Title: Observational constraints on modified gravity and dark energy

Speakers: Jian Li

Collection: Everpresent Lambda: Theory Meets Observations

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SFU

COSMOLOGICAL TESTS OF GRAVITY AND DARK ENERGY

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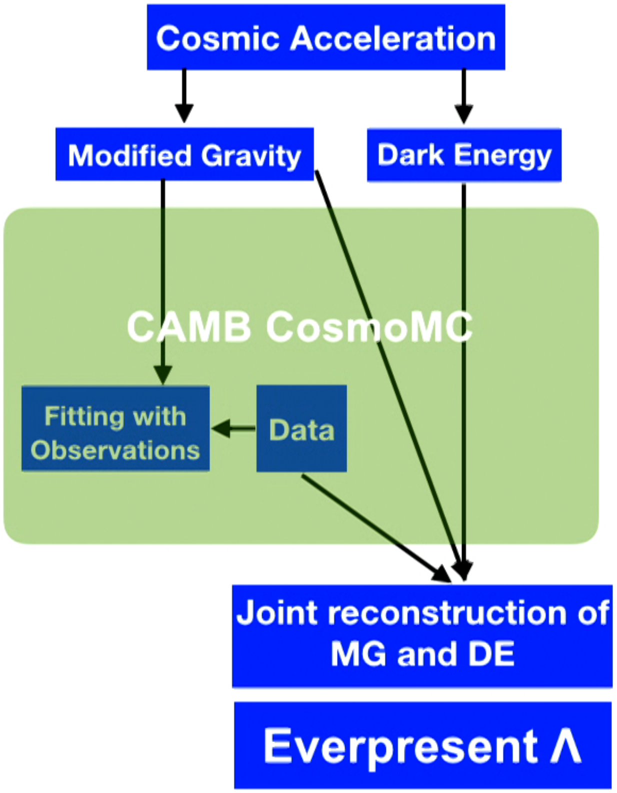
Everpresent Λ: Theory meets Observations
Perimeter, 2019

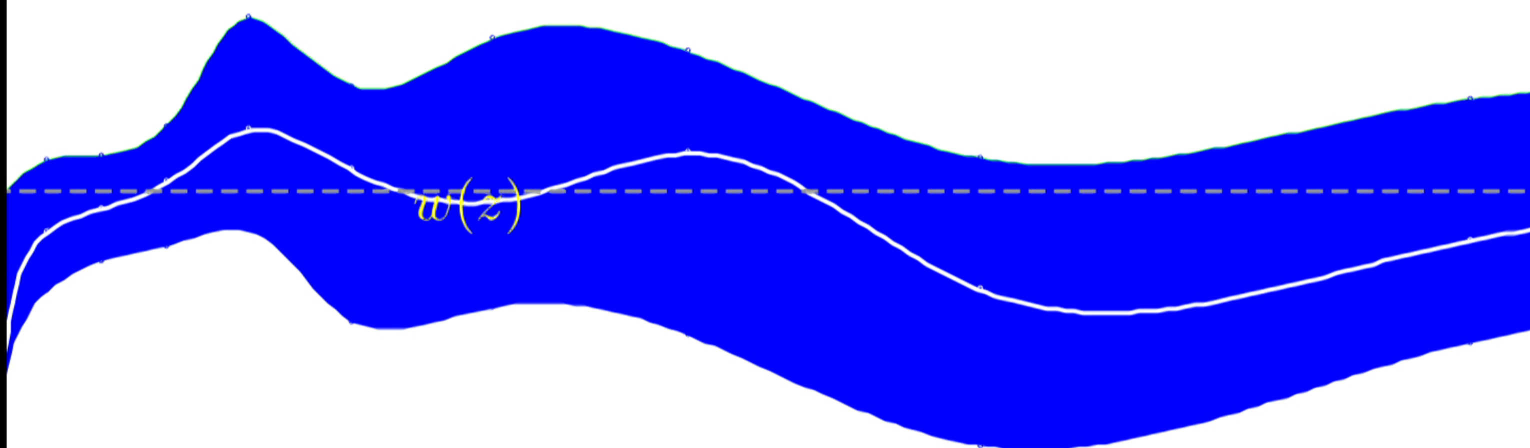
OUTLINE

- A brief introduction to CAMB and CosmoMC
  - Key diagnostics of modified gravity (MG) and dark energy (DE)
  - MG and DE using CAMB, CosmoMC
- How do we probe gravity and dark energy with observations?
  - Fitting observational data with MG models
  - Theory + Observation: Reconstruction of DE and MG from observations
- What is needed for Everpresent Λ



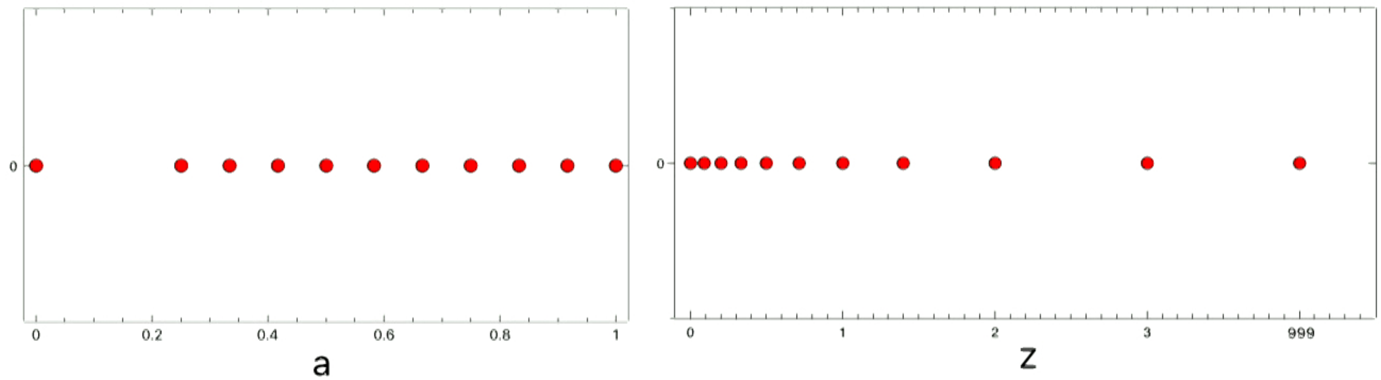
HOW DO WE PROBE GRAVITY AND DARK ENERGY FROM OBSERVATIONS?

