Studying Early Dark Energy models from different approaches

Cosmology from Home

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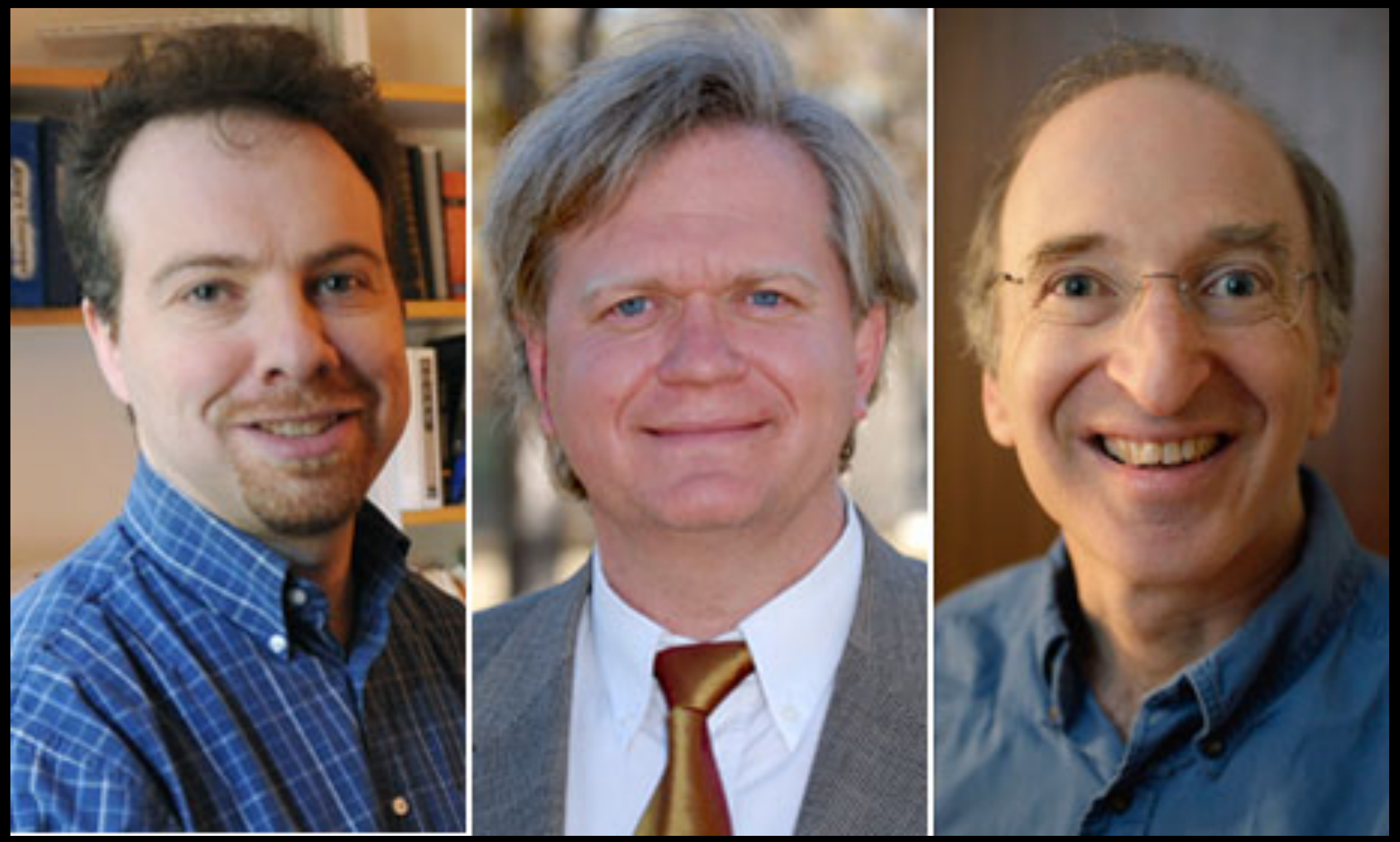
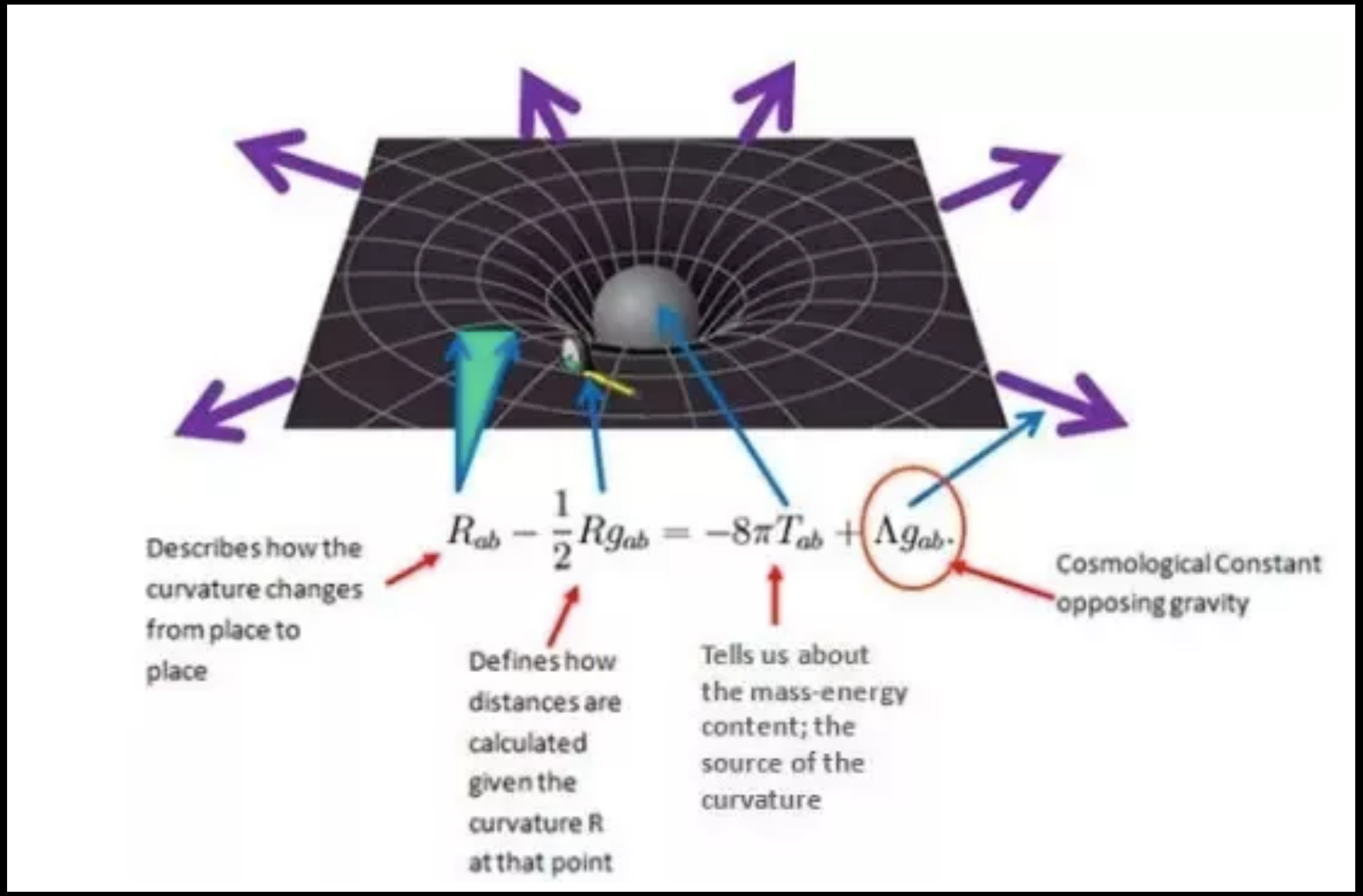
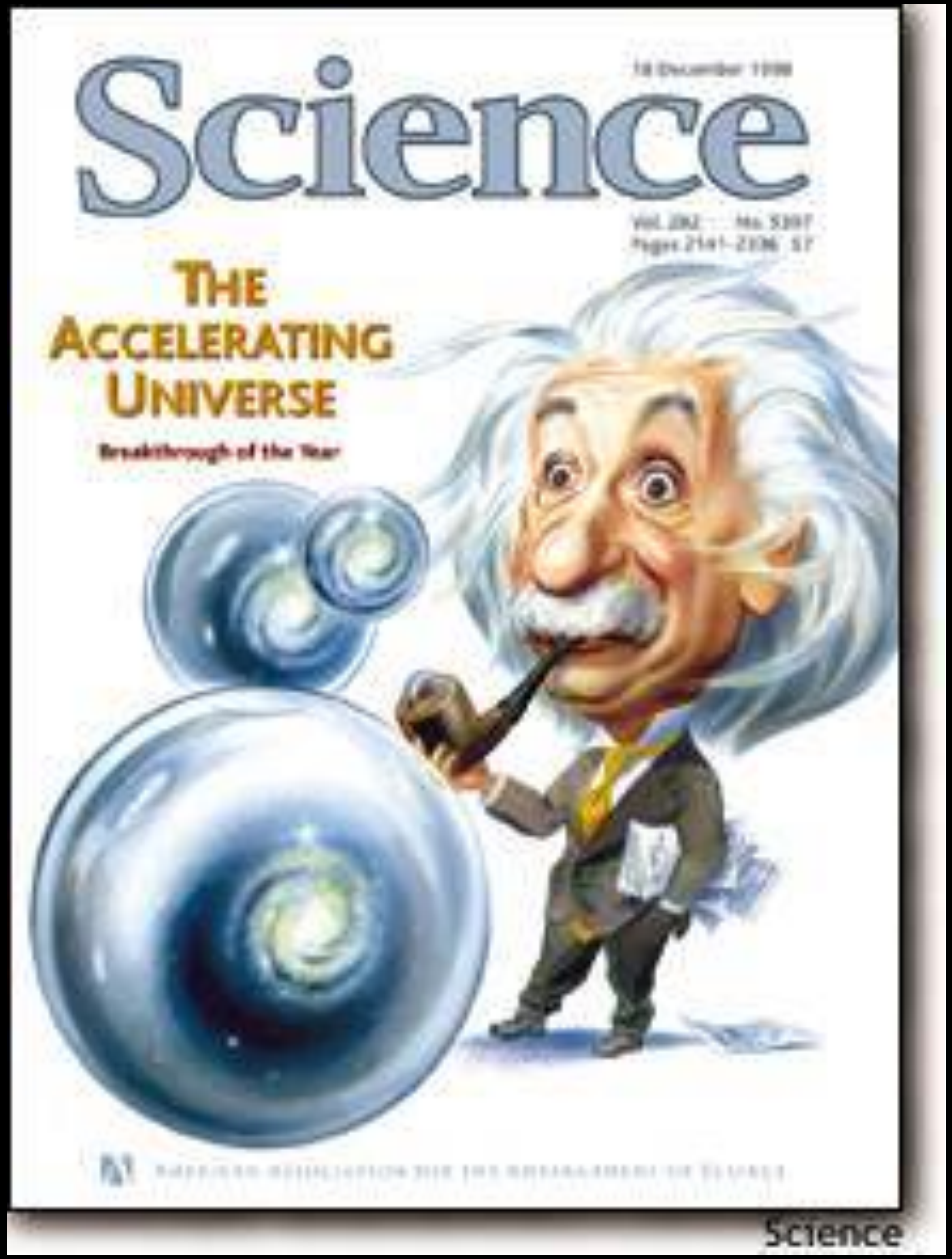
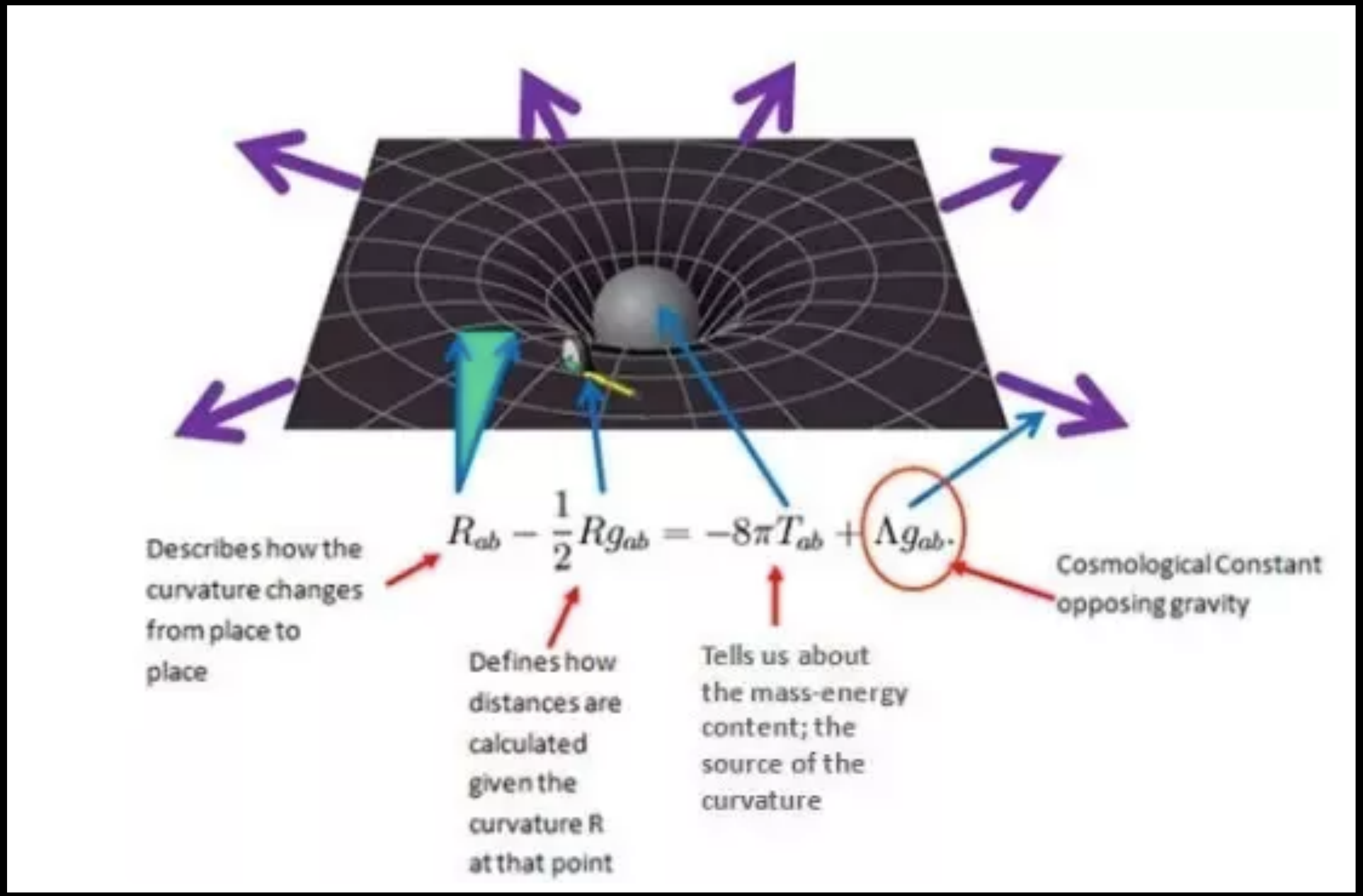
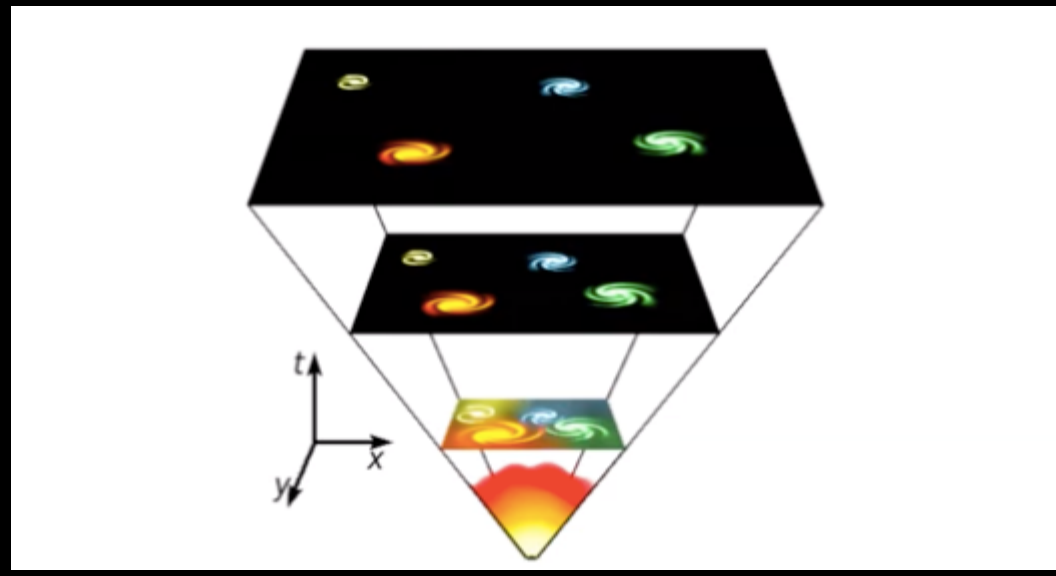


