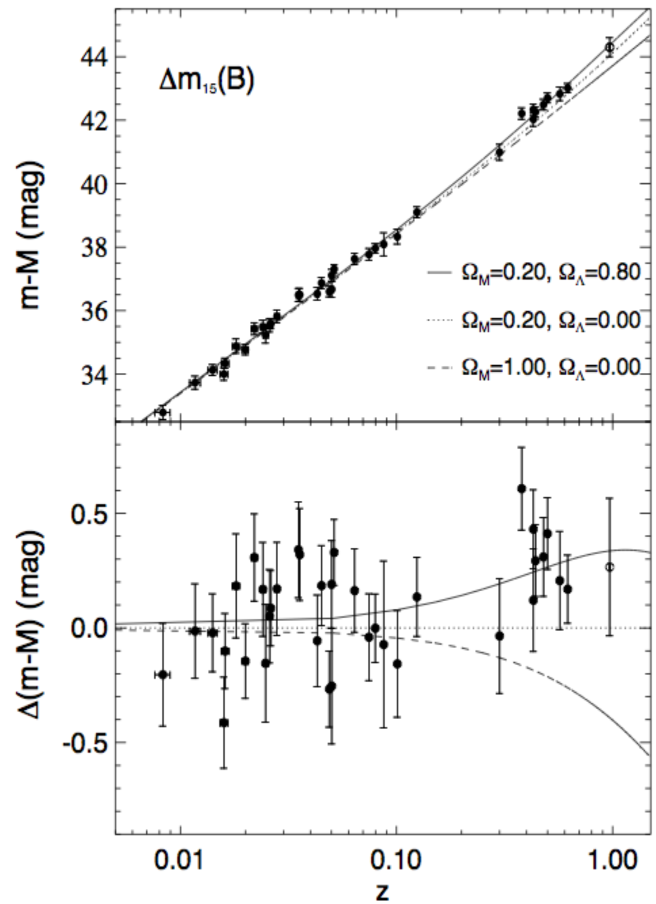


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.



… and there are reasons to keep an open mind about LCDM

… and there are reasons to keep an open mind about LCDM

- Lambda
- CDM

… and there are reasons to keep an open mind about LCDM

- Lambda
- CDM

Does the vacuum gravitate?
What sets the observed value of Lambda?

$$\rho_{\rm theory}^{\rm (vac)} = \sum_{\rm particles} [\text{0point fluctuations}] + \rho_{\rm EW}^{\rm (vac)} + \rho_{\rm QCD}^{\rm (vac)} + \ldots$$

$$\rho_{\rm obs}^{\rm (vac+\Lambda)} \sim [10^{-3} {\rm eV}]^4$$

… and there are reasons to keep an open mind about LCDM

- Lambda

- CDM

Does the vacuum gravitate?
What sets the observed value of Lambda?

$$\rho^{(\mathrm{vac})}_{\mathrm{theory}} = \sum_{\mathrm{particles}} [\mathrm{0point\ fluctuations}] + \rho^{(\mathrm{vac})}_{\mathrm{EW}} + \rho^{(\mathrm{vac})}_{\mathrm{QCD}} + \ldots$$

$$\rho^{(\mathrm{vac}+\Lambda)}_{\mathrm{obs}} \sim [10^{-3}\mathrm{eV}]^4$$

- General reasons:
  - GR is yet to be tested on cosmological scales
  - No theory of Quantum Gravity
  - No theory of the Big Bang

- Lesser, specific problems:
  - Tensions between datasets
  - Missing satellites, (non)cuspy halos, …

Questions we could ask in Cosmology

1. Is there any evidence of dynamical Dark Energy?

   The background expansion

2. Is there any evidence of modified gravity?

   Violations of the equivalence principle

   New gravitational interactions

3. If we find evidence, are 1 and 2 consistent with each other within a certain theory?

Some thoughts on model-independence

- It's always best to test a specific theory, but we also want to look for evidence of new physics in a more general way

- Theoretical priors are always necessary, so we should make them explicit to make interpretation of the results easy

- Fitting simplistic models, such as w=const or $w=w_0+(1-a)w_a$, can bias the results and hide valuable clues

The (effective) Dark Energy equation of state

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2 \left\{ \frac{\Omega_{\mathrm{r}}}{a^4} + \frac{\Omega_{\mathrm{M}}}{a^3} + \frac{\rho_{\mathrm{DE}}(a)}{\rho_c} \right\}$$

$$\dot{\rho}_{\mathrm{DE}} + 3H(\rho_{\mathrm{DE}} + p_{\mathrm{DE}}) = 0$$

Constant Dark Energy (Lambda):

$$\rho_\Lambda = -p_\Lambda = \mathrm{const}$$

$$w_\Lambda = -1$$

Time-varying Dark Energy:

$$\rho_{\mathrm{DE}}(a) = \rho_0 \exp\left[\int_a^1 3(1 + w(a'))\frac{da'}{a'}\right]$$

$$w(a) = \frac{p_{\mathrm{DE}}(a)}{\rho_{\mathrm{DE}}(a)}$$

nature astronomy

LETTERS

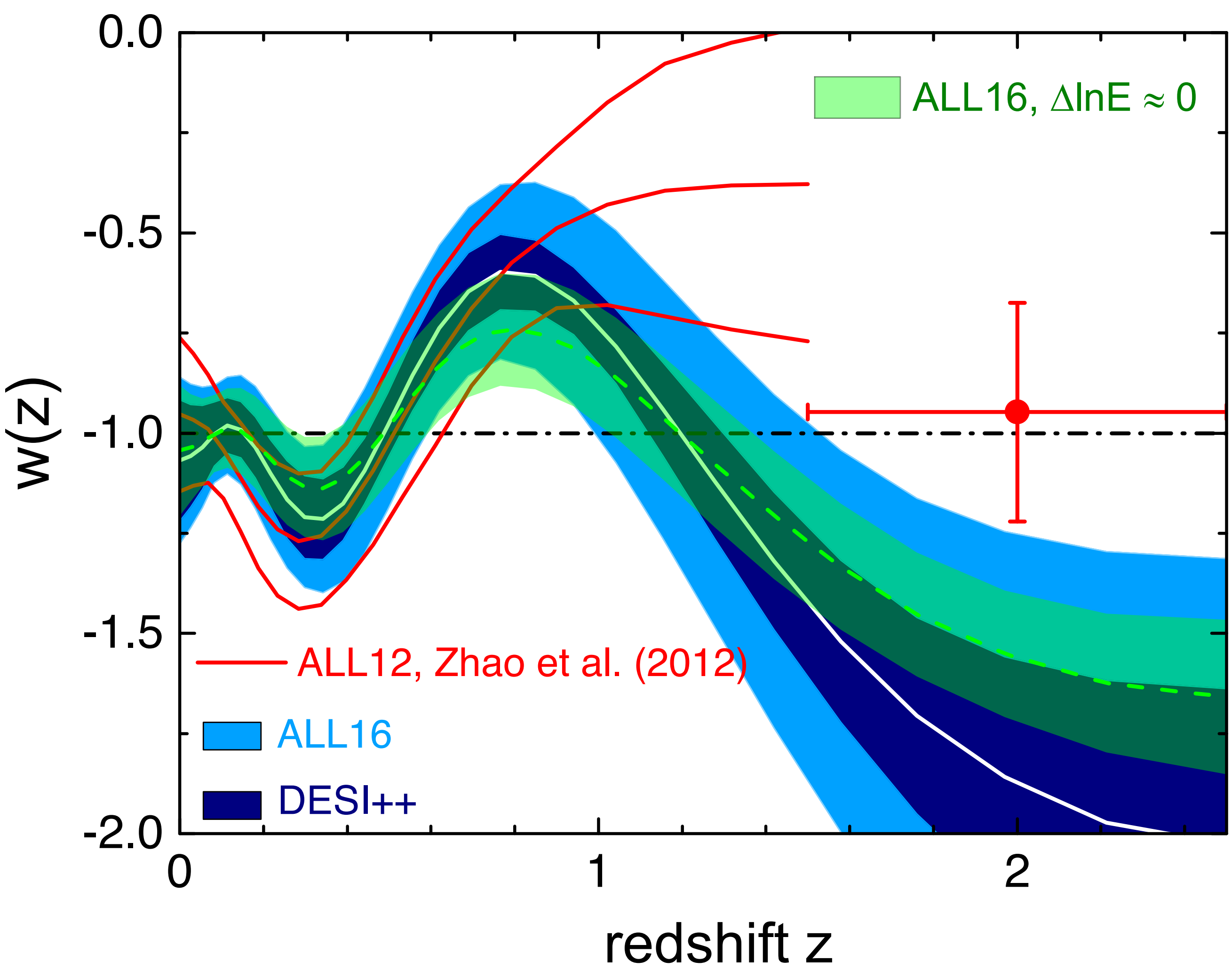
DOI: 10.1038/s41550-017-0216-z

Dynamical dark energy in light of the latest observations

Gong-Bo Zhao[1,2*], Marco Raveri[3,4], Levon Pogosian[2,5], Yuting Wang[1,2], Robert G. Crittenden[2], Will J. Handley[6,7], Will J. Percival[2], Florian Beutler[2], Jonathan Brinkmann[8], Chia-Hsun Chuang[9,10], Antonio J. Cuesta[11,12], Daniel J. Eisenstein[13], Francisco-Shu Kitaura[14,15], Kazuya Koyama[2], Benjamin L'Huillier[16], Robert C. Nichol[2], Matthew M. Pieri[17], Sergio Rodriguez-Torres[9,18,19], Ashley J. Ross[2,20], Graziano Rossi[21], Ariel G. Sánchez[22], Arman Shafieloo[16,23], Jeremy L. Tinker[24], Rita Tojeiro[25], Jose A. Vazquez[26] and Hanyu Zhang[1]

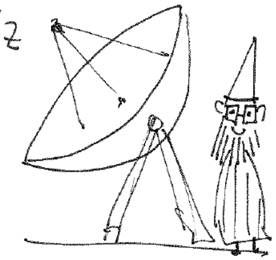
$$\frac{H^2(a)}{H_0^2} = \Omega_{\rm r} a^{-4} + \Omega_{\rm M} a^{-3} + \Omega_{\rm DE} \exp\left[\int_a^1 3(1+w(a'))\frac{da'}{a'}\right]$$