- Fitting observational data with MG parameters
- Theory + observation: Reconstruction of dark energy and modified gravity from observations



NODES AND INTERPOLATION

- 11 nodes, starts at z=999 (a =0.001); uniform in "a" after z = 3 (a = 0.25)
- At each node i, there is a { Σ_i, μ_i. w_i } (i=1,2,…,11)



- Interpolation function: Lagrange Polynomial of order 3 — tested to be very accurate.

COMPARISON AMONG DIFFERENT INTERPOLATIONS

- Interpolation function: Lagrange Polynomial of order 3

$$P_j(x) = \prod_{\substack{n=1 \\ (n \neq j)}}^{N} \frac{x - x_n}{x_j - x_n}$$

- Cubic spline, bins: less accurate

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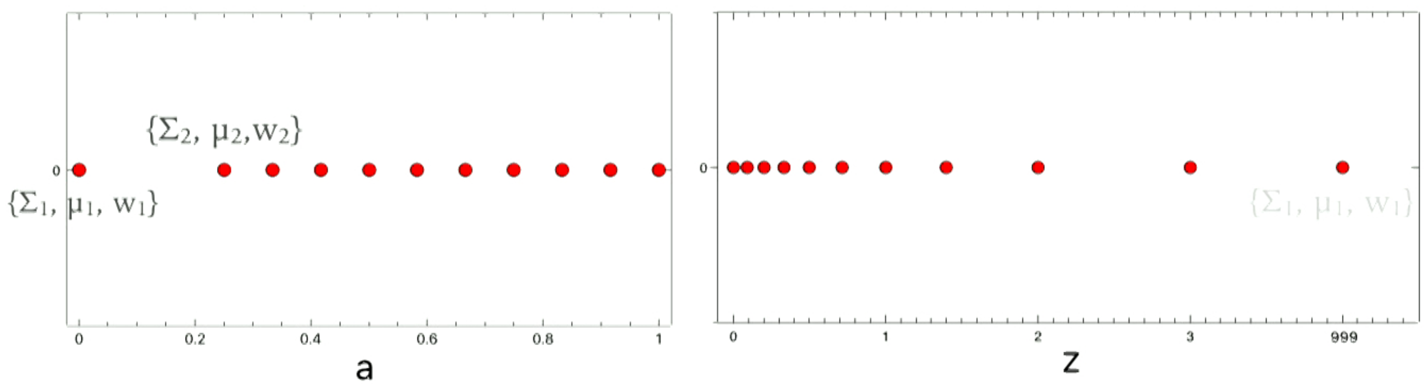

