Title: Implementing a stochastic dark energy framework into CAMB

Speakers: Levon Pogosian

Collection: Everpresent Lambda: Theory Meets Observations

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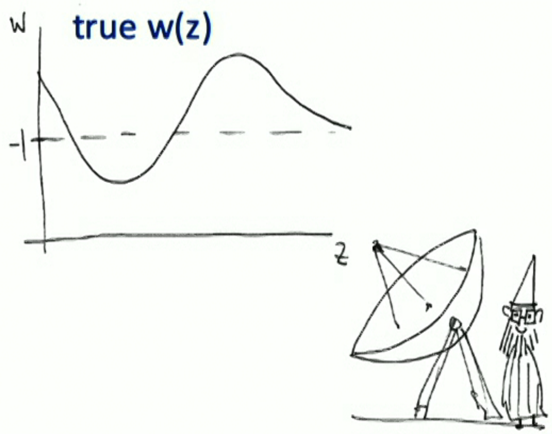
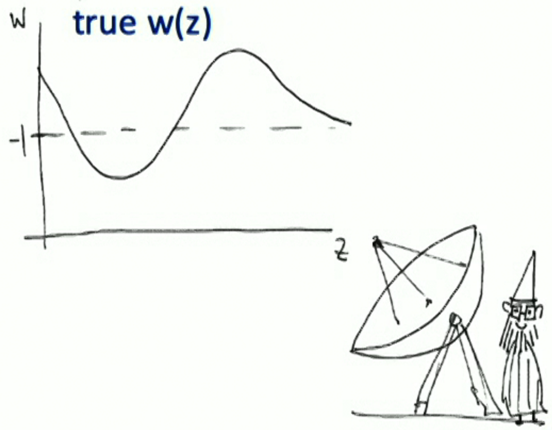
Fables of Reconstruction

Levon Pogosian
Simon Fraser University

with Robert Crittenden, Gong-Bo Zhao, Yuting Wang, Alessandra Silvestri, Jian Li and many others



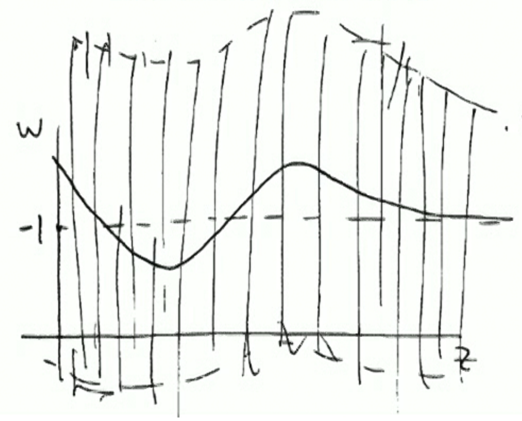
MCMC fit
using many w-bins



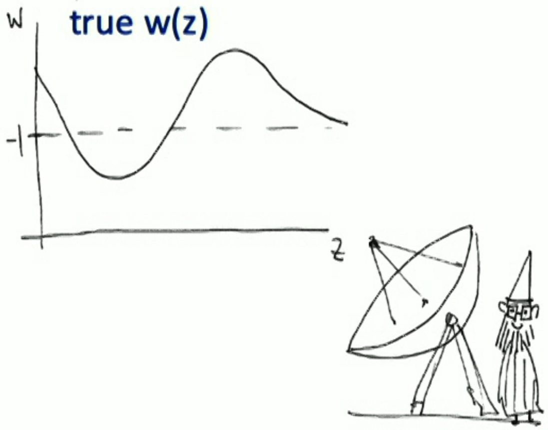
no prior

MCMC fit
using many w-bins

reconstructed w(z)

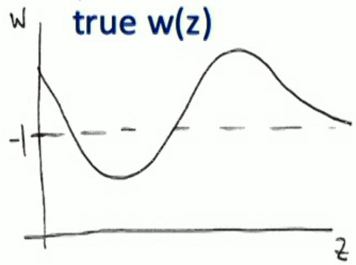


- large variance
- zero bias



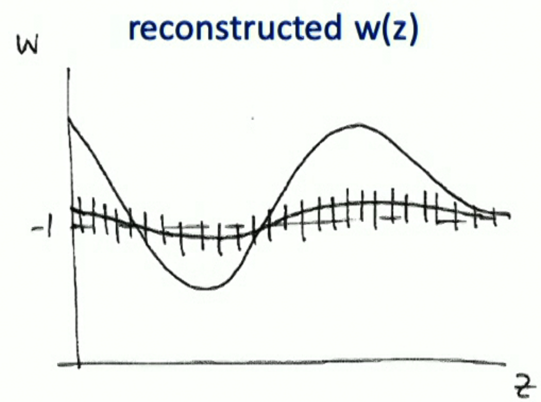
$$\chi^2_{\rm prior} = -2\ln \mathcal{P}_{\rm prior} = (\mathbf{w} - \mathbf{w}^{\rm fid})^T \mathbf{C}^{-1} (\mathbf{w} - \mathbf{w}^{\rm fid})$$

MCMC fit
using many w-bins

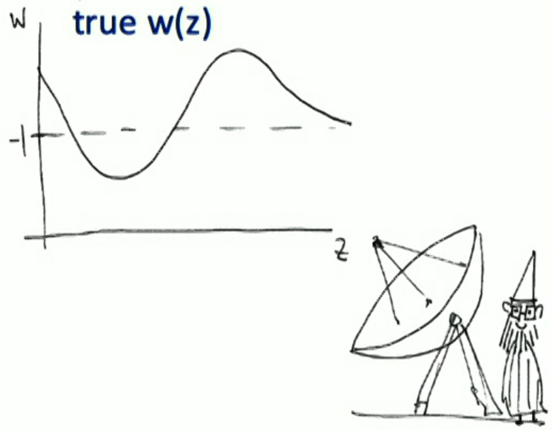


Excessively strong prior

MCMC fit
using many w-bins



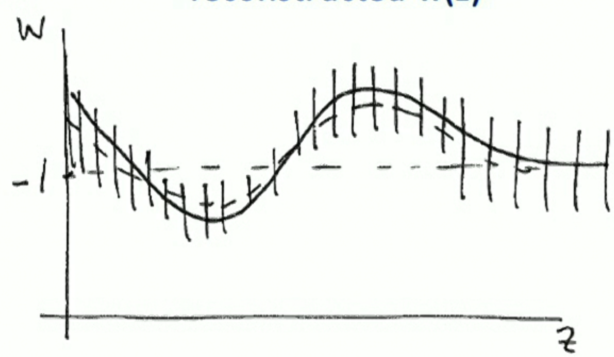
- tiny error bars (small variance)
- large bias



reasonable prior

MCMC fit
using many w-bins

reconstructed w(z)



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

What is a reasonable prior?

- Informed by theory, e.g. scalar fields

M. Raveri, P. Bull, A. Silvestri, LP, arXiv:1703.05297, PRD
J. Espejo, S. Peirone, M. Raveri, LP, A. Silvestri, K. Koyama, arXiv:1809.01121, PRD

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

- Noisy features (poorly constrained by data) determined by the prior

Fables of Reconstruction, R. Crittenden, G.-B. Zhao, LP, L. Samushia, X. Zhang, 1112.1693, JCAP

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Smooth means correlated

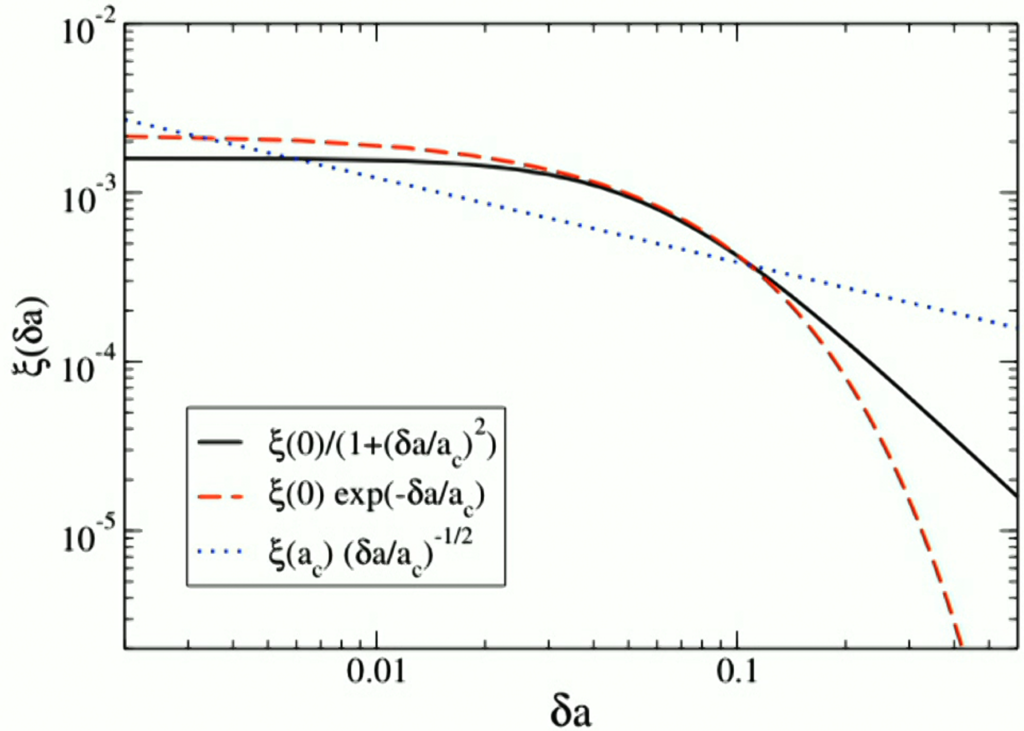
- Start with a correlation function:

$$\xi_w(|a-a'|) \equiv \left\langle [w(a)-w^{\rm fid}(a)][w(a')-w^{\rm fid}(a')] \right\rangle$$

- Make a reasonable (not unique) choice of a functional form:

$$\xi_w(\delta a) = \frac{\xi_w(0)}{1+(\delta a/a_c)^2} \qquad \delta a \equiv |a-a'|$$

