JOINT RECONSTRUCTIONS OF GROWTH AND EXPANSION HISTORIES FROM STAGE-IV SURVEYS

Rodrigo CALDERÓN

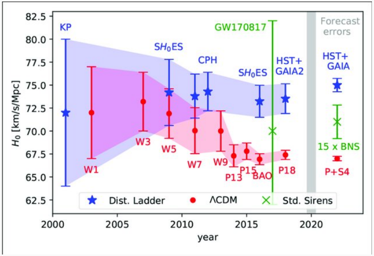
June 13, 2023 - Interactions between Particle Physics and Cosmology XVI

Postdoc at the Korea Astronomy and Space Science Institute (KASI)

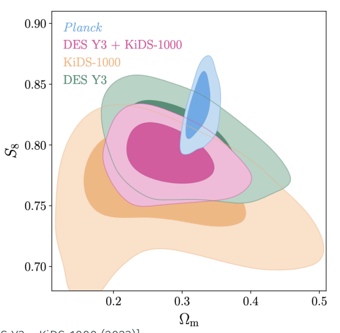
Based on: Phys. Rev. D (2022) 8, 083513 and 2301.00640 (To appear in PRD)

In Collab. with: B. L'Huillier, D. Polarski, A. Shafieloo, A. A. Starobinsky

THE CONCORDANCE MODEL AND ITS LIMITATIONS



[Ezquiaga & Zumalacárregui (2018)]



[DES Y3 + KiDS-1000 (2023)]

Shortcomings:

- Smallness of Λ (> 0)
- Dark Matter: Cold / Warm, (Self) Interacting, PBH
- H_0 / S_8-tensions
- Small-scale Issues: Core-Cusp, Satellite

Solutions:

- Systematics ?
- New Physics ?
- Both ?

“Model-independent” approach

THE SURVEY: DESI

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Figure: Dark Energy Spectroscopic Instrument (DESI)

- Large-Scale Structure survey @ Mayall (4m) Telescope (Kitt-Peak, Arizona)
- Observe 30 Million galaxies (obtain accurate redshift estimates)
- Accurate distance estimations!
- Probe the last 11 Million years of the growth of structure and expansion history

METHOD: GAUSSIAN PROCESS

GAUSSIAN PROCESS (GP) REGRESSION

"A collection of random (stochastic) variables, any finite number of which follows a (multivariate) Gaussian distribution..."

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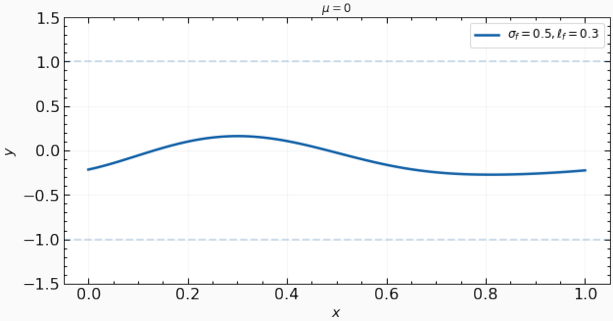
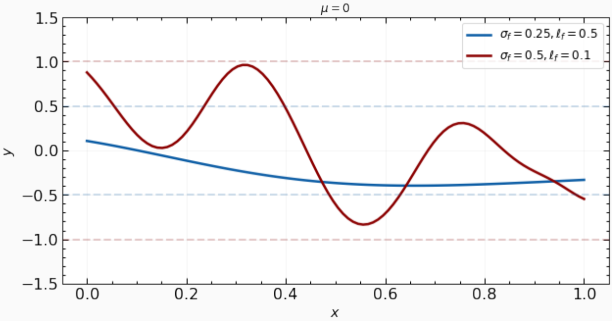
Sampling directly in the space of (continuous) functions!

$$y(x) \sim \mathcal{GP}(\mu = 0, k(\sigma_f = 0.5, \ell_f = 0.3))$$



PRIOR SAMPLING FROM A GP

$$y(x) \sim \mathcal{GP}(\mu = 0, k(\sigma_f, \ell_f))$$



METHOD: ANALYSIS

- (Flat) FLRW metric + Matter Dominated (EdS) Universe at high-z.