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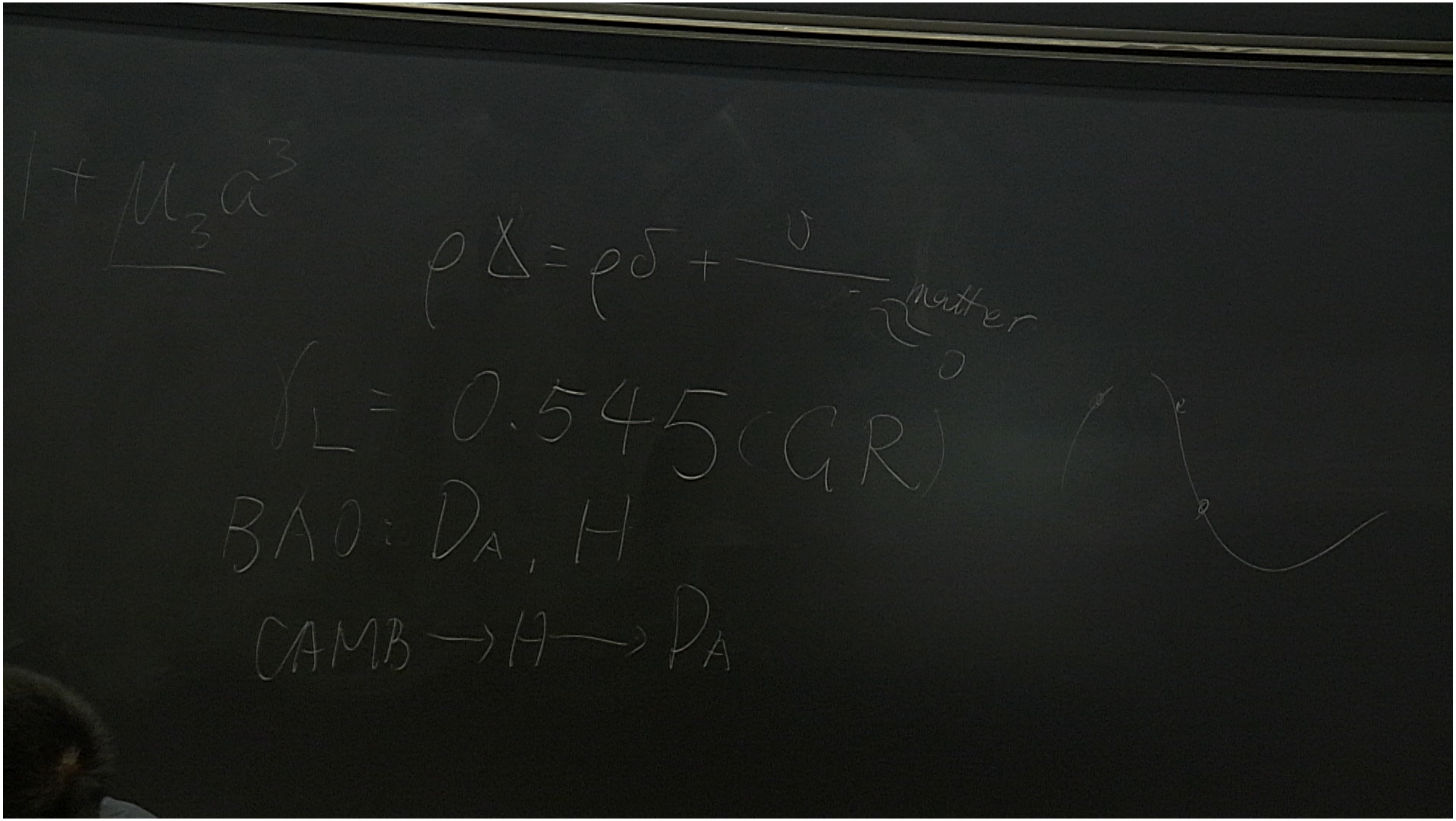
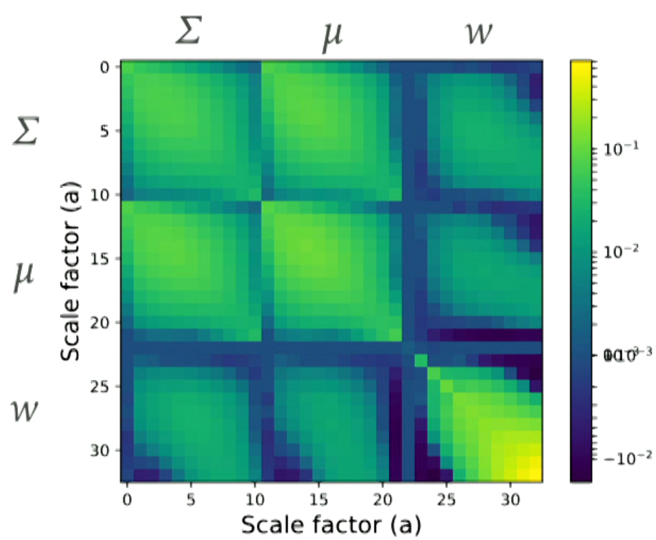

