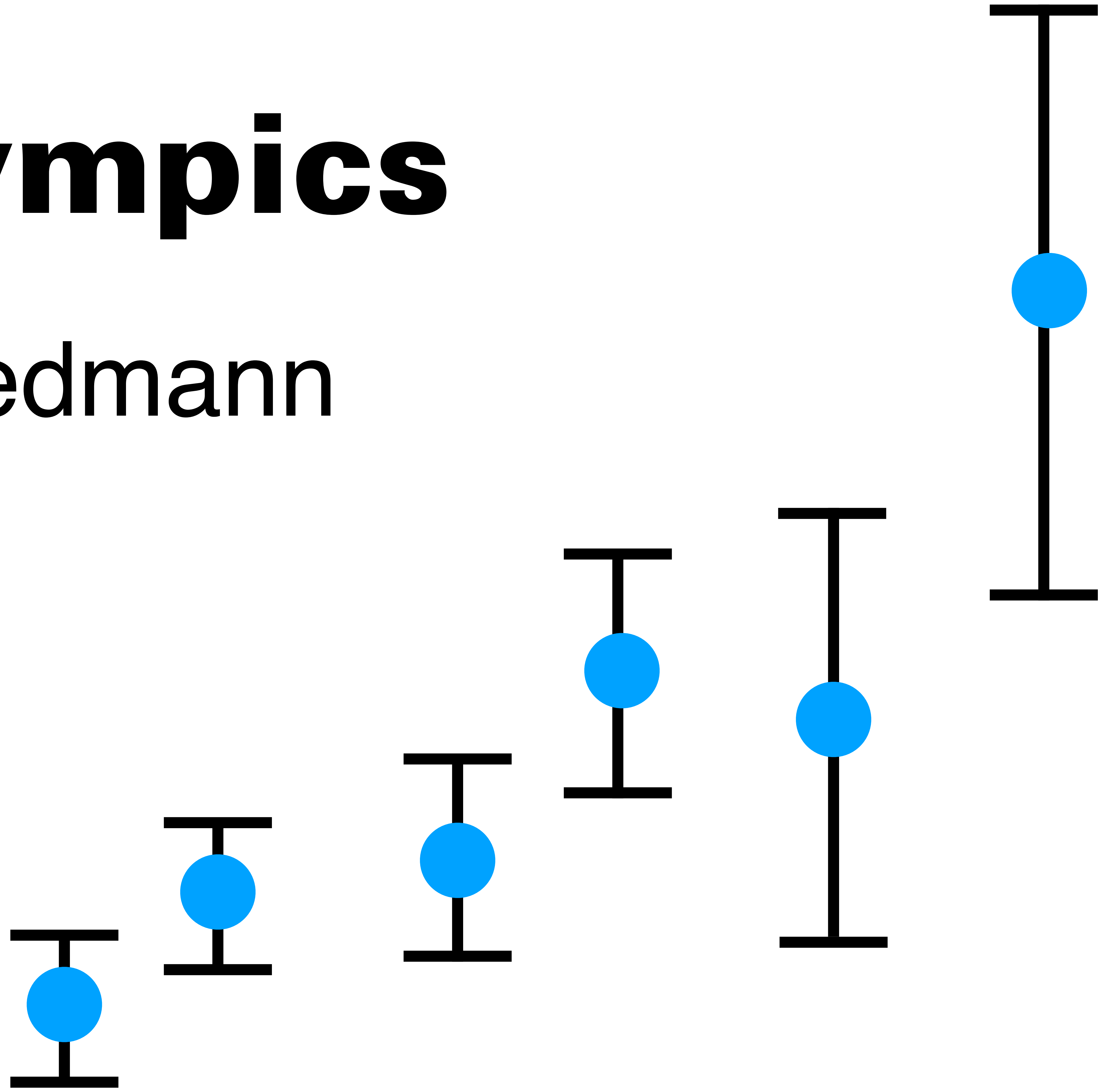
The Hubble Olympics

Regression of Eight Friedmann models



IVCAS GROUP 5

Outline

The Competition (Background and Objectives)

The Competitors (Friedmann Models)

Methodology

Results

Assumption of Cosmology

approximate isotropy and homogeneity

$$\downarrow \text{assumption}$$

$$ds^2 = -dt^2 + a(t)d\mathbf{x}$$

(*exact* isotropy and homogeneity)

The Friedmann Equation

$$ds^2 = -\, dt^2 + a(t)d\mathbf{x}$$

$$\downarrow$$

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_r(1+z)^4}$$

$H(z)$ - expansion rate of the Universe

Ω_r - fractional energy density of relativistic particles

Ω_m - fractional energy density of non-relativistic particles

The Friedmann Equation

Ω_r - negligible for the last several billion years

So $\Omega_m \approx 1$

$$H(z) = H_0\sqrt{(1+z)^3}$$

Modern Cosmology: The Problem

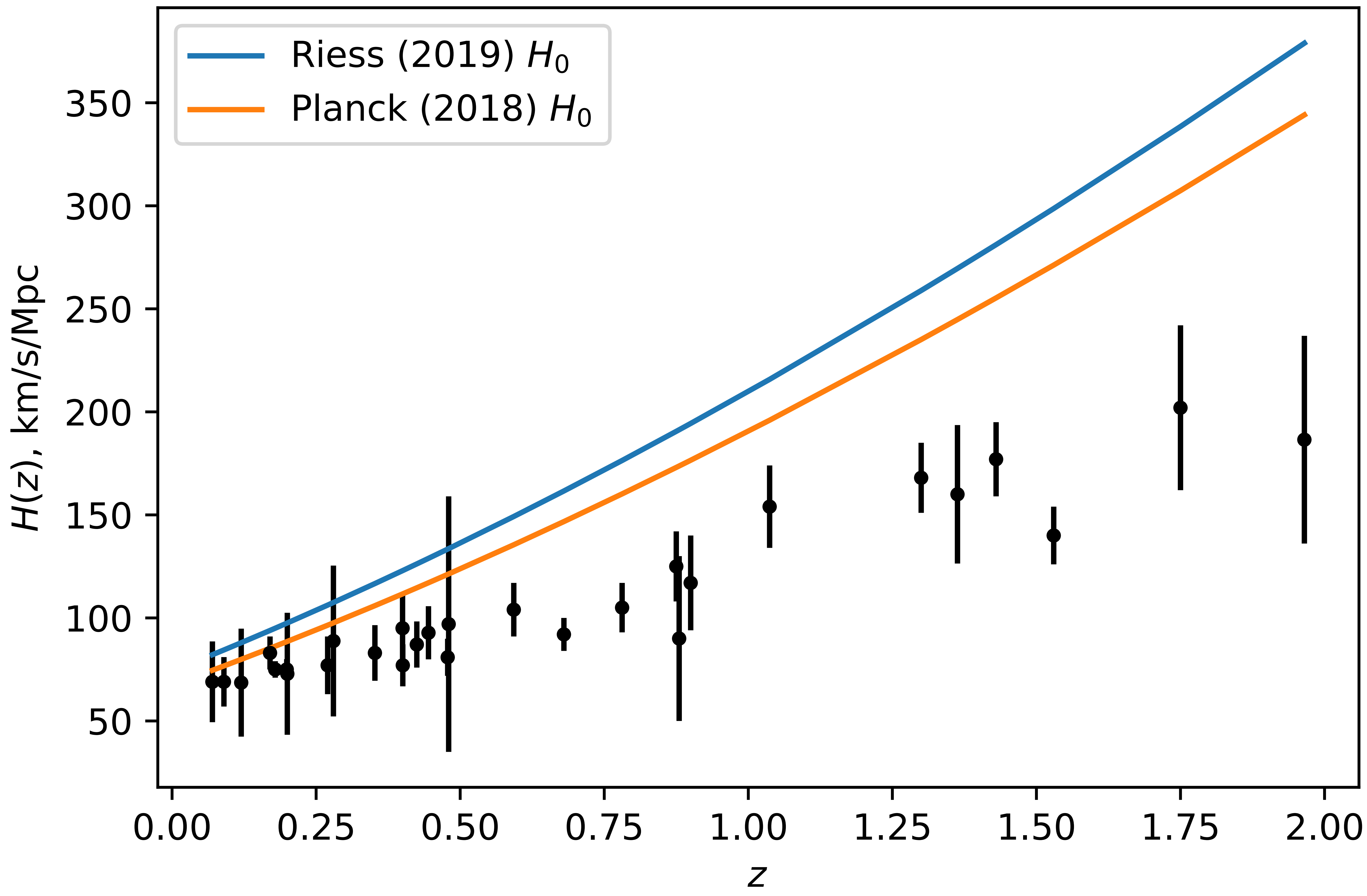


Fig. 1 Plot of matter-only Friedmann equation

Modern Cosmology: The Problem

$$H(z) = H_0\sqrt{(1+z)^3}$$

needs to be corrected.

“The Competition”/Objective

Find the best-fit parameters of corrected models of the Friedmann equation that fits the data better.

Determine the “best” model.