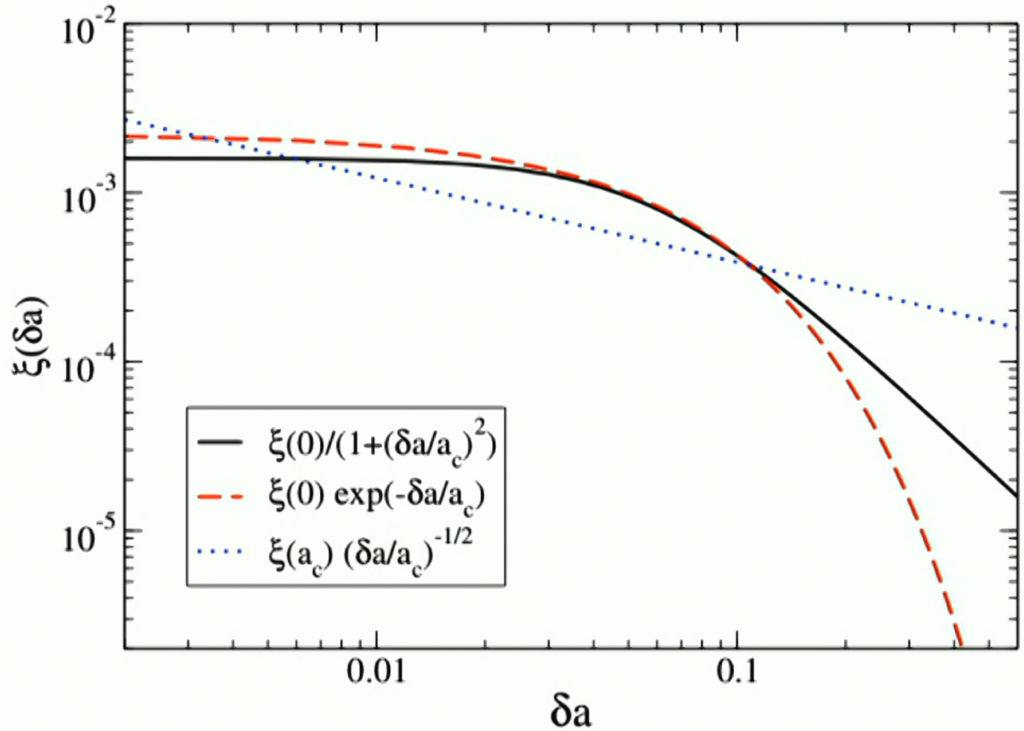
Correlation functions



- Two control parameters:

  "correlation scale" and the overall amplitude

Correlation functions



- Two control parameters:

  "correlation scale" and the overall amplitude

The prior covariance matrix

- The correlation function:

$$\xi_w(|a-a'|) \equiv \left\langle [w(a) - w^{\rm fid}(a)][w(a') - w^{\rm fid}(a')] \right\rangle$$

- The functional form:

$$\xi_w(\delta a) = \frac{\xi_w(0)}{1 + (\delta a/a_c)^2} \qquad \delta a \equiv |a - a'|$$

- Build a covariance matrix from the correlation function

$$C_{ij} \equiv \langle \delta w_i \delta w_j \rangle = \frac{1}{\Delta^2} \int_{a_i}^{a_i+\Delta} da \int_{a_j}^{a_j+\Delta} da' \xi_w(|a-a'|).$$

- Build a correlation prior from the covariance matrix

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

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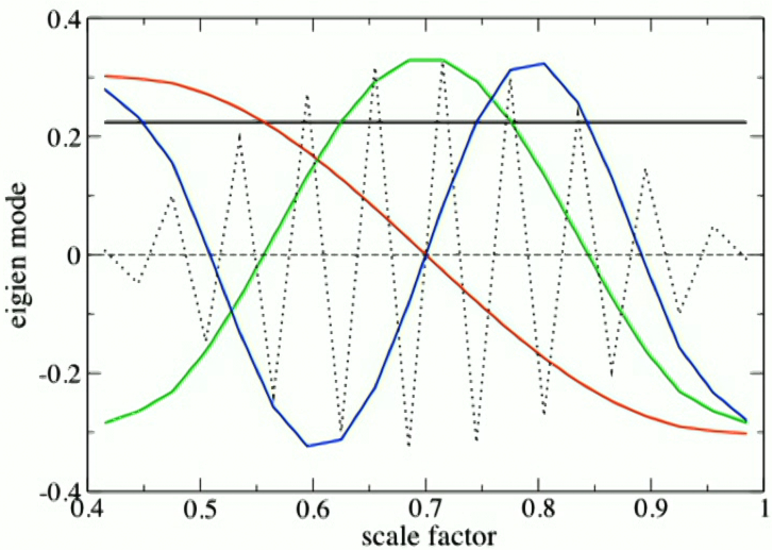
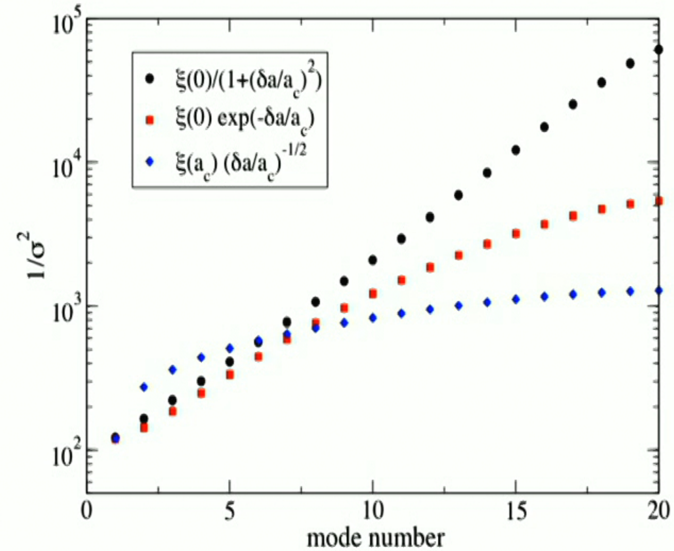
Eigenmodes and eigenvalues of the correlated prior





- High frequencies constrained best
- Low frequencies constrained worst

Wiener Filtering

Posterior: $$\mathcal{P}(\mathbf{w}|\mathbf{w}^{\rm obs}) = \mathcal{P}(\mathbf{w}^{\rm obs}|\mathbf{w}) \times \mathcal{P}_{\rm prior}(\mathbf{w})$$

Likelihood: $$\mathcal{P}(\mathbf{w}^{\rm obs}|\mathbf{w}) \propto e^{-(\mathbf{w}^{\rm obs}-\mathbf{w})^T \mathbf{F} (\mathbf{w}^{\rm obs}-\mathbf{w})/2}$$

Prior: $$\mathcal{P}_{\rm prior}(\mathbf{w}) \propto e^{-(\mathbf{w}-\mathbf{w}^{\rm fid})^T C^{-1} (\mathbf{w}-\mathbf{w}^{\rm fid})/2}$$

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$$\mathbf{F}(\mathbf{w}^{\rm recon} - \mathbf{w}^{\rm obs}) + \mathbf{C}^{-1}(\mathbf{w}^{\rm recon} - \mathbf{w}^{\rm fid}) = 0,$$

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$$\mathbf{w}^{\rm recon} = \mathbf{F}^{-1}(\mathbf{C} + \mathbf{F}^{-1})^{-1}\mathbf{w}^{\rm fid} + \mathbf{C}(\mathbf{C} + \mathbf{F}^{-1})^{-1}\mathbf{w}^{\rm obs}$$

High-pass “filter”
of the fiducial w

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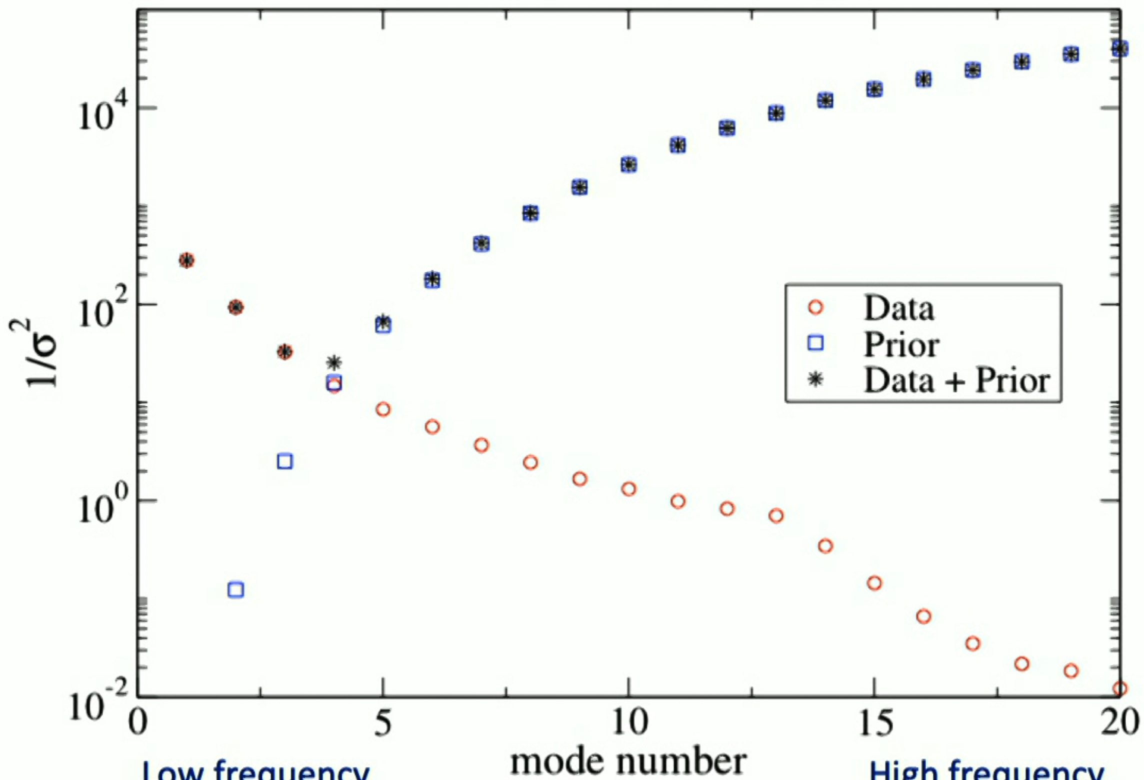
High-pass "filter" of the fiducial w