1 + u3 a3
ρΔ = ρδ +
matter
γL = 0.545 (GR)
BAO: DA, H
CAMB → H → DA

METHODOLOGY

- 11*3=33 parameters added to ΛCDM
- $\chi^2 = \chi^2_{theory} + \chi^2_{data}$

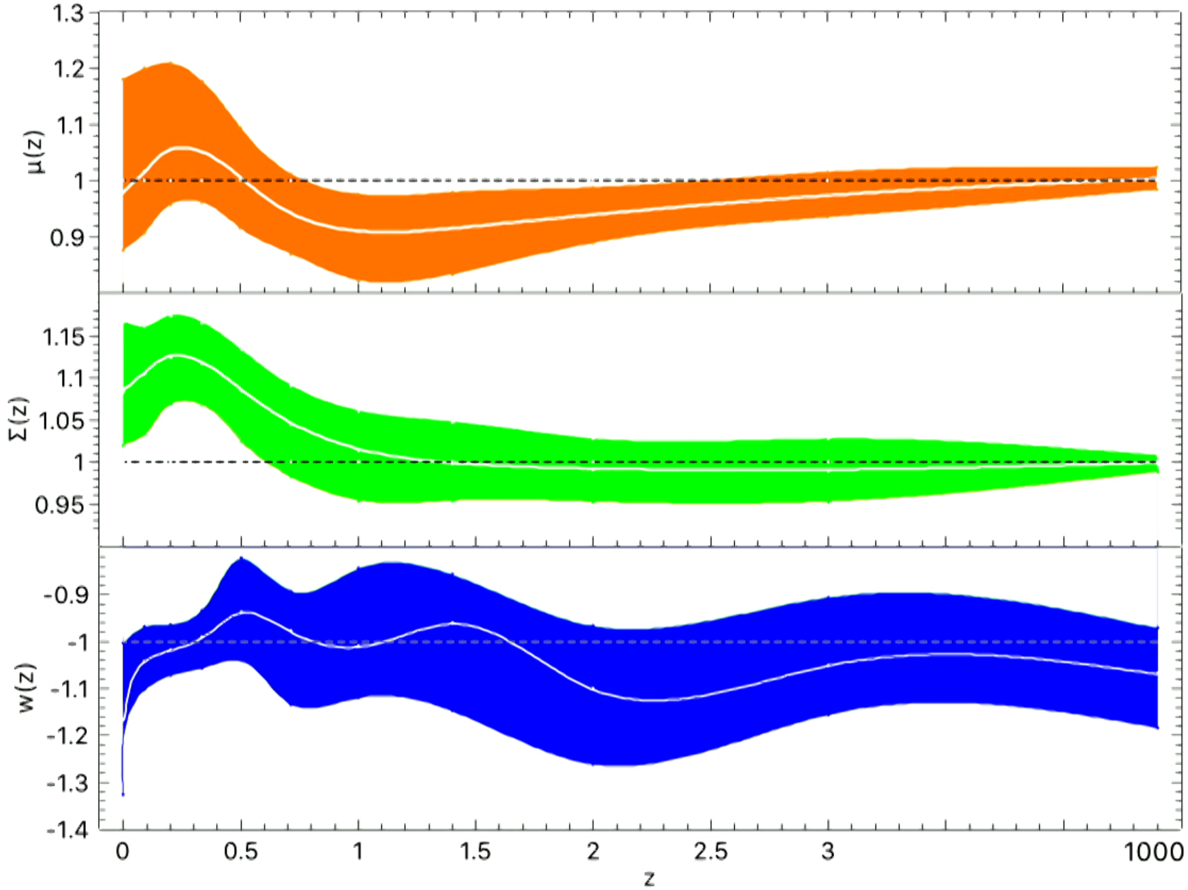
DATA 1: THEORETICAL PRIOR COVARIANCE

- Generate ensembles of Horndeski models
- Solve EoM to find 10^4 sets of { Σ(a), μ(a), w(a) }
- Find joint prior covariance for nodes of { Σ(a), μ(a), w(a) }



Espjo et al, PRD(2019)

PRELIMINARY RESULT



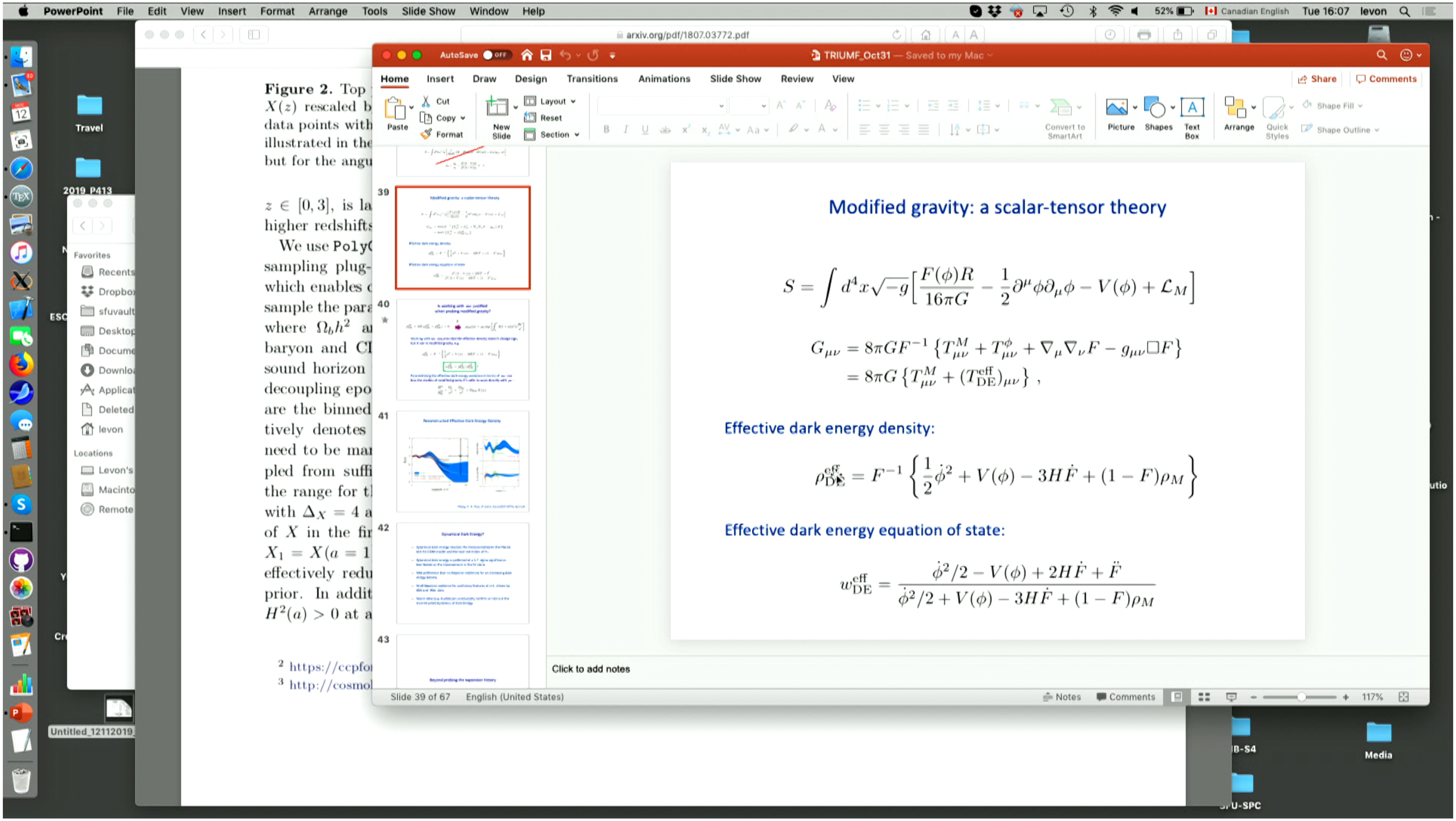
WHAT IS NEEDED FOR EVERPRESENT Λ

- For Everpresent Λ, to construct it, the covariance/correlation of w(a) or X(a) is needed.