“The Competitors”: Three Types of Models

1. **Dark Energy**
   - extraordinary energy permeates the universe

2. **Modified Gravity**
   - general relativity needs to be modified

3. **Cosmic Backreaction**
   - general relativity is correct, but assumption of exact isotropy and homogeneity is not

“The Competitors”: Dark Energy

1. The Standard LCDM Model

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

“Back-to-back champion”

“The Competitors”: Dark Energy

2. Domain Walls

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_d(1+z)^{1/3}}$$

3. Cosmic Strings

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_s(1+z)^{2/3}}$$

4. Phantom Energy

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_p(1+z)^{3(1+\omega_p)}}$$

"The Competitors": Modified Gravity

Varying-G theory: $G = G_0 f(z, b)$

$$H(z) = H_0 \sqrt{f(z, b)(1 + z)^3}$$

“The Competitors”: Modified Gravity

1. **Inverse Monomial** $$f(z, b) = \frac{1}{1 + bz}$$

2. **Exponential** $$f(z, b) = \exp b \left(\frac{1}{1 + z} - 1 \right)$$

3. **Logarithmic** $$f(z, b) = b \ln \frac{1}{1 + z} + 1$$

“The Competitors”: Cosmic Backreaction

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)(1+z)^n}$$

Methodology

Objective 1: Get best-fit parameters

Method 1: Maximum Likelihood Estimation/ Bayesian Inference with Uninformative Priors

Method 1: Maximum Likelihood Estimation

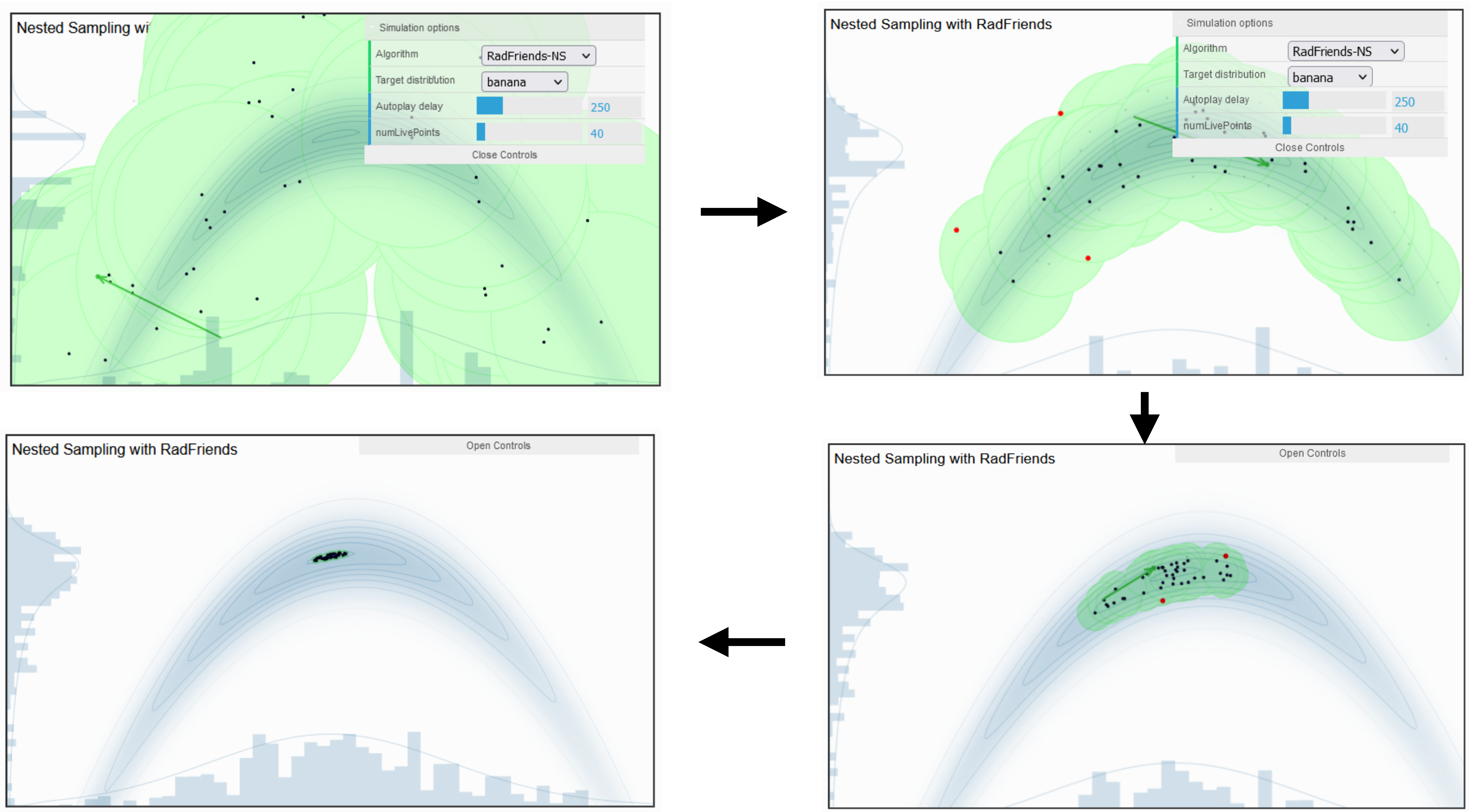
— Sample the posterior distribution of parameters as defined by Bayes theorem

— Best estimate: median of the posterior

— Assume Gaussian likelihood and flat priors for simplicity

— Package: UltraNest [1]

[1] https://johannesbuchner.github.io/UltraNest/


Nested Sampling wi
Simulation options
Algorithm
RadFriends-NS
Target distribution
banana
Autoplay delay
250
numLivePoints
40
Close Controls
Nested Sampling with RadFriends
Simulation options
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RadFriends-NS
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Open Controls
Nested Sampling with RadFriends
Open Controls