G.-B. Zhao et al, arXiv:1701.08165, Nature Astronomy



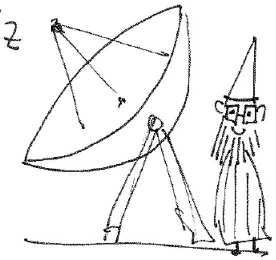
G.-B. Zhao et al, arXiv:1701.08165, Nature Astronomy

true w(z)



MCMC fit
using many w-bins

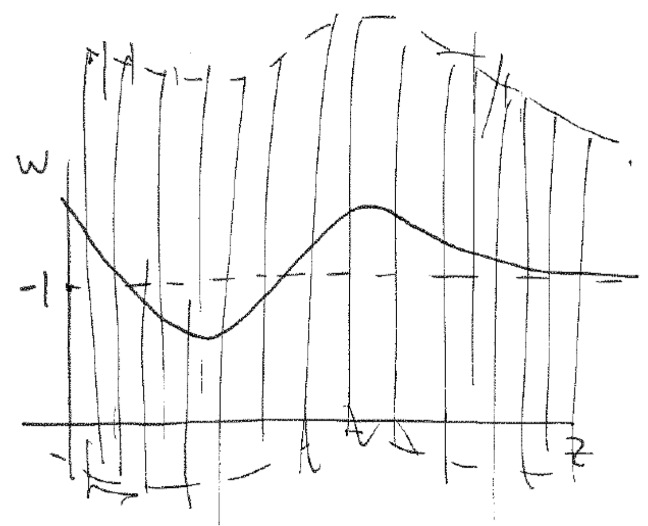
true w(z)



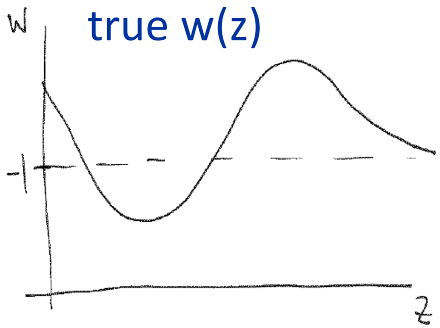
no prior

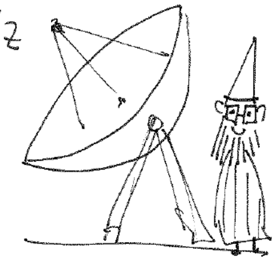
MCMC fit
using many w-bins

reconstructed w(z)



- large variance
- zero bias

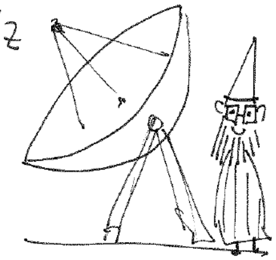




$$\chi^2_{\rm prior} = -2\ln \mathcal{P}_{\rm prior} = (\mathbf{w}-\mathbf{w}^{\rm fid})^T \mathbf{C}^{-1} (\mathbf{w}-\mathbf{w}^{\rm fid})$$

MCMC fit
using many w-bins

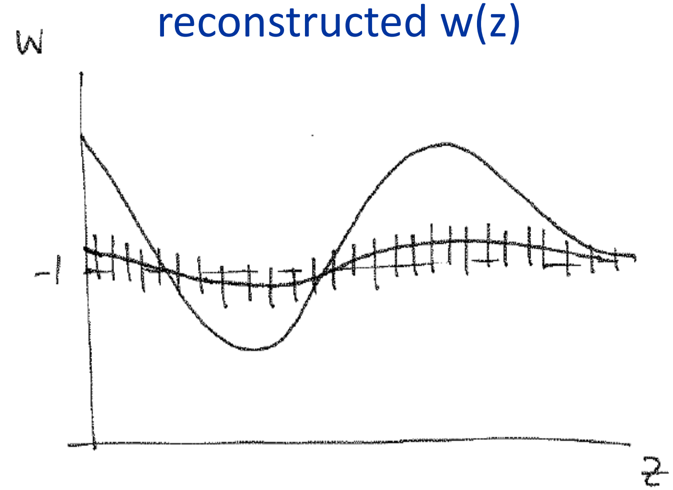
true w(z)



Excessively strong prior

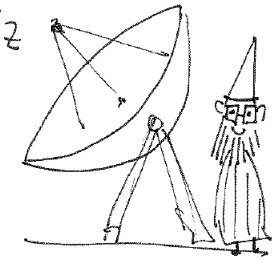
MCMC fit
using many w-bins

reconstructed w(z)



- tiny error bars (small variance)
- large bias

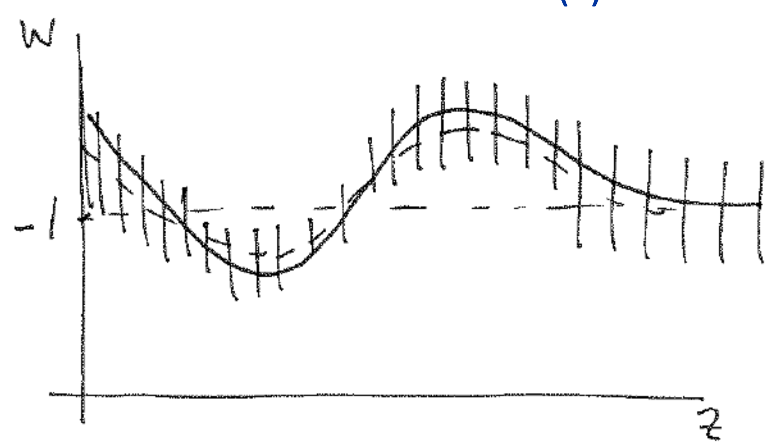
true w(z)



reasonable prior

MCMC fit
using many w-bins

reconstructed w(z)



- moderate variance
- insignificant bias, i.e. the bias is smaller than the variance

Fables of Reconstruction

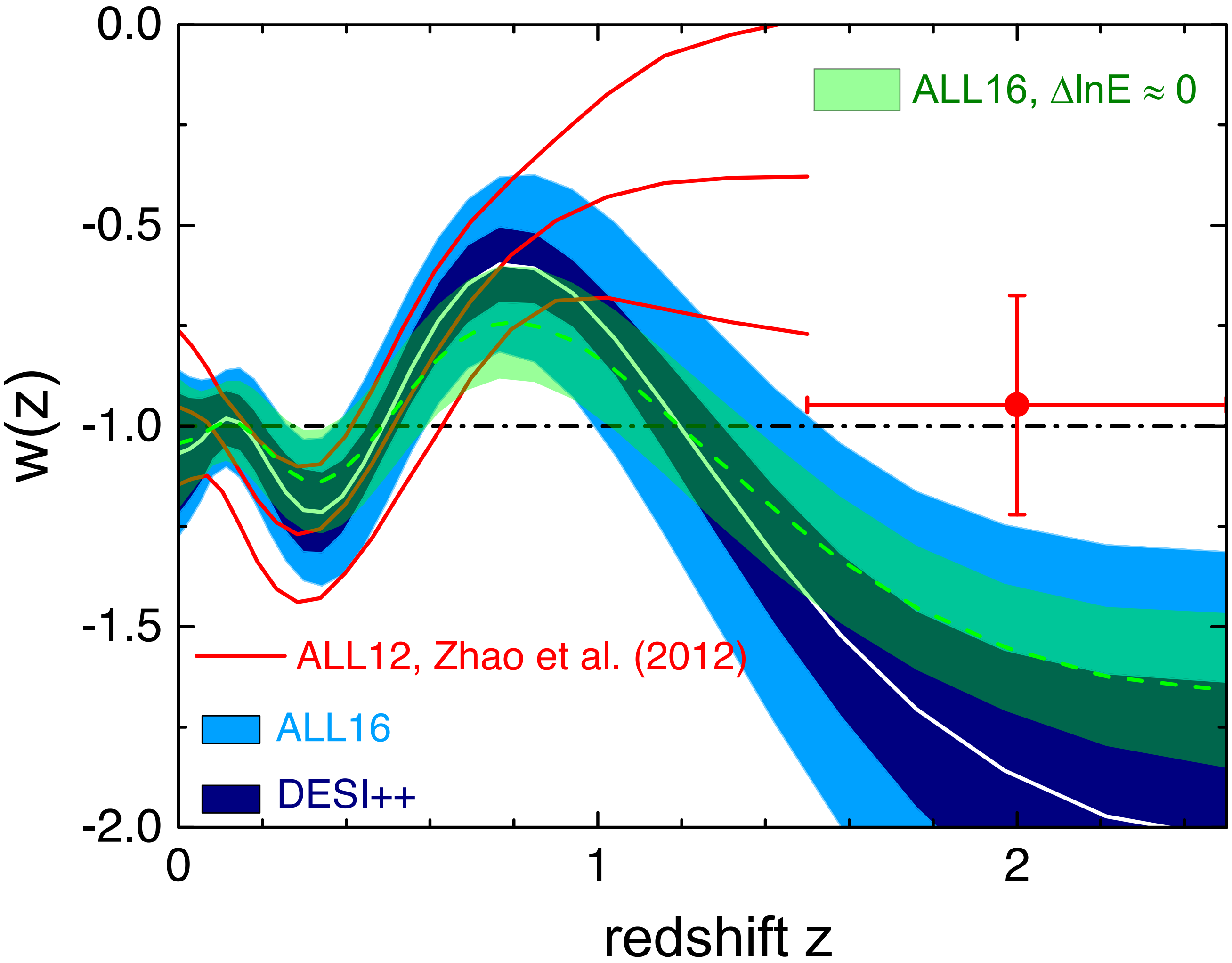
- Impose a correlation on binned w(z)

  can be derived from a broad class of theories
  see e.g. M. Raveri, P. Bull, A. Silvestri, LP, arXiv:1703.05297, PRD