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

$$X(z) = Exp\,[3\int_0^z \frac{1+w(z)}{1+z} dz]$$

Thank you! Questions?


Modified gravity: a scalar-tensor theory
$S = \int d^4x\sqrt{-g}\left[\frac{F(\phi)R}{16\pi G} - \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi) + \mathcal{L}_M\right]$
$G_{\mu\nu} = 8\pi G F^{-1}\left\{T^M_{\mu\nu} + T^\phi_{\mu\nu} + \nabla_\mu\nabla_\nu F - g_{\mu\nu}\Box F\right\}$
$= 8\pi G\left\{T^M_{\mu\nu} + (T^{\rm eff}_{\rm DE})_{\mu\nu}\right\}$,
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:
$w^{\rm eff}_{\rm DE} = \frac{\dot\phi^2/2 - V(\phi) + 2H\dot F + \ddot F}{\dot\phi^2/2 + V(\phi) - 3H\dot F + (1-F)\rho_M}$
TRIUMF_Oct31 — Saved to my Mac
Click to add notes
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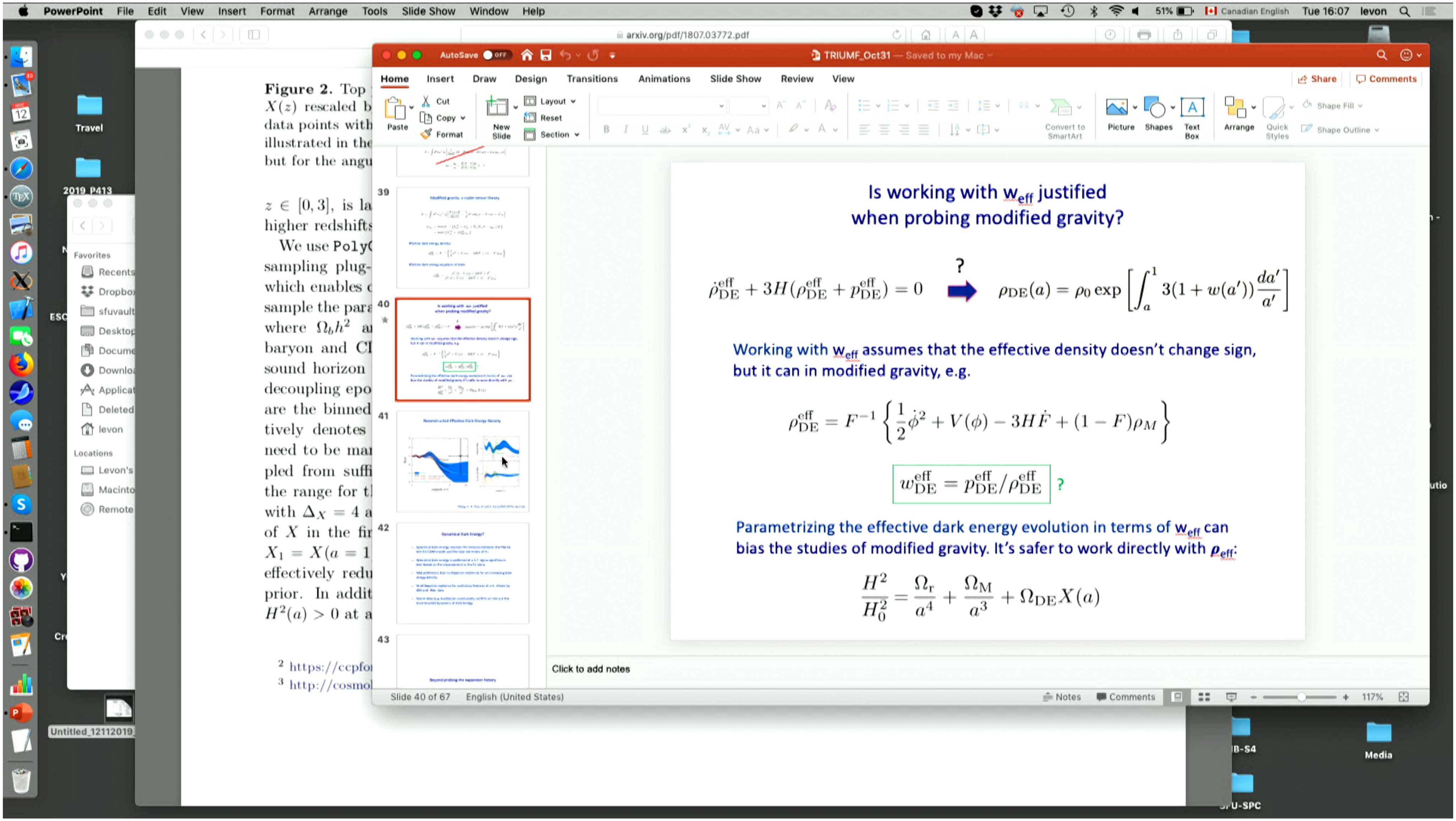
English (United States)
arxiv.org/pdf/1807.03772.pdf