Objective 2: Get “best” model

Method 2: Calculate Bayes factors

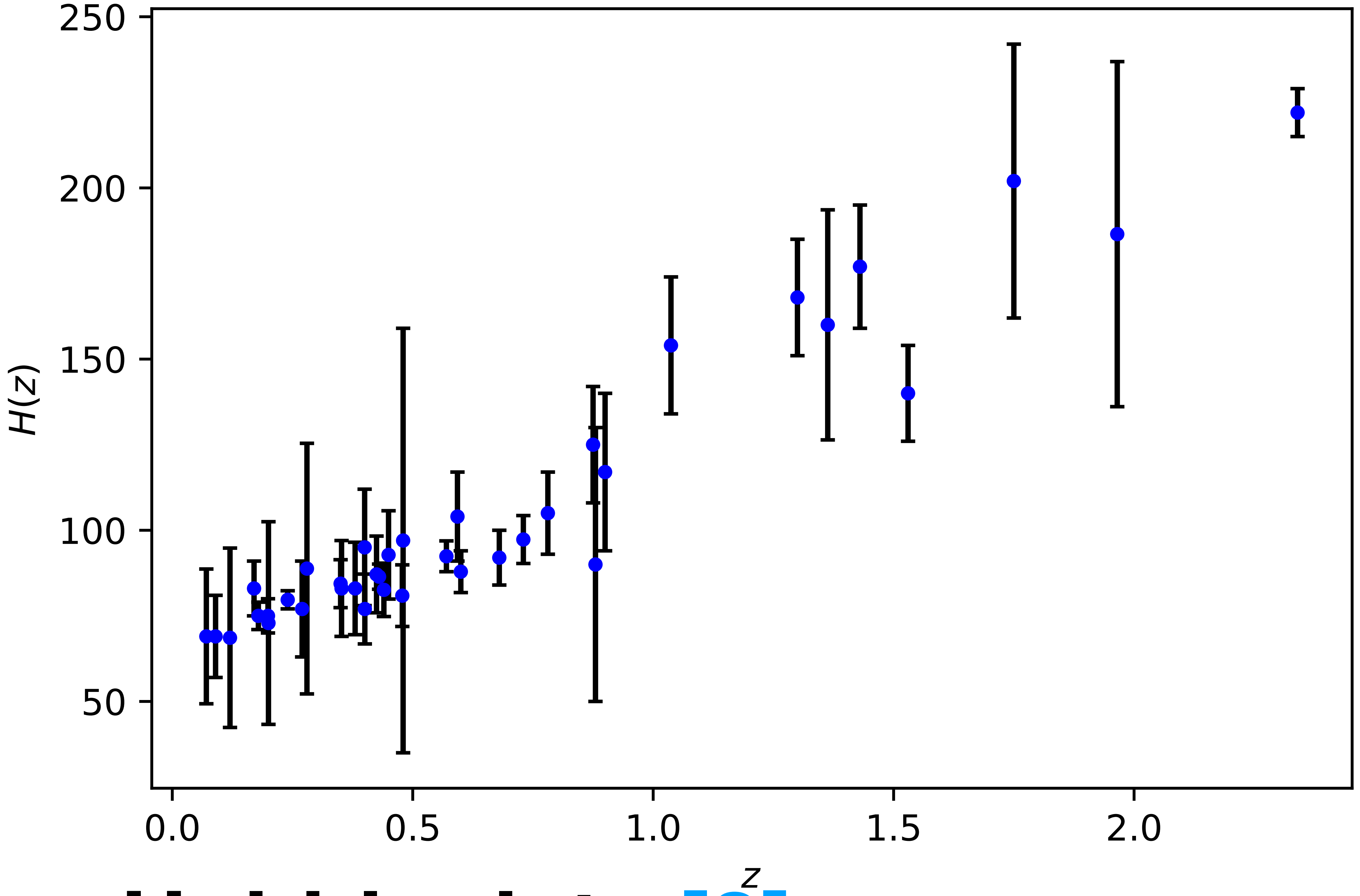
Method 2: Calculate Bayes factors

— Calculate the evidence ln Z of each model via UltraNest

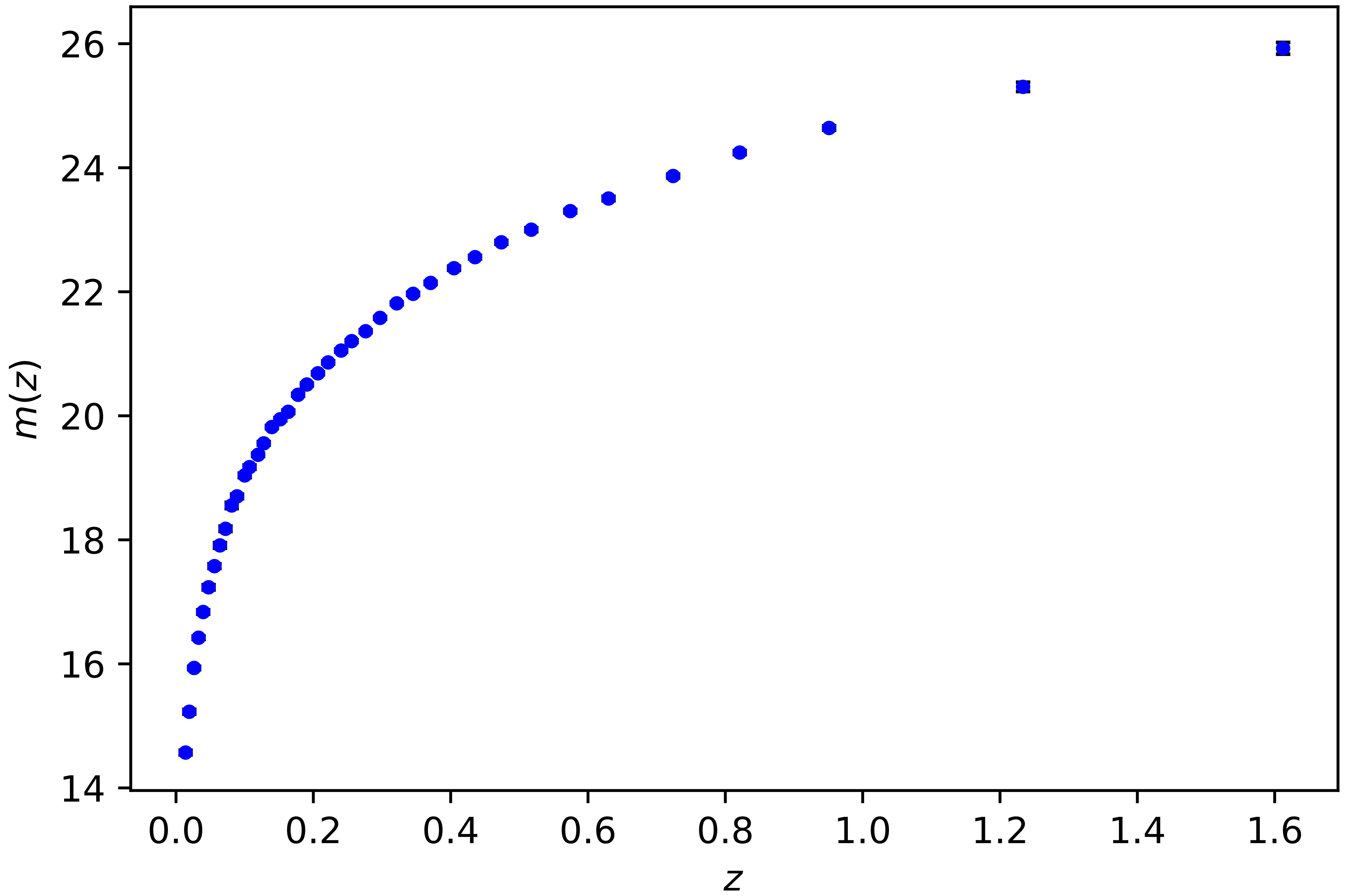
— Compute the Bayes factor of model 1 and model 2:

$$\ln B_{12} = \ln Z_1 - \ln Z_2$$

Dataset



Hubble data [2]



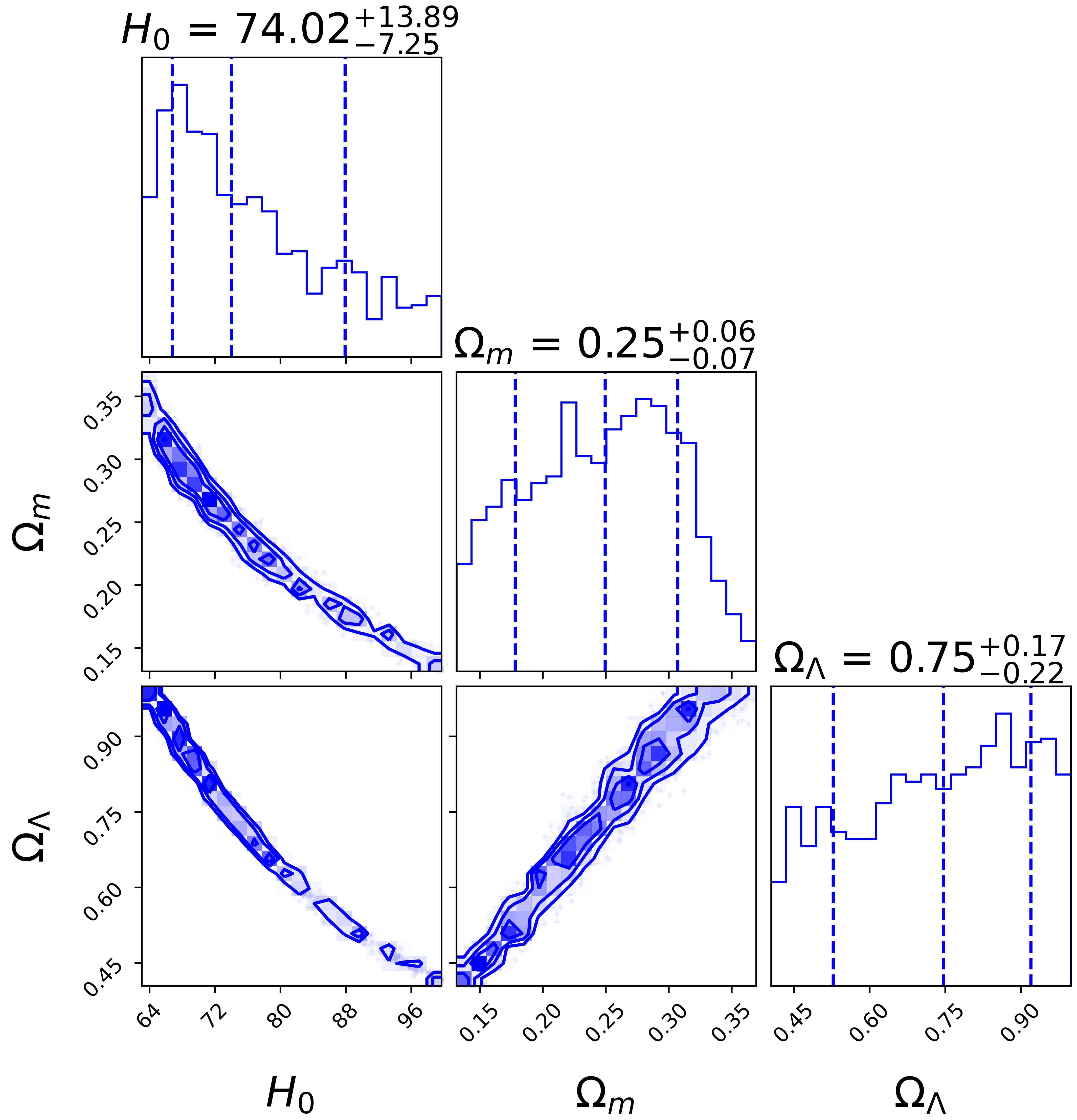
Apparent magnitude data [3]

[2] D. Jyoti Gogoi & U. Dev. Goswami. Cosmology with a new f(R) gravity model in Palatini formalism. https://arxiv.org/abs/2108.01409
[3] D. M. Scolnic et al. The Complete Light-curve Sample of Spectroscopically Confirmed Type Ia Supernovae from Pan-STARRS1 and Cosmological Constraints from The Combined Pantheon Sample. https://arxiv.org/abs/1710.00845

