Model-independent reconstruction of Horndeski gravity using late-time Hubble data (2105.12970 & 2106.08688)

Reggie Bernardo, Jackson Levi Said

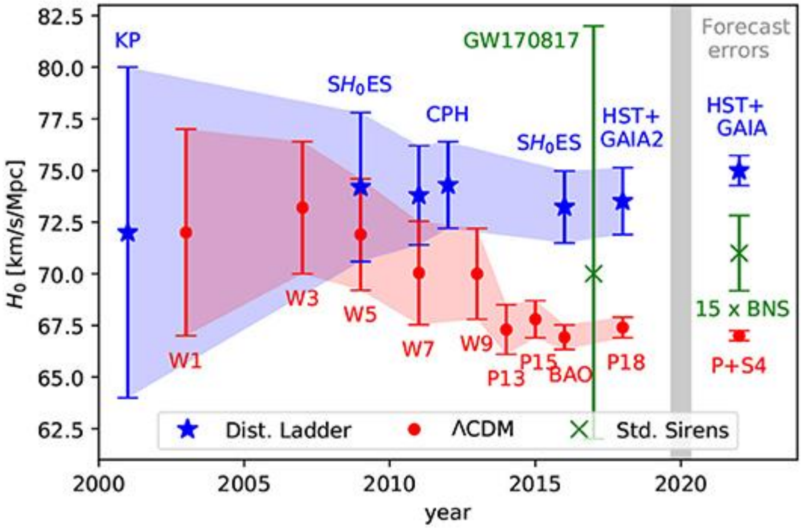
University of the Philippines

09September2021@ALTECOSMOFUN

Outline

1. Motivation
2. Gaussian processes, late-time data
   - Basics, kernel selection
   - Late-time Hubble data: CC, SNe, BAO
3. Results
   - Horndeski gravity + GP
   - Constraints on the dark energy equation of state $w(z)$
     - Introducing a compactified version $\arctan(1 + w(z))$
4. Outlook

Background: Modified gravity, The Hubble tension, All that



Hubble Tension. Ezquiaga, J. M., & Zumalacárregui, M. (2018). Dark energy in light of multi-messenger gravitational-wave astronomy. *Frontiers in Astronomy and Space Sciences*, *5*, 44.

The solution?

- *f*(*R*), Galileon ghost gondensate, generalized Galileons, Teleparallel Gravity, etc.
- Relaxed Cosmological Principle
- Interacting dark energy models
- ???

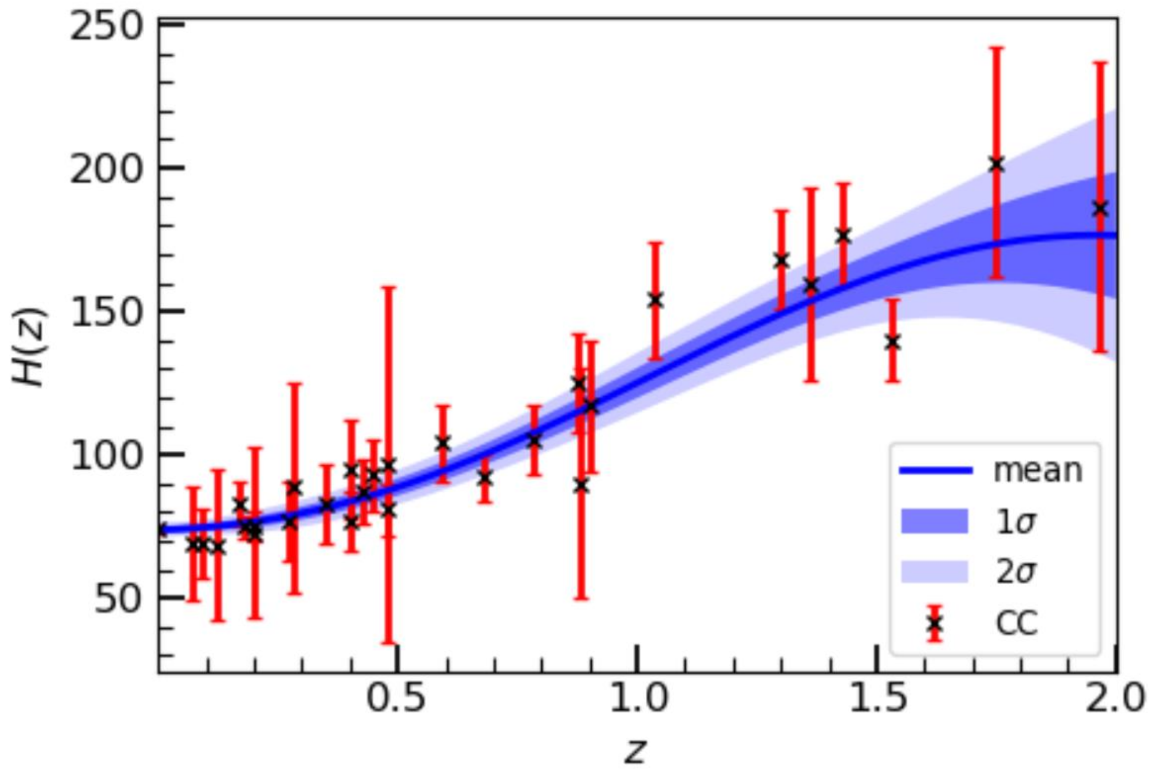
2103.01183, Di Valentino, *et al.*, In the Realm of the Hubble tension - a Review of Solutions.