Low-pass "filter" of the observed w

Data meets Prior

Forecast for EUCLID-like SNe, H(z); Planck CMB



Low frequency

High frequency

Wiener Filtering

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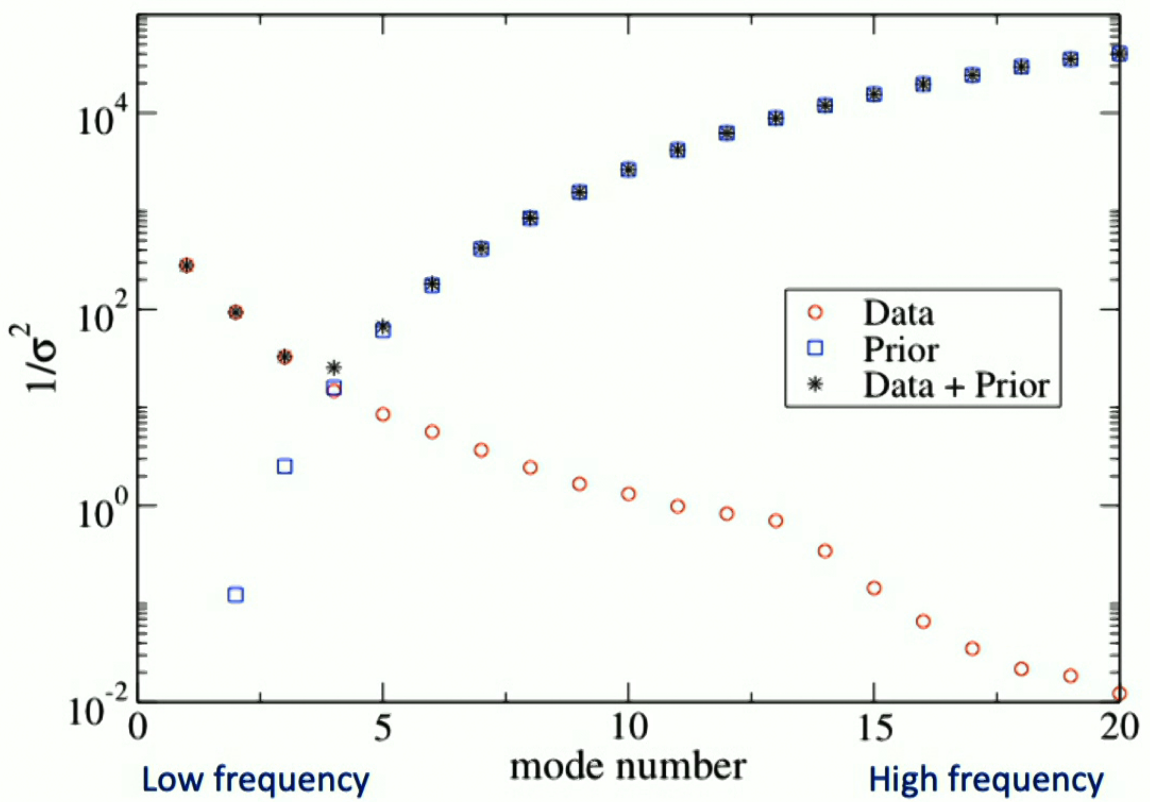
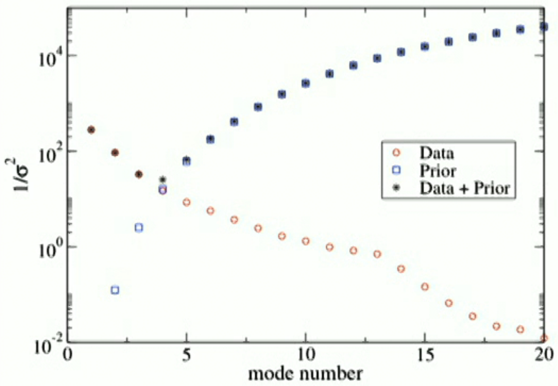
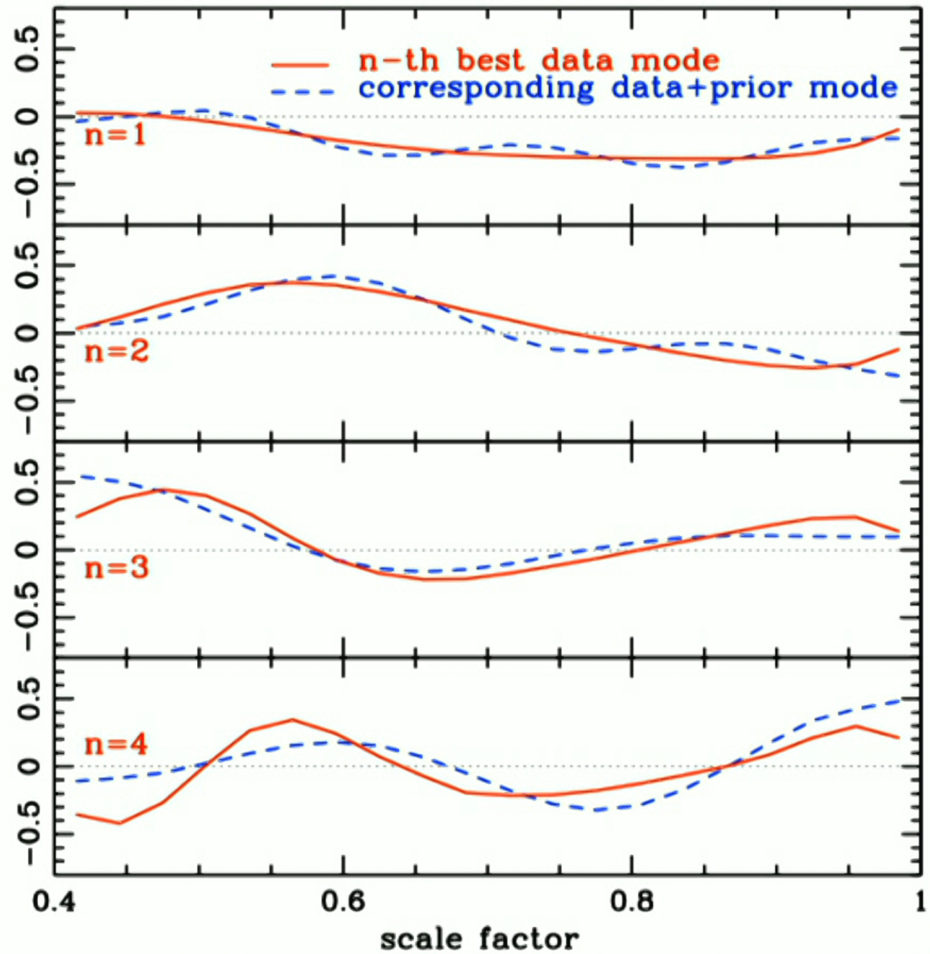


Surviving data eigenmodes

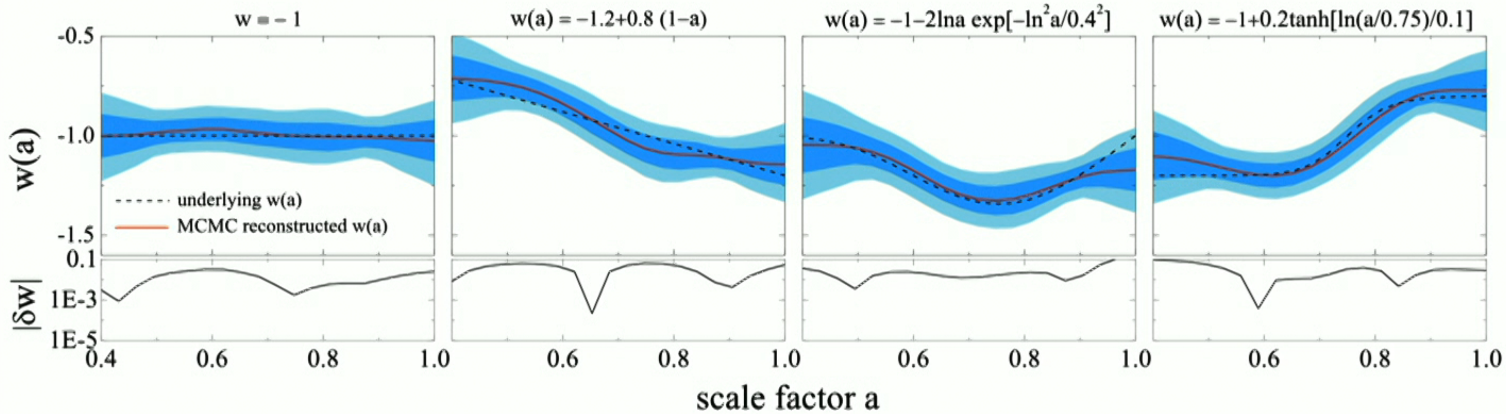


a_c=0.06
prior on mean w = 0.02



Reconstructions using mock datasets

Planck + Euclid



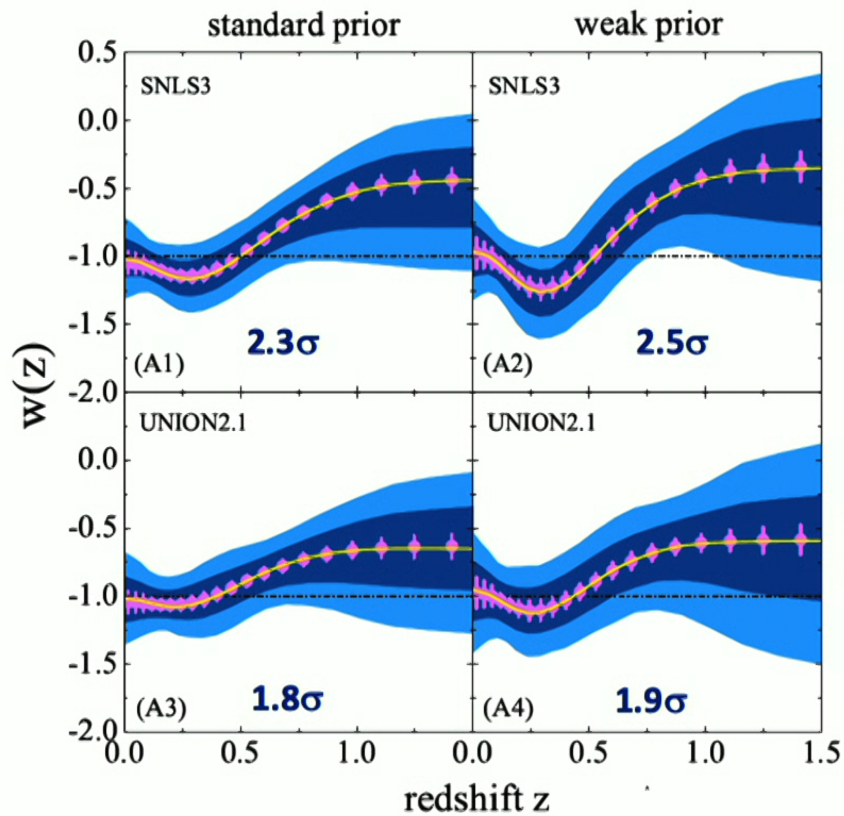
$$\chi^2 = \chi^2_{\rm data} + \chi^2_{\rm prior}$$