Results

Corner Plots

Dark Energy: LCDM

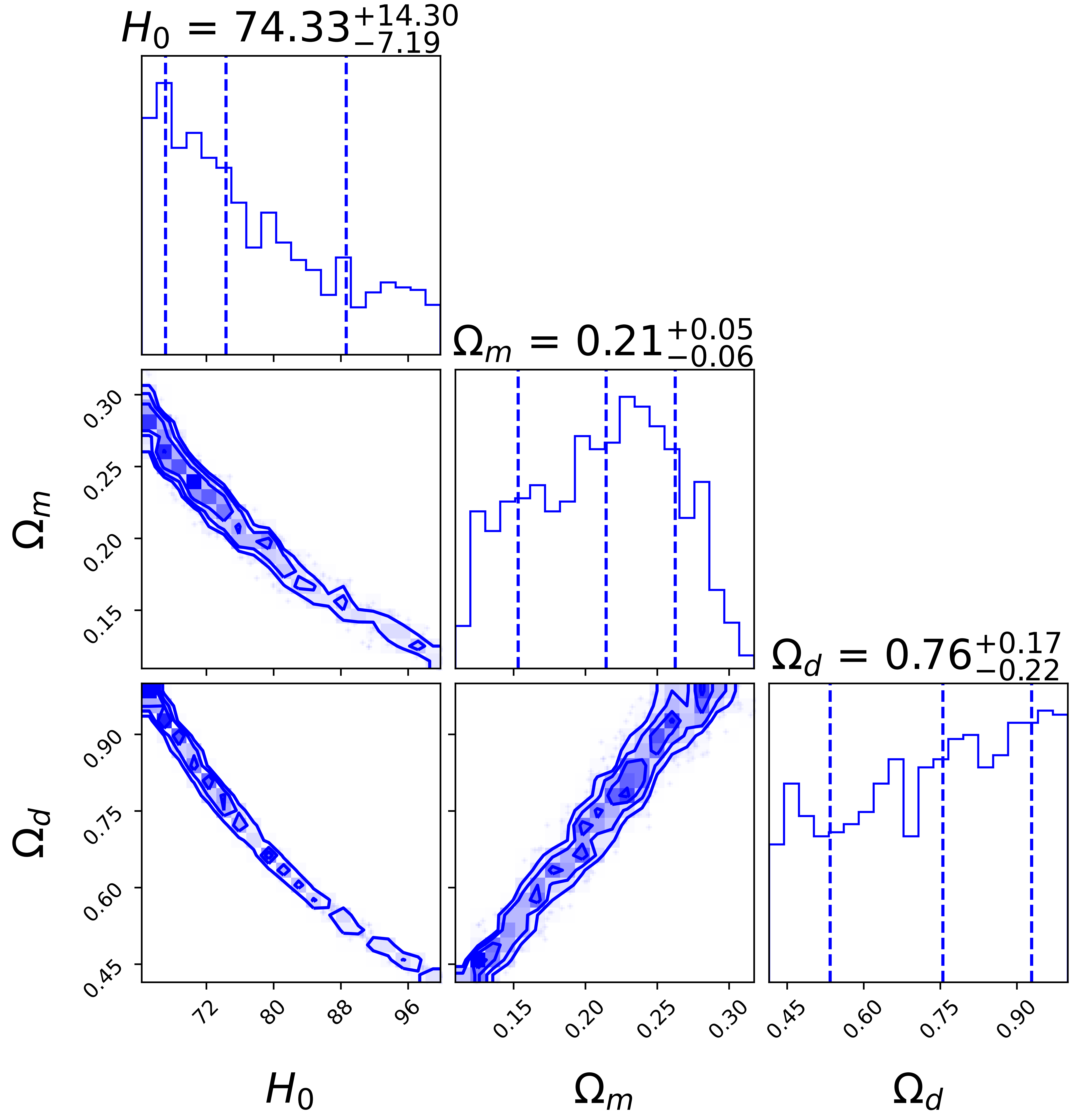


Priors: $H_0 \in [0,100]$

$\Omega_m \in [0,1]$

$\Omega_\Lambda \in [0,1]$

Dark Energy: Domain Walls

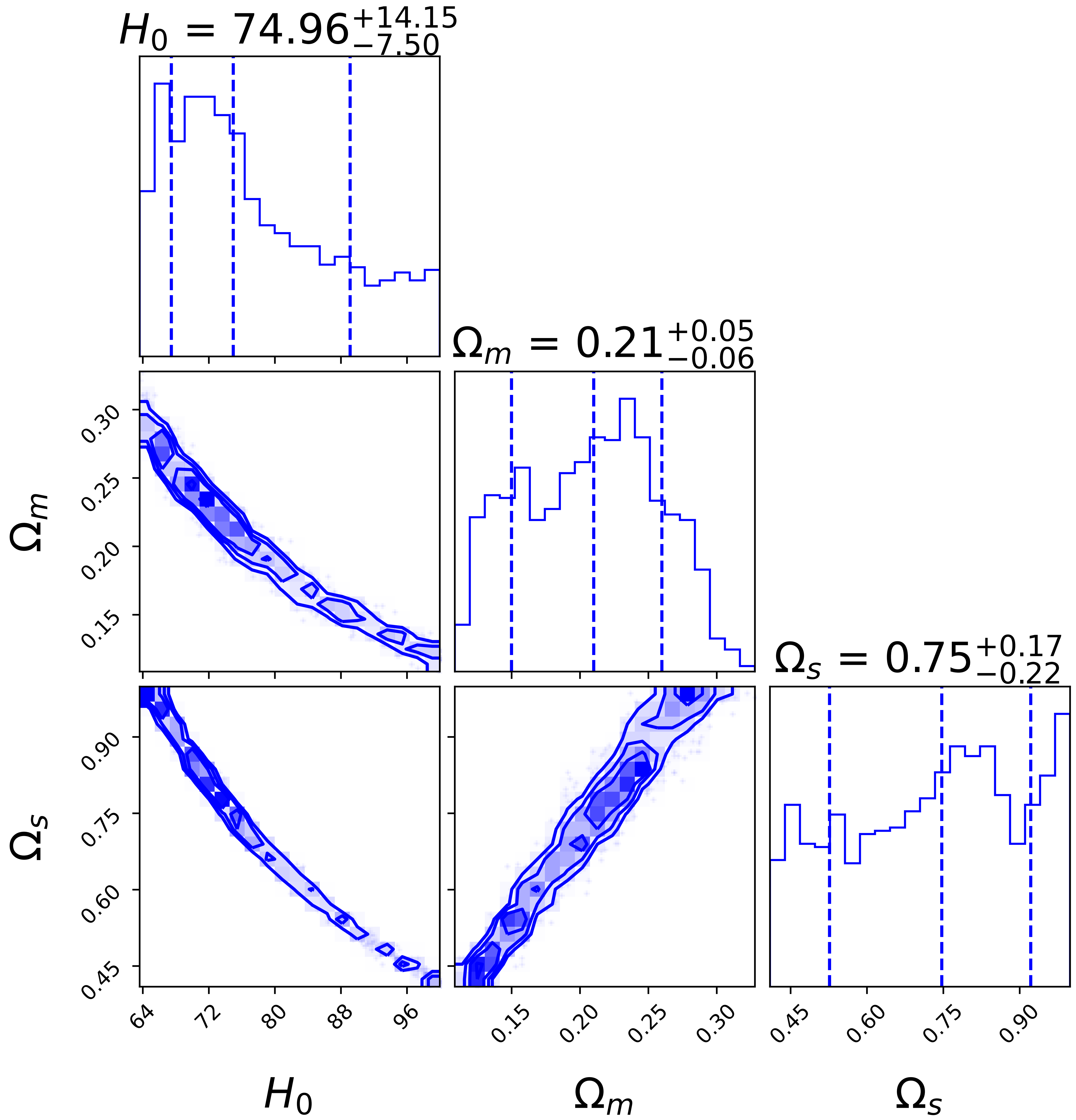


Priors: $H_0 \in [0,100]$

$\Omega_m \in [0,1]$

$\Omega_d \in [0,1]$

Dark Energy: Cosmic Strings

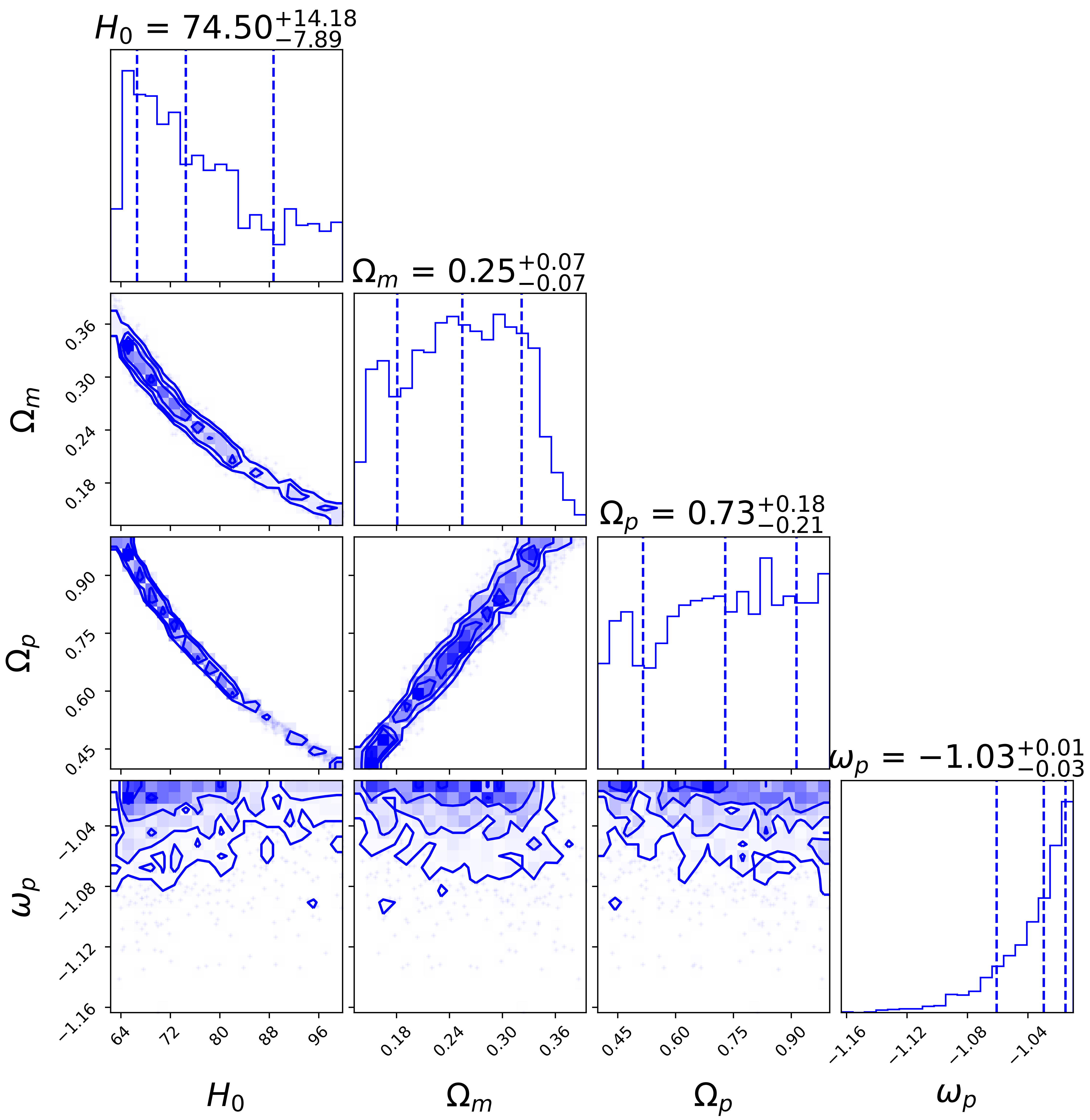