Is working with w_eff justified
when probing modified gravity?
$\dot\rho_{\rm DE}^{\rm eff} + 3H(\rho_{\rm DE}^{\rm eff} + p_{\rm DE}^{\rm eff}) = 0$? $\rho_{\rm DE}(a) = \rho_0 \exp\left[\int_a^1 3(1+w(a'))\frac{da'}{a'}\right]$
Working with w_eff assumes that the effective density doesn't change sign,
but it can in modified gravity, e.g.
$\rho_{\rm DE}^{\rm eff} = F^{-1}\left\{\frac{1}{2}\dot\phi^2 + V(\phi) - 3H\dot F + (1-F)\rho_M\right\}$
$w_{\rm DE}^{\rm eff} = p_{\rm DE}^{\rm eff}/\rho_{\rm DE}^{\rm eff}$?
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:
$\frac{H^2}{H_0^2} = \frac{\Omega_r}{a^4} + \frac{\Omega_M}{a^3} + \Omega_{\rm DE}X(a)$
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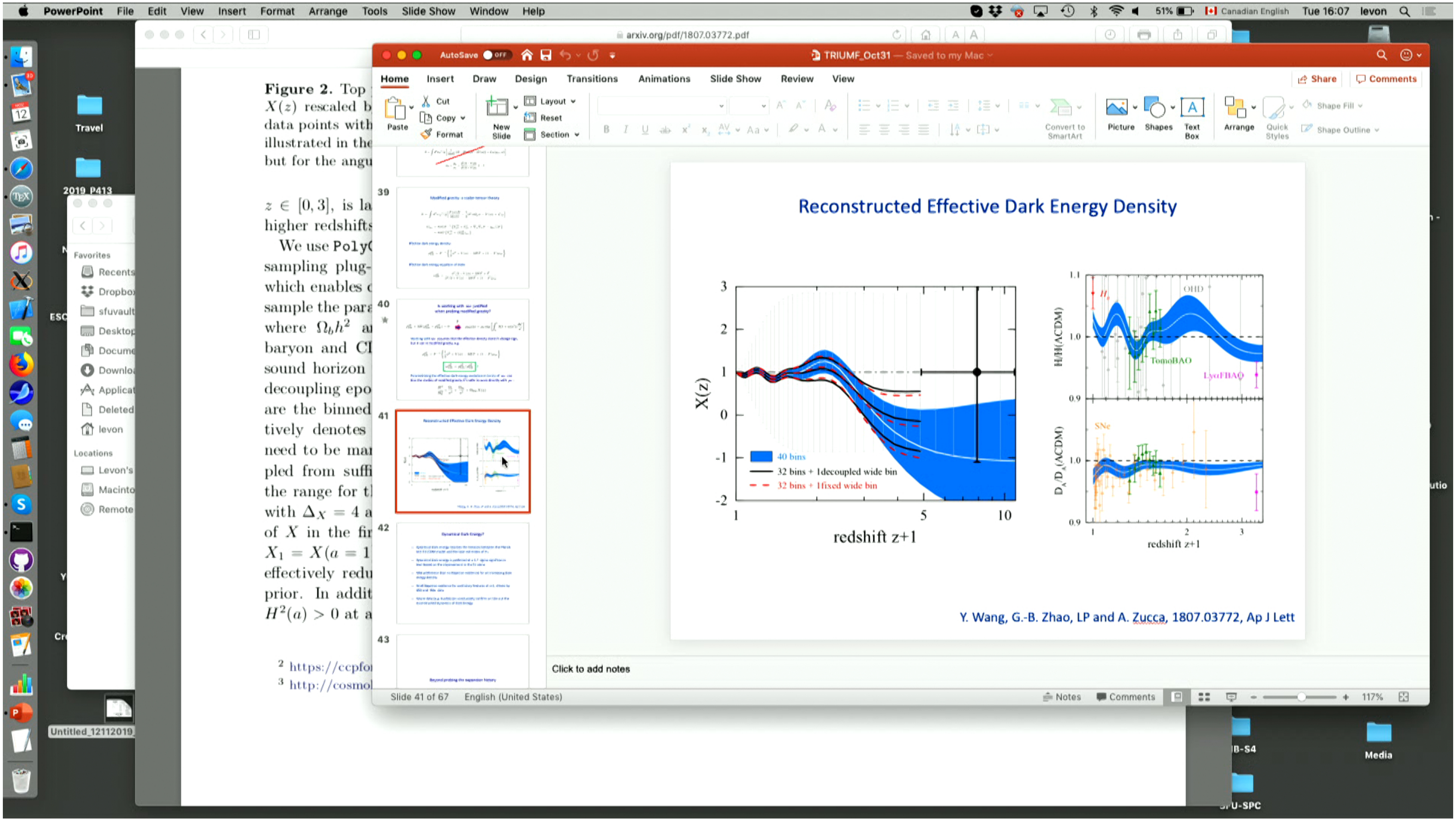
Reconstructed Effective Dark Energy Density
X(z)
redshift z+1
40 bins
32 bins + 1decoupled wide bin
32 bins + 1fixed wide bin
H/H(ΛCDM)
OHD
TomoBAO
LyαFBAO
SNe
redshift z+1
Y. Wang, G.-B. Zhao, LP and A. Zucca, 1807.03772, Ap J Lett
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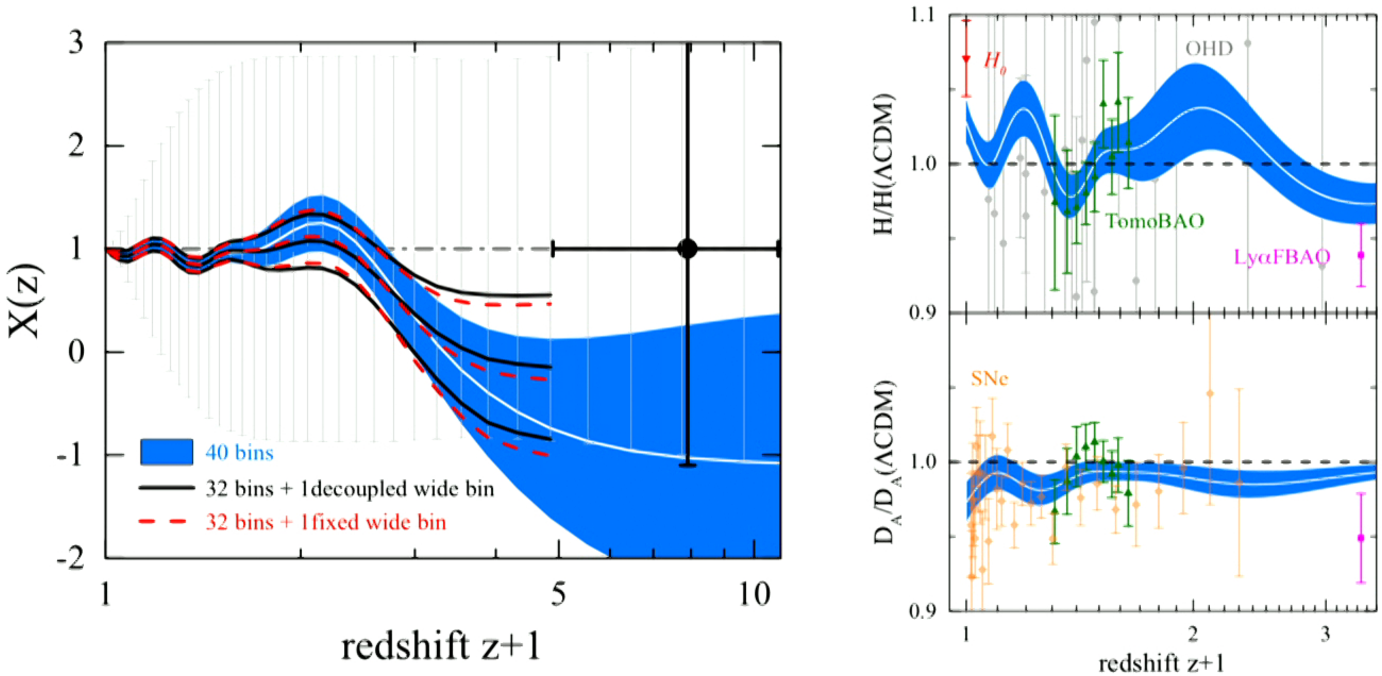
Reconstructed Effective Dark Energy Density