Reconstruction from the 2012 data

- CMB from WMAP7
- Supernovae
  - Union 2.1, Suzuki et al, ApJ (2012)
  - SNLS 3, Conley et al, ApJS (2011)
- Baryon Acoustic Oscillations
  - SDSS-II, SDSS-III BOSS, 6dF, WiggleZ
- Redshift Space Distortions
  - SDSS-II, SDSS-III BOSS, 6dF, WiggleZ
- H(z) compilation
  - Moresco et al, 1201.6658

G-B Zhao, R. Crittenden, L. Pogosian, X. Zhang, arXiv:1207.3804, PRL

Reconstruction from the 2012 data



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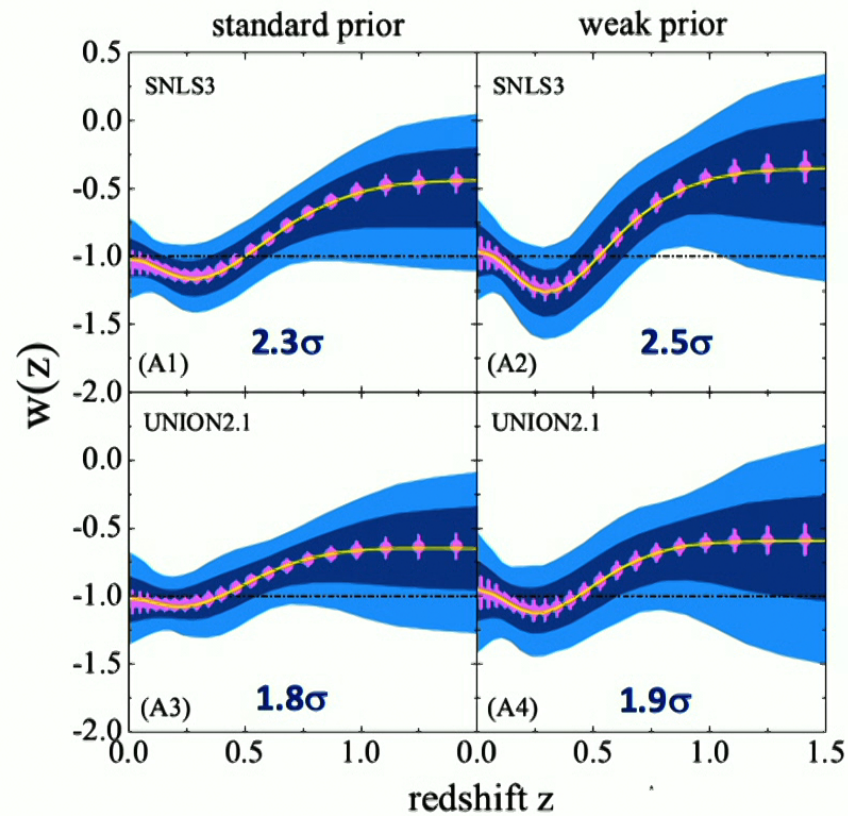

G-B Zhao, R. Crittenden, L. Pogosian, X. Zhang, arXiv:1207.3804, PRL

Examining the Bayesian evidence

$$E \equiv \int d^n\mathbf{P}\,\mathcal{P}(\mathbf{D}|\mathbf{P})\,\mathcal{P}_{\rm prior}(\mathbf{P})$$

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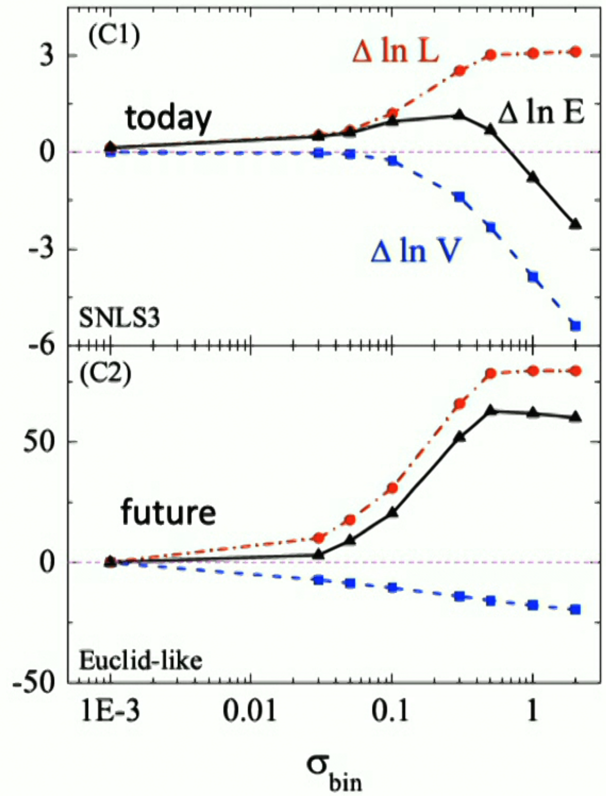
$$E \equiv \int d^n\mathbf{P}\,\mathcal{P}(\mathbf{D}|\mathbf{P})\,\mathcal{P}_{\rm prior}(\mathbf{P})$$

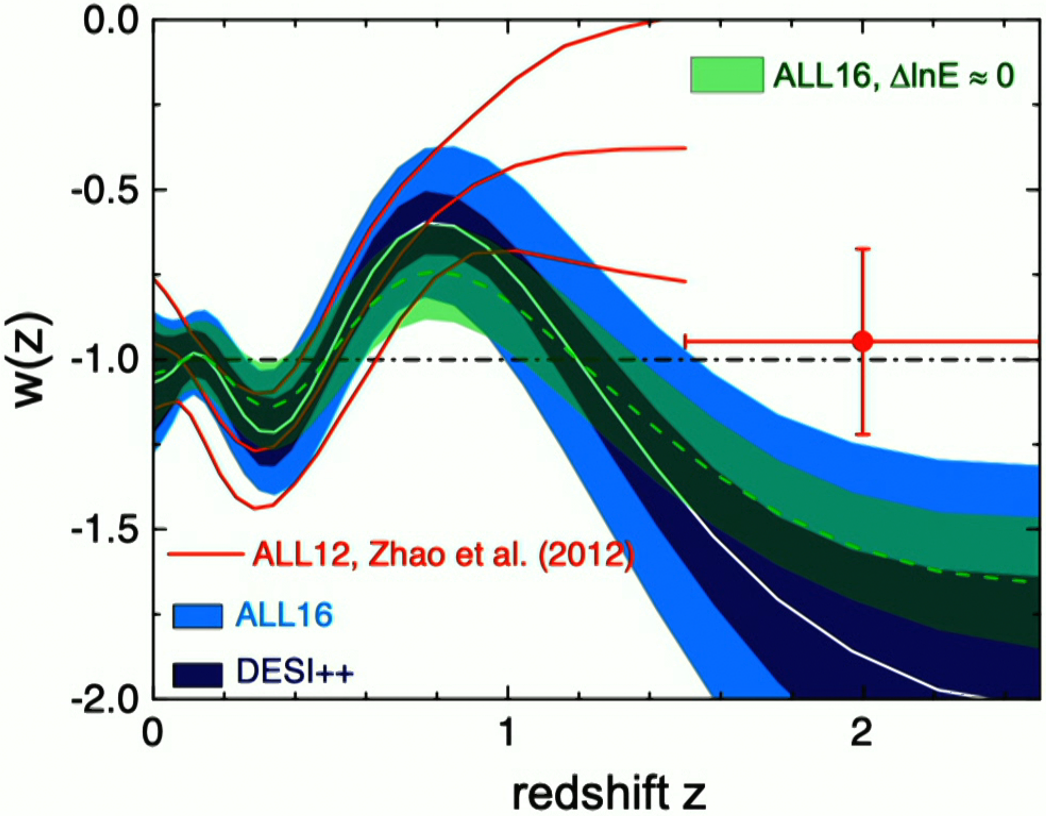
- The best fit model fits data better than Lambda, but it has more parameters
- Does improvement in the fit justify adding new parameters?
- Note – even though the number of bins is large, the effective number of free parameters is small because the prior constrains most of the degrees of freedom

Ratio of evidences: the Bayes' factor



In the absence of a firm theoretical prediction for a prior, the departure from LCDM is considered significant if the Bayes' factor remains large for a wide range of priors parameters, e.g. σ_{bin} .