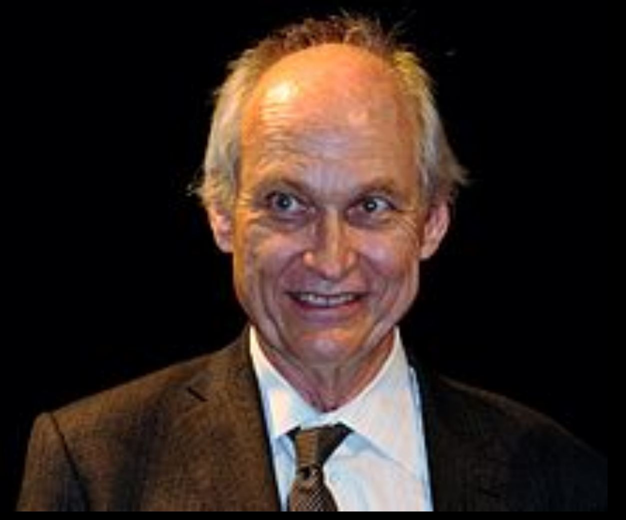
Adam Riess Brian Schmidt Saul Perlmutter

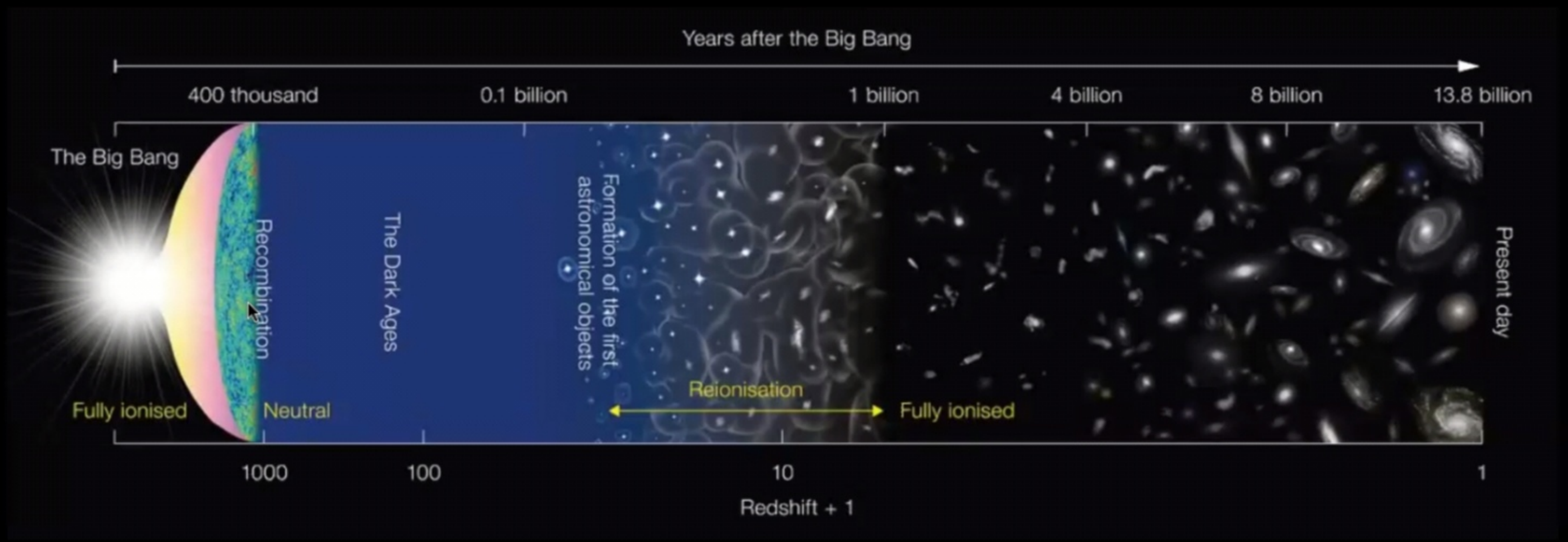


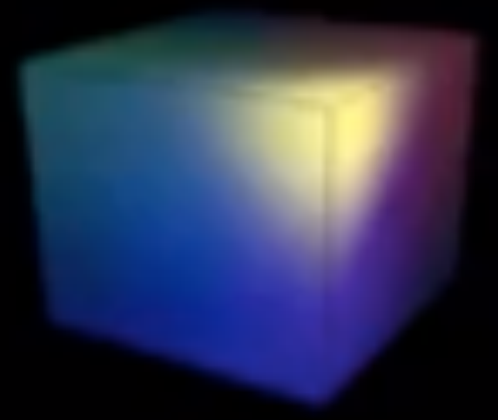












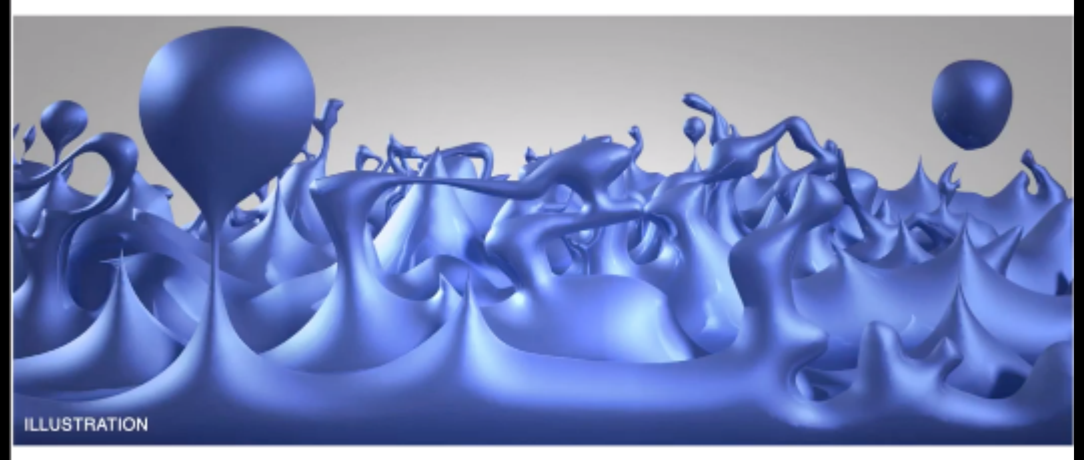
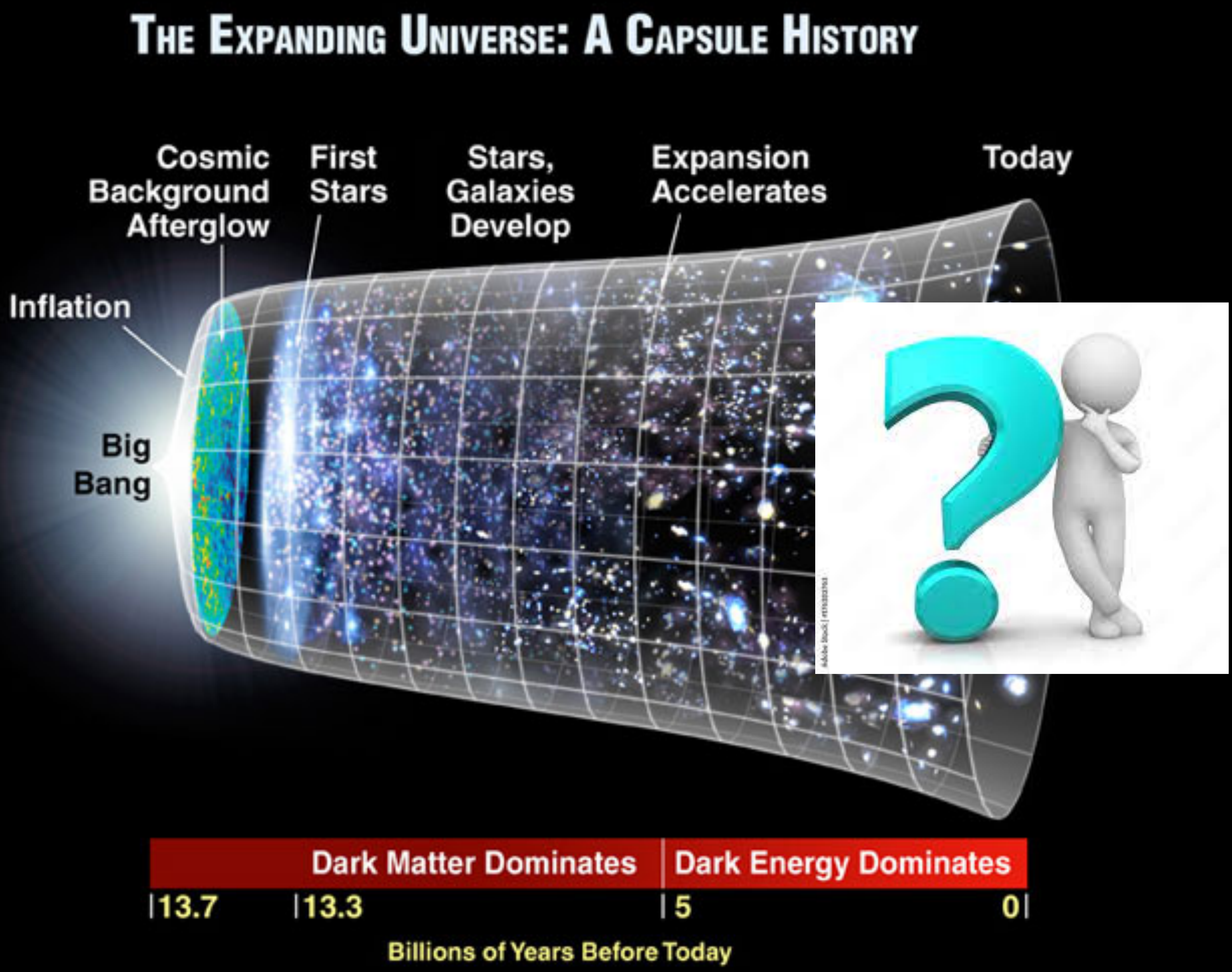
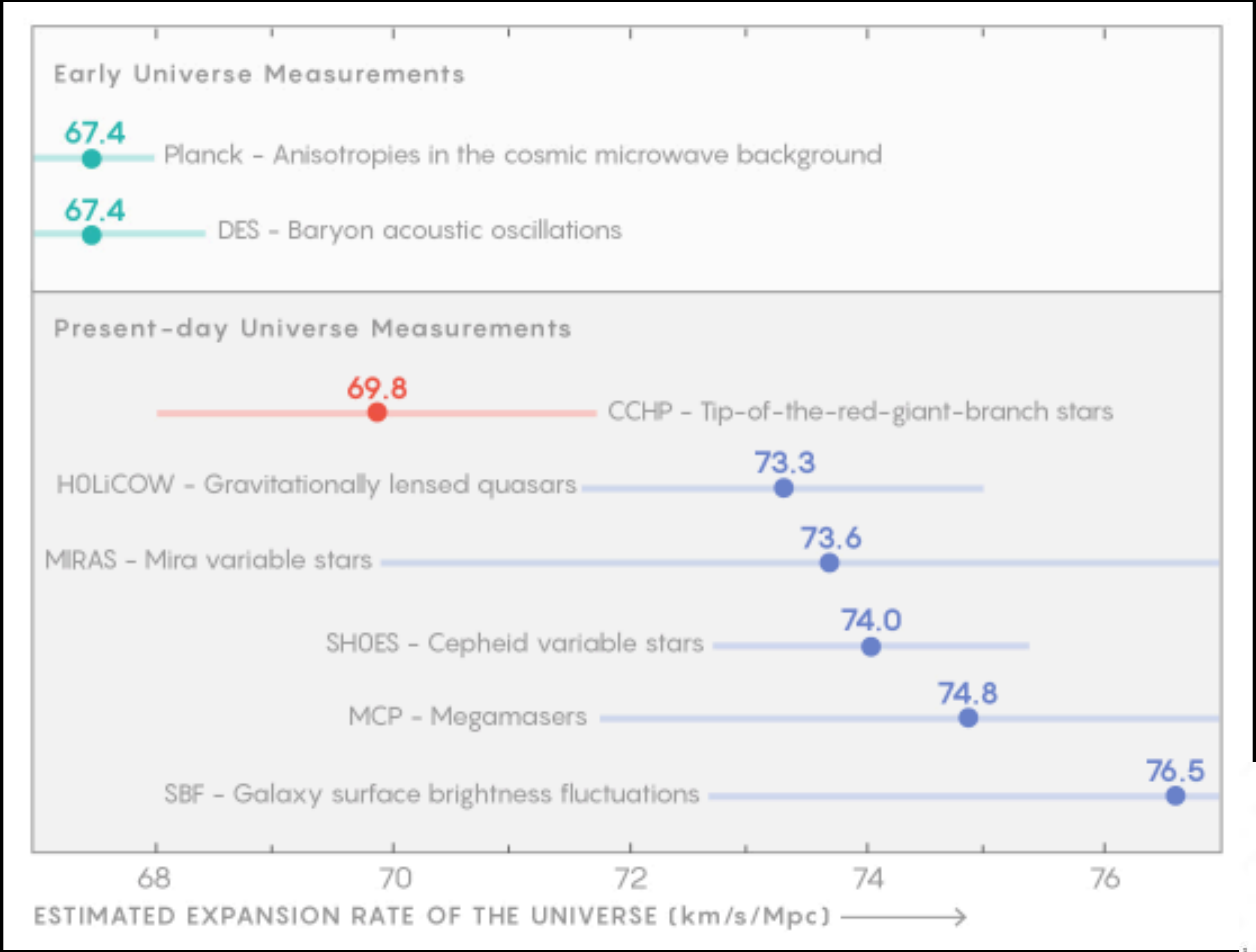


Image Credit: NASA/CXC/M. Weiss


THE EXPANDING UNIVERSE: A CAPSULE HISTORY
Cosmic Background Afterglow
First Stars
Stars, Galaxies Develop
Expansion Accelerates
Today
Inflation
Big Bang
Dark Matter Dominates
Dark Energy Dominates
13.7
13.3
5
0
Billions of Years Before Today