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

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ABSTRACT

We reconstruct evolution of the dark energy (DE) density using a nonparametric Bayesian approach from a combination of latest observational data. We caution against parameterizing DE in terms of its equation of state as it can be singular in modified gravity models, and using it introduces a bias preventing negative effective DE densities. We find a 3.7σ preference for an evolving effective DE density with interesting features. For example, it oscillates around the ΛCDM prediction at $z \lesssim 0.7$, and could be negative at $z \gtrsim 2.3$; dark energy can be pressure-less at multiple redshifts, and a short period of cosmic deceleration is allowed at $0.1 \lesssim z \lesssim 0.2$. We perform the reconstruction for several choices of the prior, as well as a evidence-weighted reconstruction. We find that some of the dynamical features, such as the oscillatory behaviour of the DE density, are supported by the Bayesian evidence, which is a first detection of a dynamical DE with a positive Bayesian evidence. The evidence-weighted reconstruction prefers a dynamical DE at a $(2.5 \pm 0.06)\sigma$ significance level.

Keywords: Cosmology: dark energy

1. INTRODUCTION

Since becoming the working model of cosmology following the discovery of cosmic acceleration (Riess et al. 1998; Perlmutter et al. 1999), the Λ Cold Dark Matter which is the framework for the present understanding of particle interactions.

The recent exquisite measurements of the CMB temperature and polarization by Planck (Planck Collaborahttps://arxiv.org/pdf/1807.03772.pdf

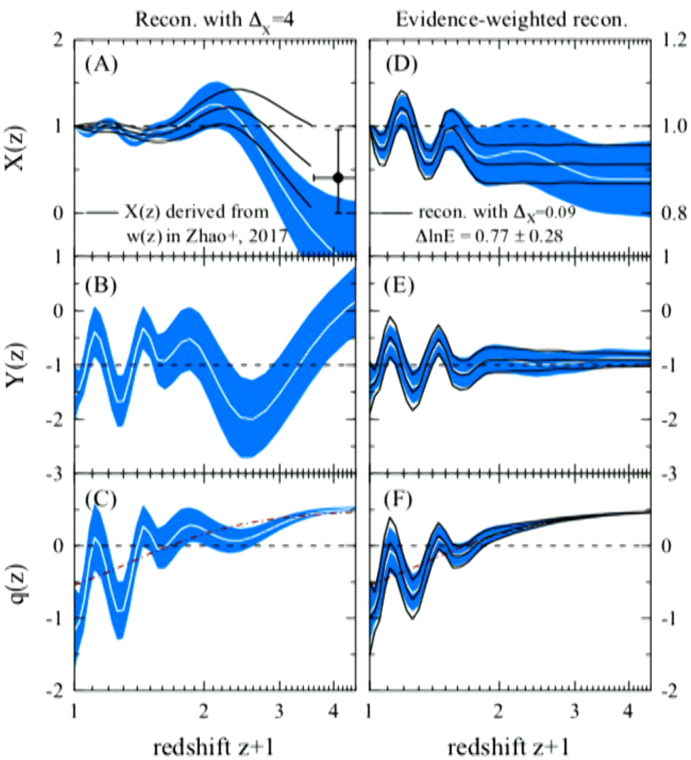

Figure 1. Panel (A): $X(z)$ (best-fit and 68% CL uncertainty) reconstructed using our standard correlated prior (blue filled band) compared to $X(z)$ derived from $w_{\rm DE}^{\rm eff}(z)$ reconstructed in (Zhao et al. 2017) (black curves and a data point with error bars); Panel (B): the reconstructed effective DE pressure $Y(z) = P_{\rm DE}^{\rm eff}(z)/\rho_c^{\rm eff}(0)$; Panel (C): the recon-