- Smooth features (well constrained by data) not biased by the prior

- Rapid variations of w(z) (poorly constrained by data) disfavoured by the prior

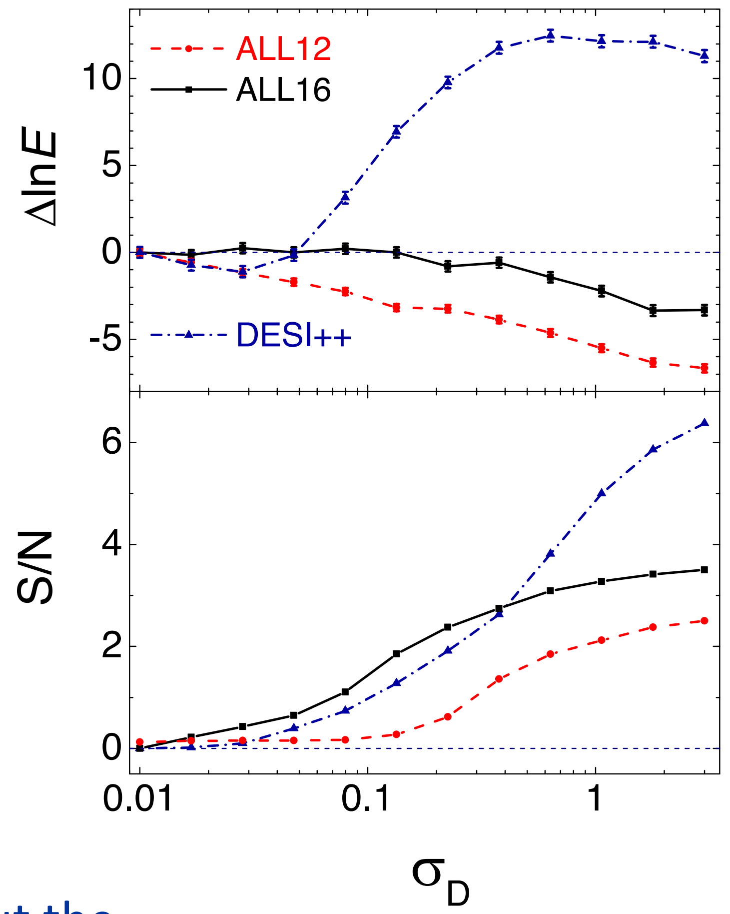
Crittenden, Zhao, LP, Samushia, Zhang, 1112.1693, JCAP’12



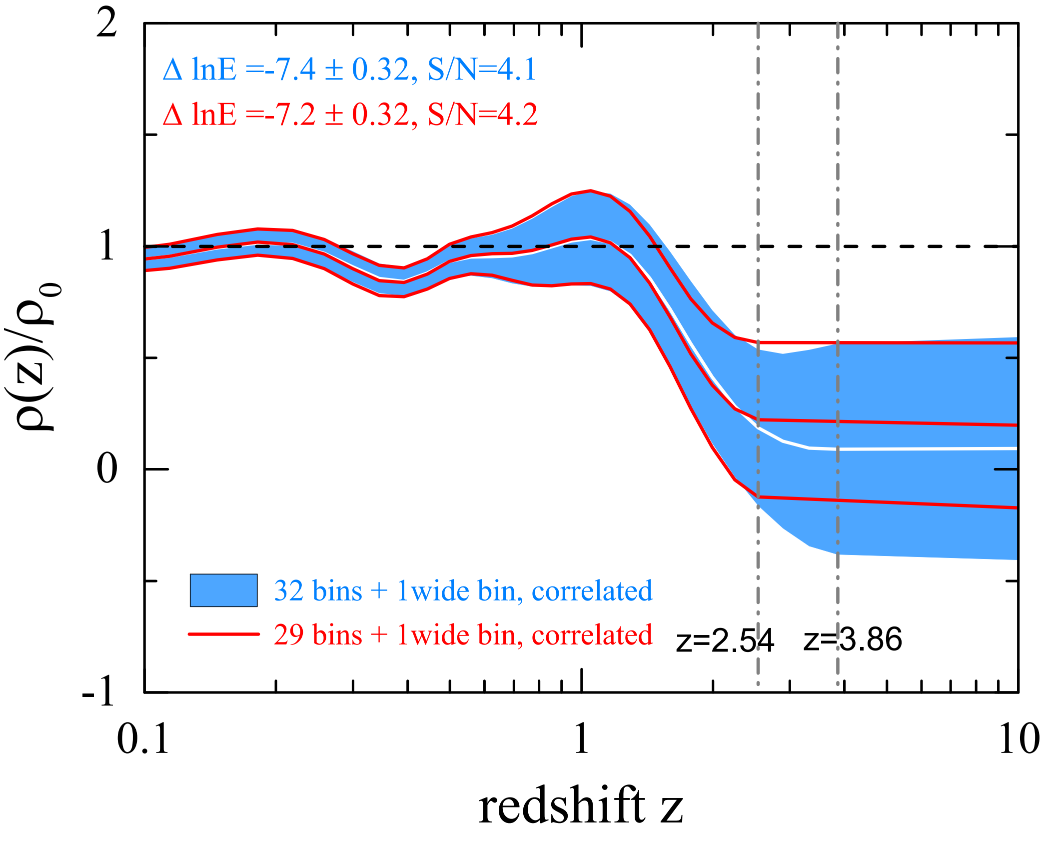
G.-B. Zhao et al, arXiv:1701.08165, Nature Astronomy

Dynamical Dark Energy?

- Dynamical dark energy is preferred at a 3.5-sigma significance level based on the improvement in the fit alone
- It resolves the tensions between the Planck best fit LCDM model and the local estimates of H_0 and the high-z Ly-alpha BAO
- Effectively, 4 additional degrees of freedom
- Current Bayesian evidence is comparable to that of LCDM, no preference for dynamics
- Evidence increased since 2012
- Future data can conclusively confirm or rule out the reconstructed dynamics of Dark Energy

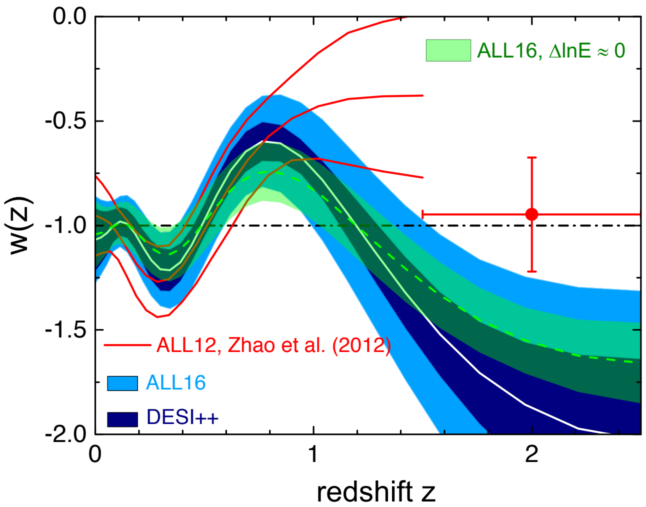


Reconstructed Dark Energy Density



Y. Wang, G.-B. Zhao and LP, in preparation

What could this be?

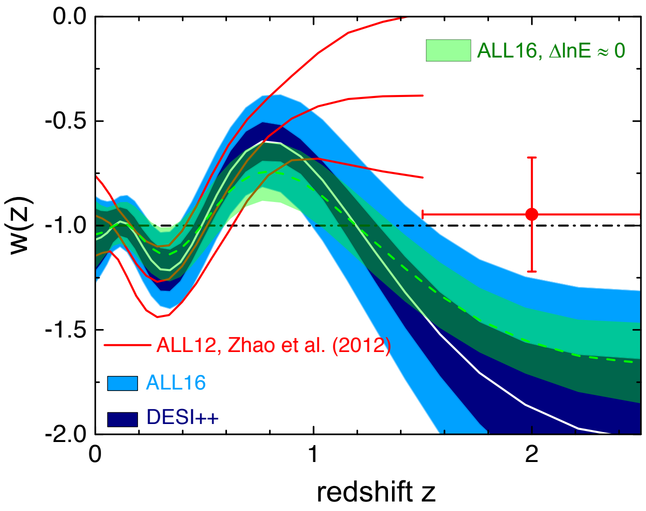


General Relativity with a minimally coupled scalar field (quintessence)

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{16\pi G}\{R - \partial^\mu\phi\partial_\mu\phi - 2V(\phi)\} + \mathcal{L}_M(g_{\mu\nu},\psi)\right]$$

$$w_\phi = \frac{p_\phi}{\rho_\phi} = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)} \geq -1$$

What could this be?



Modified gravity: a scalar-tensor theory

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{16\pi G}\left\{\Omega(\phi)R - \partial^\mu\phi\partial_\mu\phi - 2V(\phi)\right\} + \mathcal{L}_M(g_{\mu\nu}, \psi)\right]$$

$$w_{\rm eff} = \frac{p_{\rm eff}}{\rho_{\rm eff}} = \frac{\dot{\phi}^2/2 - V(\phi) + 2H\dot{\Omega} + \ddot{\Omega}}{\dot{\phi}^2/2 + V(\phi) - 3H\dot{\Omega} + (1-\Omega)\rho_M}$$

Phenomenology of Scalar-Tensor Theories

Generalized Brans-Dicke models (e.g. “chameleon”, f(R), “symmetron”)

Varying Gravitational Coupling

$$S = \int d^4x \sqrt{-g} \left[\frac{A^{-2}(\phi)}{16\pi G} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) + \mathcal{L}_M(g_{\mu\nu}, \psi) \right]$$

In the “Einstein” frame: $\tilde{g}_{\mu\nu} = A^{-2}(\phi) g_{\mu\nu}$

Modified Dynamics Of Matter

$$S = \int d^4x \sqrt{-\tilde{g}} \left[\frac{\tilde{R}}{16\pi G} - \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \tilde{V}(\phi) + \mathcal{L}_M(A^2(\phi) \tilde{g}_{\mu\nu}, \psi) \right]$$

Phenomenology of Scalar-Tensor Theories

"Spacetime tells matter how to move; matter tells spacetime how to curve."