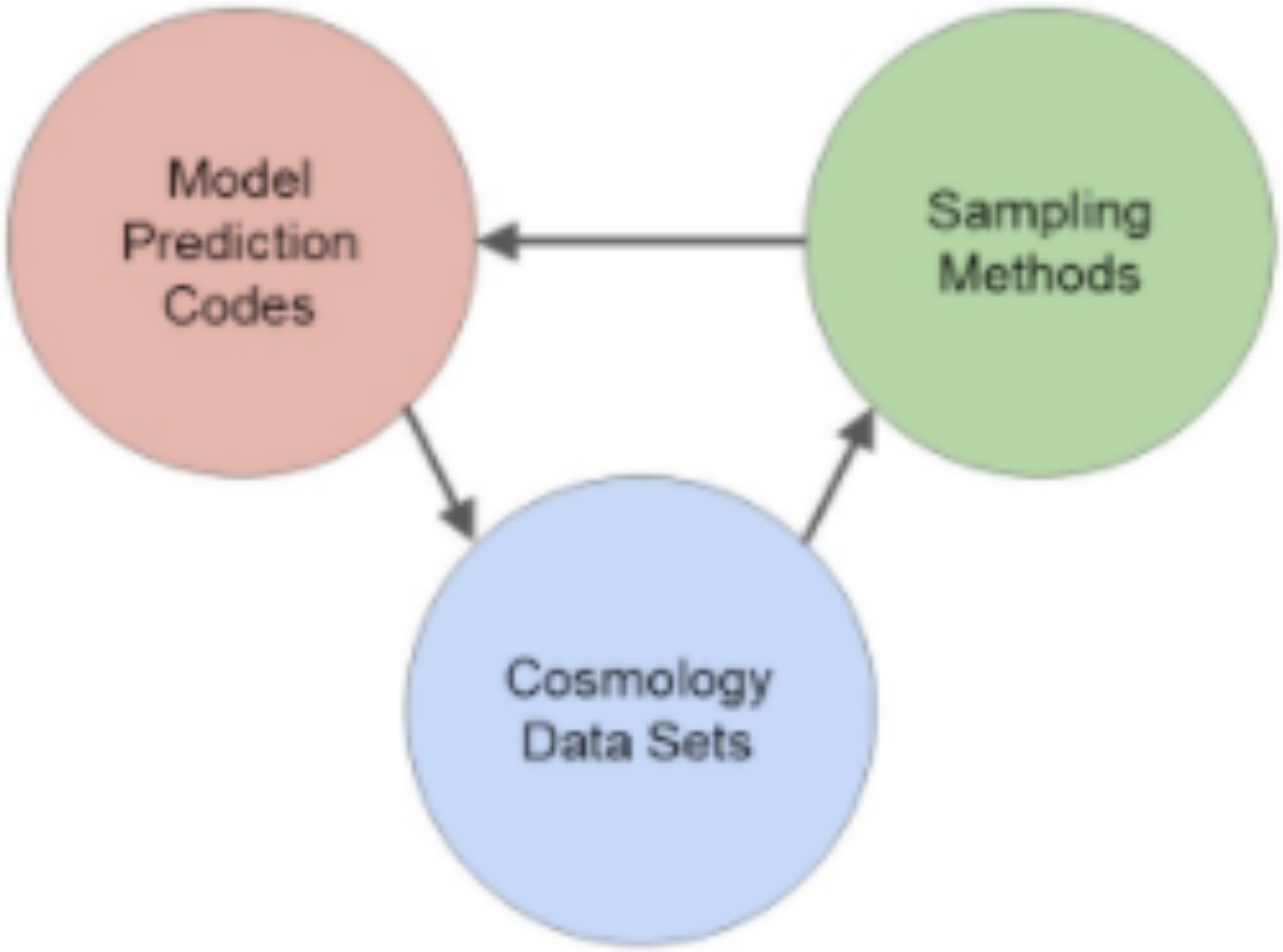
Credits: NASA Goddard


Early Universe Measurements
67.4
Planck - Anisotropies in the cosmic microwave background
67.4
DES - Baryon acoustic oscillations
Present-day Universe Measurements
69.8
CCHP - Tip-of-the-red-giant-branch stars
73.3
H0LiCOW - Gravitationally lensed quasars
73.6
MIRAS - Mira variable stars
74.0
SH0ES - Cepheid variable stars
74.8
MCP - Megamasers
76.5
SBF - Galaxy surface brightness fluctuations
68
70
72
74
76
ESTIMATED EXPANSION RATE OF THE UNIVERSE (km/s/Mpc)

CosmoSIS

* CosmoSIS is a cosmological parameter estimation code. Version 1.6.

