PARAMETRIC APPROACH FOR DARK ENERGY

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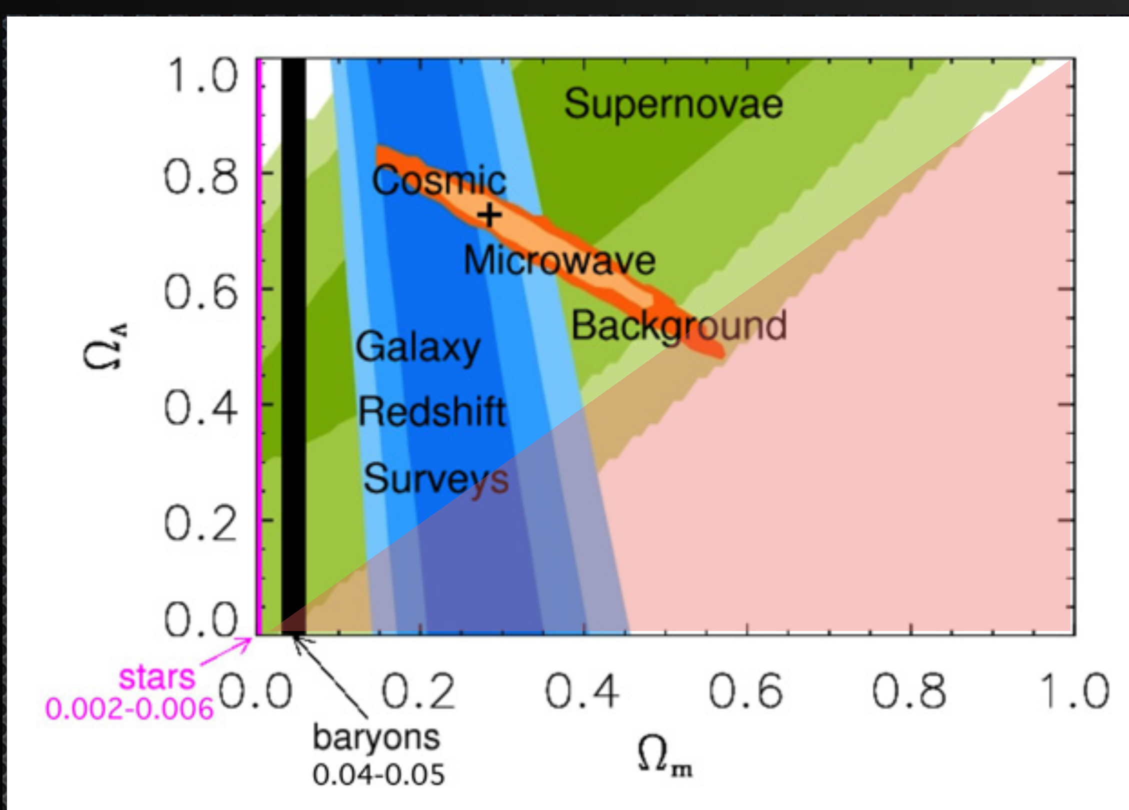
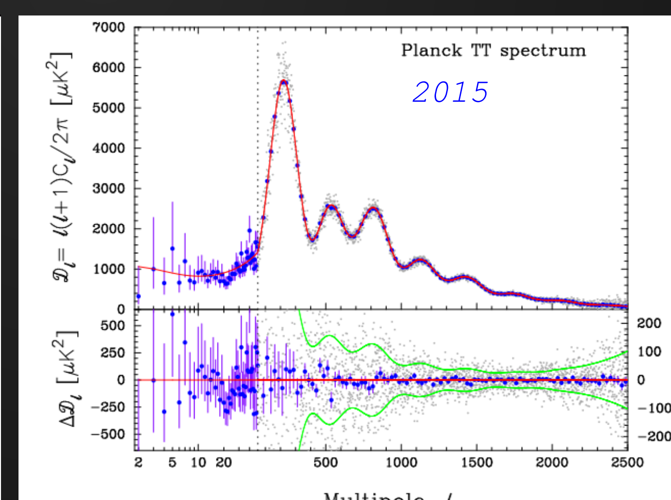
Outline