Reconstruction from the 2016 data



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

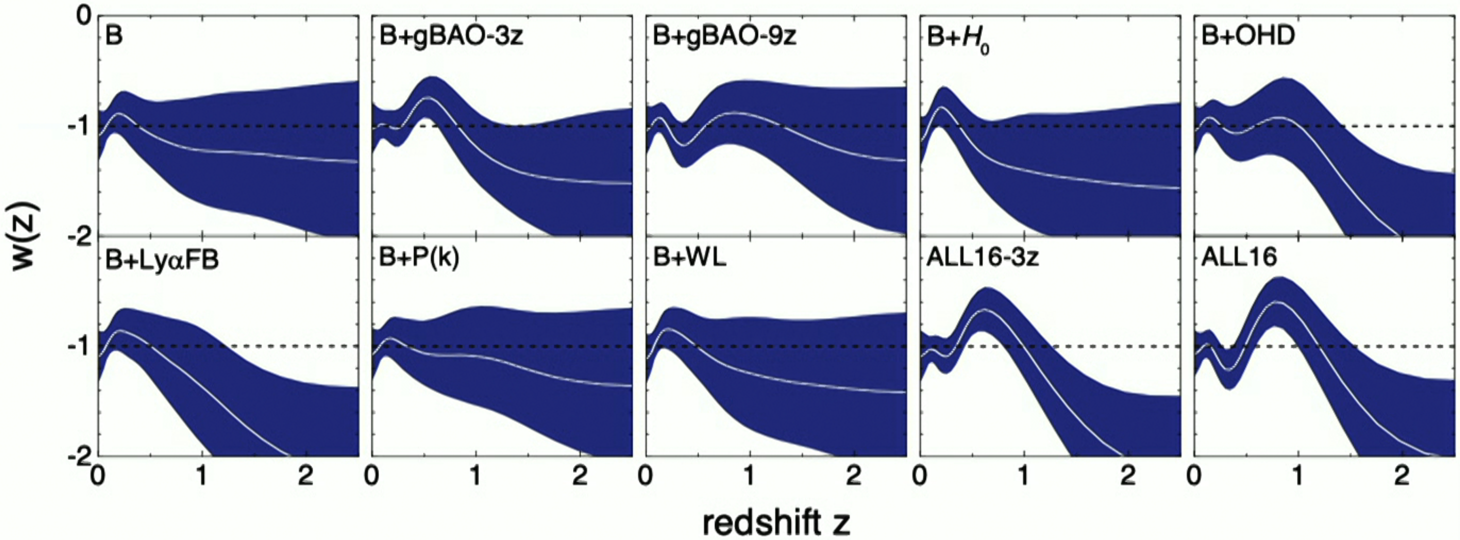
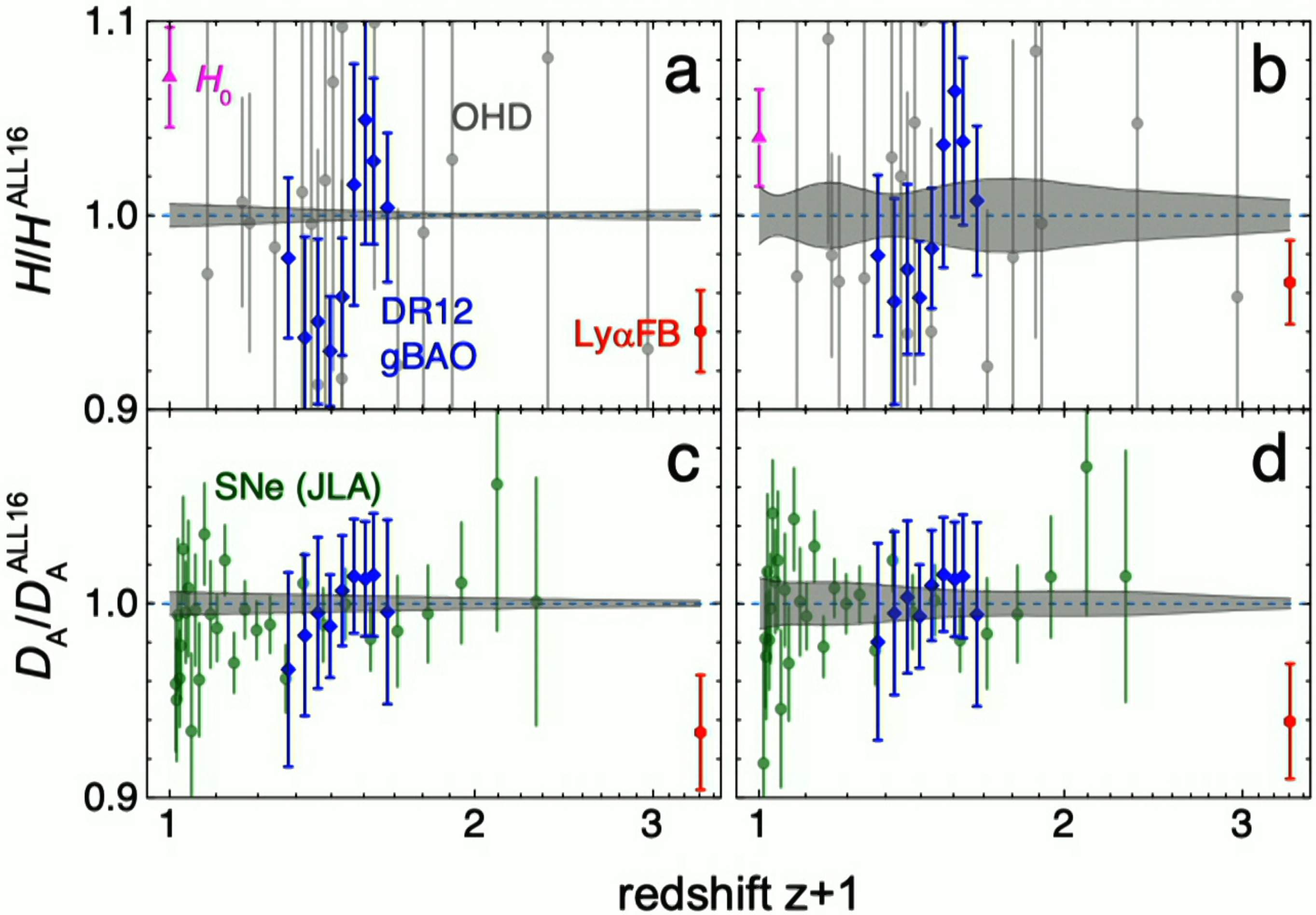


Table 1 | The improved χ^2 with respect to that of the ΛCDM model

	P15	JLA	gBAO	$P(k)$	WL	H_0	LyαFB	OHD
$\chi^2_{w(z)\mathrm{CDM}} - \chi^2_{\Lambda\mathrm{CDM}}$	−0.7	−1.6	−2.8	+1.1	−0.1	−2.9	−3.7	−2.3
$\chi^2_{w\mathrm{CDM}} - \chi^2_{\Lambda\mathrm{CDM}}$	0.0	+0.5	+0.7	+0.4	+0.2	−2.9	−0.2	0.0
$\chi^2_{w_0w_a\mathrm{CDM}} - \chi^2_{\Lambda\mathrm{CDM}}$	−0.7	+0.4	+0.9	+0.5	+0.4	−2.7	−0.3	0.0

The changes in χ^2 of individual datasets between the ALL16 best-fit $w(z)$CDM, wCDM and w_0w_aCDM models and the ΛCDM model.

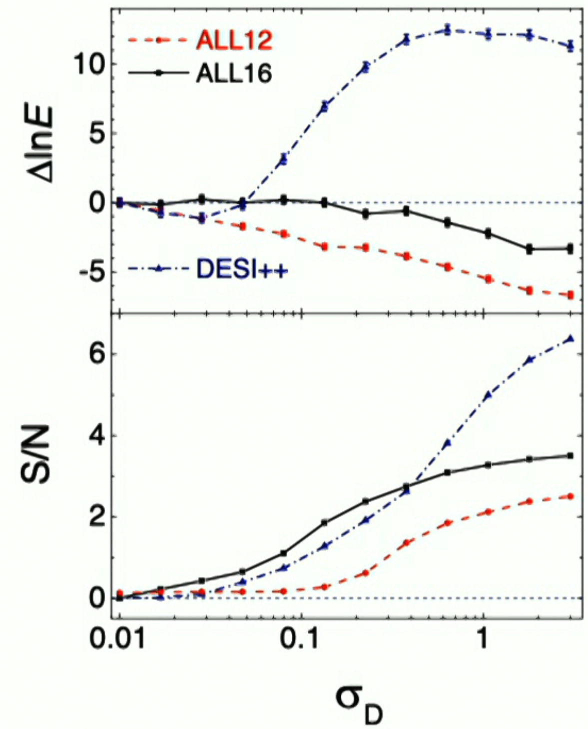
G.-B. Zhao et al, arXiv:1701.08165, Nature Astronomy



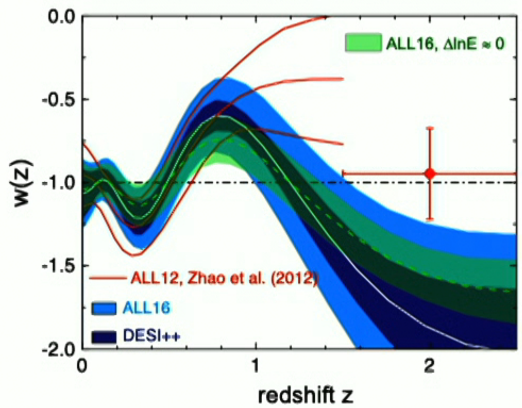
1.1
1.0
0.9
H/H^ALL16
D_A/D_A^ALL16
a
b
c
d
H0
OHD
DR12
gBAO
LyαFB
SNe (JLA)
1
2
3
redshift z+1

Ratio of evidences: the Bayes' factor

- Dynamical dark energy is preferred at a 3.5-sigma significance level based on the improvement in the fit alone
- Effectively, 4 additional degrees of freedom
- No Bayesian preference for dynamics
- Evidence increased since 2012
- Future data can conclusively confirm or rule out this dynamical dark energy



If this was real, what could it be?



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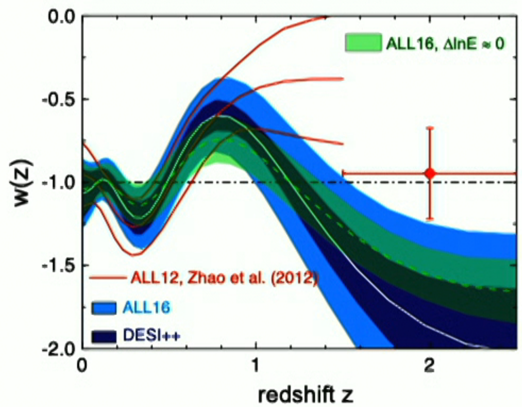

General Relativity with a minimally coupled scalar field (quintessence)

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

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

Modified gravity: a scalar-tensor theory

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

$$\begin{aligned} G_{\mu\nu} &= 8\pi G F^{-1}\left\{T^M_{\mu\nu} + T^\phi_{\mu\nu} + \nabla_\mu\nabla_\nu F - g_{\mu\nu}\Box F\right\} \\ &= 8\pi G\left\{T^M_{\mu\nu} + (T^{\rm eff}_{\rm DE})_{\mu\nu}\right\}\ , \end{aligned}$$

Effective dark energy density:

$$\rho^{\rm eff}_{\rm DE} = F^{-1}\left\{\frac{1}{2}\dot\phi^2 + V(\phi) - 3H\dot F + (1-F)\rho_M\right\}$$

Effective dark energy equation of state:

$$w^{\rm eff}_{\rm DE} = \frac{\dot\phi^2/2 - V(\phi) + 2H\dot F + \ddot F}{\dot\phi^2/2 + V(\phi) - 3H\dot F + (1-F)\rho_M}$$