Can we constrain modified gravity in a model-independent manner?

Based on: 2105.12970 & 2106.08688

Gaussian processes + Late-time data

- *Nonparameteric* method for reconstructing observational data
- *Integrates* well with *Late-time Hubble data* (e.g., CC, SNe)
- Advantages:
  - (Cosmology) model-independent
  - Bayesian -> Mean + Uncertainty
  - Easy to implement
- Challenges:
  - Overfitting
  - Kernel selection (2106.08688)



GP Reconstruction of Cosmic Chronometers data set. Hubble function $H(z)$ as a function of the redshift z.

main / notebooks / supp_ntbks_arxiv.2106.08688 / gp_abcsmc_reconstruction.ipynb

reggiebernardo added 1702.00418 to CC references   Latest com

1 contributor

1016 lines (1016 sloc) | 523 KB

Gaussian processes with approximate Bayesian computation and sequential Monte for the reconstruction of late-time Hubble data

Investigation of kernel selection for the Gaussian process using various cosmological datasets (2106.08688). This notebook (https://pyabc.readthedocs.io/en/latest/) for approximate Bayesian computation with sequential Monte-Carlo for model selection. The analysis is first one using cosmic chronometers and the second one using the compressed Pantheon samples.

References to the data can be found at the end of the notebook.

In [1]:
```
%matplotlib inline
import numpy as np
import matplotlib.pyplot as plt
import os
import tempfile
import scipy.stats as st
```

Horndeski gravity

The Action (def. $X = -(\partial\phi)^2/2$)

$$S_g[g,\phi] = \int d^4x\sqrt{-g}\Big(F(\phi)R + K(\phi,X) - G(\phi,X)\partial^2\phi + \cdots\Big) \quad (1)$$

- Discovery: derived in the 1970s, gained popularity in the late 2000s
- Most general scalar-tensor theory with second-order field equations
- Phenomenologically rich
- Subclasses: *f*(*R*), Brans-Dicke theory, Galileons, Fab Four, etc.

Quintessence Reconstruction

- Quintessence dark energy: $K(\phi, X) \rightarrow X - V(\phi)$
- Field equations:

$$3H^2 = \rho_\phi + \rho_m \tag{2}$$

$$2\dot{H} + 3H^2 = P_\phi + P_m \tag{3}$$

where

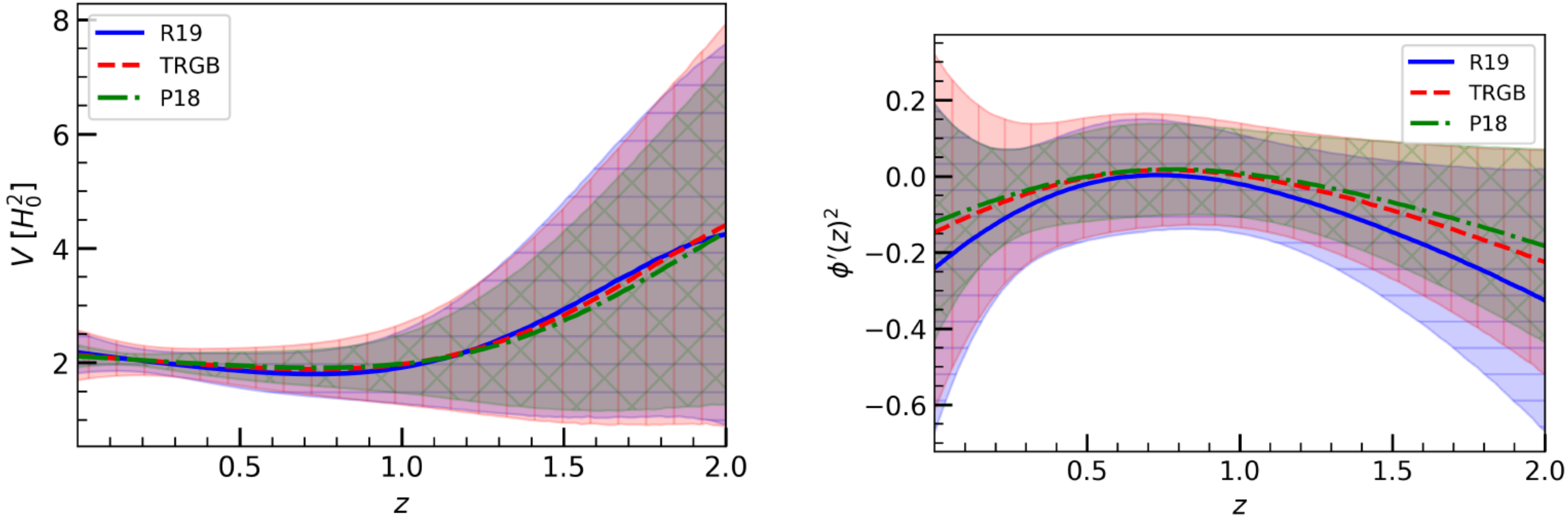
$$\rho_\phi = \left(\dot{\phi}^2/2\right) + V(\phi) \tag{4}$$

$$P_\phi = \left(\dot{\phi}^2/2\right) - V(\phi) \tag{5}$$

- Add and Subtract Eqs. 2 and 3:

$$\dot{\phi}^2[H, \rho_m, P_m], V[H, \rho_m, P_m] \tag{6}$$

Quintessence Reconstruction



(**left**) Reconstructed quintessence potential $V(z)$ and (**right**) $\phi'(z)^2$ for varying H_0 prior. The filled-hatched regions show the 2σ confidence intervals. Hatches: ("--": R19), ("|": TRGB), ("×": P18).