GOAL: RECONSTRUCT DE WITH MINIMAL ASSUMPTIONS

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- The Data:

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- The Data:
    - Baryon Acoustic Oscillations (**BAO**) - *DESI* $(14\mathrm{K}\,\mathrm{deg}^2)$ survey :

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    - Transversal : $d_A(z)/r_s(z_d)$ $\quad r_s$: "sound horizon"

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    - Radial : $H(z)r_s(z_d)$

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    - Transversal : $d_A(z)/r_s(z_d)$ r_s : "sound horizon"
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  - Redshift-Space Distortions (**RSD**) - *DESI* $(14\mathrm{K}\,\mathrm{deg}^2)$ survey :

$$f\sigma_8(z) \equiv f(z)\,\delta(z)\,\frac{\sigma_{8,0}}{\delta(z=0)}\ , \quad \sigma_{8,0}^{\mathrm{fid}} = 0.81.$$

$$\delta \equiv \frac{\rho(x,t)-\bar{\rho}}{\bar{\rho}}\ , \ f \equiv \frac{\delta\prime}{\delta}$$

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- Jointly reconstruct Growth and Expansion histories

$$\boxed{\ddot{\delta} + 2H\dot{\delta} = 4\pi\, G_{\mathrm{eff}}(z)\,\rho\,\delta}$$

Model $f_{\rm DE} \equiv \frac{\rho_{\rm DE}(z)}{\rho_{\rm DE,0}} \sim \mathcal{GP}(\mu = 1, K(\sigma_f, \ell_f))$

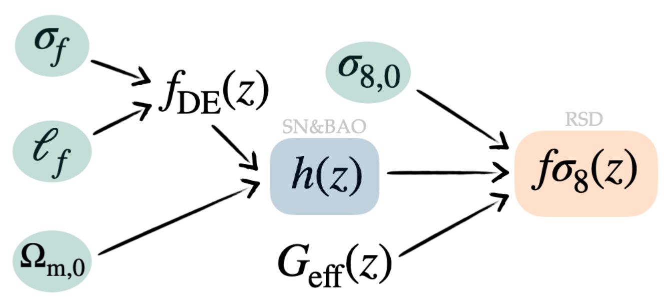

Figure: Schematic representation of our reconstruction method

$\longrightarrow$ Sample $\theta = \{\Omega_m, \sigma_8, \sigma_f, \ell_f\}$ using MCMC methods!

$$\chi^2_{\rm tot} = \chi^2_{\rm SN} + \chi^2_{\rm BAO} + \chi^2_{\rm RSD}$$

RESULTS: GR

RECONSTRUCTING $f_{\mathrm{de}}(z)$

$$h^2(z) = \Omega_{m,0}(1+z)^3 + (1-\Omega_{m,0}) \cdot f_{\mathrm{DE}}(z)$$

$$f_{\mathrm{DE}} \sim \mathcal{GP}(\mu = 1, K(\sigma_f, \ell_f))$$

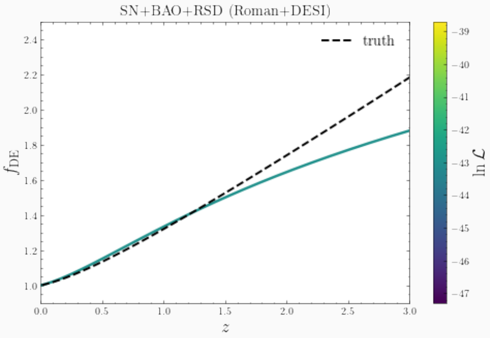

Figure: Samples of f_{DE} and their likelihood to DESI+Roman-like (mock) data

Minimal Assumptions:

- $f_{\mathrm{DE}} \equiv$ DE+any additional (exotic) component!
- (Flat) FLRW + EdS (+ GR)