Is working with w_{eff} justified when probing modified gravity?

$$\dot{\rho}_{\rm DE}^{\rm eff} + 3H(\rho_{\rm DE}^{\rm eff} + p_{\rm DE}^{\rm eff}) = 0 \quad \overset{?}{\Longrightarrow} \quad \rho_{\rm DE}(a) = \rho_0 \exp\left[\int_a^1 3(1+w(a'))\frac{da'}{a'}\right]$$

Working with w_{eff} assumes that the effective density doesn't change sign, but it can in modified gravity, e.g.

$$\rho_{\rm DE}^{\rm eff} = F^{-1}\left\{\frac{1}{2}\dot{\phi}^2 + V(\phi) - 3H\dot{F} + (1-F)\rho_M\right\}$$

$$\boxed{w_{\rm DE}^{\rm eff} = p_{\rm DE}^{\rm eff}/\rho_{\rm DE}^{\rm eff}} \; ?$$

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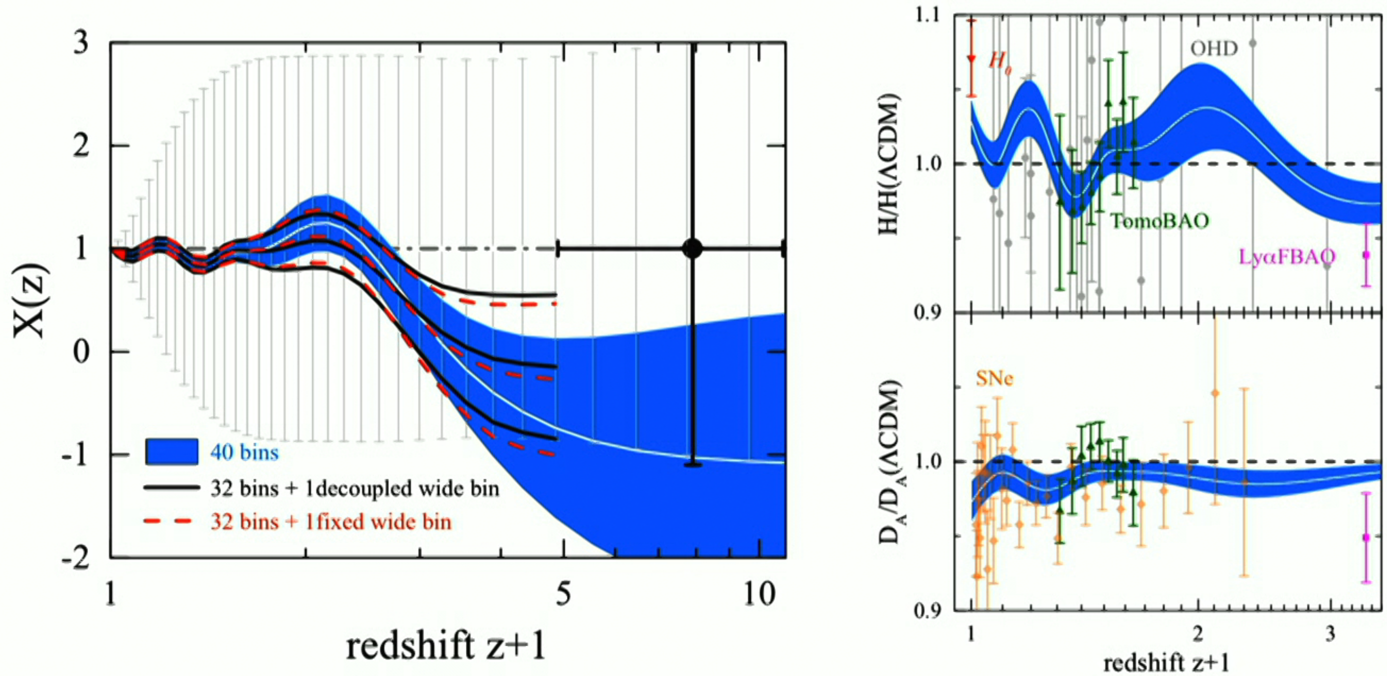
$$\boxed{w_{\rm DE}^{\rm eff} = p_{\rm DE}^{\rm eff}/\rho_{\rm DE}^{\rm eff}} \; ?$$

Parametrizing the effective dark energy evolution in terms of w_{eff} can bias the studies of modified gravity. It's safer to work directly with ρ_{eff}:

$$\frac{H^2}{H_0^2} = \frac{\Omega_{\rm r}}{a^4} + \frac{\Omega_{\rm M}}{a^3} + \Omega_{\rm DE}X(a)$$

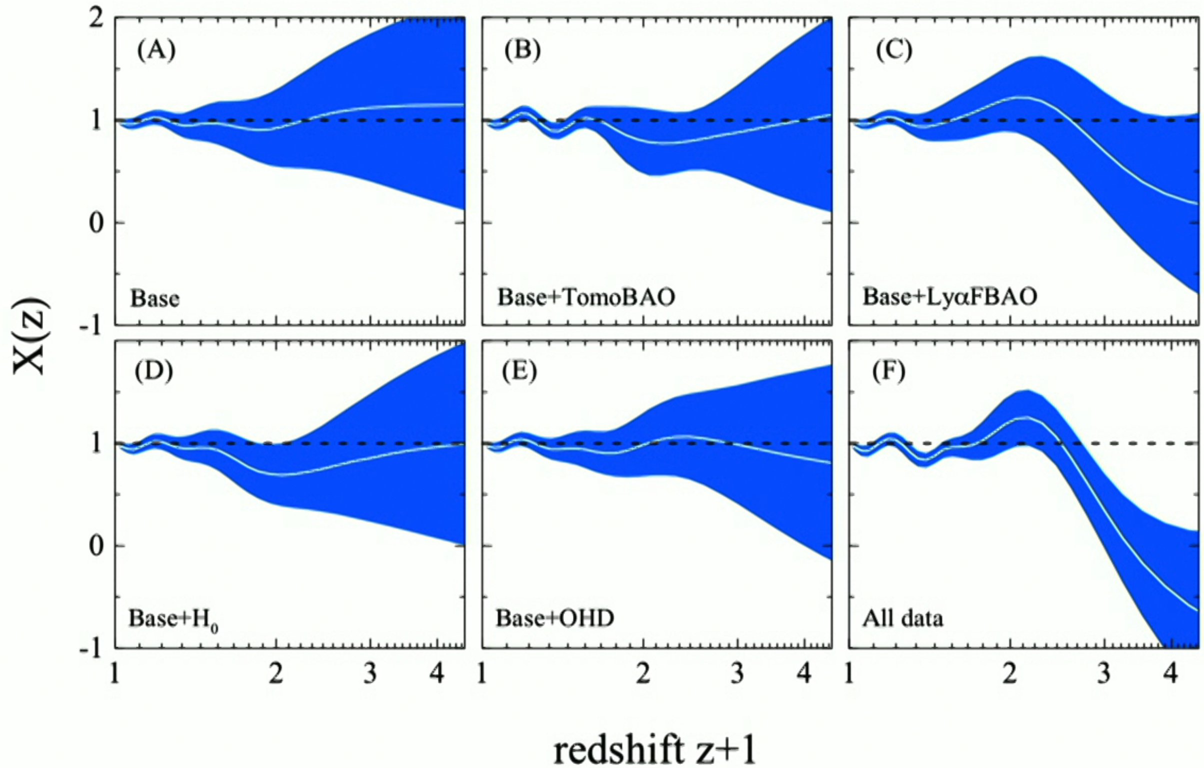
Reconstructed Effective Dark Energy Density