Dark Energy Equation of State

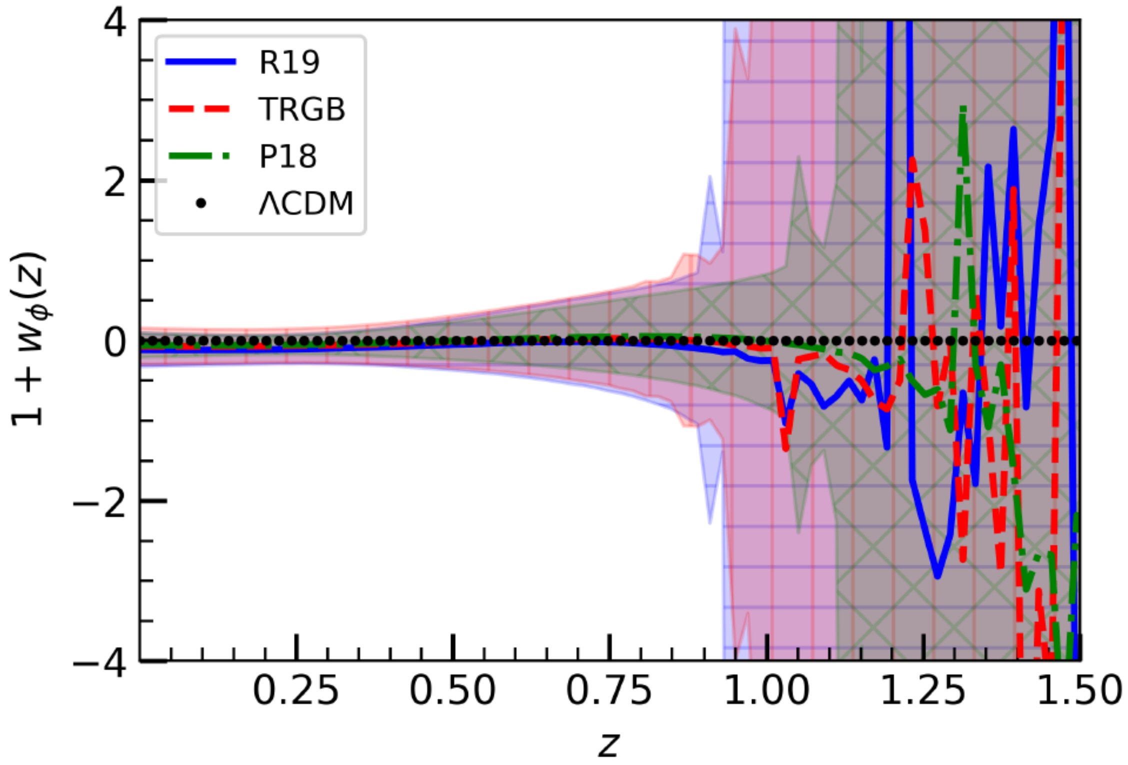
- DE EoS:

$$w(z) = P_\phi/\rho_\phi \qquad (7)$$

- An obstacle (at high z):

ρ_ϕ crosses zero	➡	Loss of predictability

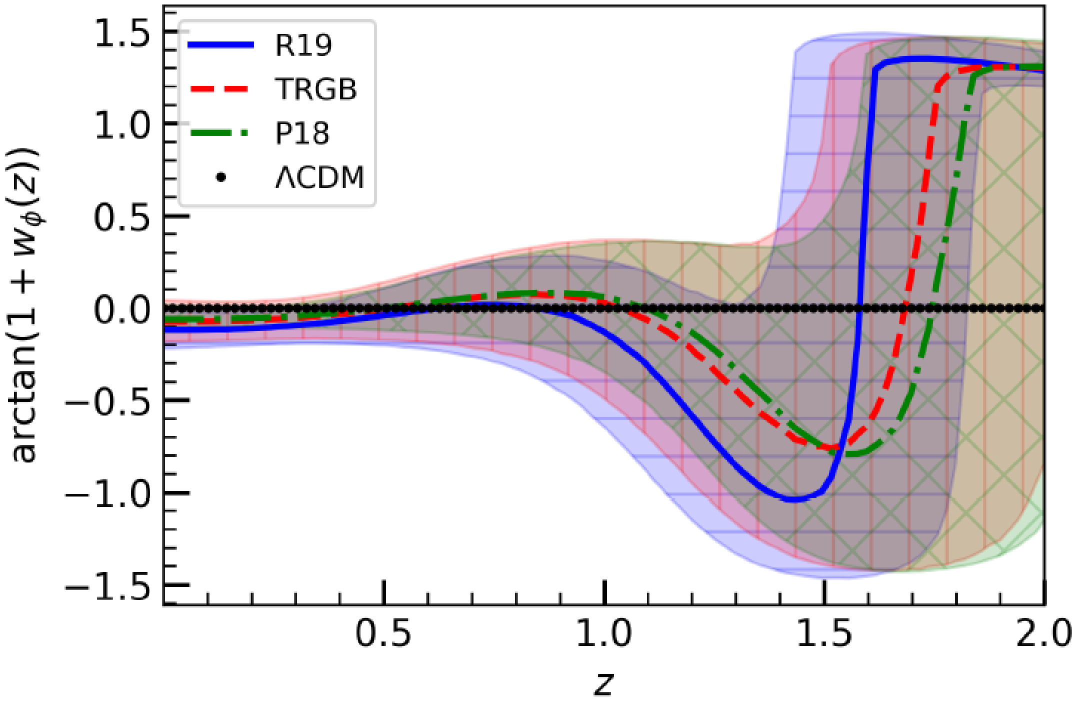
- No prob for low z; *but* what about high z?