$\longrightarrow$ With given $h(z)$, can solve for the growth-rate $f\sigma_8$:

$$f' + \left(f + 2 + \frac{h'}{h}\right) f - \frac{3}{2}\Omega_m = 0$$

$$f \equiv \delta'/\delta, \; ' \equiv \frac{d}{d\ln a}$$

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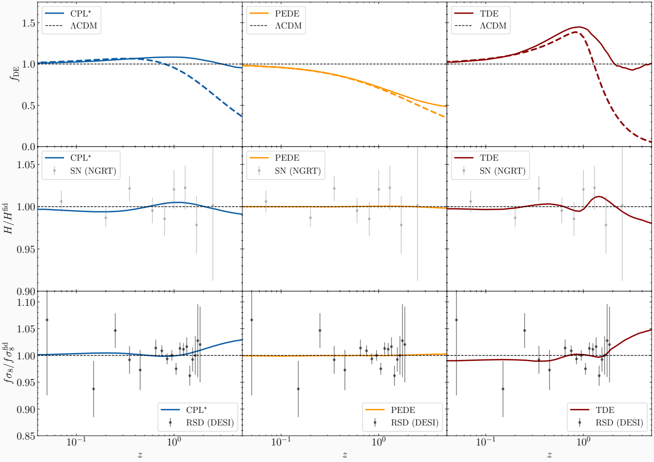


Figure: Reconstruction of *3 different* fiducial DE models (at 95% CL) using SN+BAO+RSD forecasted (Stage-IV) data

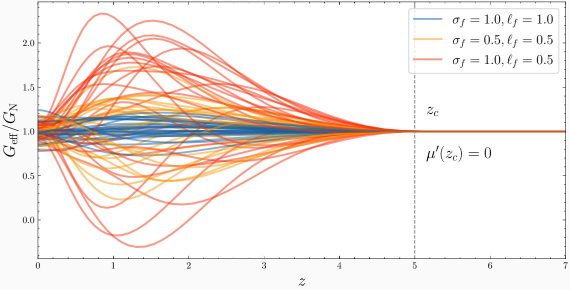
BEYOND GENERAL RELATIVITY

$$-\frac{k^2}{a^2}\Phi = 4\pi G_{\rm eff}(z,k)\delta\rho_m$$

We model $G_{\rm eff}(z)$ as a GP centered around Newton's constant G, such that $\mu(z) \equiv G_{\rm eff}/G$

$$\mu(z;\sigma_f,\ell_f,z_c) = \begin{cases} \mathcal{GP}(\bar{f}=1, k(\sigma_f,\ell_f)), & \text{for } z < z_c \\ 1, & \text{for } z \geq z_c. \end{cases} \quad (1)$$

with $\mu'(z_c) = 0$, so that we (smoothly) recover GR at large-z.



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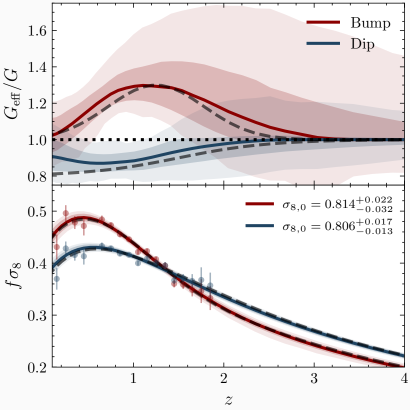

Figure: Reconstructions of $\mu \equiv G_{\rm eff}/G$ from RSD mocks, assuming $h(z)$ as determined by the SN+BAO chains.

We use the reconstructed expansion history $h(z)$ from the SN+BAO chains

$$f' + \left(f + 2 + \frac{h'}{h}\right) f = \frac{3}{2}\Omega_m \, \mu(z).$$

$\longrightarrow$ Sample $\theta = \{\sigma_8; \sigma_f, \ell_f, z_c\}$!

$$\sigma_{8,0}^{\rm fid} = 0.81$$

Two profiles, purely phenomenological "Toy-models"

Can represent a large class of models!

RECONSTRUCTING $\mu(z)$

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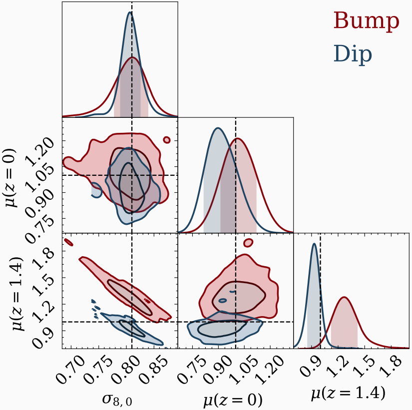

Figure: Reconstructions of $\mu \equiv G_{\rm eff}/G$ at two redshifts $z = 0, 1.4$, assuming $h(z)$ as determined by the SN+BAO chains.