* It consolidates and connects together existing code for predicting cosmic observables, and makes mapping out experimental likelihoods with a range of different techniques much more accessible.

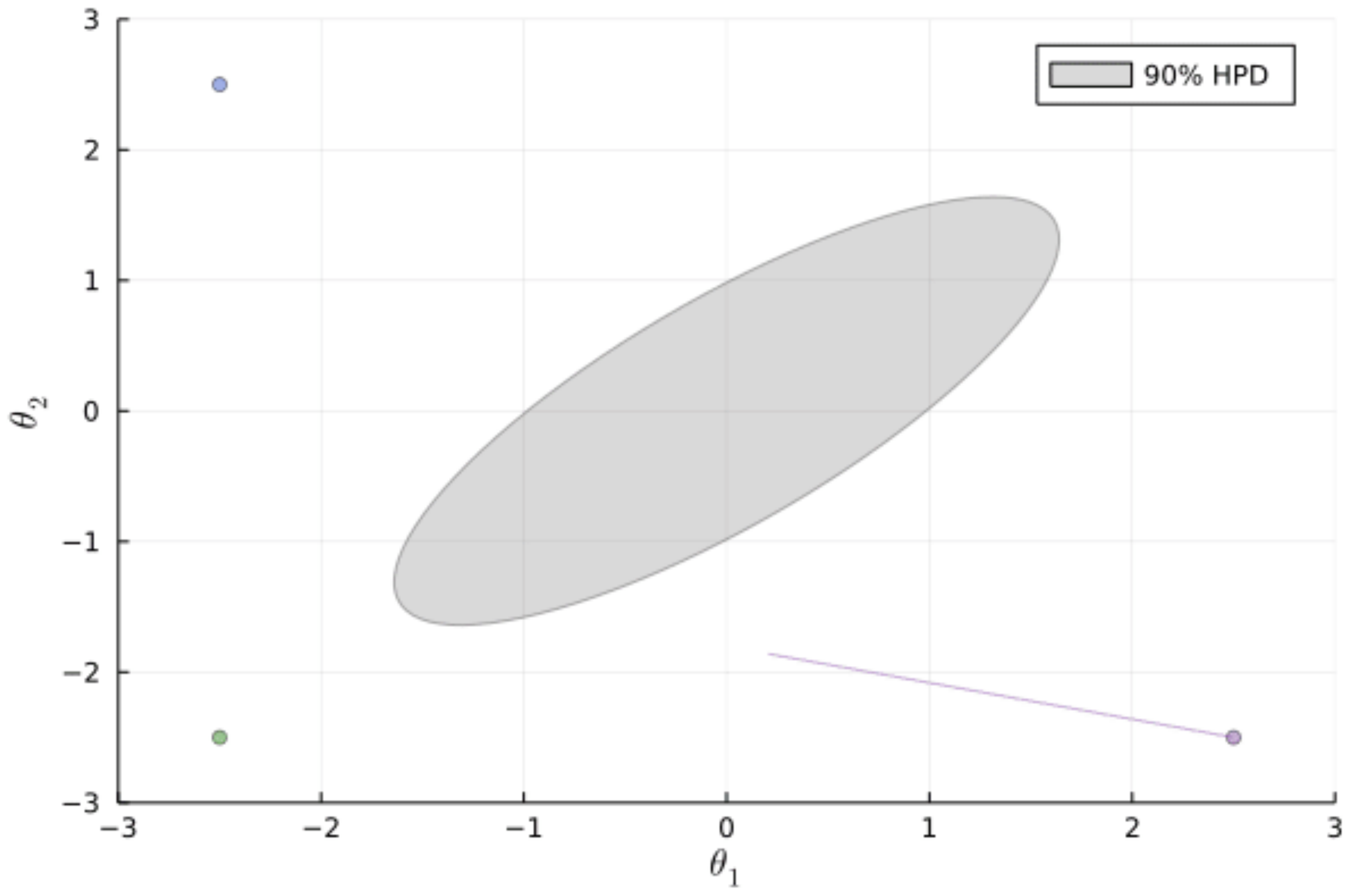


Zuntz et al. 2014

Sampler: EMCEE

Monte-Carlo Markov Chain that uses an ensemble of 'walkers' that explore the parameter space. Each walker chooses another walker at random and proposes along the line connecting the two of them using the Metropolis acceptance rule. The proposal scale is given by the separation of the two walkers.

Parameter	Type	Meaning	Default
walkers	integer	number of walkers in the space	
samples	integer	number of jumps to attempt per walker	
nsteps	integer	number of sample steps taken in between writing output	
random_start	bool	whether to start the walkers at random points in the prior instead of near the start. Usually a bad idea	N
start_points	string	a file containing starting points for the walkers. If not specified walkers are initialized randomly from the prior distribution.	(empty)
covmat	string	a file containing a covariance matrix for initializing the walkers.	(empty)



PASP, 125, 925, 306-312

CosmoSIS + EMCEE sampler hiperparameters

Walkers: 1024

Samples: 1000

Nsteps: 20

Random start: True

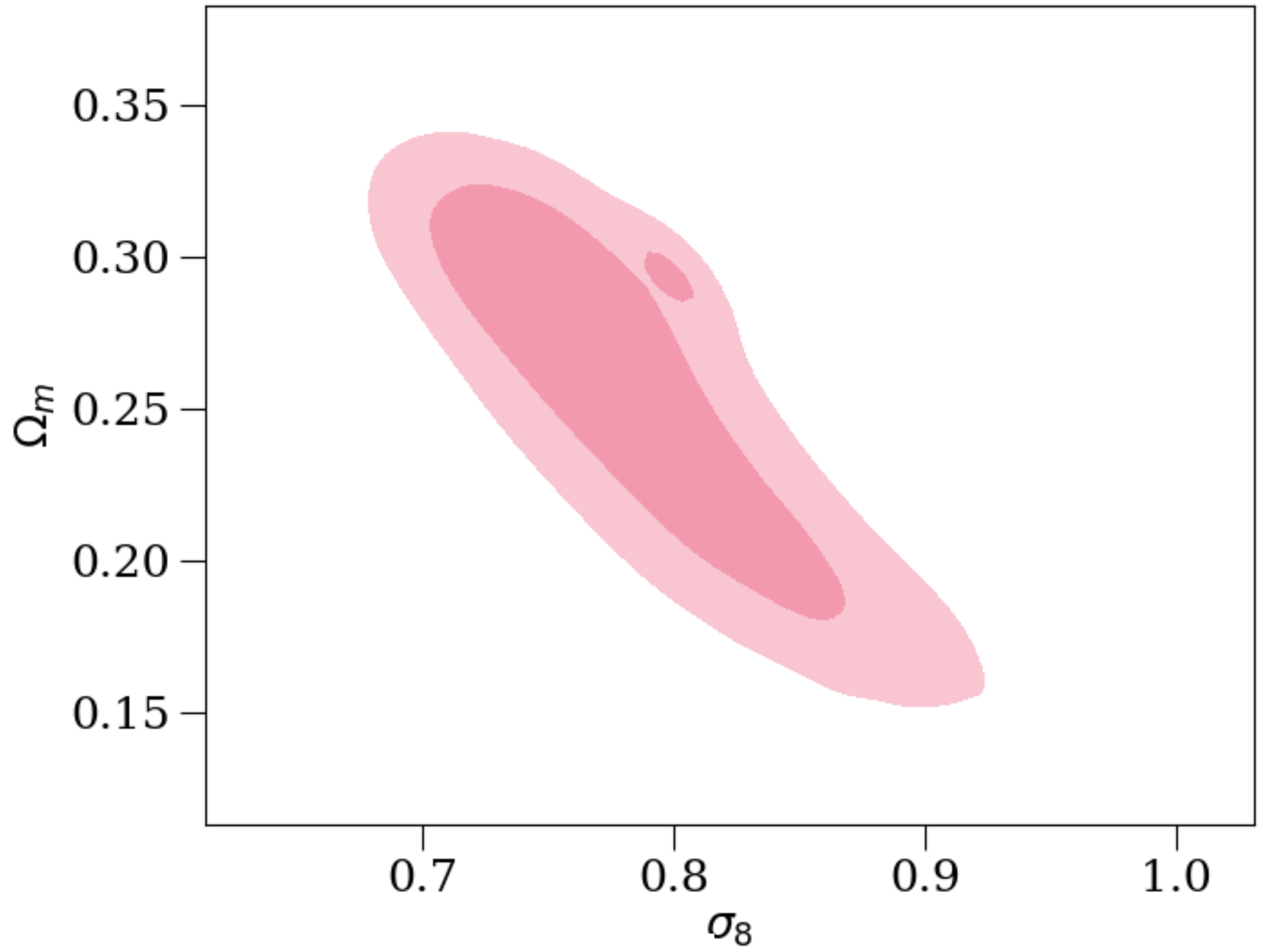
Additional packages: Consistency, CAMB, Growth Structure, SLTD

Minimum acceptance fraction: 0.25

Model 1. CPL

Linear evolution of the state equation with the scale factor a (Chevallier & Polarski 2001, Linder 2003).