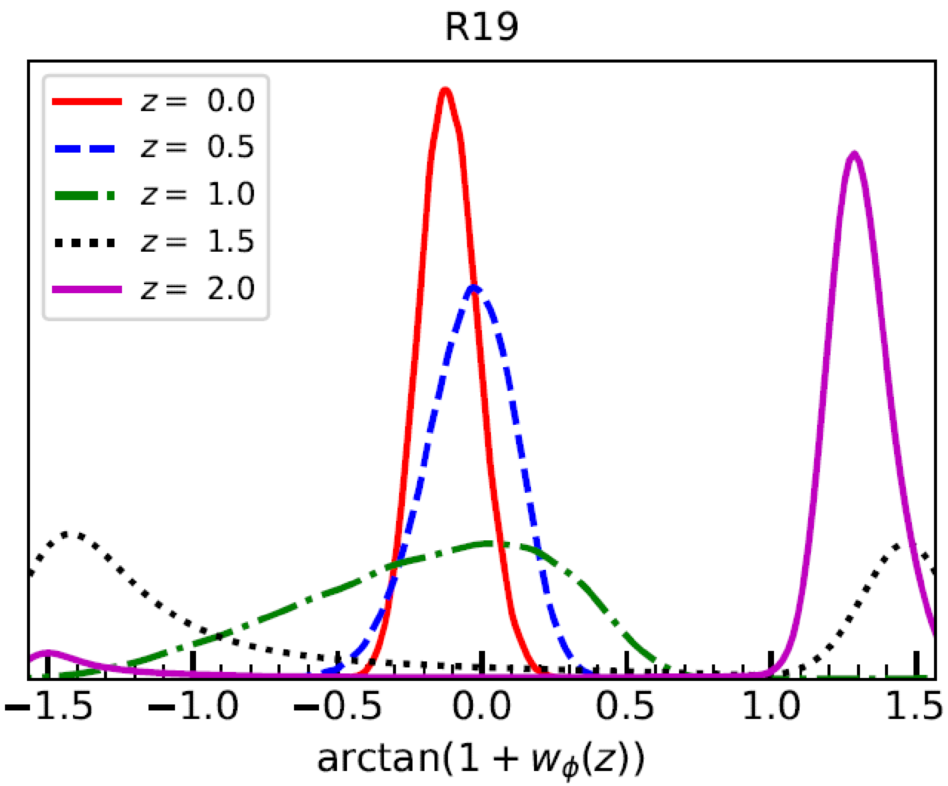


Reconstructed equation of state of quintessence dark energy. The uncertainty blows up when the energy density approaches zero.

A *Compactified* Dark Energy Equation of State

(**left**) A compactified DE EoS, $\arctan\left(1 + w_\phi(z)\right)$ and (**right**) the corresponding posteriors at various redshifts. Filled-hatched regions show the **median** and the 34.1% probability mass above and below. Hatches: ("--": R19), ("|": TRGB), ("×": P18).





Horndeski Gravity Reconstruction

- ***Quintessence*** [Tsamis & Woodard, hep-ph/9712331]:

$$K(\phi, X) \to X - V(\phi), G(\phi, X) = 0, F(\phi) = 1/2 \qquad (8)$$

- ***Designing* Horndeski** [Arjona, Cardona, & Nesseris, 1904.06294]:

$$K(\phi, X) \to K(X), G(\phi, X) = G(X), F(\phi) = 1/2 \qquad (9)$$

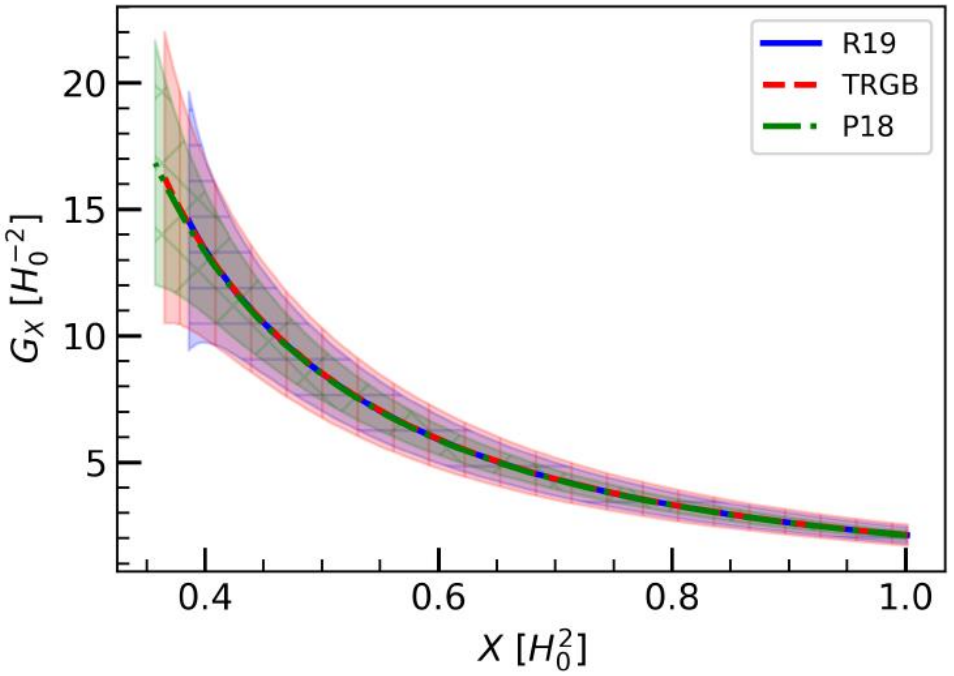
- ***Tailoring* Horndeski** [RCB & Ian Vega, 1903.12578]:

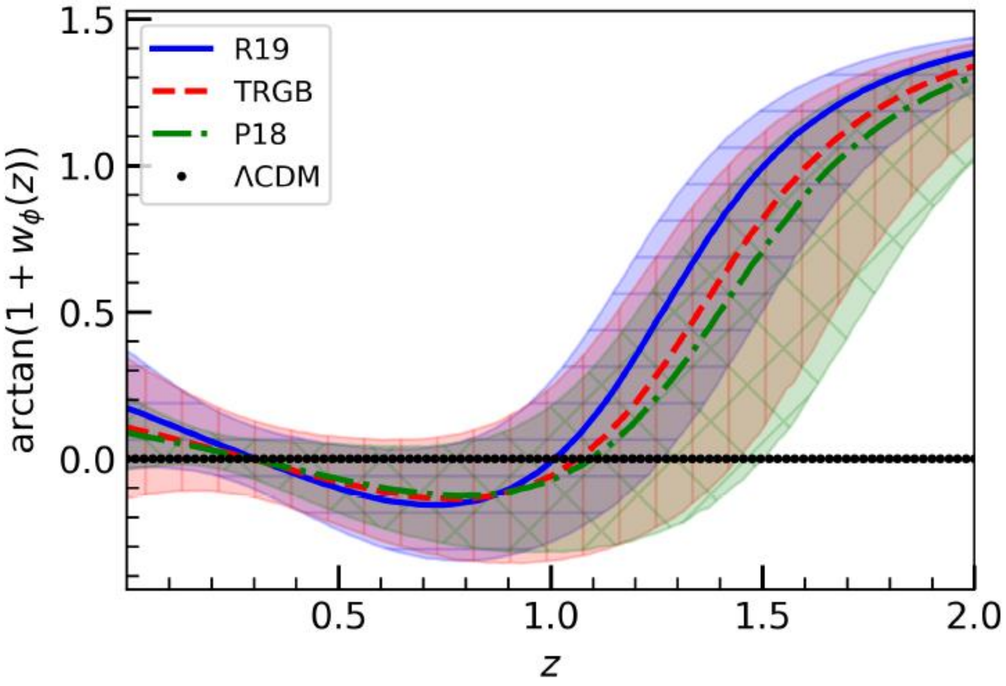
$$K(\phi, X) \to X - 2\Lambda, G(\phi, X) = G(X), F(\phi) = 1/2 \qquad (10)$$

Designing Horndeski ($J \neq 0$)

(**left**) The braiding potential in HDES and (**right**) the compactified DE EoS. Filled-hatched regions show the median and the 34.1% probability mass above and below.

Hatches: ("--": R19), ("|": TRGB), ("×": P18).