John A. Wheeler (1911-2008)

Photons and matter respond to different spacetimes

Non-relativistic matter

- sources the curvature perturbation $\boldsymbol{\Phi}$
- responds to the Newtonian potential $\boldsymbol{\Psi}$
- $\boldsymbol{\Phi}$ and $\boldsymbol{\Psi}$ are NOT the same in scalar-tensor theories
- feels a "fifth force" mediated by the scalar field $\vec{f} = -\vec{\nabla}\Psi - \frac{d \ln A(\phi)}{d\phi}\vec{\nabla}\phi$

Photons

- respond to $(\boldsymbol{\Phi}+\boldsymbol{\Psi})/2$
- do not feel a "fifth force"

Phenomenology of Scalar-Tensor Theories

General Relativity

$$\Psi = \Phi$$
$$-k^2\Phi = -k^2\left(\frac{\Phi+\Psi}{2}\right) = 4\pi G a^2 \delta\rho$$

Modified Gravity

"G_{matter}"

$$-k^2\Psi = 4\pi\, \mu(a,k) G\, a^2\delta\rho$$
$$\Phi = \gamma(a,k)\, \Psi$$
$$-k^2\left(\frac{\Phi+\Psi}{2}\right) = 4\pi\, \Sigma(a,k) G\, a^2\delta\rho$$

"G_{light}"

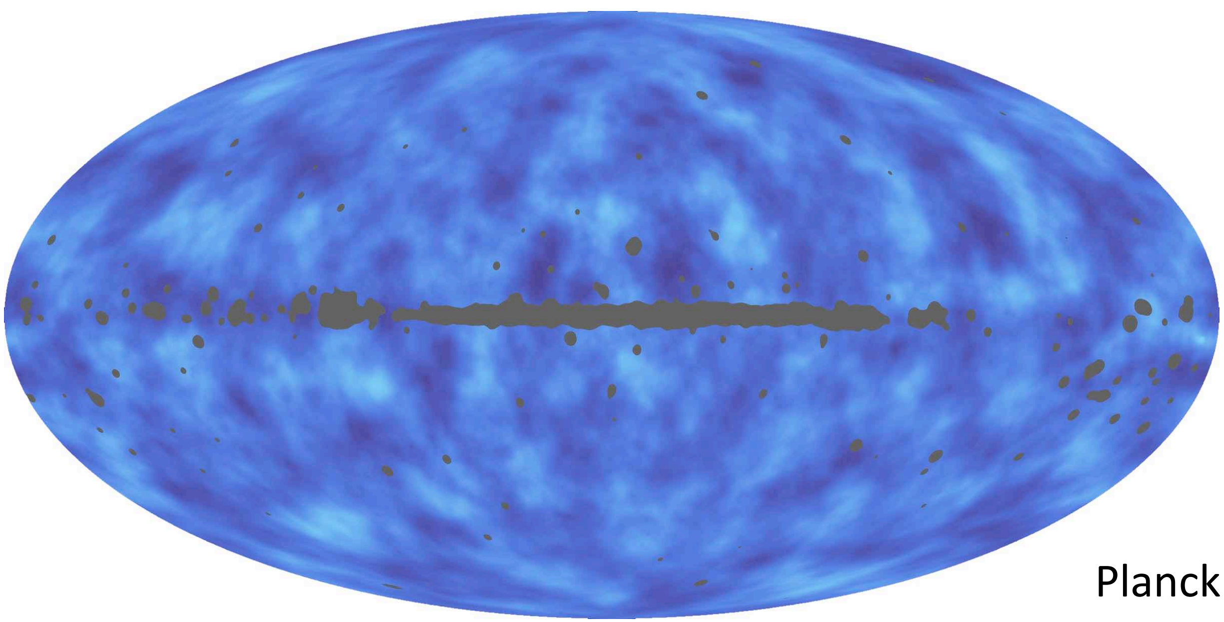
A smoking gun of new gravitational physics

$$\boxed{G_{matter} \neq G_{light} \quad \text{or} \quad \Phi \neq \Psi}$$

Gravitational Lensing

$$\text{Distortion} \propto \int dz\, \partial_\perp(\Phi + \Psi)$$

Hubble

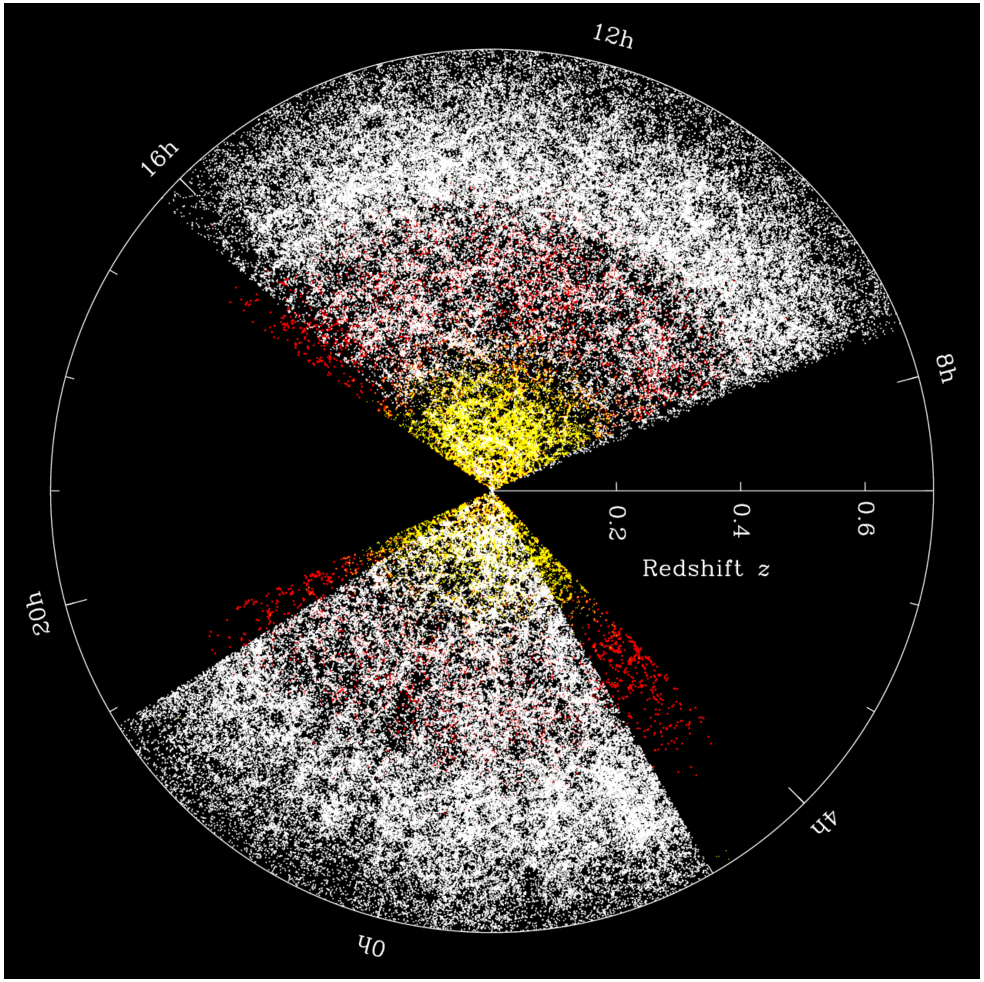


Planck

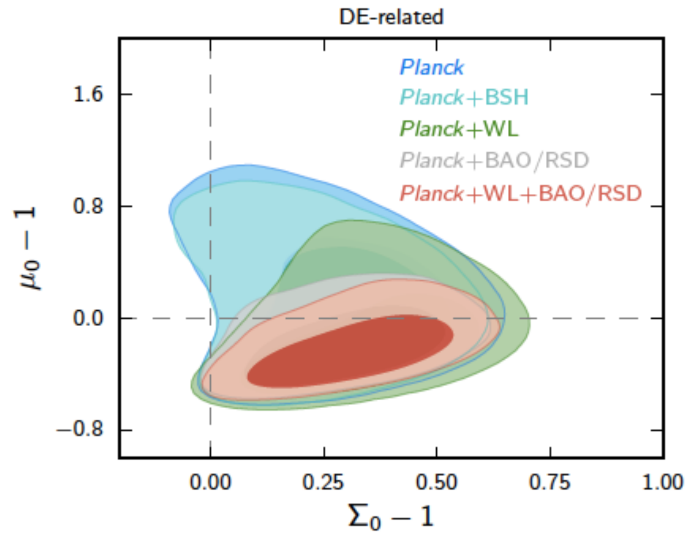
Galaxy Clustering

Redshift distortions
due to peculiar motion

$$V' + V = \frac{k}{aH}\Psi$$



Planck 2015 results. XIV. Dark energy and modified gravity

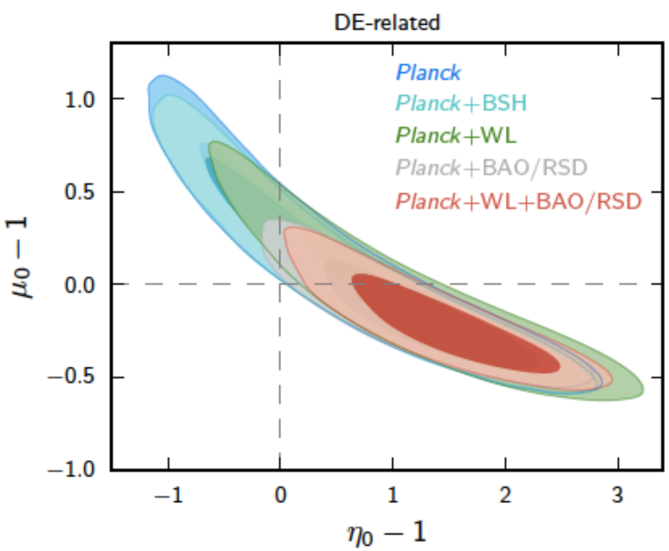


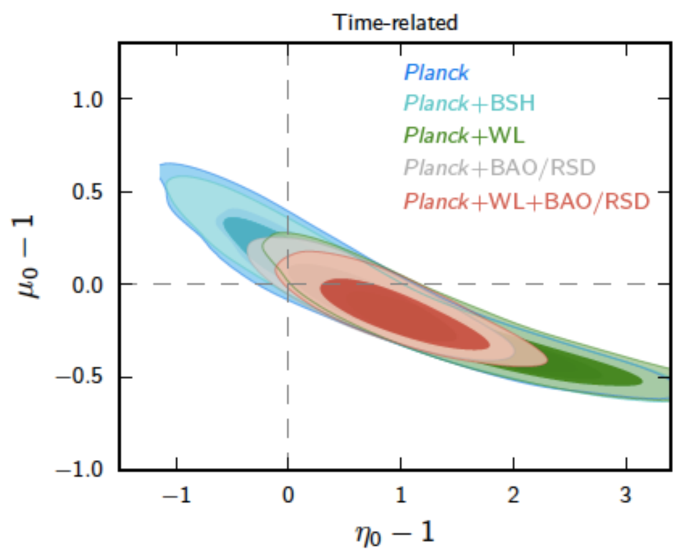
$$\mu < 1$$

$$\gamma > 1$$

$$\Sigma > 1$$

What would it say about gravity?