$$\omega = \omega_0 + \omega' \cdot (1 - a)$$



Scolnic et al. 2018

Chuang et al. 2011; Beutler et al. 2012

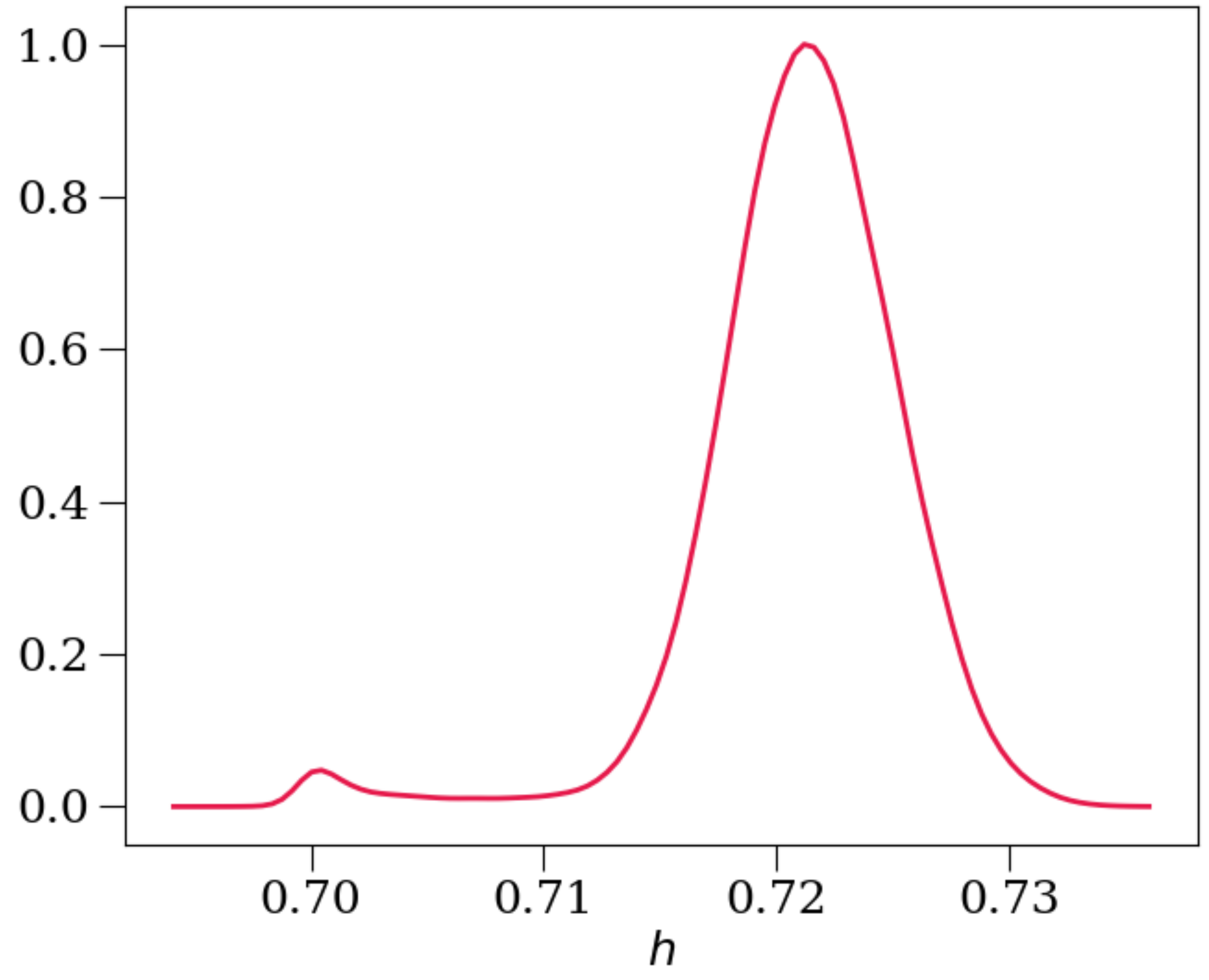
Alam et al. 2015

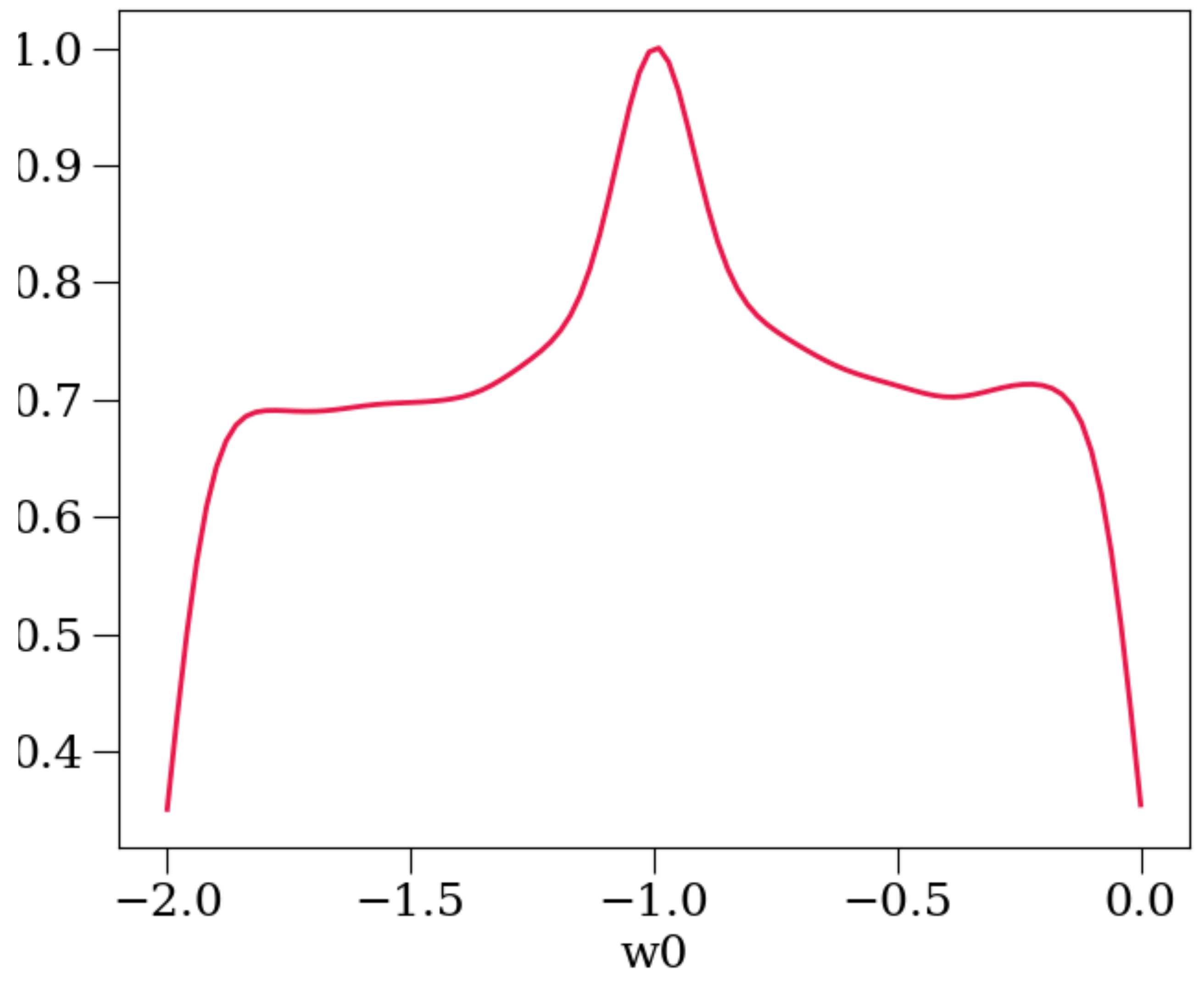
Beringer et al. 2012

Ade et al. 2013 Planck Collaboration

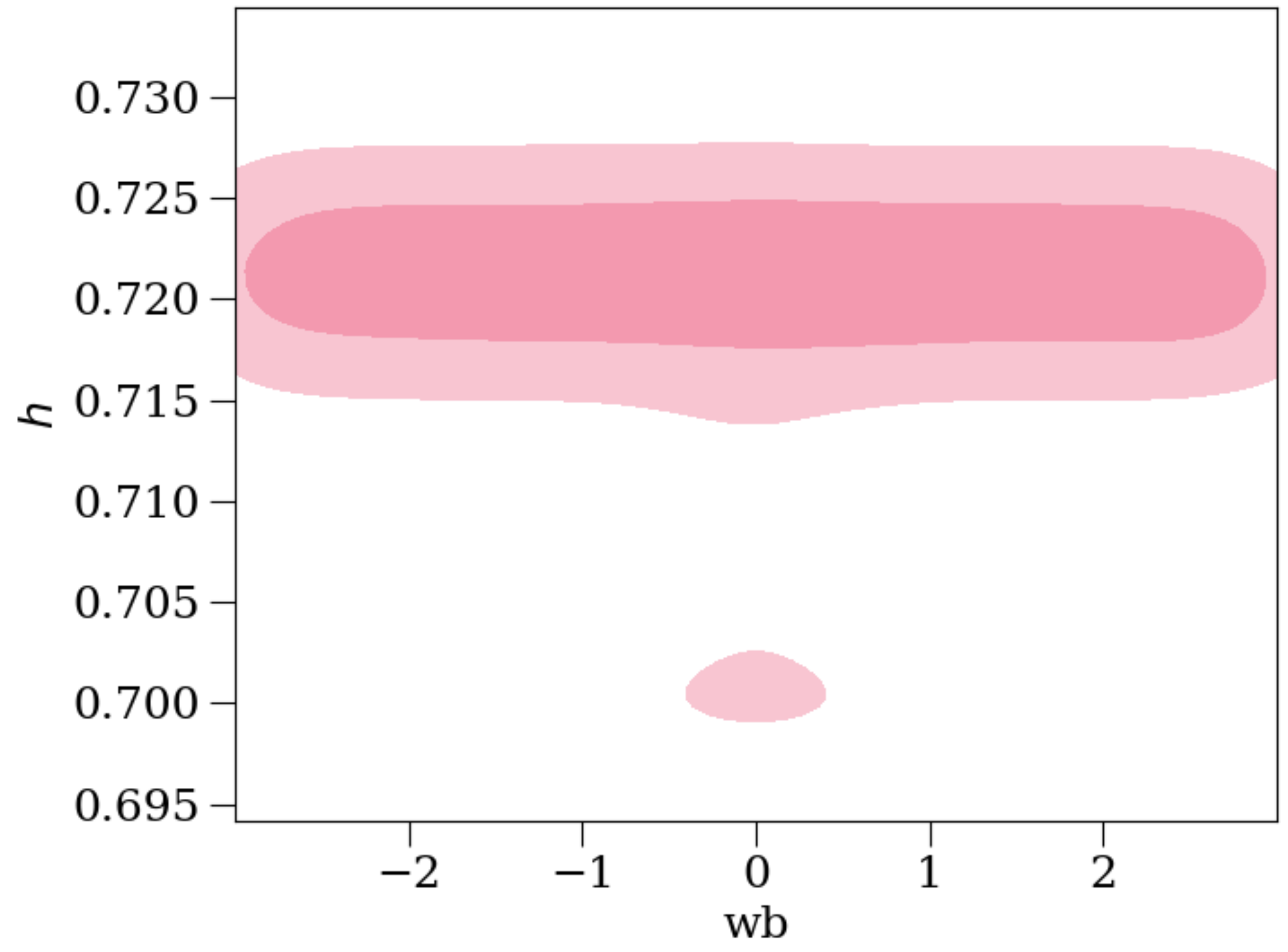
Riess et al. 2016

Suyu et al. 2018; Bonvin et al. 2017



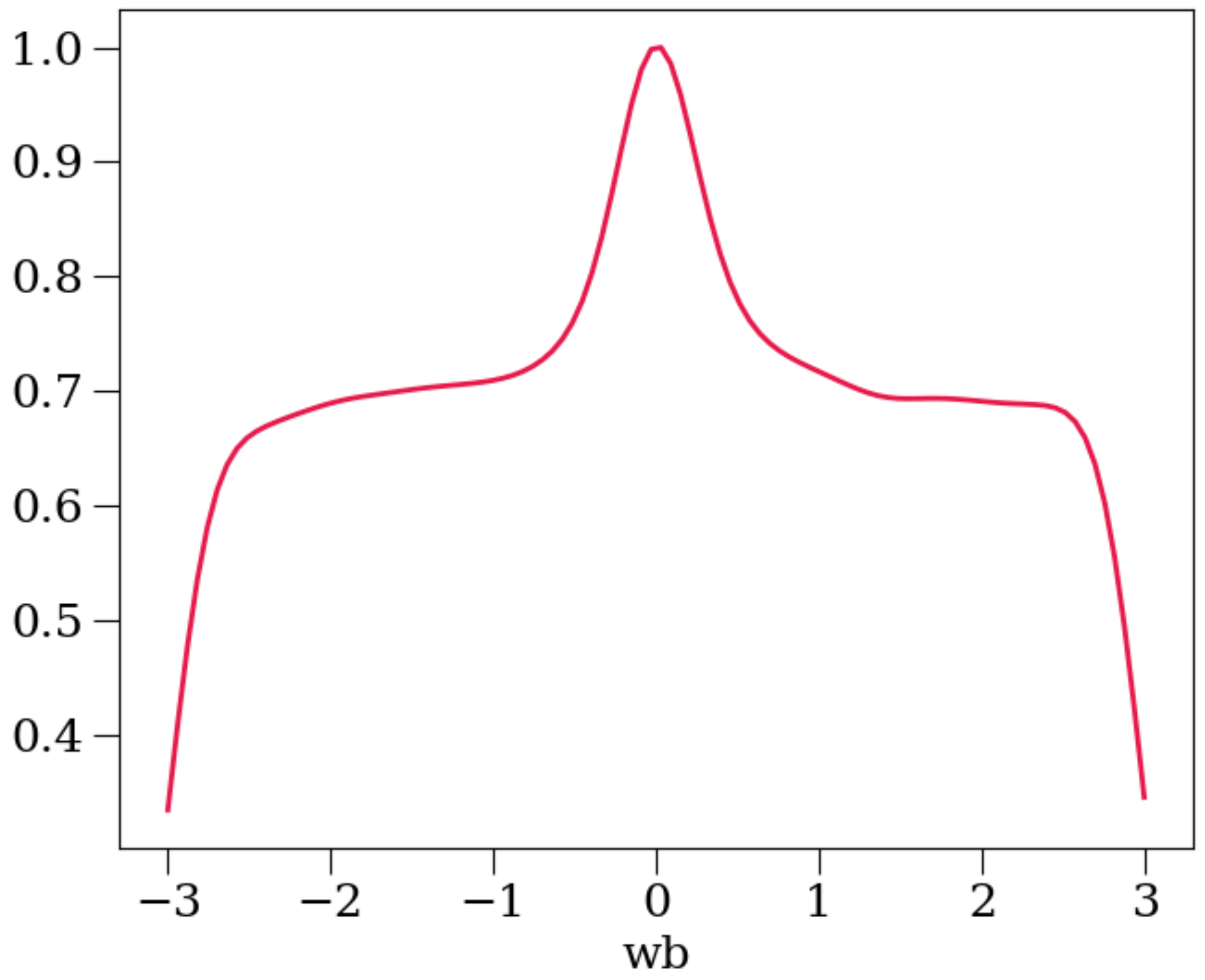


Model 2



Toy model with quadratic dependence with the scale factor a.

$$\omega = \omega_a + \omega_b \cdot a^2$$



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Suyu et al. 2018; Bonvin et al. 2017

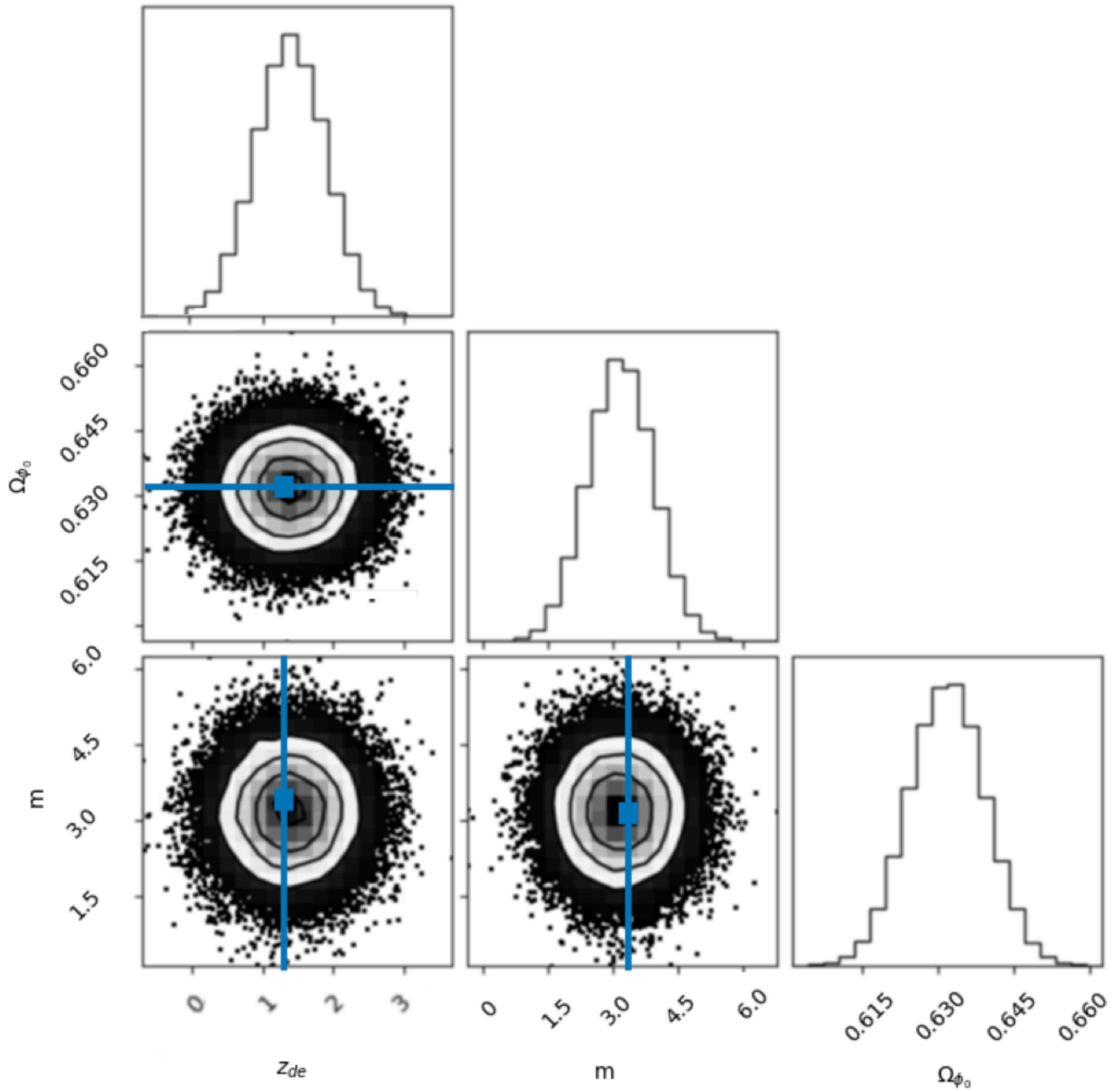
Model 3. First method

* Ω_ϕ should be strictly positive, [0,1] in the Concordance model.

* Negative values of **m** lead to an inverted transition between the radiation and the De-Sitter attractors (the latter occurring first than the former), which