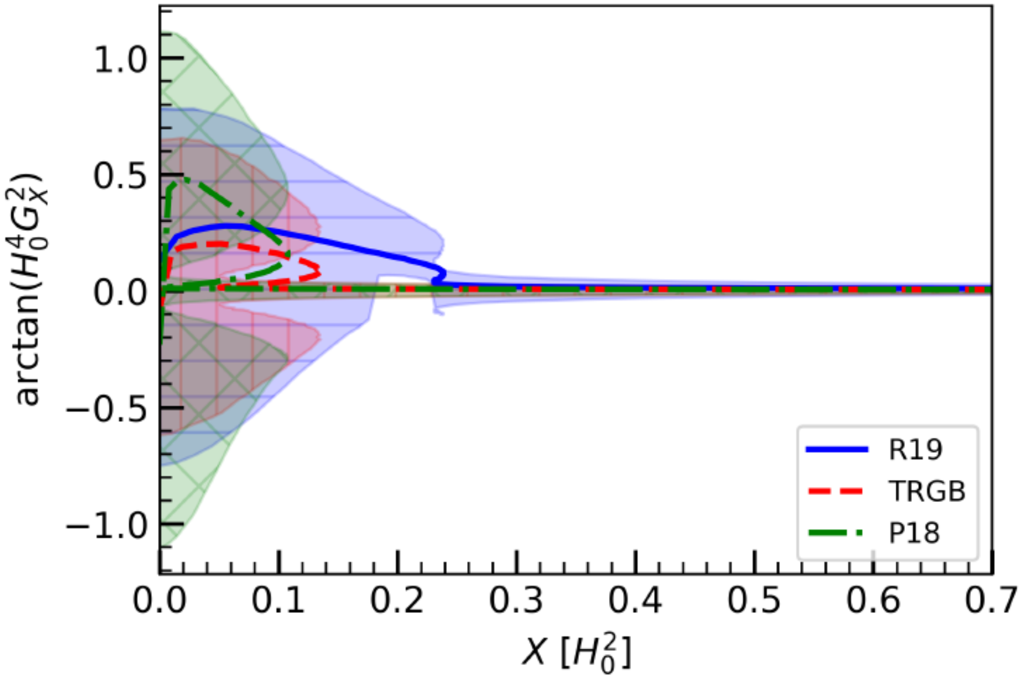


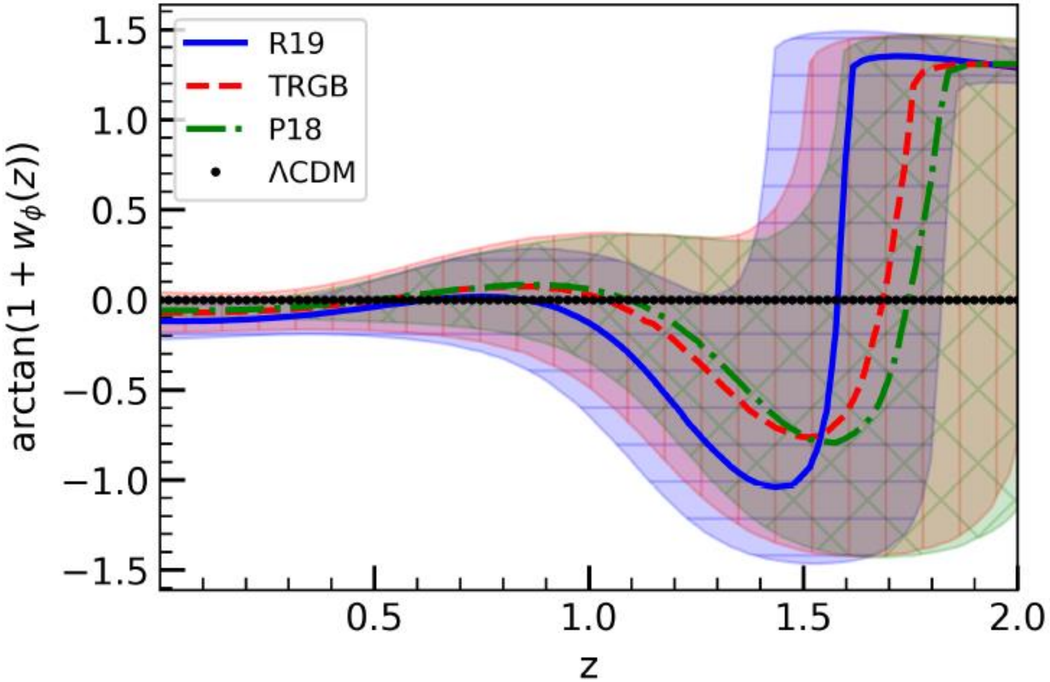


Tailoring Horndeski ($J = 0$)

(**left**) The braiding potential in HDES and (**right**) the compactified DE EoS. Filled-hatched regions show the median and the 34.1% probability mass above and below.

Hatches: (“--”: R19), (“|”: TRGB), (“×”: P18).





Constraints on the DE EoS

Constraints on the DE EoS in Horndeski cosmology. The columns R19, TRGB, and P18 stand for the GP analysis using the corresponding H_0 priors. P18 priors for Ωs. For designer Horndeski, $c_0 = H_0^{n+2}$, $n = 1$, and $J = H_0$ were assumed.

	$w_{\rm DE}\,(z=0)$		
Theory + parameters	$H_0^{\rm R19}$	$H_0^{\rm TRGB}$	$H_0^{\rm P18}$
Quintessence + (Ω_{m0})	-1.1 ± 0.1	-1.1 ± 0.1	-1.06 ± 0.08
Designer Horndeski + $(\Omega_{m0}, \Omega_\Lambda, c_0, n, \mathcal{J})$	-0.8 ± 0.2	-0.9 ± 0.3	-0.9 ± 0.1
Tailoring Horndeski + $(\Omega_{m0}, \Omega_\Lambda)$	-1.1 ± 0.1	-1.1 ± 0.1	-1.06 ± 0.08
ΛCDM	-1		
w_0CDM (Planck + SNe + BAO)	-1.03 ± 0.03		
$w_0 w_a$CDM (Planck + SNe + BAO)	-0.96 ± 0.08		

Outlook

- GP + Late-time Data -> Constraints on Modified Gravity potentials
- Improvements:
  - ML side: Kernel selection, overfitting, GP vs ANN vs GA vs…Parametric Methods
  - On the DE EoS: An improved reconstruction at high z, e.g., compactified DE EoS
- Constraints on Linear Observables (Φ, Ψ)

References

[1] 2105.12970, **RCB**, Levi Said (2021), *A data-driven Reconstruction of Horndeski gravity via the Gaussian processes*.

[2] 2106.08688, **RCB**, Levi Said (2021), *Towards a model-independent reconstruction approach for late-time Hubble data*.

[3] 2103.01183, Di Valentino, *et al*. (2021), *In the Realm of the Hubble tension - a Review of Solutions*.

[4] 1807.09241, Ezquiaga & Zumalacárregui (2018), *Dark energy in light of multi-messenger gravitational-wave astronomy*.