struction results. If X_i were assumed to be independent, fitting them to data would yield large uncertainties, rendering the reconstruction useless. Moreover, treating the bins as completely independent is an unreasonably strong assumption as, in any specific theory, the effective DE density would be correlated at nearby points in a. Motivated by these considerations, we use the method of (Crittenden et al. 2012, 2009) and introduce a prior that correlates the neighbouring bins. Specifically, we take $X(a)$ to be a Gaussian random variable with a given correlation ξ between its values at a and a', *i.e.*, $\xi(|a-a'|) \equiv \langle [X(a) - X^{\rm fid}(a)][X(a') - X^{\rm fid}(a')] \rangle$. Here, $X^{\rm fid}(a)$ is a reference fiducial model, and the correlation function ξ is chosen so that it is nonzero for $|a-a'|$ below a given "correlation length" a_c, and approaches zero at larger separations. We adopt the CPZ form (Crittenden et al. 2012, 2009) for the correlation, namely, $\xi(|a-a'|) = \xi(0)/[1 + (|a-a'|/a_c)^2]$, where $\xi(0)$ sets the strength of the prior. The latter can be related to the expected variance in the mean value of X as $\sigma_m^2 \simeq \pi\xi(0)a_c/(a_{\rm max} - a_{\rm min})$. In practice, we set σ_m and a_c, and derive the corresponding $\xi(0)$.

As our "standard" working prior we adopt $a_c = 0.06$ and $\sigma_m = 0.04$, which were the values used in (Zhao et al. 2017) to reconstruct $w_{\rm DE}(a)$. Their physical meaning is, of course, different, as $w_{\rm DE}$ and X are related

Table 2. The best-fit values and the 68% CL uncertainties of cosmological parameters in the ΛCDM and XCDM models.

	ΛCDM	XCDM
$\Omega_b h^2$	0.0224 ± 0.00013	0.0223 ± 0.00016
$\Omega_c h^2$	0.1189 ± 0.00087	0.1203 ± 0.00141
Θ_s	1.0412 ± 0.00029	1.0411 ± 0.00032
$X(z=0.08)$	1	0.926 ± 0.056
$X(z=0.18)$	1	1.042 ± 0.062
$X(z=0.39)$	1	0.835 ± 0.068
$X(z=1.16)$	1	1.251 ± 0.282
$X(z=2.24)$	1	0.076 ± 0.438
$\Omega_{\rm M}$	0.302 ± 0.005	0.288 ± 0.008
$H_0[{\rm kms^{-1}Mpc^{-1}}]$	68.41 ± 0.387	70.30 ± 0.998

SNe by 4.9, 4.3, 4.1 and 4.1 respectively, meaning that it is these datasets that contribute the most to the features in X.

In Fig. 1, in addition to X, we show the normalized effective DE pressure, $Y(z) \equiv P_{\rm DE}^{\rm eff}(z)/\rho_{\rm DE}^{\rm eff}(0)$[5] derived via $Y = -X + \frac{1}{3}{\rm d}X/{\rm d}z(1+z)$, and the deceleration parameter, $q(z)$. As shown in panel (B), $Y(z)$ oscillates around the ΛCDM prediction of -1, and, interestingly, DE is within $\sim 1\sigma$ of having zero pressure at $z \simeq 0.1, 0.5,$ 0.9 and $z \geq 3$. Panel (C) shows $q(z)$ oscillating around

climbing towards positive values as Δ_X increases, with a peak showing up at $\Delta_X \sim 0.1$, and drops below zero for $\Delta_X \gtrsim 0.4$. This motivates us to consider an evidence-weighted reconstruction, which linearly combines reconstructions with different Δ_X, weighted by the Bayesian evidence, *i.e.*,

$$Z_W(z) \equiv \frac{\sum_i \left[Z(z;\Delta_{X_i}) e^{\Delta \ln {\rm E}(\Delta_{X_i})}\right]}{\sum_i \left[e^{\Delta \ln {\rm E}(\Delta_{X_i})}\right]} \qquad (2)$$

where $Z = X, Y, q$. The evidence-weighted reconstructions are shown in panels (D-F) of Fig. 1. They retain the key features of the best-fit XCDM shown in panels (A-C), but at a lesser significance. In particular, the overall significance of the deviation from ΛCDM reduces to $(2.5 \pm 0.06)\sigma$. Panels (D-F) show the the results for $\Delta_X = 0.09$, which corresponds to the maximal Bayesian evidence $\Delta{\rm lnE} = 0.77 \pm 0.28$. We find them to be quite similar, as expected, since the linear combination in the evidence-weighted reconstruction is dominated by the component with maximal weight.

4. CONCLUSION AND DISCUSSIONS

Different levels of tension among various kinds of observations within the framework of ΛCDM necessitates the exploration of extended cosmological models beyond ΛCDM. As was shown in an earlier study (Zhao et al.