is not consequent with the thermal history of the Universe. On the other hand, $m = 0$ produces no transition whatsoever, then, **m** is strictly positive in the framework of the Standard Model.

* The redshift of matter - dark energy equality, z_{DE} has already occurred since the Universe is experiencing an accelerated expansion $0 < z_{de} < 1.5$. The upper limit takes into account that cosmic structure was formed during the matter domination epoch, and that has been observed through different with different surveys to-date 2dFGRS, 6dFGS, WiggleZ and the Sloan Digital Sky Survey SDSS.

García et al. 2021



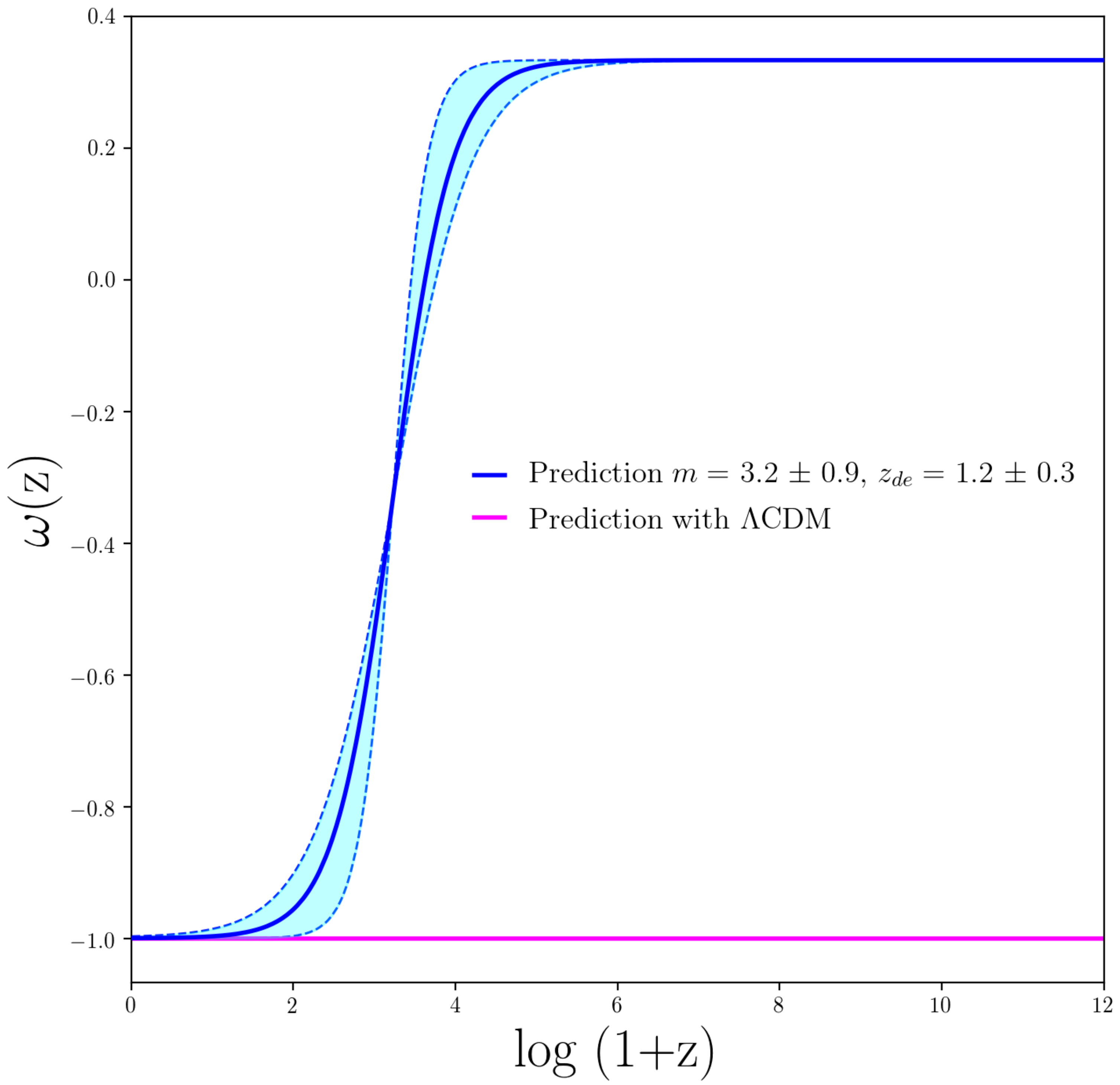
Model 3. First method

Summary of the best values of the free parameters of the DE model and comparison with the ΛCDM. Column 1: parameter name. Column 2: estimates for our model. Column 3: ΛCDM comparison (Planck Collaboration et al., 2018).