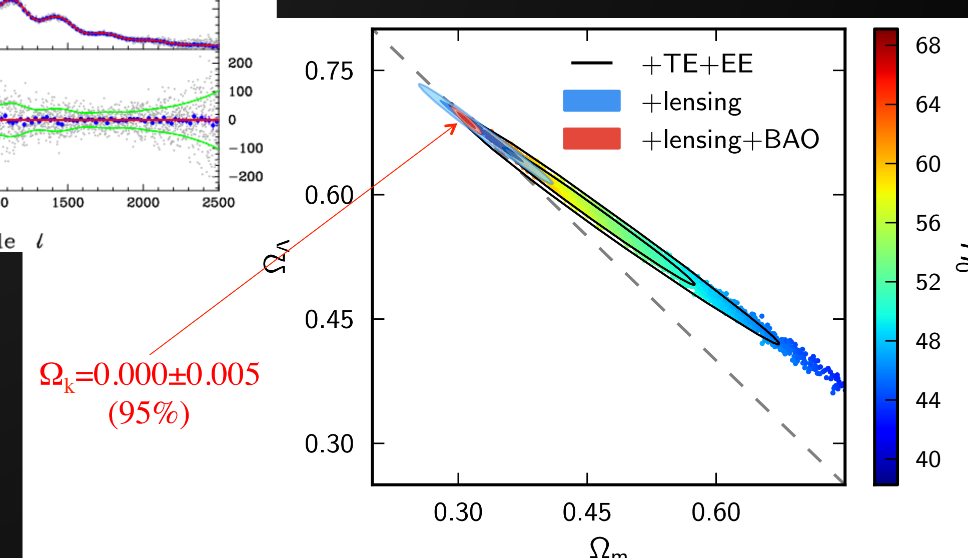
- Accelerated expansion
- Dark Energy
- Parametrization inspired in Quintessence
  - Implementation to observational data
  - Tensions
- Parametrization inspired in Modified Gravity
  - Implementation to observational data
  - Tensions

Accelerated Expansion •

- The current observations point to an acceleration in the expansion rate of the Universe.
- Our current paradigm is that we live in a flat and expanding Universe, dominated by a dark component and it is supported by measurements of SNeIa luminous distance, temperature fluctuations of the CMB, cluster abundances, galaxy surveys, the age of the Universe.







Many current and future experiments are focusing on discover the nature of the Dark energy component:

- eBOSS
- DESI
- LSST
- Euclid

eBOSS at a glance
Dark-time observations
Fall 2014 - Spring 2020
1000 fibers per 7 deg^2 plate Wavelength: 360-1000 nm, resolution R~2000
375,000 luminous red galaxies over 7500 deg^2, 0.6 < z < 0.8
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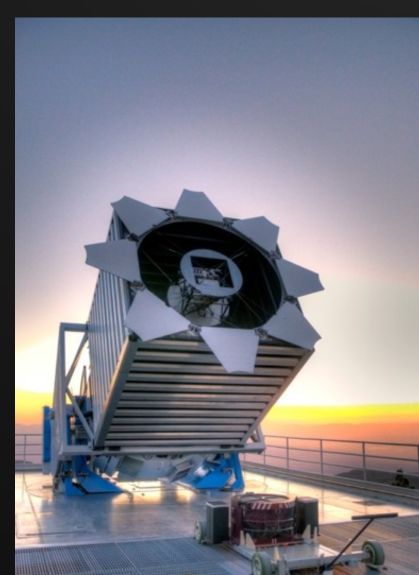
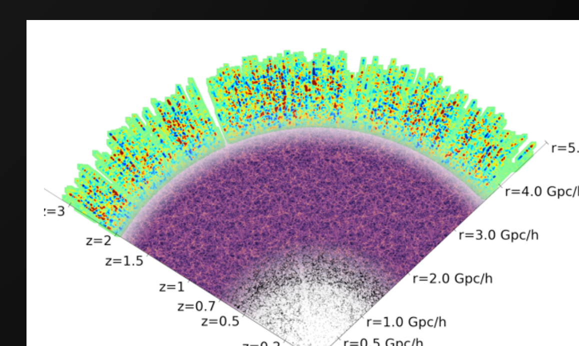
260,000 emission line galaxies over 1500 deg^2, 0.6 < z < 1.0
740,000 quasars over 7500 deg^2, 0.9 < z < 3.5
1–2% distance measurements from baryon acoustic oscillations between 0.6 < z < 2.5





Dark energy

Standard (Cosmological) Model

Inflation

Early era of accelerated expansion.

Initial conditions for structure formation.