Priors: $H_0 \in [0,100]$

$\Omega_m \in [0,1]$

$\Omega_s \in [0,1]$

Dark Energy: Phantom Energy

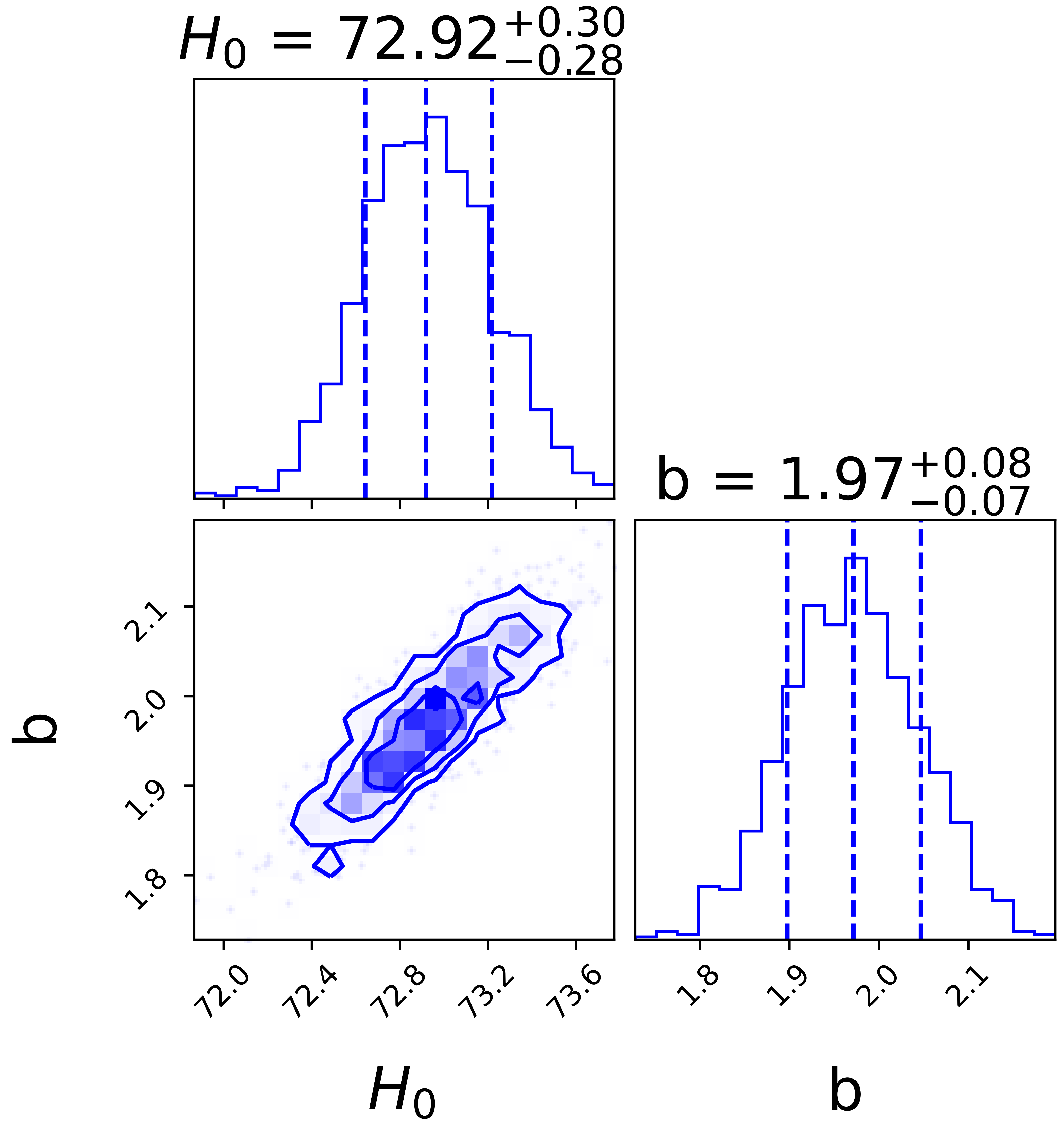


Priors: $H_0 \in [0,100]$

$\Omega_m \in [0,1]$

$\Omega_p \in [0,1]$

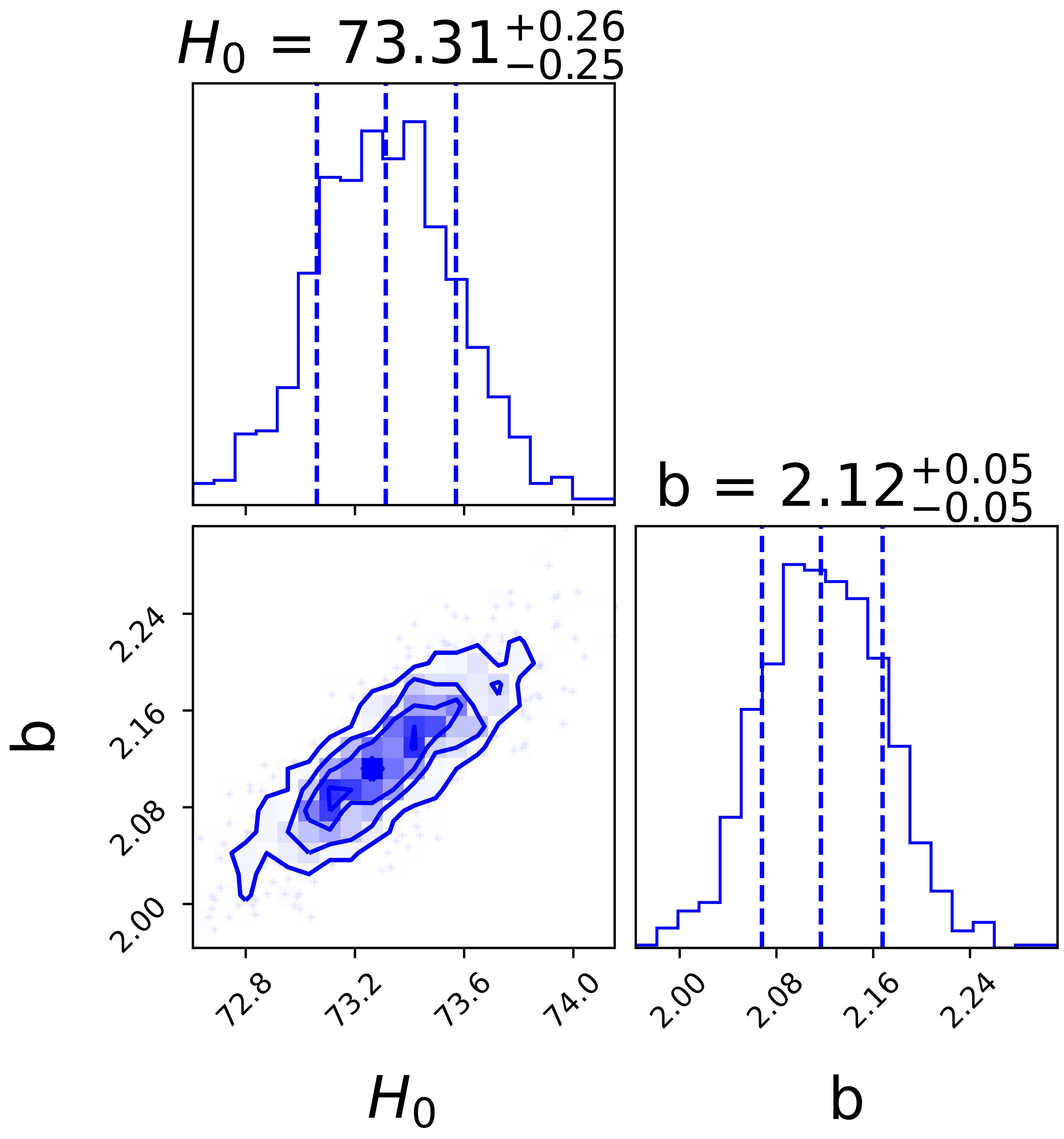
$\omega_p \in [-3, -1.01]$



Modified Gravity: Inverse Monomial

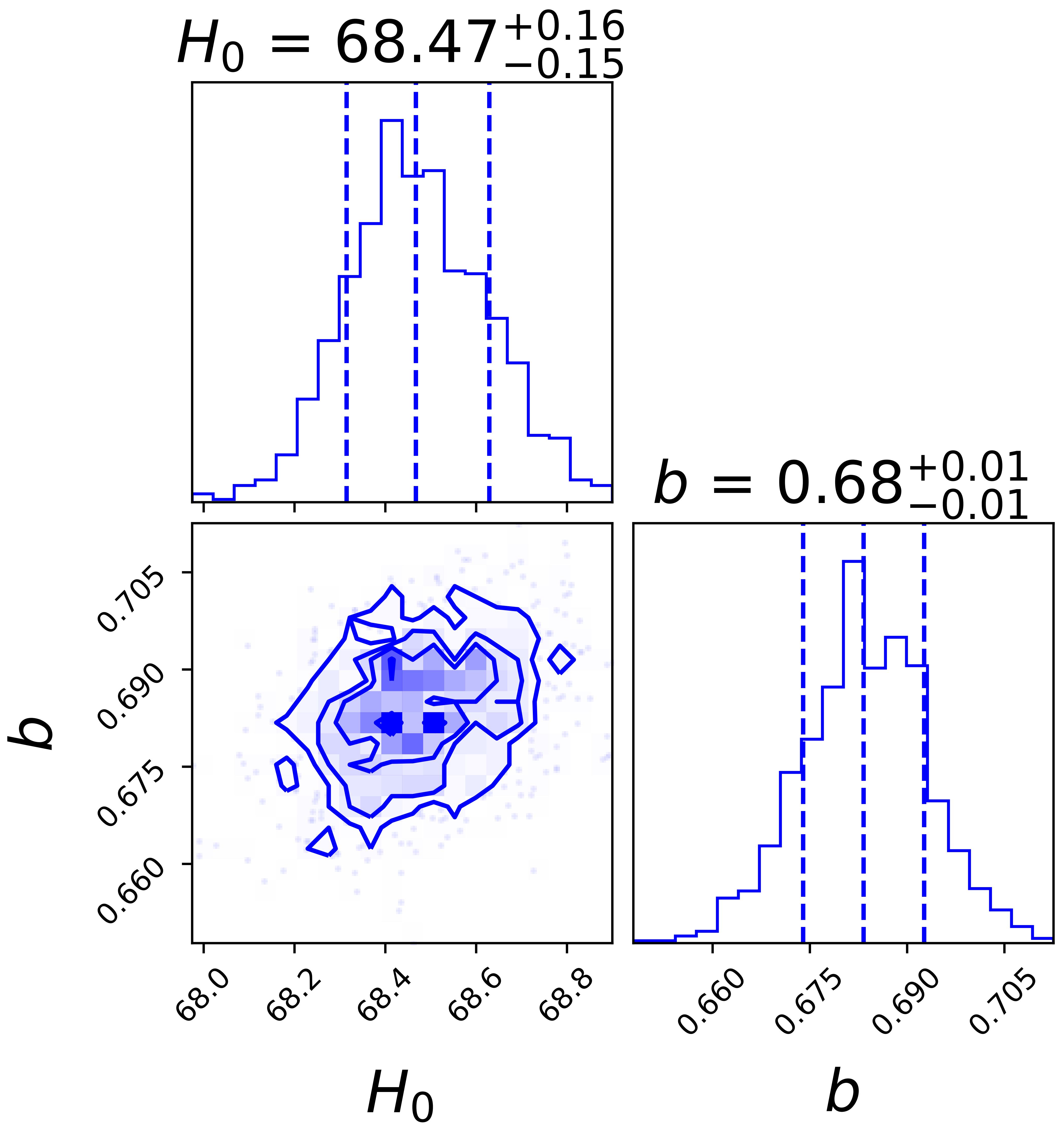
Priors: $H_0 \in [0,100]$