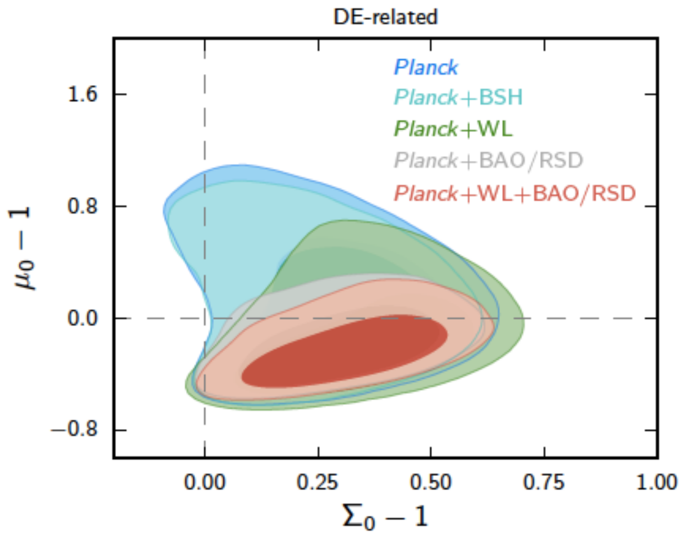
Phenomenology of generalized Brans-Dicke models

Attractive force mediated by the scalar: $\vec{f} = -\vec{\nabla}\Psi - \frac{d\ln A(\phi)}{d\phi}\vec{\nabla}\phi$

Range of the force set by the Compton length λ_C

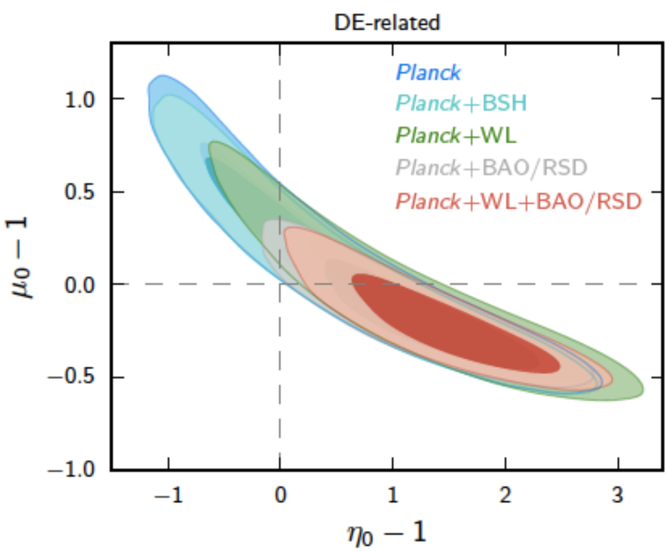
$$\left.\begin{aligned} G_{\rm matter} &= A^2 G \quad \text{for} \quad \lambda > \lambda_C \\ G_{\rm matter} &> A^2 G \quad \text{for} \quad \lambda < \lambda_C \\ G_{\rm light} &= A^2 G \quad \text{for all} \quad \lambda \end{aligned}\right\} \xrightarrow{A^2 \approx 1} \boxed{\begin{aligned} \mu &\geq 1 \\ \Sigma &= 1 \\ \gamma &\leq 1 \end{aligned}}$$

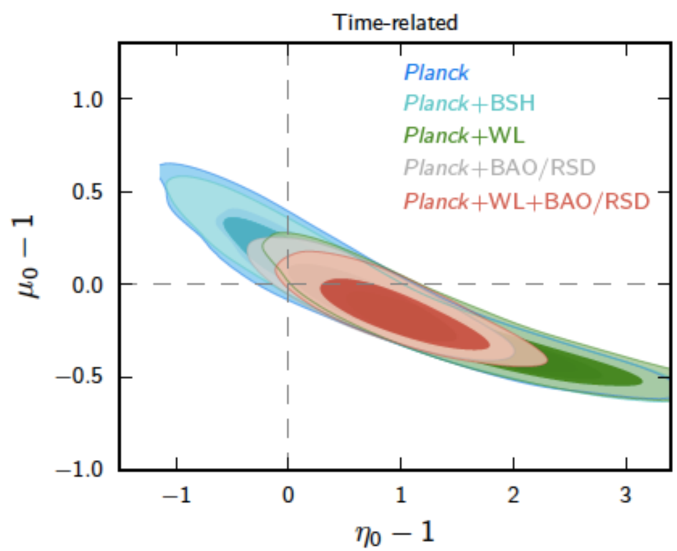
Planck 2015 results. XIV. Dark energy and modified gravity



$$\mu < 1$$
$$\gamma > 1$$
$$\Sigma > 1$$

would rule out all GBD models





More General Scalar-Tensor Theories

Gregory Horndeski, *Talking About Gravity*

G. W. Horndeski, Int. J. Theor. Phys (1974)
C. Deffayet, X. Gao, D. A. Steer, and G. Zahariade, PRD (2011)

The Horndeski Lagrangian

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[\sum_{i=2}^{5} \mathcal{L}_i + \mathcal{L}_{\mathrm{m}}[g_{\mu\nu}] \right]$$

$$\mathcal{L}_2 = K(\phi, X) , \qquad X = -\phi^{;\mu}\phi_{;\mu}/2$$

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

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

$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5X}(\phi, X) \left[(\Box\phi)^3 + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi \right]$$

Phenomenology of Horndeski theories: Speed of Gravity

The speed of gravitational waves can be different from the speed of light

$$S = \int dt d^3 x a^3 \left[\text{other terms} + \frac{M_*^2}{4} \left(\dot{h}_T^2 - \frac{1+\alpha_T}{a^2} (\vec{\nabla} h_T)^2 \right) \right]$$

$$\alpha_T = 2X(2G_{4,X} - 2G_{5,\phi} - (\ddot{\phi} - \dot{\phi} H) G_{5,X}) M_*^{-2}$$

Modified speed of gravity if $G_{4,X}$ is not zero, or G_5 is not constant

THE ASTROPHYSICAL JOURNAL LETTERS

Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A

B. P. Abbott[3], R. Abbott[3], T. D. Abbott[4], F. Acernese[5,6], K. Ackley[7,8], C. Adams[9], T. Adams[10], P. Addesso[11], R. X. Adhikari[3], V. B. Adya[12] +Show full author list

Published 2017 October 16 •

The Astrophysical Journal Letters, Volume 848, Number 2

Focus on the Electromagnetic Counterpart of the Neutron Star Binary Merger GW170817

Abstract

On 2017 August 17, the gravitational-wave event GW170817 was observed by the Advanced LIGO and Virgo detectors, and the gamma-ray burst (GRB) GRB 170817A was observed independently by the *Fermi* Gamma-ray Burst Monitor, and the Anti-Coincidence Shield for the Spectrometer for the *International Gamma-Ray Astrophysics Laboratory*. The probability of the near-simultaneous temporal and spatial observation of GRB 170817A and GW170817 occurring by chance is 5.0×10^{-8}.

arXiv.org > astro-ph > arXiv:1710.05877

Search or A

(Help | Advance

Astrophysics > Cosmology and Nongalactic Astrophysics

Dark Energy after GW170817

Paolo Creminelli, Filippo Vernizzi

(Submitted on 16 Oct 2017)

The observation of GW170817 and its electromag
speed of light, with deviations smaller than a few
result for models of dark energy and modified gr
tuning, the speed of gravitational waves must be
also for nearby solutions obtained by slightly cha
various operators must satisfy precise relations t
Dark Energy and in the covariant one, for Hornde
simplification is dramatic: of the three functions
remains and reduces to a standard conformal co
deduced relations among operators do not introd
quantum corrections.

arXiv.org > astro-ph > arXiv:1710.05893

Astrophysics > Cosmology and Nongalactic Astrophysics

Implications of the Neutron Star Merger GW170817 for C Scalar-Tensor Theories

Jeremy Sakstein, Bhuvnesh Jain

(Submitted on 16 Oct 2017 (v1), last r

The LIGO/VIRGO collaboration
neutron star merger (GW1708
burst GRB 170817A). The close
speed of photons and graviton
cosmological scalar-tensor gra
ΛCDM. First, for the most gen
parameters appearing in the ef
scales; we present the results

arXiv.org > astro-ph > arXiv:1710.05901

Astrophysics > Cosmology and Nongalactic Astroph

Dark Energy after GW170817

Jose María Ezquiaga (1 and 2), Miguel Zumalacárregui

(Submitted on 16 Oct 2017)

vave (GW) astronomy ha
ciated electromagnetic
70817A constrain the s
f dark energy (DE), sho
sfavored. As an exampl
hich predicts a variable
ly eliminates any cosmo
nd most beyond Horndo
fic beyond Horndeski th
theories in which c_g =
nds. Our conclusions ca
ed such as Einstein-Aet

arXiv.org > astro-ph > arXiv:1710.06394

Search or Arti

(Help | Advanced s

Astrophysics > Cosmology and Nongalactic Astrophysics

Strong constraints on cosmological gravity from GW170817 and GRB 170817A

Tessa Baker (Oxford U.), Emilio Bellini (Oxford U.), Pedro G. Ferreira (Oxford U.), Macarena Lagos (Chicago U., KICP), Johannes Noller (Zurich, ETH), Ignacy Sawicki (Prague, Inst. Phys.)

(Submitted on 17 Oct 2017)

The detection of an electromagnetic counterpart (GRB 170817A) to the gravitational wave signal (GW170817) from the merger of two neutron stars opens a completely new arena for testing theories of gravity. We show that this

Implications of GW170817 and GRB170817A

- Modified Gravity theories predicting a different speed of Gravity at low redshifts ($0<z<0.01$) are ruled out
- Self-accelerating models, e.g. Galileons, are severely constrained
- The speed of Gravity can still vary at $0.01<z<1000$ …

Phenomenology of Horndeski theories: Σ-μ

The Super-Compton Limit: $\lambda >> \lambda_C$

$$\Sigma_0 = \frac{m_{\rm Pl}^2}{M_*^2}\left(1+\frac{\alpha_T}{2}\right)$$

$$\gamma_0 = \frac{1}{1+\alpha_T}$$

$$\mu_0 = \frac{m_{\rm Pl}^2}{M_*^2}(1+\alpha_T)$$

$\Sigma \neq \mu$ on super-Compton scales would signal a modified speed of GW

LP & Silvestri, arXiv:1606.05339, PRD

Phenomenology of Horndeski theories: Σ-μ

The Sub-Compton Limit: $\lambda \ll \lambda_C$

$$\mu_\infty = \frac{m_0^2}{M_*^2}(1 + \alpha_T + \beta_\xi^2)$$

$$\Sigma_\infty = \frac{m_0^2}{M_*^2}\left(1 + \frac{\alpha_T}{2} + \frac{\beta_\xi^2 + \beta_B \beta_\xi}{2}\right)$$