Y. Wang, G.-B. Zhao, LP and A. Zucca, 1807.03772, Ap J Lett

Reconstructed Dark Energy Density

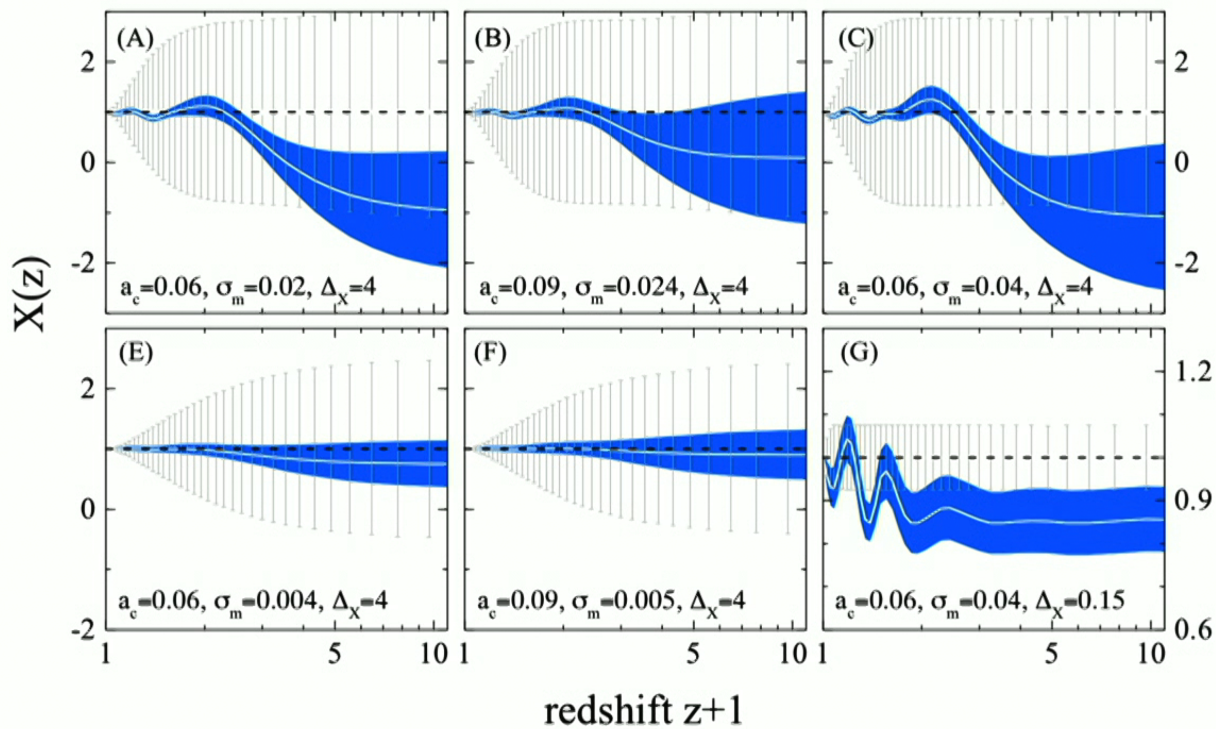
The effect of individual datasets



Y. Wang, G.-B. Zhao and LP, 1807.03772

Reconstructed Dark Energy Density

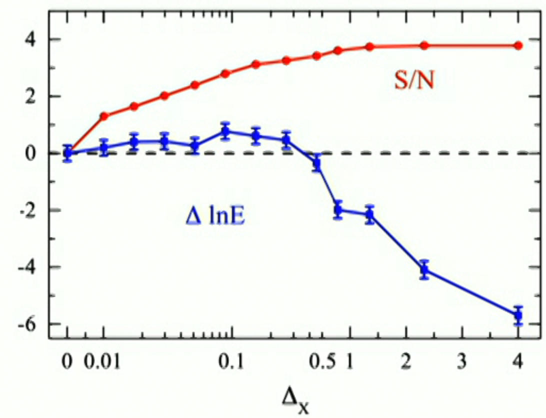
The effect of different priors

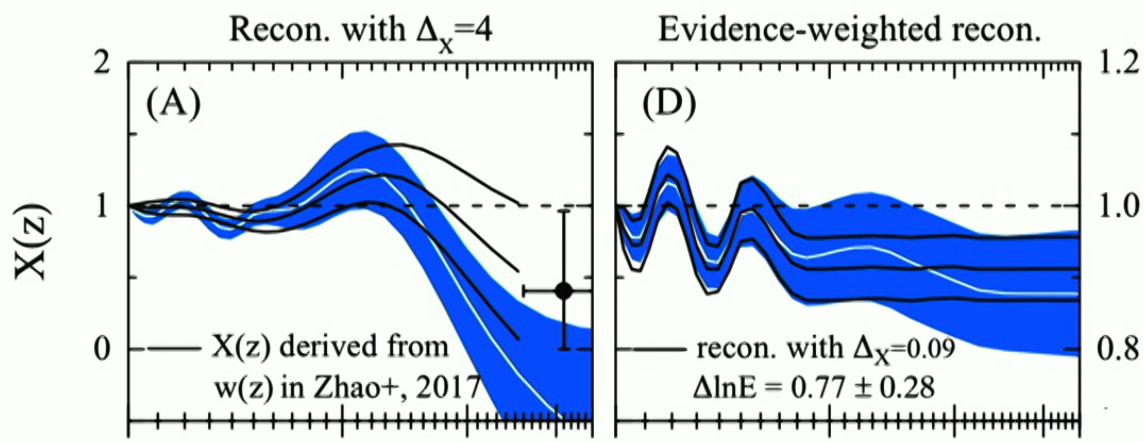


Y. Wang, G.-B. Zhao and LP, 1807.03772

Evidence weighted reconstruction

$$Z_W(z) \equiv \frac{\sum_i \left[Z(z; \Delta_{X_i}) e^{\Delta \ln \mathrm{E}(\Delta x_i)} \right]}{\sum_i \left[e^{\Delta \ln \mathrm{E}(\Delta x_i)} \right]}$$

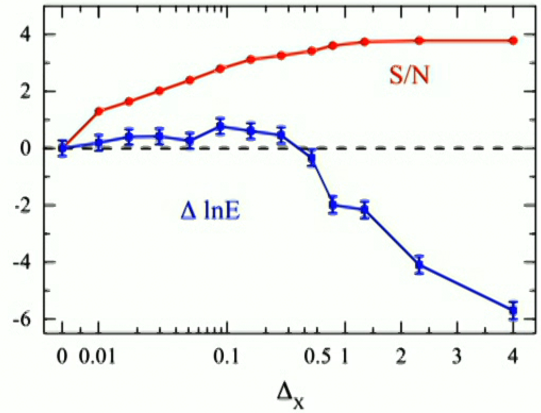


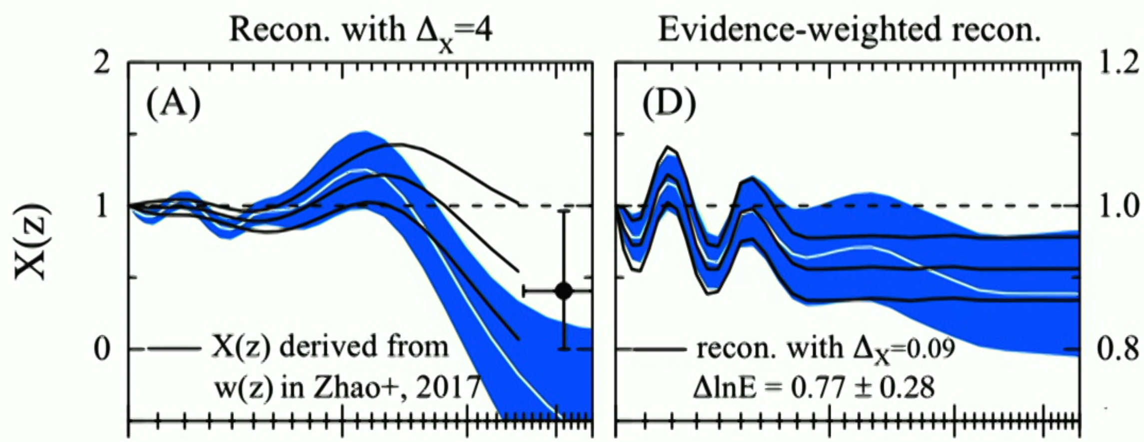


Y. Wang, G.-B. Zhao and LP, 1807.03772

Evidence weighted reconstruction

$$Z_W(z) \equiv \frac{\sum_i \left[Z(z;\Delta_{X_i})e^{\Delta \ln \mathrm{E}(\Delta_{X_i})}\right]}{\sum_i \left[e^{\Delta \ln \mathrm{E}(\Delta_{X_i})}\right]}$$





Y. Wang, G.-B. Zhao and LP, 1807.03772

Dynamical Dark Energy?

- Dynamical dark energy resolves the tensions between the Planck best fit LCDM model and the local estimates of H_0
- Dynamical dark energy is preferred at a 3.7-sigma significance level based on the improvement in the fit alone
- Mild preference (but no Bayesian evidence) for an increasing dark energy density
- Small Bayesian evidence for oscillatory features at z<1, driven by BAO and SNIa data
- Future data (e.g. Euclid) can conclusively confirm or rule out the reconstructed dynamics of Dark Energy

Phenomenology of Scalar-Tensor Theories

Theories of Jordan-Brans-Dicke type, with a canonical kinetic term
(e.g. "chameleon", f(R), "symmetron")

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

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

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

Beyond probing the expansion history

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 the "fifth force"

Phenomenology of Scalar-Tensor Theories

General Relativity

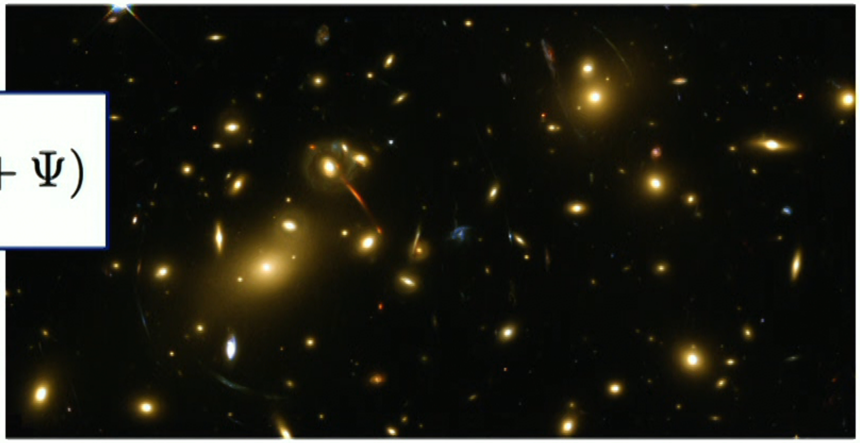
$$\begin{aligned} \Psi &= \Phi \\ -k^2\Phi &= -k^2\left(\frac{\Phi+\Psi}{2}\right) = 4\pi G a^2\delta\rho \end{aligned}$$

Modified Gravity

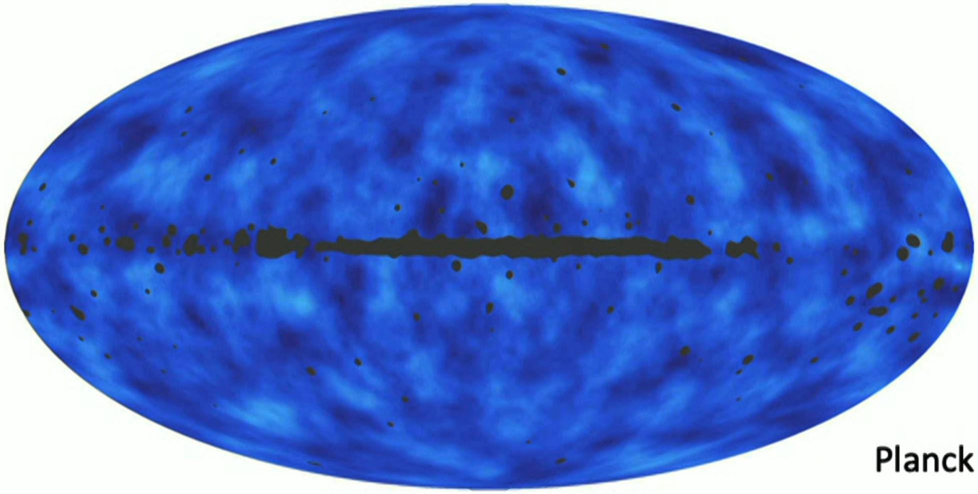
$$\begin{aligned} -k^2\Psi &= 4\pi\ \mu(a,k)G\ a^2\delta\rho \\ \Phi &= \gamma(a,k)\ \Psi \\ -k^2\left(\frac{\Phi+\Psi}{2}\right) &= 4\pi\ \Sigma(a,k)G\ a^2\delta\rho \end{aligned}$$