Parameter	Our model	ΛCDM model
Ω_{ϕ_0}	0.631 ± 0.005	0.6889 ± 0.0056
m	3.2 ± 0.9	–
z_{de}	1.2 ± 0.3	–
Ω_{m_0}	0.369 ± 0.005	0.3111 ± 0.0056
ω_0	-0.976 ± 0.358	-1

The equation of state of our early dark energy candidate is given by:

$$\omega_\phi(z) = \frac{4/3}{\left(\frac{1+z_*}{1+z}\right)^m + 1} - 1. \qquad z_* = \frac{z_{eq} + z_{de}}{2}$$



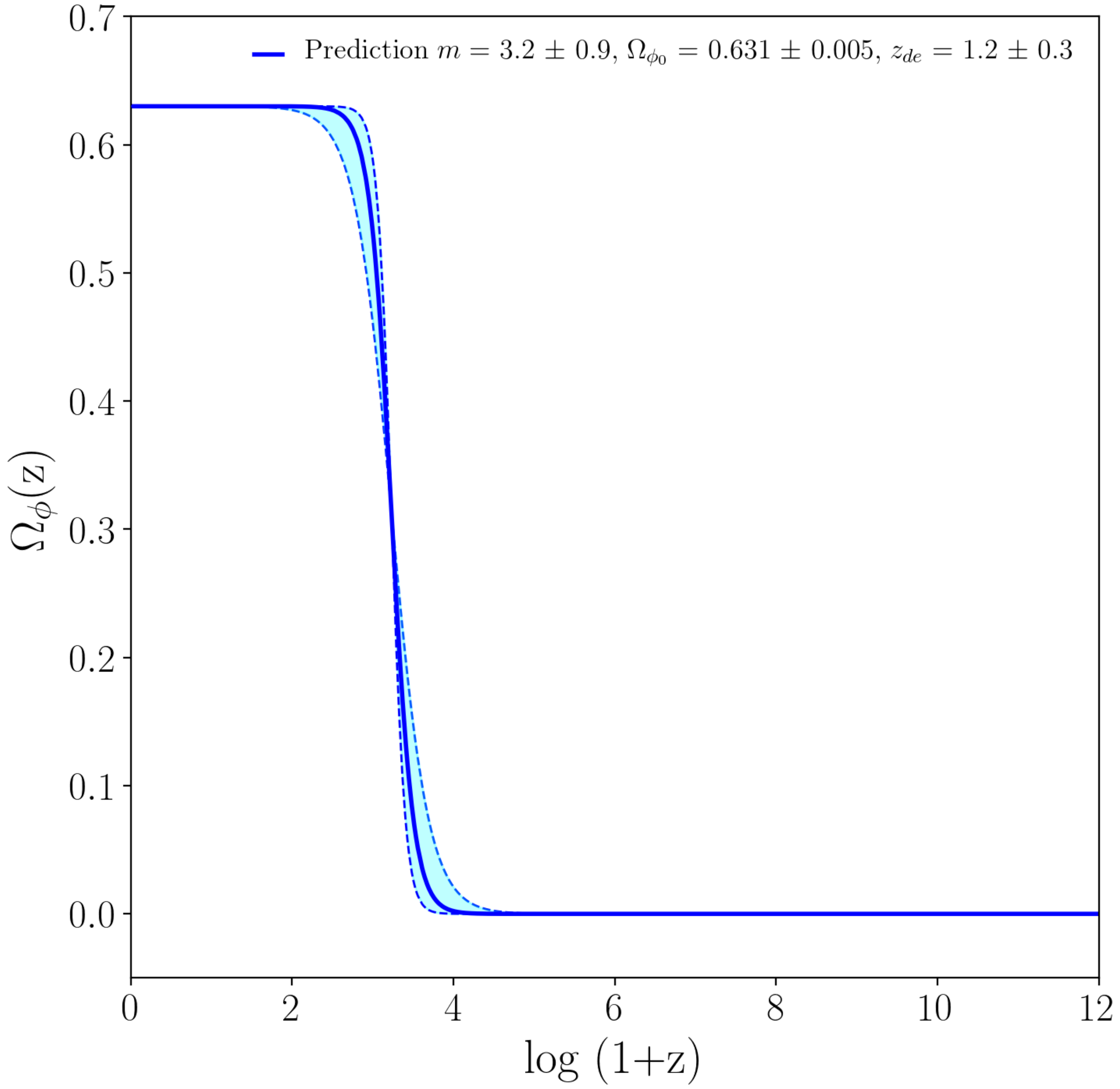
Equation of state w(z) as a function of redshift z.

The energy density fraction associated with the dark energy field is:

$$\Omega_\phi(z) = \frac{\rho_0}{\rho_{\rm cr}} = \frac{\Omega_{\phi 0} \cdot f(z)}{\Omega_{\phi 0} \cdot f(z) + \Omega_{m0} \cdot (1+z)^3}.$$

The age of the Universe in the framework of a dark energy component is:

$$t_0 = 13.441 \pm 0.004 \ \ \text{Gyr}.$$



Dark energy density fraction evolution with redshift z.

García et al. 2021

Model 3 with CosmoSIS

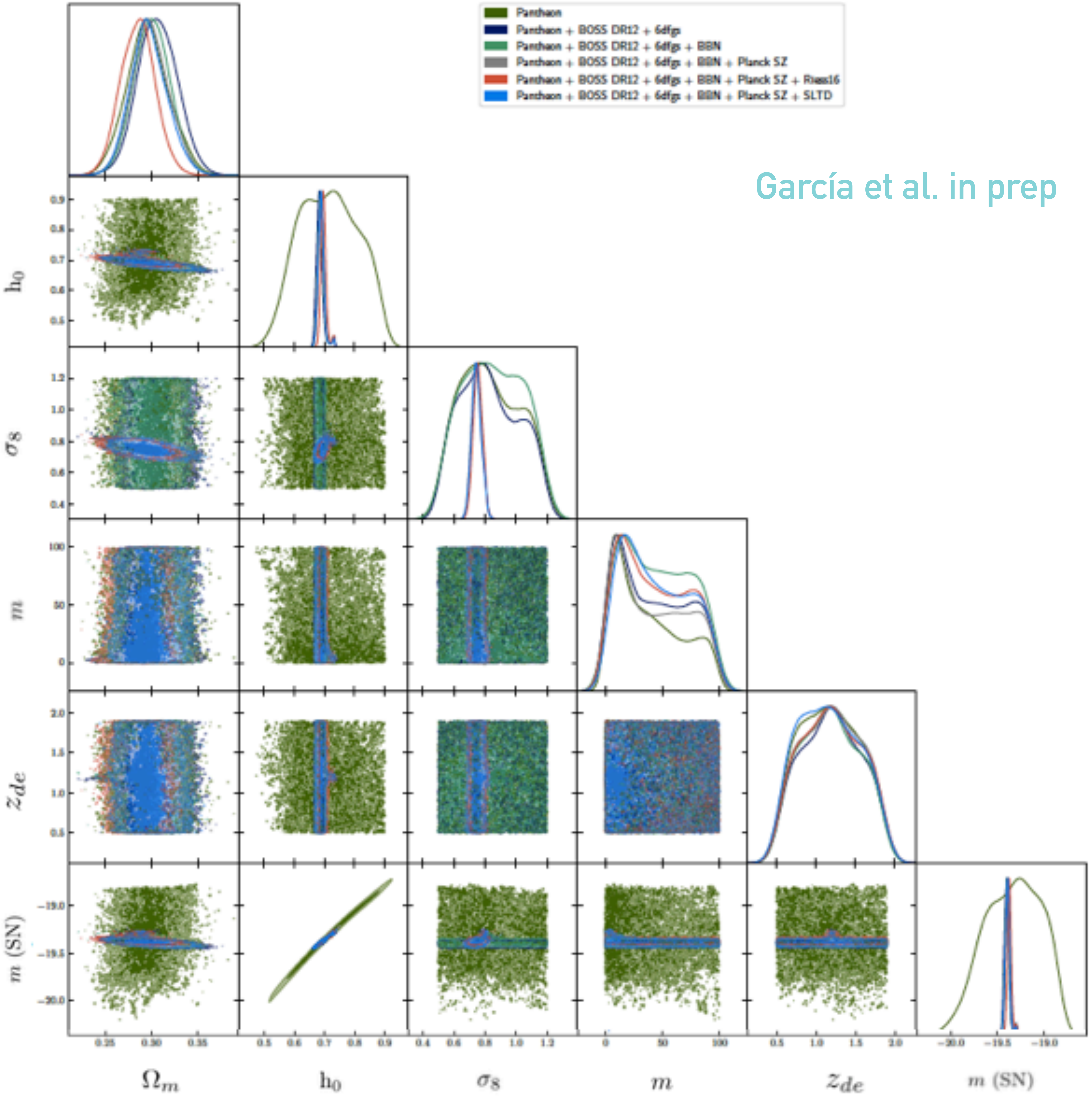
Using the concordance cosmology, we skip computing the value of Ω_ϕ. Instead, we explore the parameter space for Ω_m, and set Ω_k = 0.

$$\omega(z) = \frac{4/3}{\left(\frac{1+z_*}{1+z}\right)^m + 1} - 1$$

$$z_* = \frac{z_{eq} + z_{DE}}{2}$$

Work in collaboration with Prof. Leonardo Castañeda

(Universidad Nacional de Colombia)



García et al. in prep

Model 4. Modified Chaplygin gas

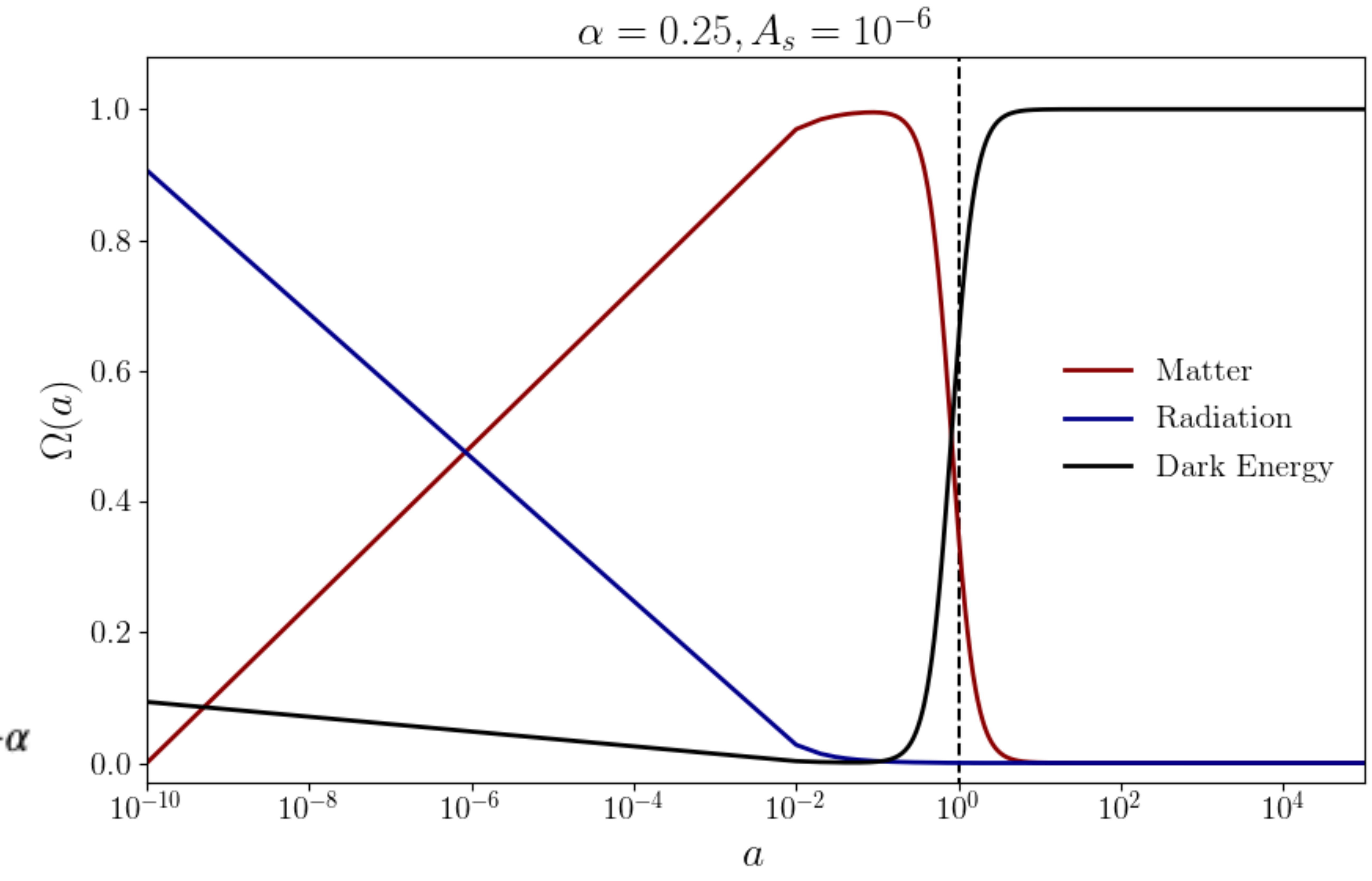
$$\mathcal{L}_{nled} \equiv -\mathcal{F}\, f(\mathcal{F})$$