Fifth force

Conjecture: expect Σ-1 and μ-1 to be of the same sign

LP & Silvestri, arXiv:1606.05339, PRD

Large-scale structure phenomenology of viable Horndeski theories

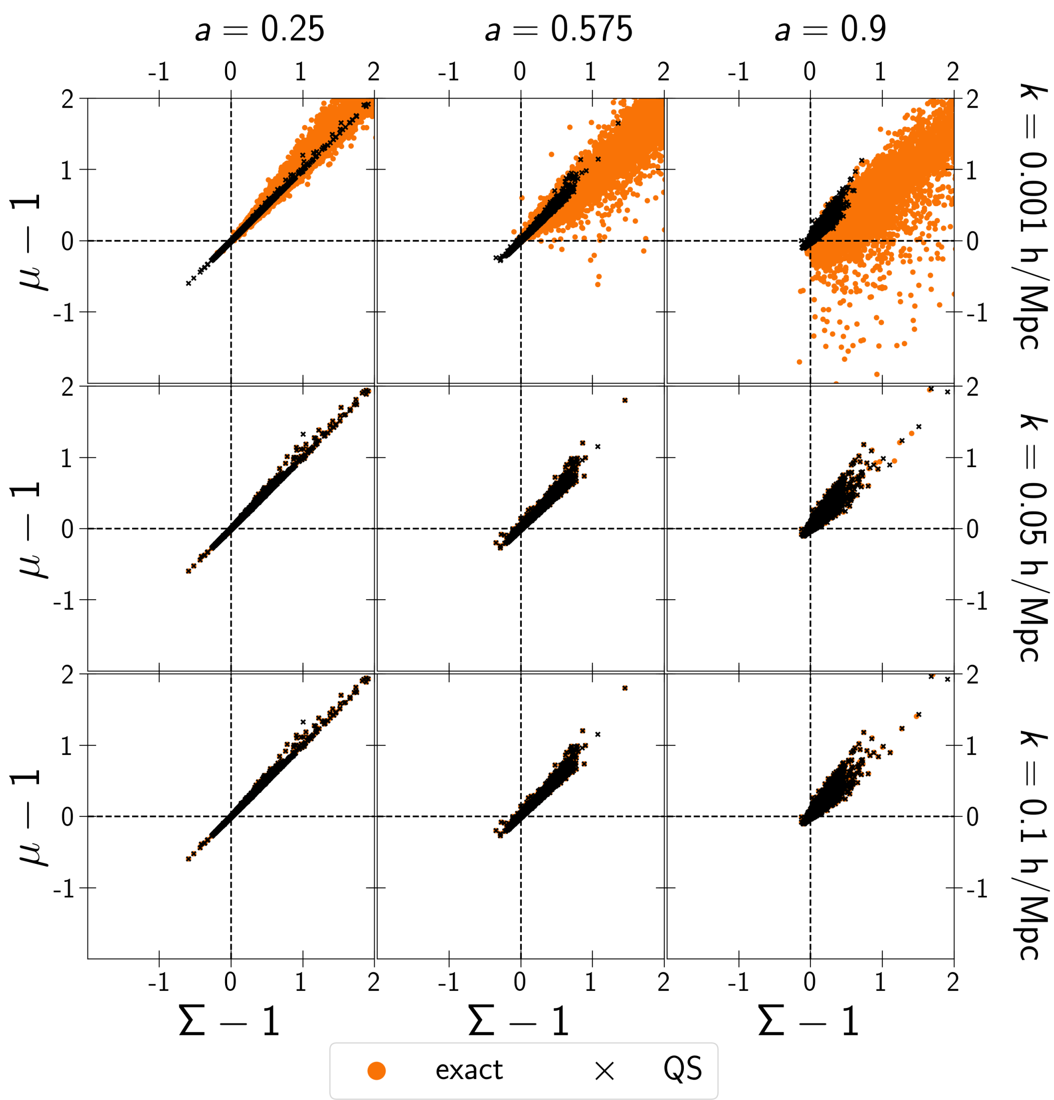
Simone Peirone, Kazuya Koyama, Levon Pogosian, Marco Raveri, Alessandra Silvestri

(Submitted on 1 Dec 2017)

Phenomenological functions Σ and μ, also known as $G_{\rm light}/G$ and $G_{\rm matter}/G$, are commonly used to parameterize modifications of the growth of large-scale structure in alternative theories of gravity. We study the values these functions can take in Horndeski theories, i.e. the class of scalar-tensor theories with second order equations of motion. We restrict our attention to models that are in a broad agreement with tests of gravity and the observed cosmic expansion history. In particular, we require the speed of gravity to be equal to the speed of light today, as required by the recent detection of gravitational waves and electromagnetic emission from a binary neutron star merger. We examine the correlations between the values of Σ and μ analytically within the quasi-static approximation, and numerically, by sampling the space of allowed solutions. We confirm the conjecture made in [Pogosian:2016pwr] that $(\Sigma - 1)(\mu - 1) \geq 0$ in viable Horndeski theories. Along with that, we check the validity of the quasi-static approximation within different corners of Horndeski theory. Our results show that, even with the tight bound on the present day speed of gravitational waves, there is room within Horndeski theories for non-trivial signatures of modified gravity at the level of linear perturbations.

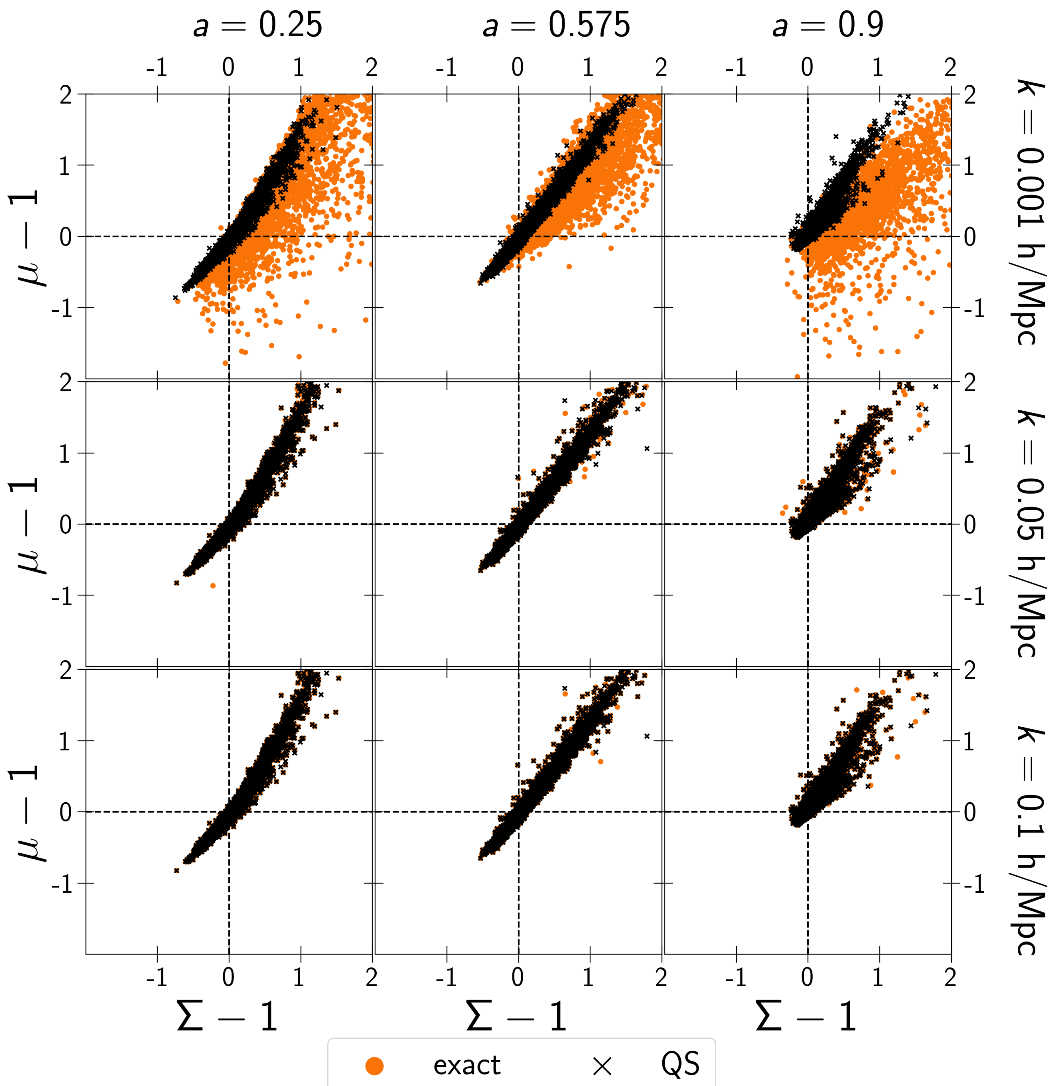
Comments: 12 pages, 5 figures
Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**
Cite as: arXiv:1712.00444 [astro-ph.CO]