We use the reconstructed expansion history $h(z)$ from the SN+BAO chains

$$f' + \left(f + 2 + \frac{h'}{h}\right) f = \frac{3}{2}\Omega_m \,\mu(z).$$

$\longrightarrow$ Sample $\theta = \{\sigma_8; \sigma_f, \ell_f, z_c\}$!

- Unbiased estimation of $\sigma_{8,0}$!
- At $z = 1.4$, DESI could distinguish the bump (in Red) from GR at $\gg 2\sigma$!

RECONSTRUCTING $\mu(z)$

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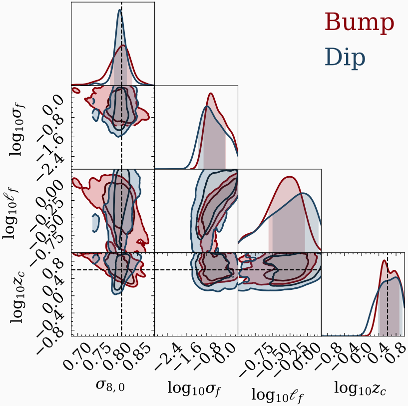

Figure: Constraints on cosmo+hyper parameters from RSD mocks, assuming $h(z)$ as determined by the SN+BAO chains.

We use the reconstructed expansion history $h(z)$ from the SN+BAO chains

$$f' + \left(f + 2 + \frac{h'}{h}\right) f = \frac{3}{2}\Omega_m \, \mu(z).$$

$\longrightarrow$ Sample $\theta = \{\sigma_8; \sigma_f, \ell_f, z_c\}$

The posteriors of the hyperparameters indicate the underlying theory of gravity is not consistent with GR ($\sigma_f \neq 0$)!

CONCLUSION

- "Model-independent" approach to **jointly** reconstruct both Growth & Expansion Histories with minimal assumptions
  - (Flat) FLRW + EdS
- **Accurately** reconstruct the Dark Energy evolution $f_{\rm DE}(z)$ & $G_{\rm eff}(z)$
- Unbiased estimation of cosmological parameters: Ω_m, σ_8
- Assuming Λ+GR can **severely bias** our interpretation of the results
- DESI+Roman-like can potentially detect deviations from Λ+GR
  - Euclid, Rubin (LSST), CMB-S4, + many more...

QUESTIONS?

DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

DESI is currently gathering data !
(already has more than all previous galaxy surveys combined)

$\longrightarrow$ Stay tuned!

`calderon@kasi.re.kr`

Thank you for your attention

BACKUP

$(\Omega_{m,0}, \sigma_{8,0})$ FREE - NO ASSUMPTIONS

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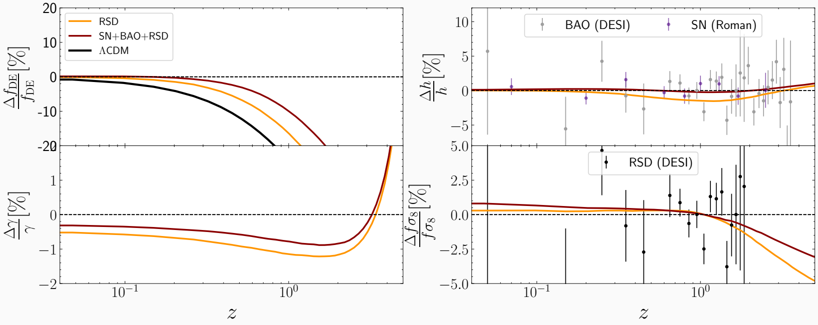

Figure: Reconstruction of background + perturbed quantities (at 68% CL) from various Stage-IV surveys. Marginalized over Ω_m and σ_8.