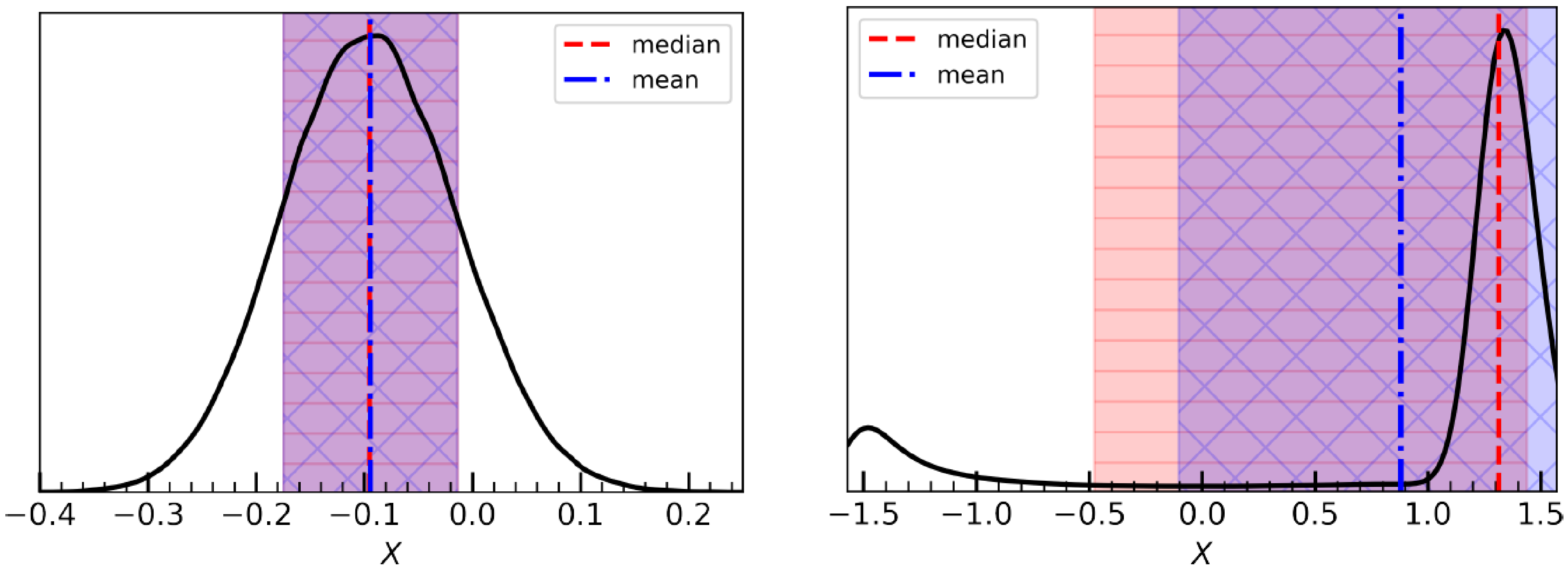
[5] hep-ph/9712331], Tsamis & Woodard (1998), *Nonperturbative models for the quantum gravitational backreaction on inflation*.

[6] 1904.06294, Arjona, Cardona, & Nesseris (2019), *Designing Horndeski and the effective fluid approach.*

[7] [1903.12578, **RCB** & Vega (2019), *Tailoring cosmologies in cubic shift-symmetric Horndeski gravity*.