Horndeski models with c_{gw}=c at all times



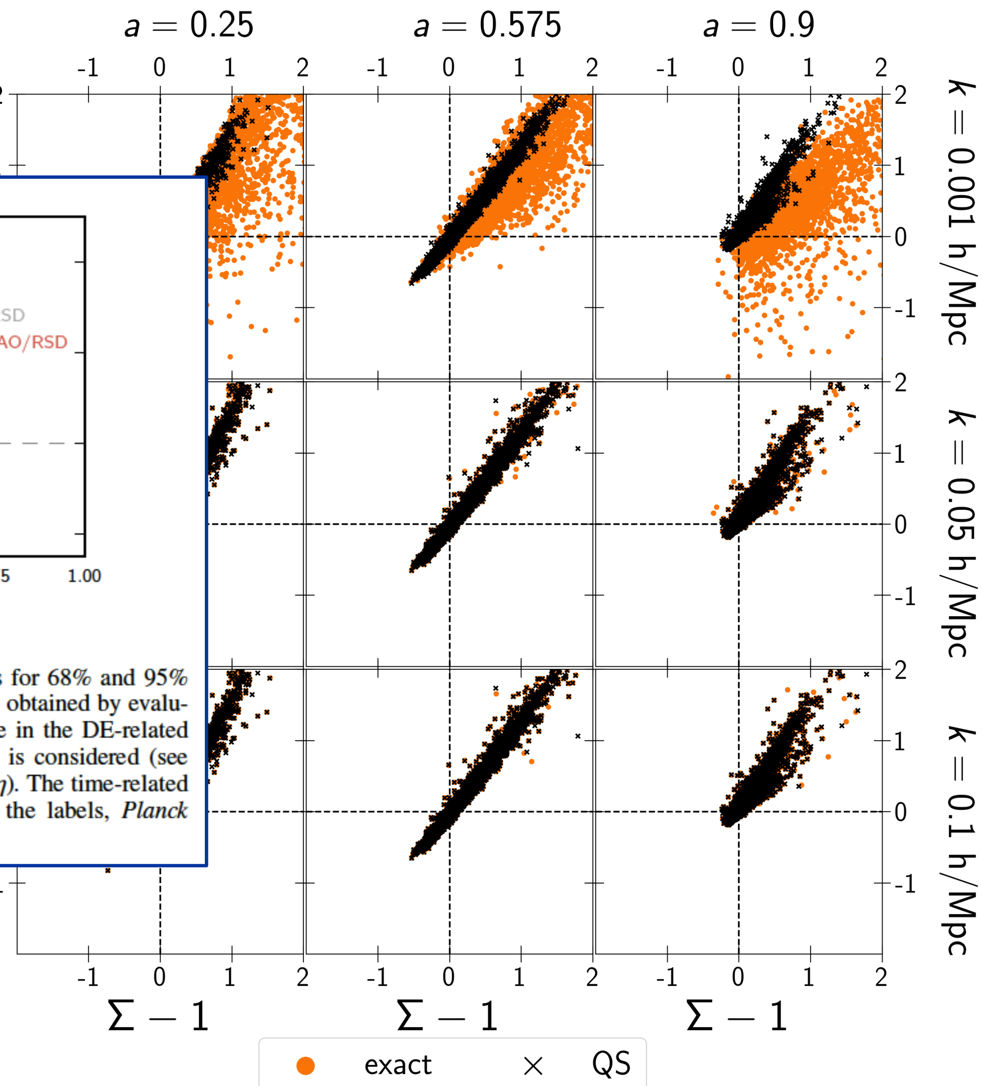
S. Peirone, M. Raveri, LP, A. Silvestri, K. Koyama, 1712.00444

Horndeski models with c_{gw}=c today



S. Peirone, M. Raveri, LP, A. Silvestri, K. Koyama, 1712.00444

Horndeski models with c_{gw}=c today



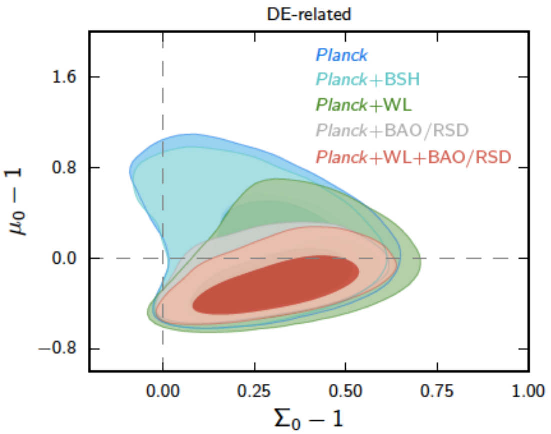


Fig. 15. Marginalized posterior distributions for 68% and 95% C.L. for the two parameters $\{\mu_0 - 1, \Sigma_0 - 1\}$ obtained by evaluating Eqs. (46) and (47) at the present time in the DE-related parametrization when no scale dependence is considered (see Sect. 5.2.2). Σ is obtained as $\Sigma = (\mu/2)(1+\eta)$. The time-related evolution would give similar contours. In the labels, *Planck* stands for *Planck* TT+lowP.

S. Peirone, M. Raveri, LP, A. Silvestri, K. Koyama, 1712.00444

Large-structure phenomenology with Σ and μ

- model-independent doesn't mean "anything goes"; even within a broad class of Horndeski theories there are very clear trends

- $\Sigma \neq 1$ or $\mu<1$ disfavors generalized Brans-Dicke theories (e.g. f(R), chameleon, symmetrons)

- $\Sigma \neq \mu$ rules out Cubic Galileons

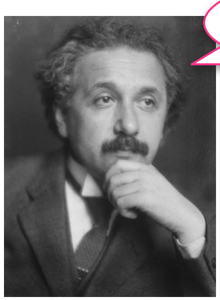
- $(\Sigma - 1)(\mu - 1) < 0$ strongly disfavors all Horndeski theories

- additional information if scale-dependence is detected in Σ or μ

LP & Silvestri, arXiv:1606.05339, PRD
S. Peirone, M. Raveri, LP, A. Silvestri, K. Koyama, 1712.004444

Summary

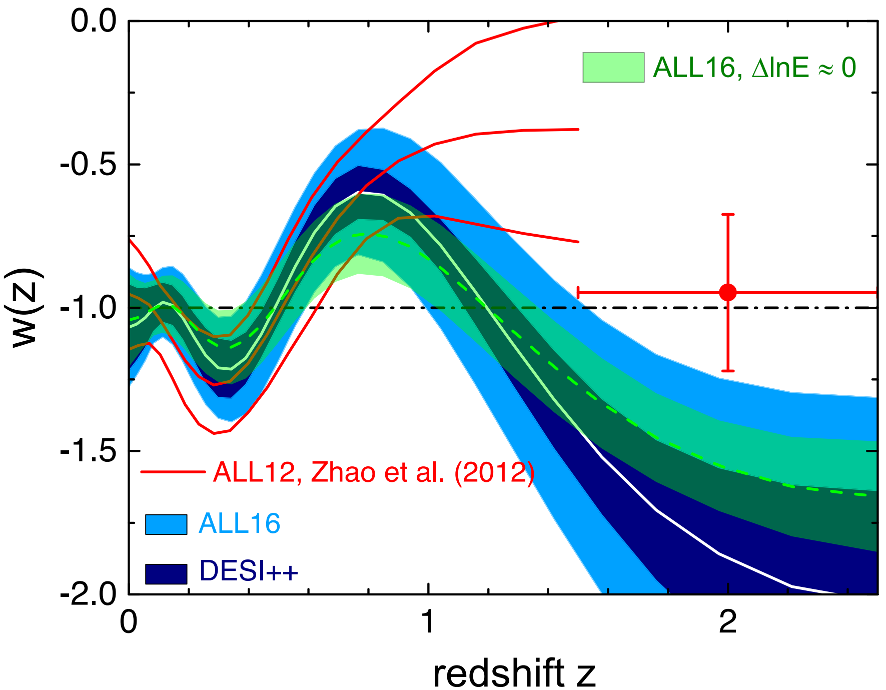
The universe surprised us before

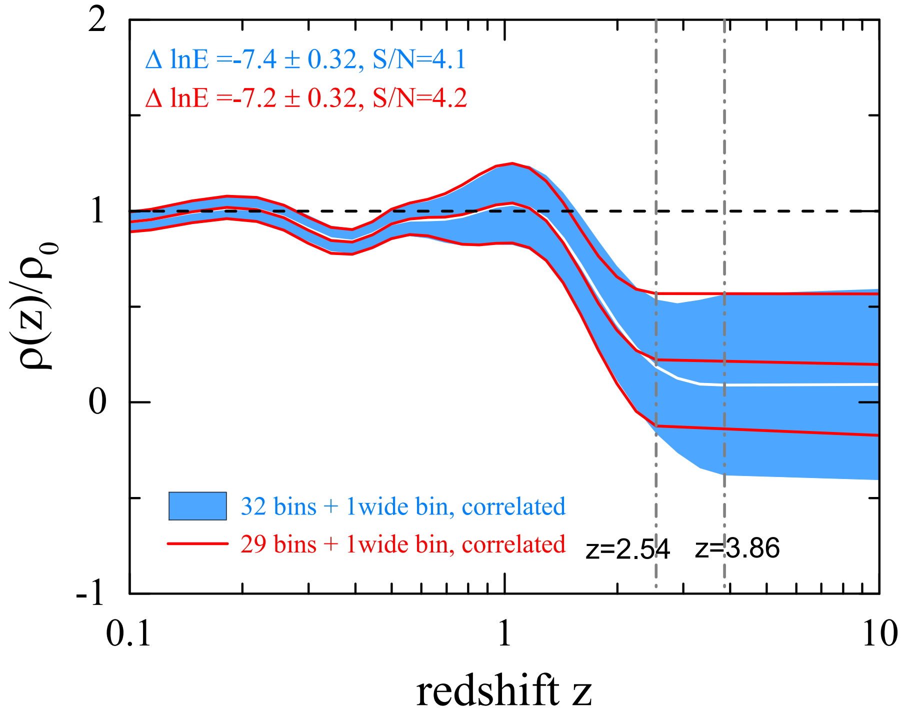


There are good reasons to keep an open mind about LCDM

Summary

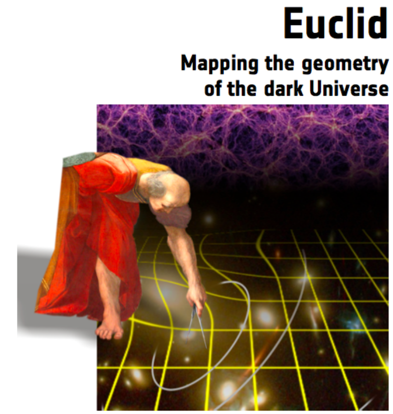
The data seems to prefer less dark energy density in the past





- suggests modified gravity or interaction between CDM and Dark Energy
- good reasons to probe large scale structure in the 1<z<3 range