Gravitational Lensing

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



Hubble



Planck

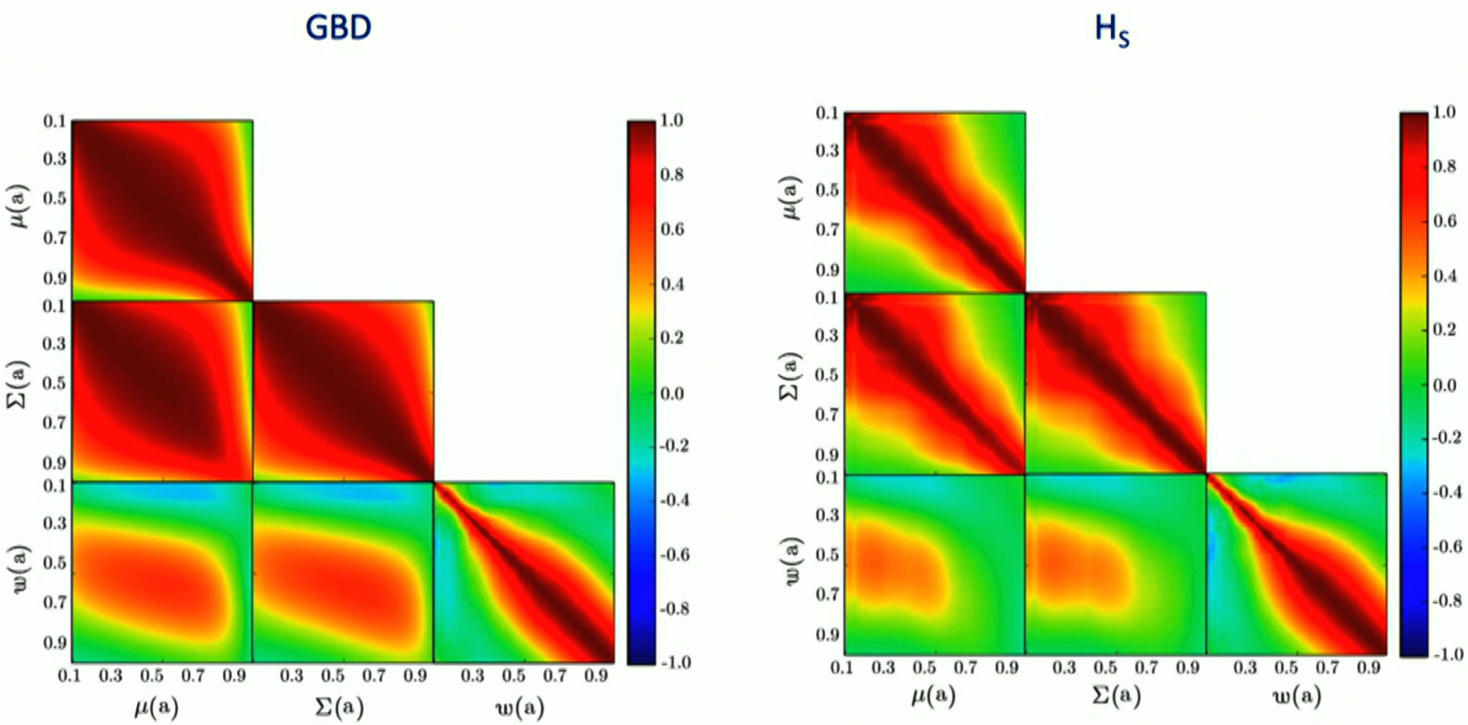
Phenomenology of Horndeski

$$S = \int d^4x \sqrt{-g} \left\{ \frac{m_0^2}{2}\Omega(t) R + \Lambda(t) - c(t)\delta g^{00} + \frac{M_2^4(t)}{2}(\delta g^{00})^2 - \frac{\bar{M}_1^3(t)}{2}\delta g^{00}\delta K^i{}_i - \frac{\bar{M}_2^2(t)}{2}\left(\delta K^i{}_i{}^2 - \delta K^i{}_j \delta K^j{}_i + 2\delta g^{00}\delta R^{(3)}\right) \right\} + S_{matter}[g_{\mu\nu}]$$

- Generate an ensemble of EFT functions
  - Parameterize the EFT functions as Pade polynomials (9th order)
  - Sample the coefficients, filter out unphysical solutions
- Filter out models with
  - unacceptable background expansion histories
  - unacceptable gravitational wave speed
  - unacceptable variations of the Newton's constant

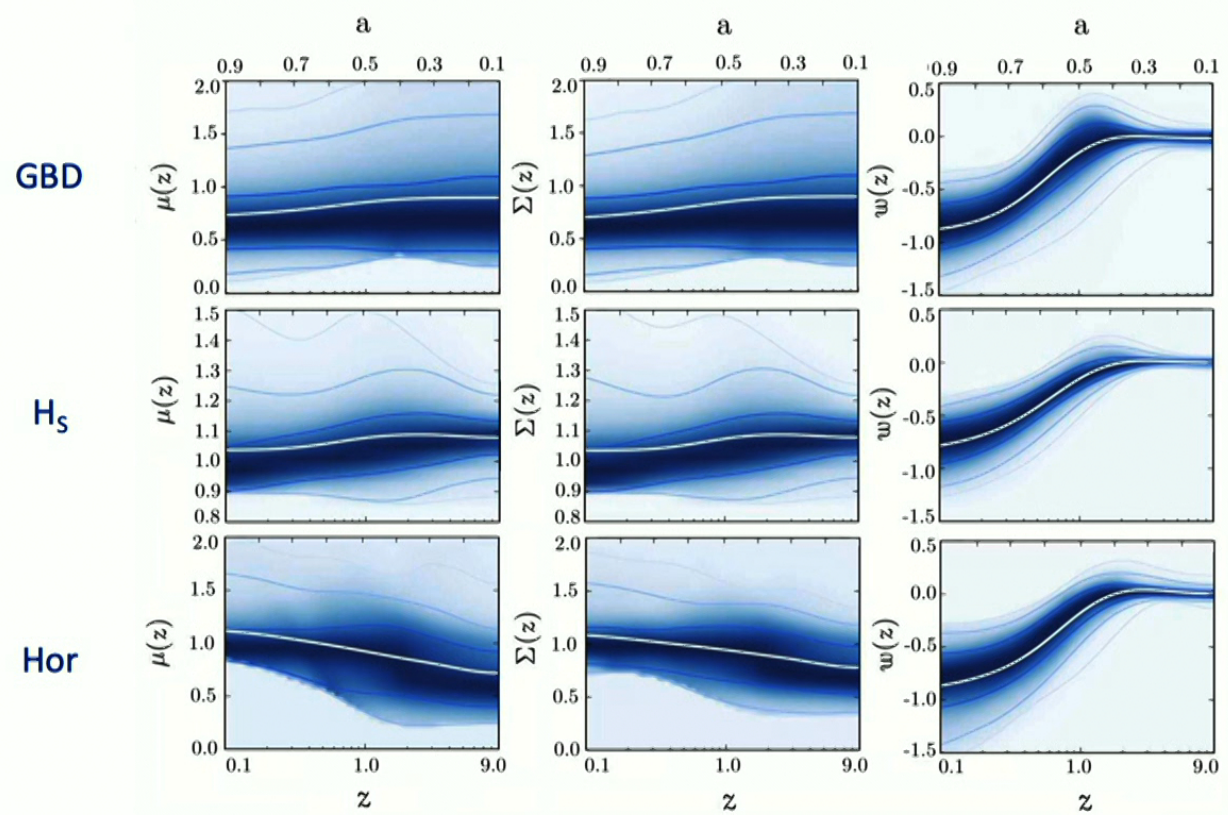
J. Espejo, S. Peirone, M. Raveri, LP, A. Silvestri, K. Koyama, arXiv:1809.01121

Prior Correlations (theories with c_T=1)



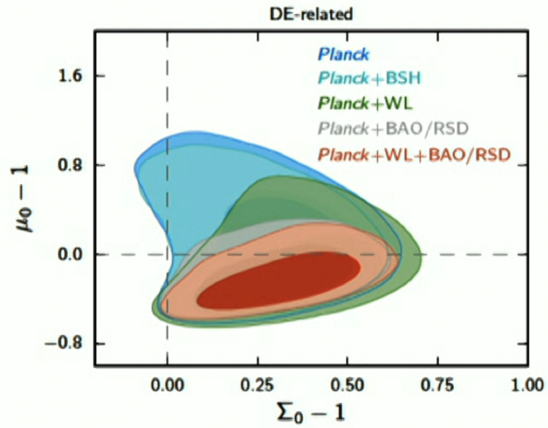
J. Espejo, S. Peirone, M. Raveri, LP, A. Silvestri, K. Koyama, arXiv:1809.01121

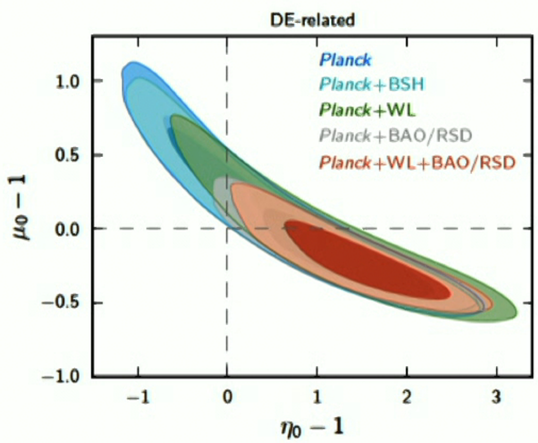
Prior mean and the variance

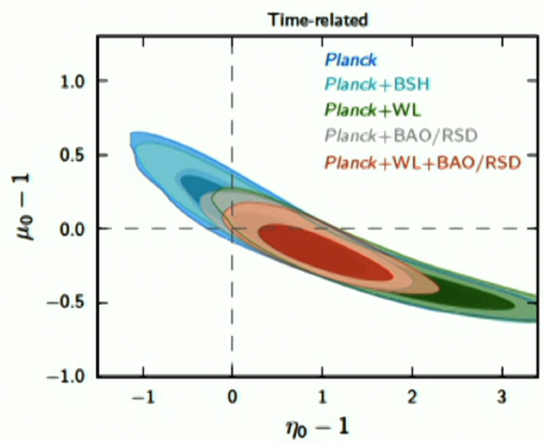


J. Espejo, S. Peirone, M. Raveri, LP, A. Silvestri, K. Koyama, arXiv:1809.01121

Planck 2015 results. XIV. Dark energy and modified gravity







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Beyond probing the expansion history