$b \in [0,4]$

Modified Gravity: Exponential



Priors: $H_0 \in [0,100]$

$b \in [0,4]$

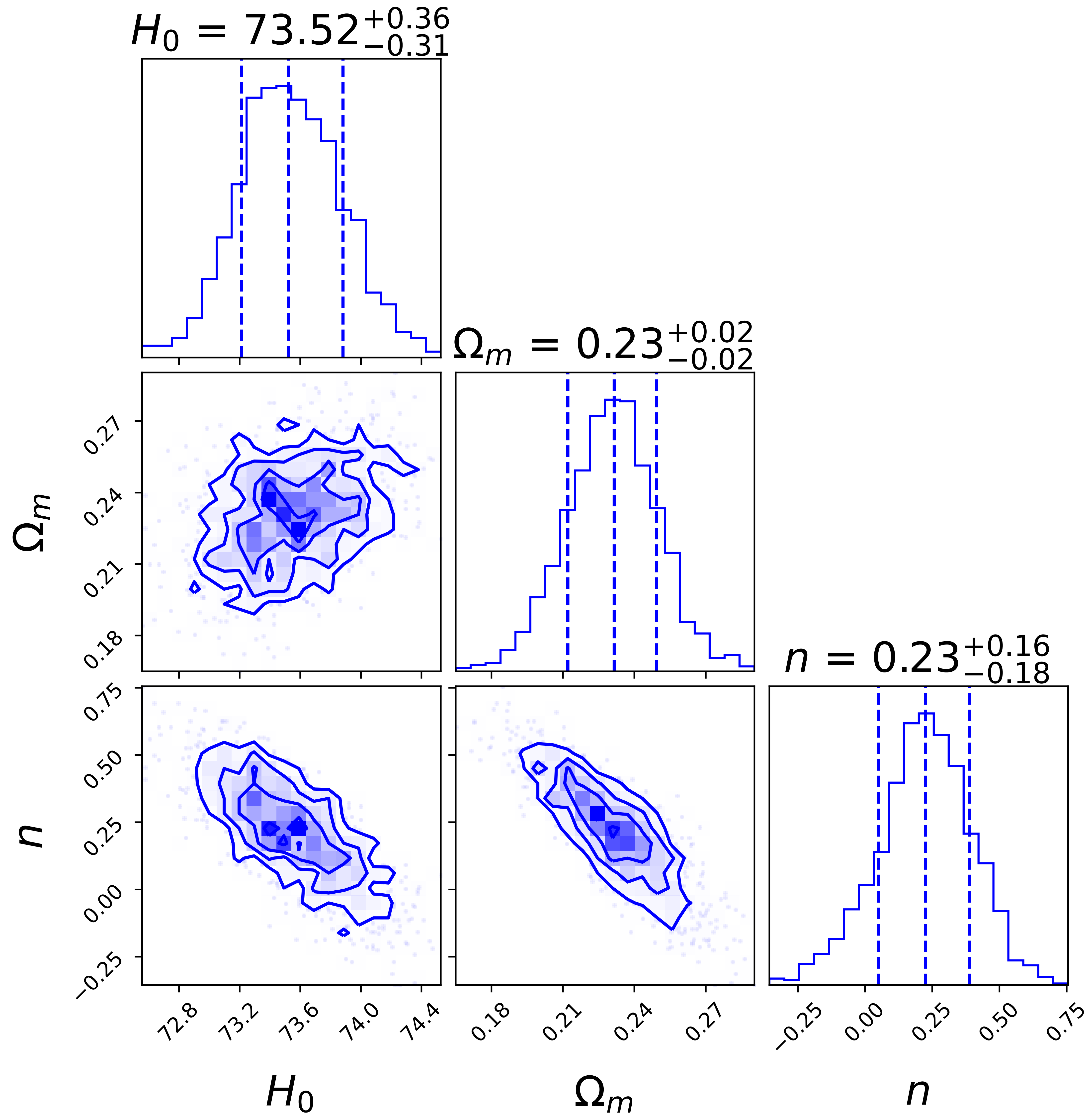


Modified Gravity: Logarithmic

Priors: $H_0 \in [0,100]$

$b \in [0,0.8]$

Backreaction

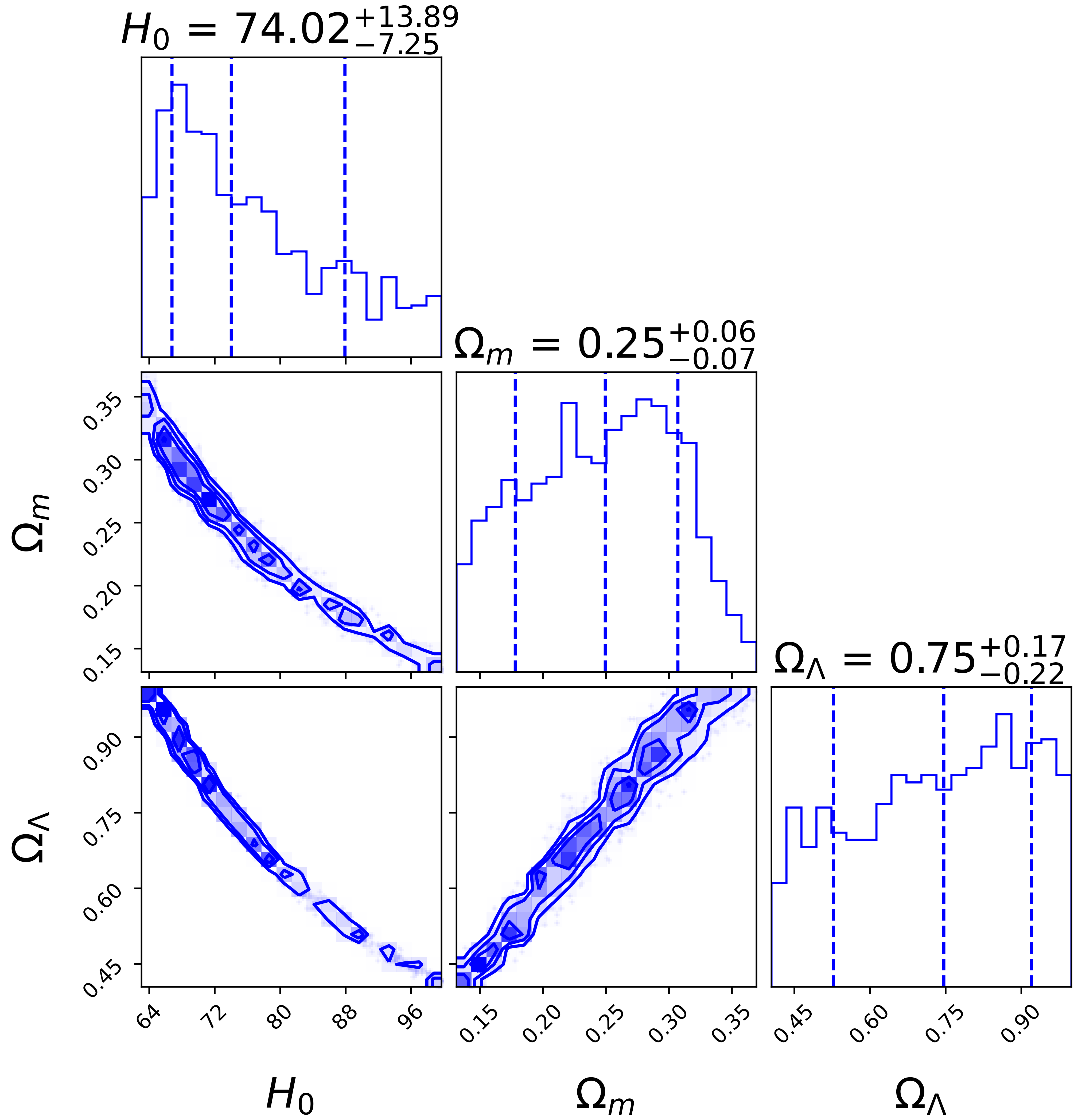


Priors: $H_0 \in [0,100]$

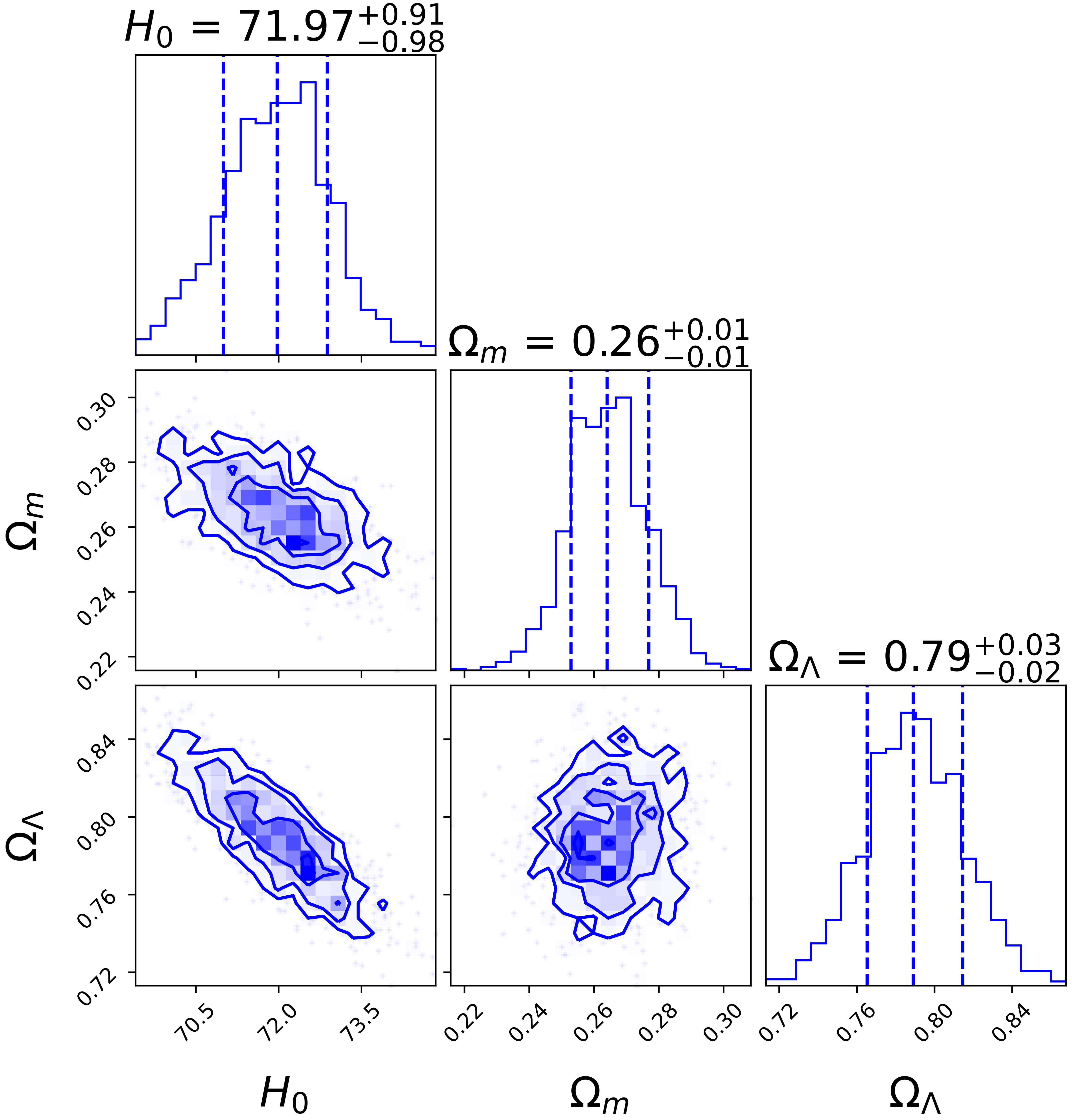
$\Omega_m \in [0,1]$

$n \in [-4,4]$

Effects of Prior