Summary

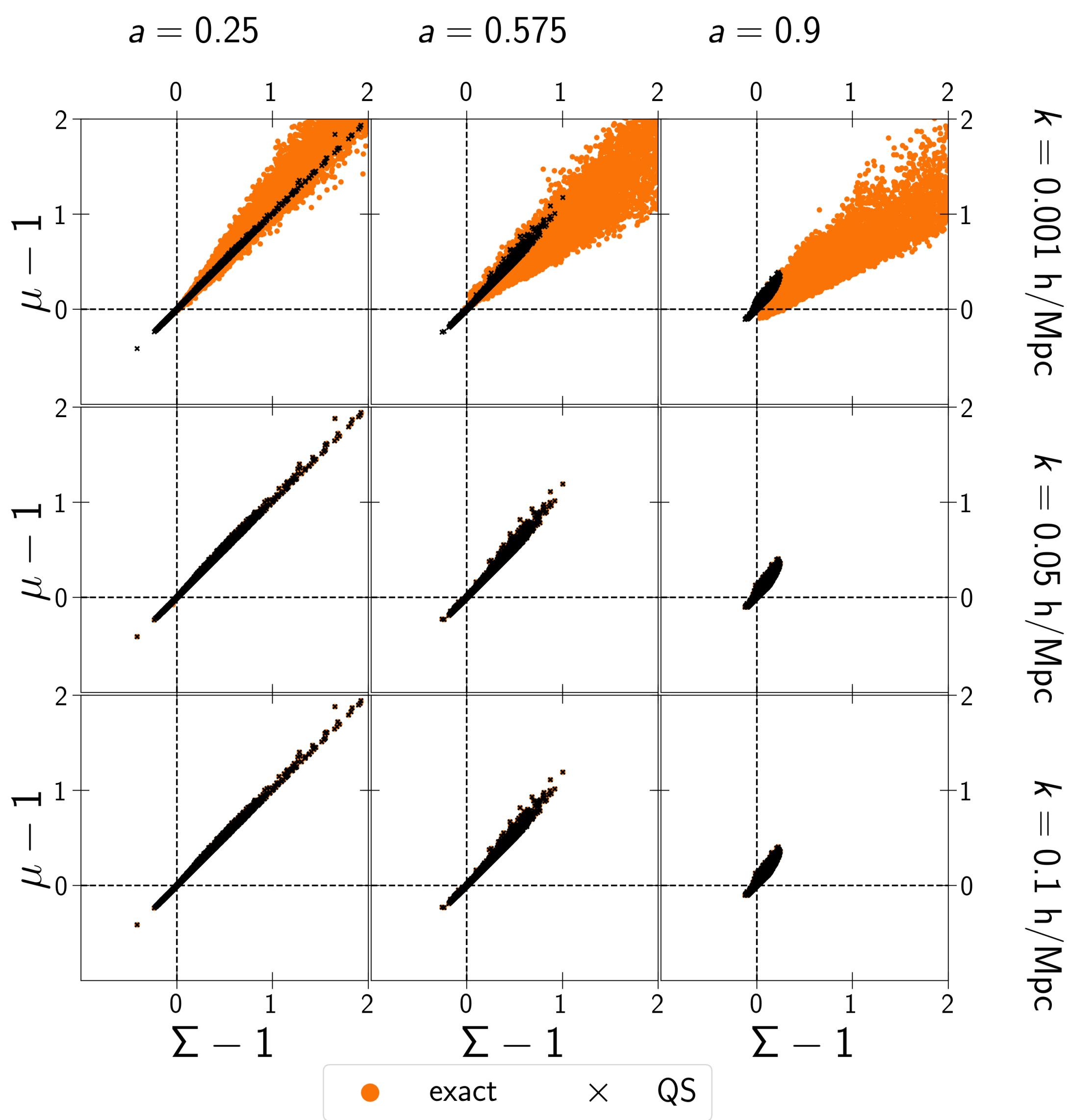


Future surveys, such as Euclid and LSST, can constrain many degrees of freedom of w, Σ and μ

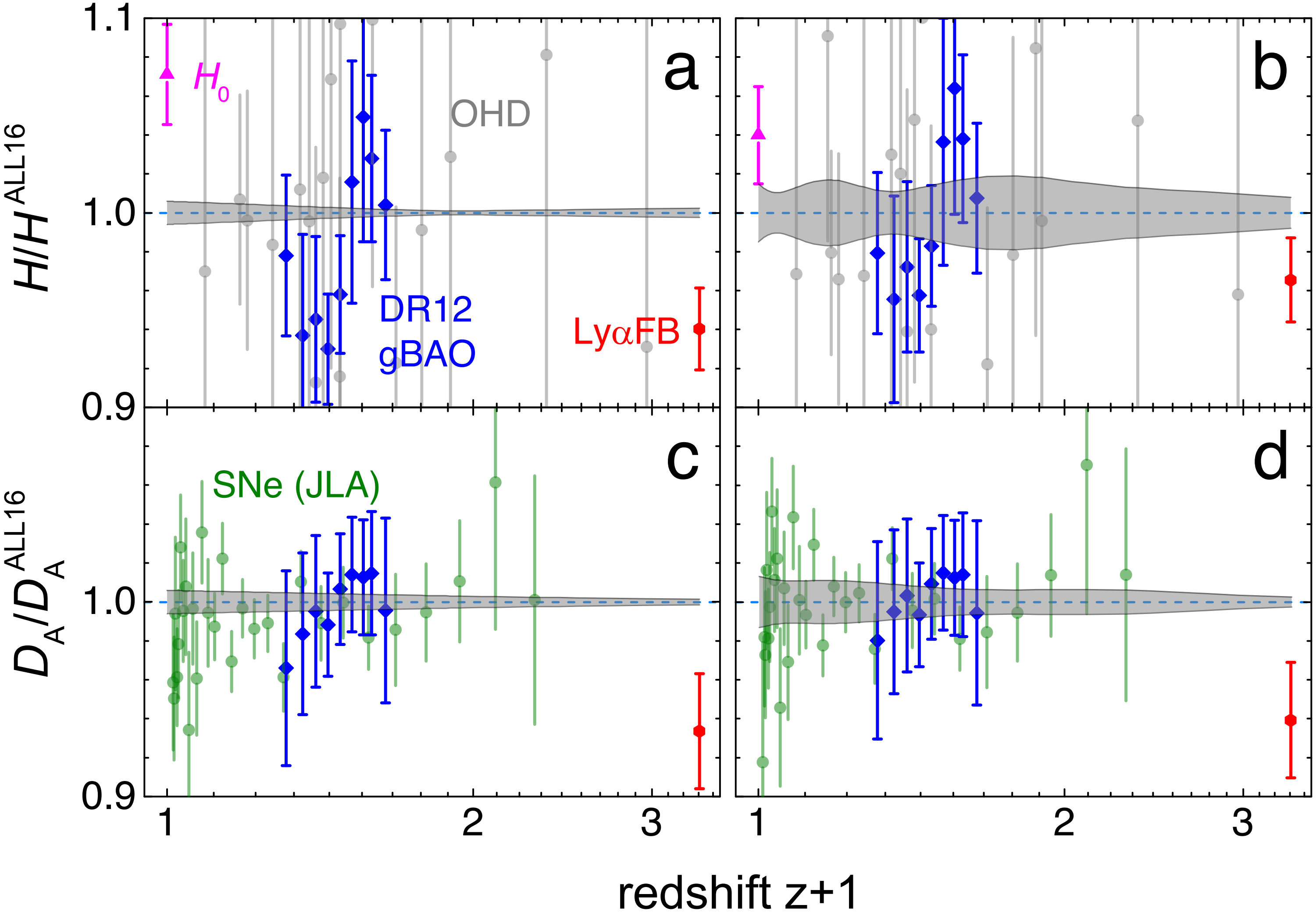
The challenge for theorists is to find meaningful questions such phenomenological tests can answer

It is possible to rule out large classes of modified gravity models by testing the mutual consistency of w, Σ and μ

Generalized Brans-Dicke models

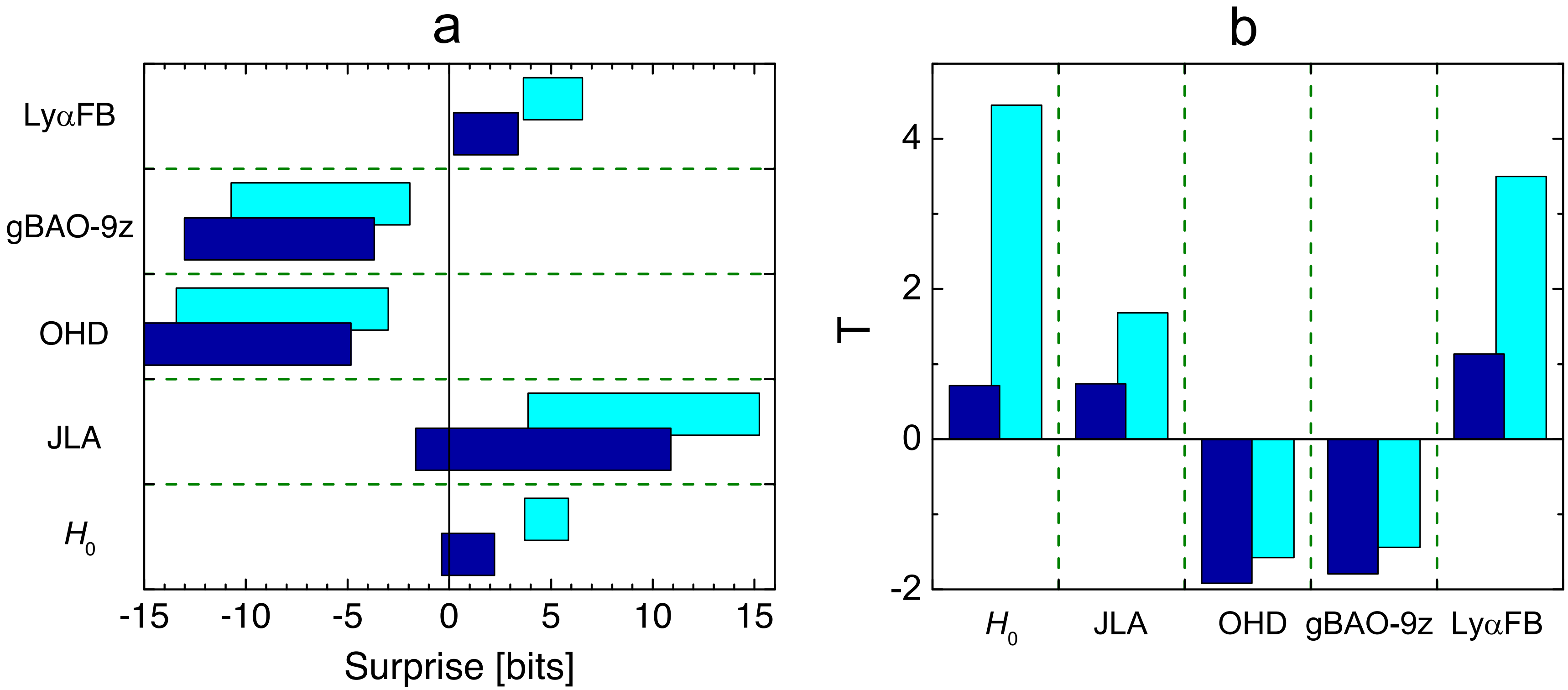


S. Peirone, M. Raveri, LP, A. Silvestri, K. Koyama, in prep.



G.-B. Zhao et al, arXiv:1701.08165, Nature Astronomy

Surprise and Tension



G.-B. Zhao et al, arXiv:1701.08165, Nature Astronomy