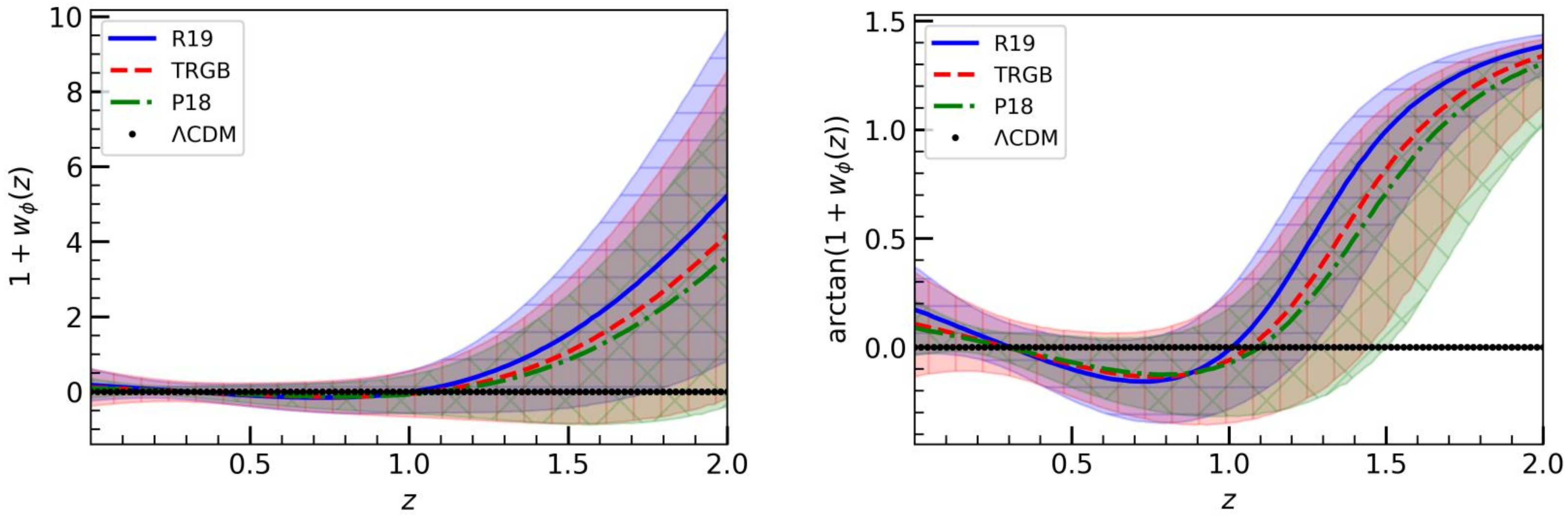
Extra Slides

Statistics of a Compactified Random Variable



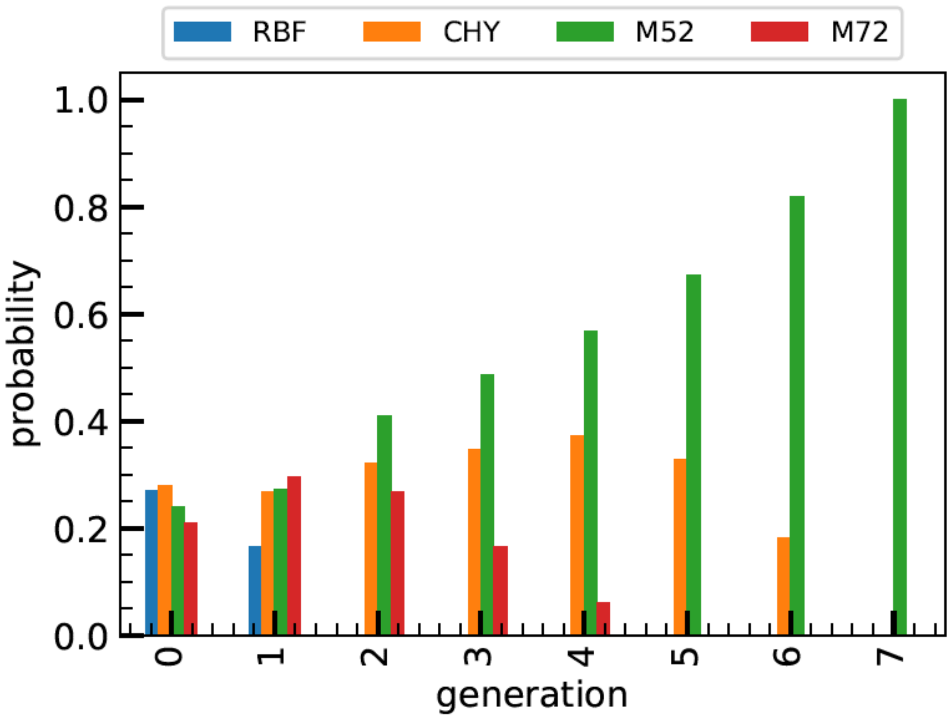
Distributions of a compactified random variable X when it is (**left**) approximately Gaussian-distributed and (**right**) bimodal. The red-dashed and blue-dash-dotted lines show the median and the mean, respectively. Red-filled ("--" hatched) region shows the 34.1% probability mass above and below the median. Blue-filled ("x" hatched) region shows the mean +/- 1σ confidence intervals.

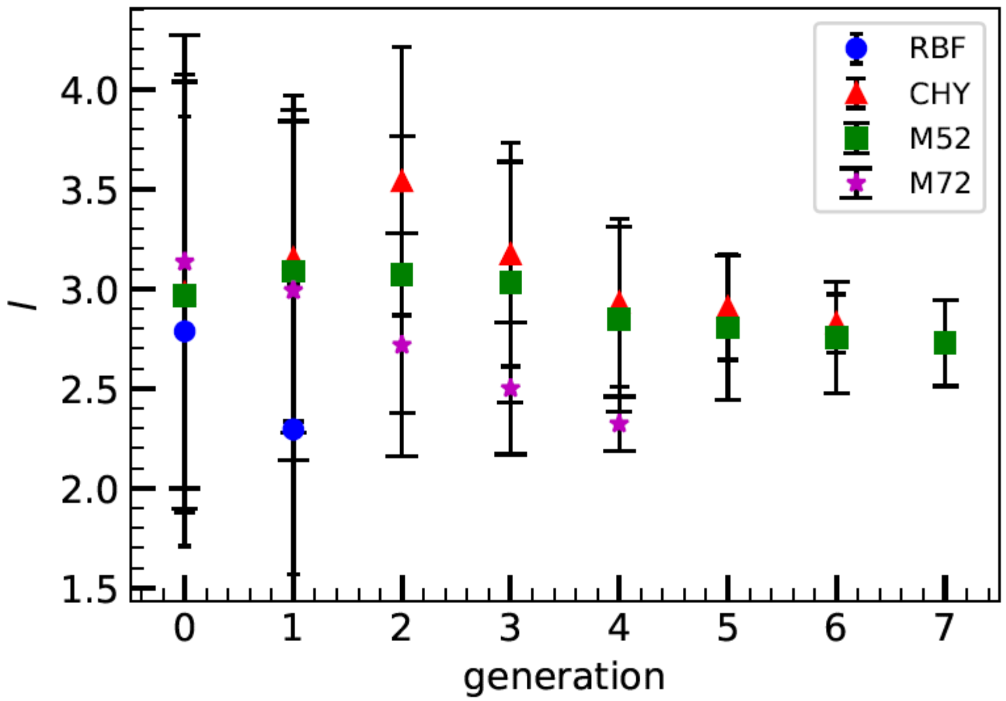
Statistics of a Compactified Random Variable



GP posteriors of (**left**) a random variable and (**right**) its compactified version.

Kernel Selection





(**left**) *Kernel posteriors* in a joint kernel space per generation obtained using Approximate Bayesian Computation and (**right**) the corresponding evolution of the hyperperameters per kernel.