$$f(\mathcal{F}) = \left(\beta \mathcal{F}^{-(1+\alpha)} + 1\right)^{\frac{1}{1+\alpha}}$$

$$p = \frac{1}{3}\rho\left(1 - 4\frac{\beta}{\rho^{1+\alpha}}\right)$$

$$\beta = (1 - A_s)\rho_{de,0}^{1+\alpha} = (1 - A_s)(\Omega_{de,0}\rho_{\text{crit}})^{1+\alpha}$$

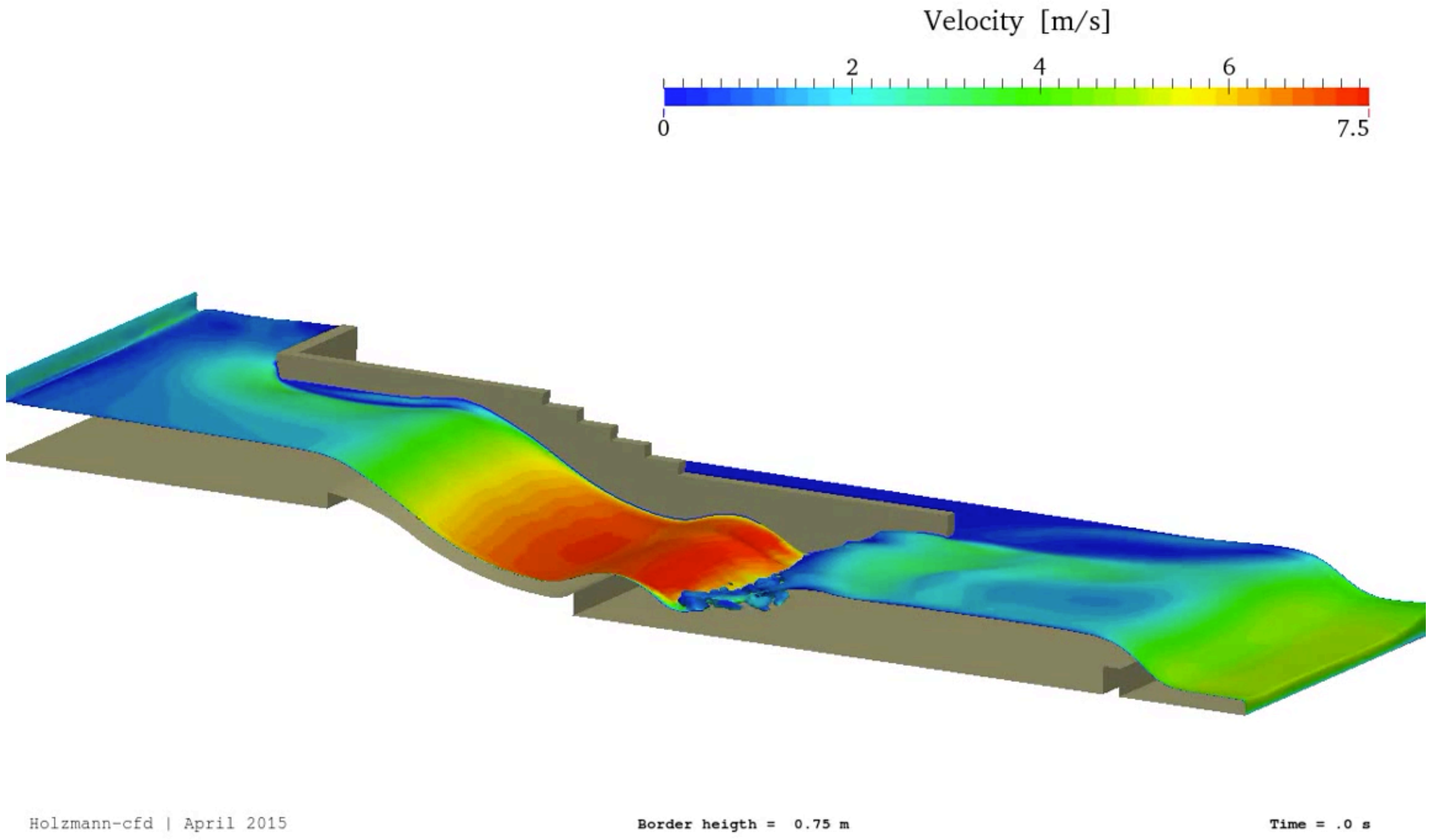
with $\rho_{\text{crit}} = 1.88\times10^{-29}\ \mathrm{h}_0^2 \cdot \mathrm{g} \cdot \mathrm{cm}^{-3}$.



CFD and OpenFoam

Computational Fluid Dynamics (CFD) refers to the prediction of fluid motion and forces by computation using numerical analysis.

CFD involves the solution of partial differential equations (PDEs), principally the conservation laws of mass and linear momentum that govern fluid motion and forces.



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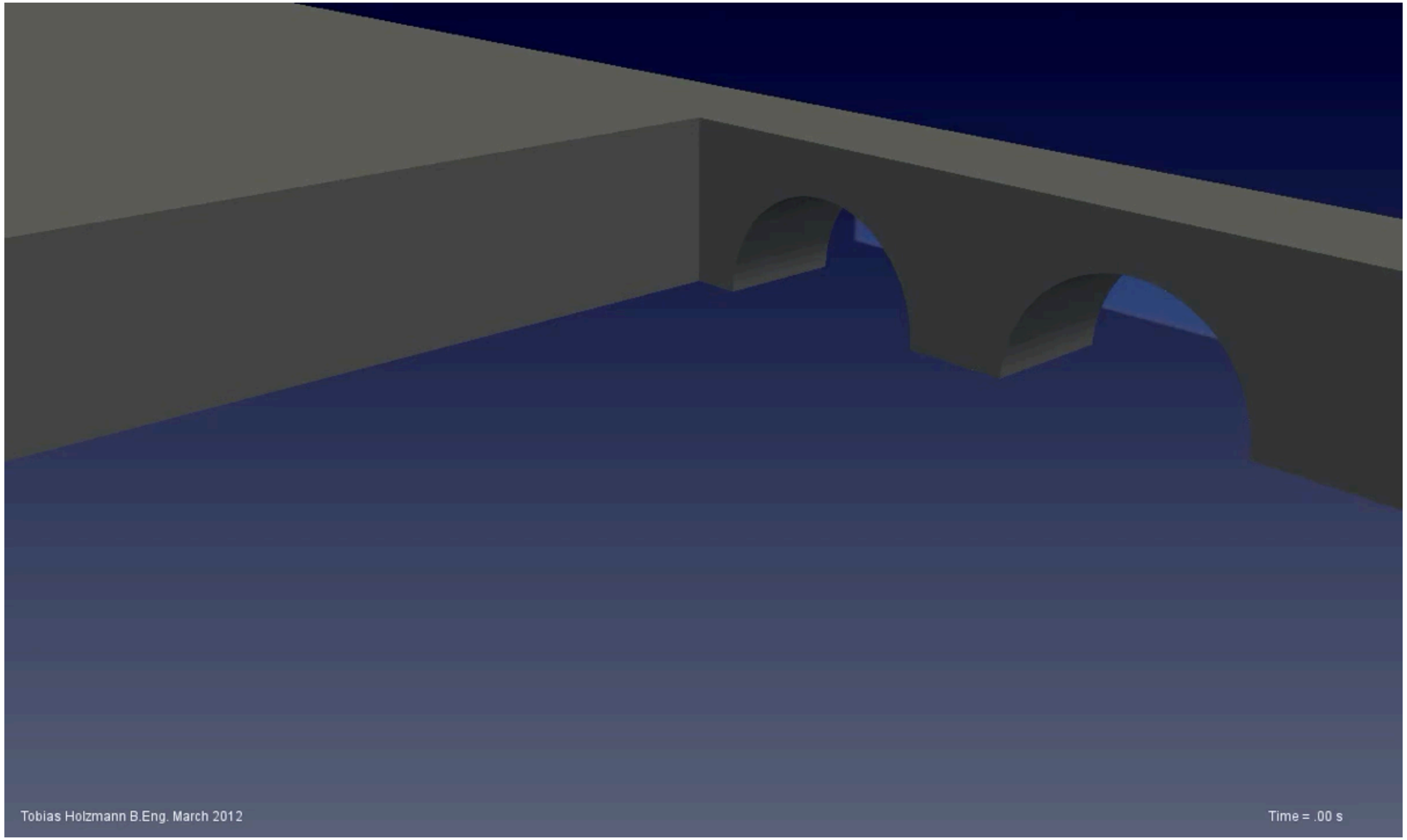
CFD and OpenFoam

OpenFOAM® is the leading free, open source software for computational fluid dynamics (CFD), owned by the OpenFOAM Foundation and distributed exclusively under the General Public Licence (GPL). The GPL gives users the freedom to modify and redistribute the software and a guarantee of continued free use.



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Conclusions & Perspectives

- The current Hubble tension (and in at some degree, the sigma-8 tension) could be addressed by introducing dynamical dark energy models that have non-negligible contributions to the Hubble parameter in the early Universe.

- These models produce a faster evolution of the structure, since they departure from the radiation domination epoch earlier than the ΛCDM model. Further analysis is needed to understand in depth the impact of these early dark energy models.

- Next steps for this investigation aim to:

  * Include other cosmological likelihoods in CosmoSIS,

  * Explore other cosmological estimators & observational constraints that allow us to validate / exclude the present parametrizations of the equation of state.

- Euclid, Nancy Grace Roman Space Telescope (WFIRST: Wide-Field Infrared Survey Telescope), Vera Rubin Observatory (Large Synoptic Survey Telescope), JWST.

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