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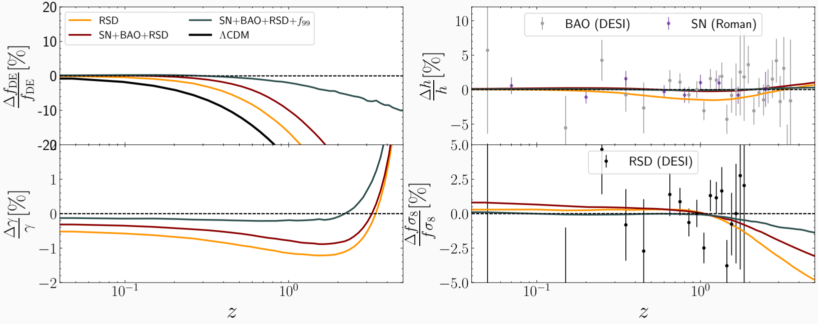

Figure: Reconstruction of background + perturbed quantities (at 68% CL) from various Stage-IV surveys. Marginalized over Ω_m and σ_8.

Introduce $f_{99} \equiv \rho_{\rm DE}(z=99)/\rho_{\rm DE,0}$ as free parameter.

$\longrightarrow$ Accounts for (non-negligible) contribution from DE at high-z & removes bias in (Ω_m, σ_8)

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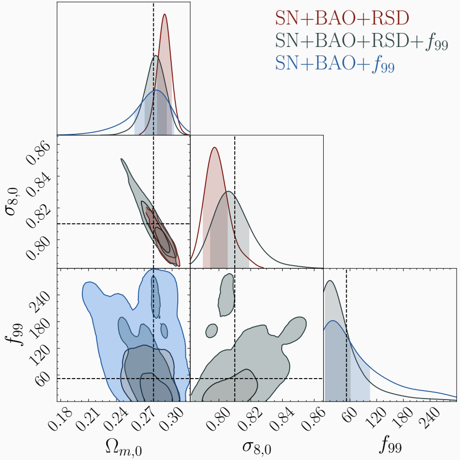
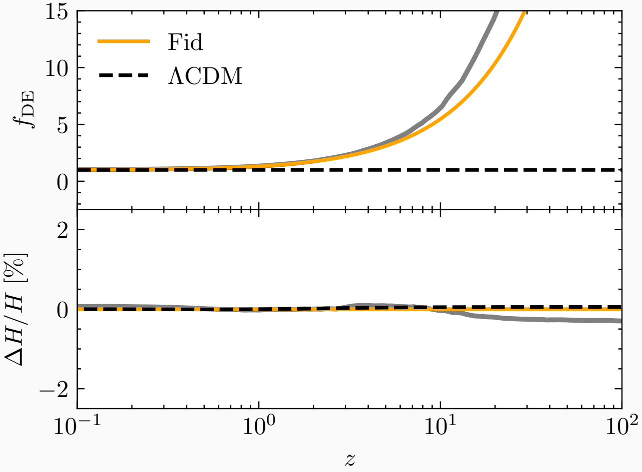


Figure: Posterior distributions for the cosmological parameters

Most analyses assume ΛCDM! ($\Omega_m^{\Lambda\mathrm{CDM,bf}} = 0.31$ vs. $\Omega_m^{\mathrm{fid}} = 0.28$)



INCORRECTLY ASSUMING Λ

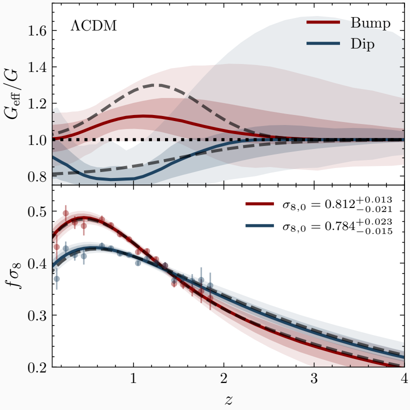


Figure: Reconstructions of $\mu \equiv G_{\rm eff}/G$ from RSD mocks, assuming ΛCDM's best-fit $h(z)$.

Assuming $H(z) = H^{\rm bestfit}_{\Lambda\rm CDM}$

$$f' + \left(f + 2 + \frac{h'}{h}\right) f = \frac{3}{2}\Omega_m\, \mu(z).$$

$\longrightarrow$ Sample $\theta = \{\sigma_8; \sigma_f, \ell_f, z_c\}$!

Incorrectly assuming DE is constant (Λ) leads to:

- Degraded reconstruction of $\mu(z)$ for the bump (in Red)
- Biased estimation of $\sigma_{8,0} \sim 0.78$ ($\sigma^{\rm fid}_{8,0} = 0.81$) for the dip (in Blue)