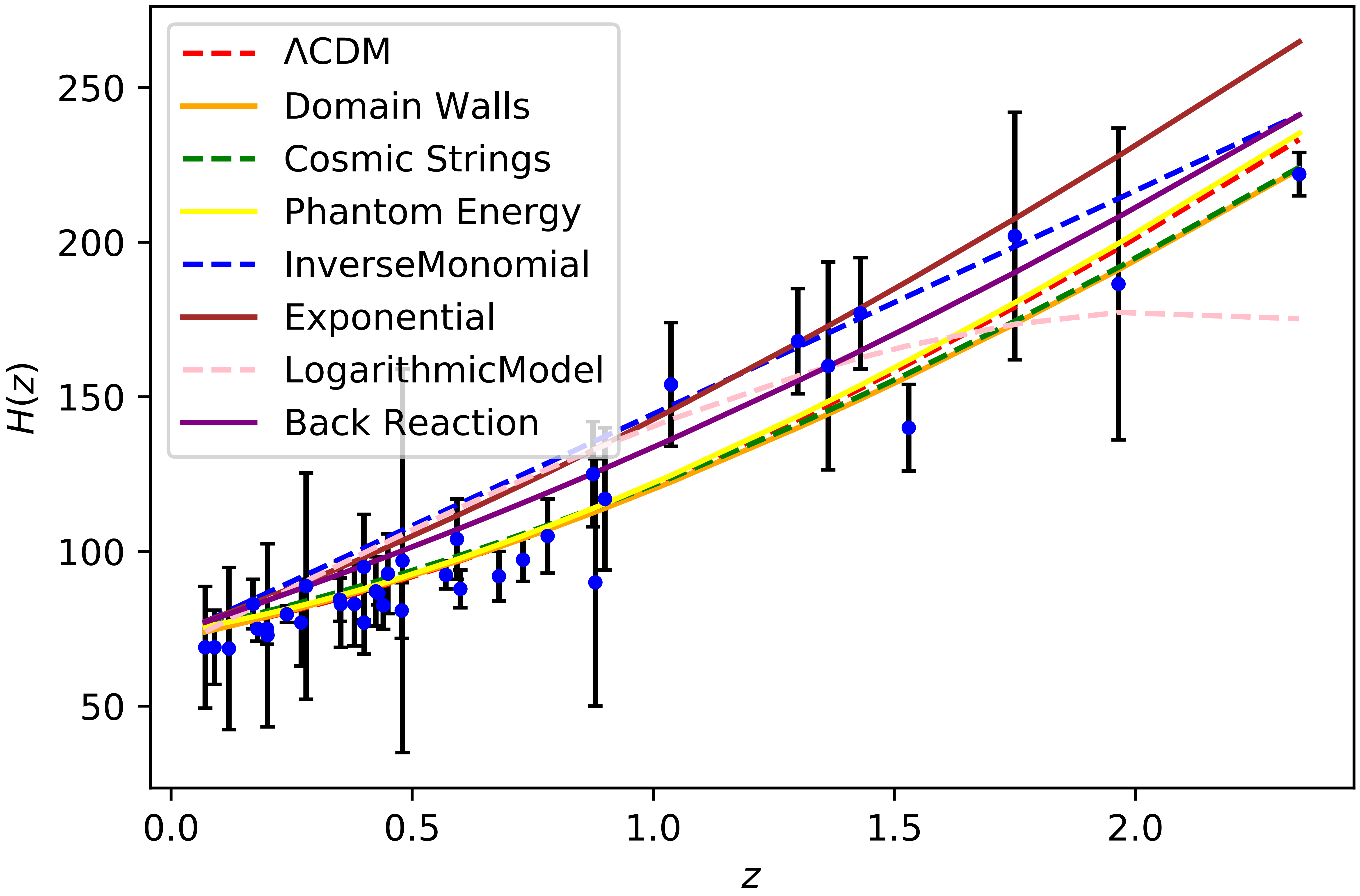


Uniform Prior

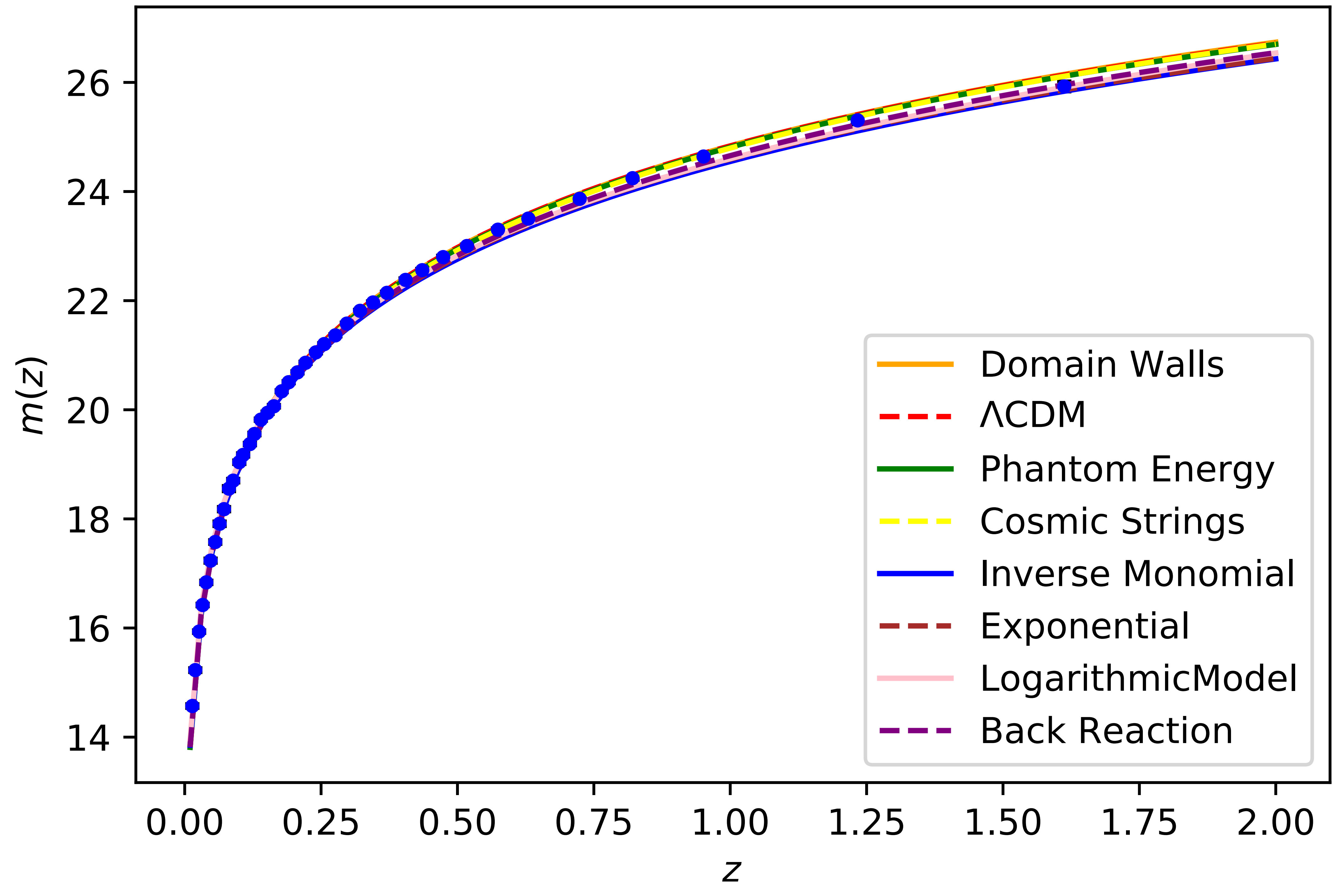


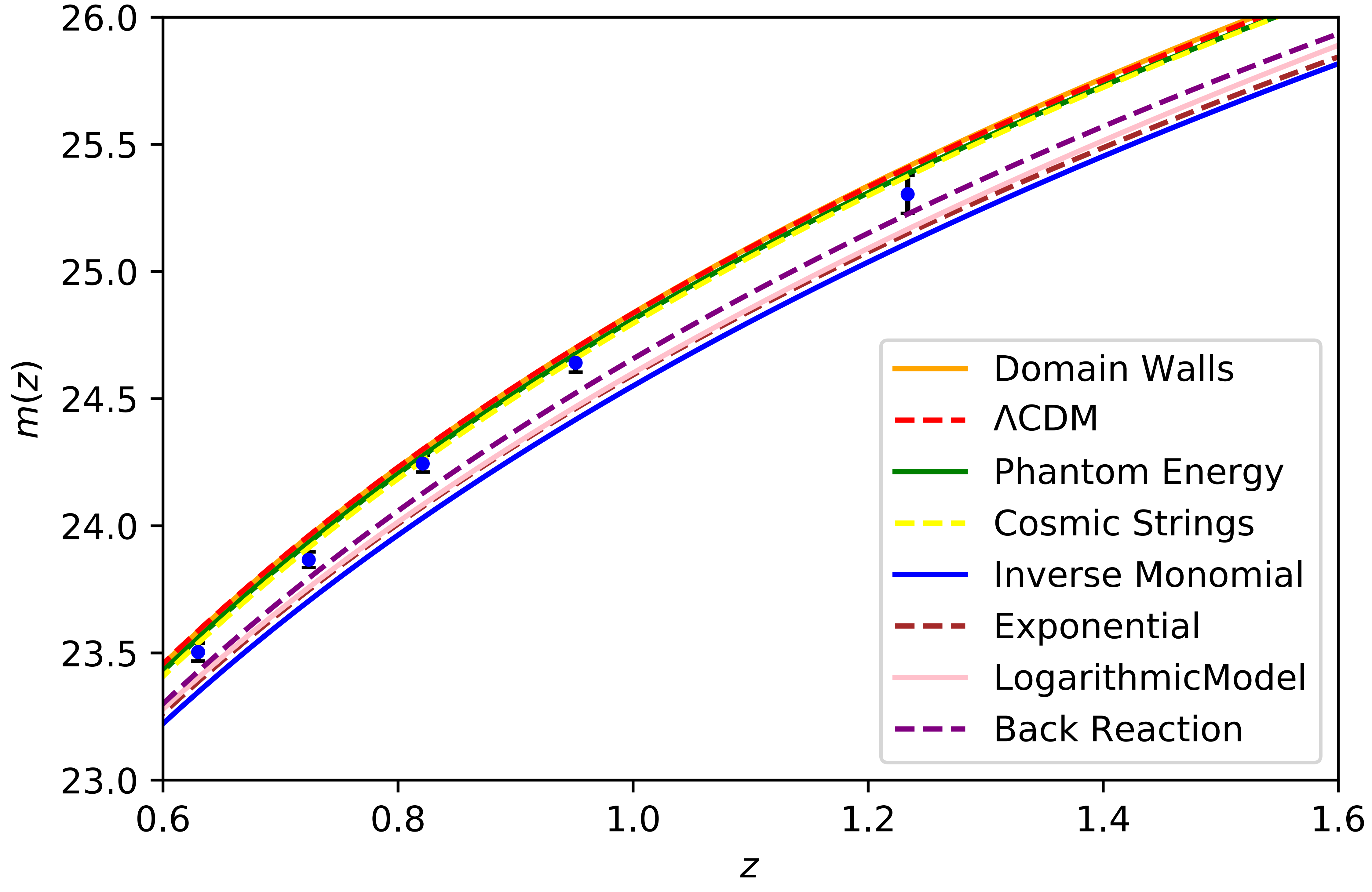
Gaussian Prior

Best-Fit Plots: Hubble function



Best-Fit Plots: Apparent magnitude





Rankings

Rankings

	MODEL	BAYES FACTOR
"Disqualified"	**Mod. Grav. Inv. Mon.** $f(z, b)$	15.452 ± 0.385 **Strong preference for LCDM**
	Mod. Grav. Log. $f(z, b)$	220.721 ± 0.436 **Super strong preference for LCDM**

Rankings

	MODEL	BAYES FACTOR	
	LCDM		
1st	Domain Walls	-0.677 ± 0.381	Inconclusive
	Cosmic Strings	-0.65 ± 0.591	Inconclusive
	Mod. Grav. Exp. $f(z, b)$	-0.196 ± 0.374	Inconclusive
2nd	Backreaction	1.34 ± 0.428 Weak preference for LCDM	
3rd	Phantom Energy	4.12 ± 0.45 Moderate preference for LCDM	

THANK YOU