Standard Model Particles

Baryons = nucleons, e^-
Radiation = γ, ν
Other species: relevant only at very early time

.

Dark Matter

Some for of matter that dilutes as

$$\rho_{DM} \sim a^{-3}$$

and does not interact with light

Cosmological Principle *

Isotropy and Homogeneity

$$ds^2 = -dt^2 + \frac{a(t)^2 dr^2}{1-kr^2} + [a(t)r]^2 d\Omega^2$$

General Relativity *

$$R_{\mu\nu} - \mathcal{R}/2 = 8\pi G T_{\mu\nu}$$

Successful description of solar system phenomena
Gravity is weak but always attractive!
Dominant interaction on cosmic scales.

Cosmological Constant *

The Universe expansion seems to accelerate
Cosmological constant term with $\rho_\Lambda \sim cte$
Repulsive gravitational effect!

Dark Energy

Cosmological Constant *

The Universe expansion seems to accelerate

Cosmological constant term with $\rho_\Lambda \sim cte$

Repulsive gravitational effect!

Simplest model of dark energy

$$w_{DE} = -1$$

Which corresponds to the energy scale

$$\rho_\Lambda = \frac{3H_0^2}{8\pi G} \approx 10^{-47}\mathrm{Gev}^4$$

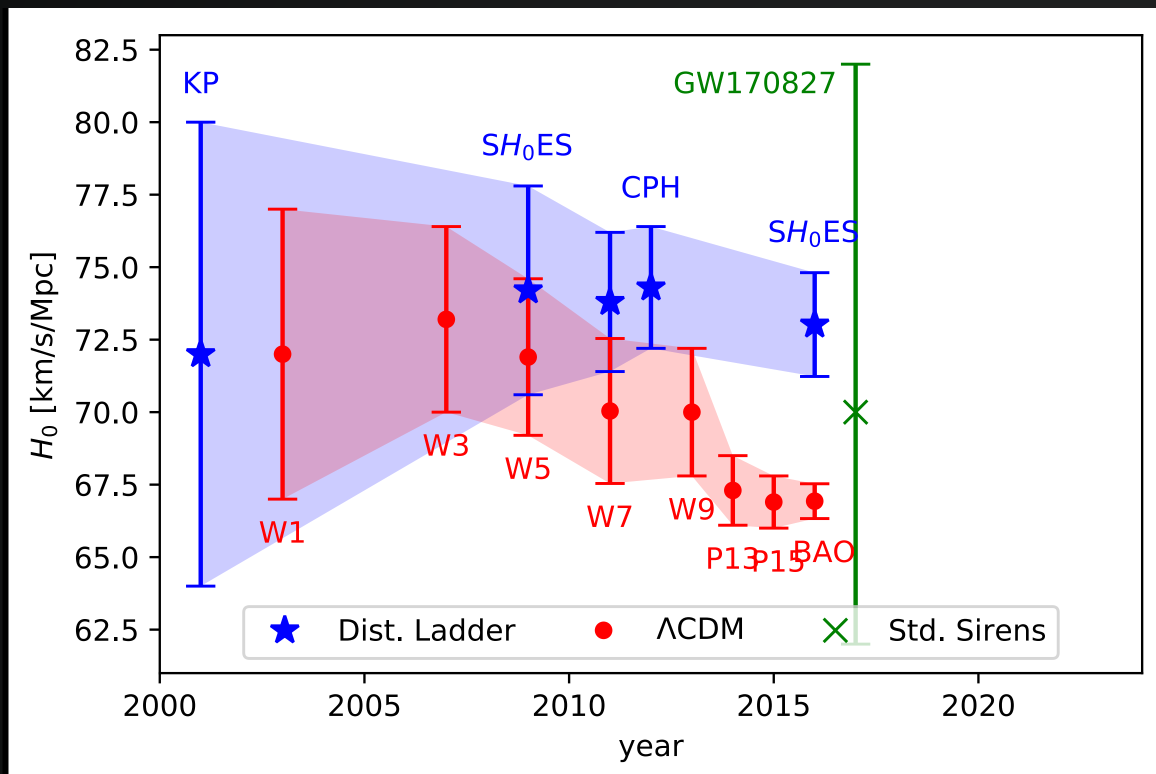
If this is originated from vacuum energy in particle physics

$$\rho_{vac} \approx m_{pl} \approx 10^{74}\mathrm{Gev}^4$$

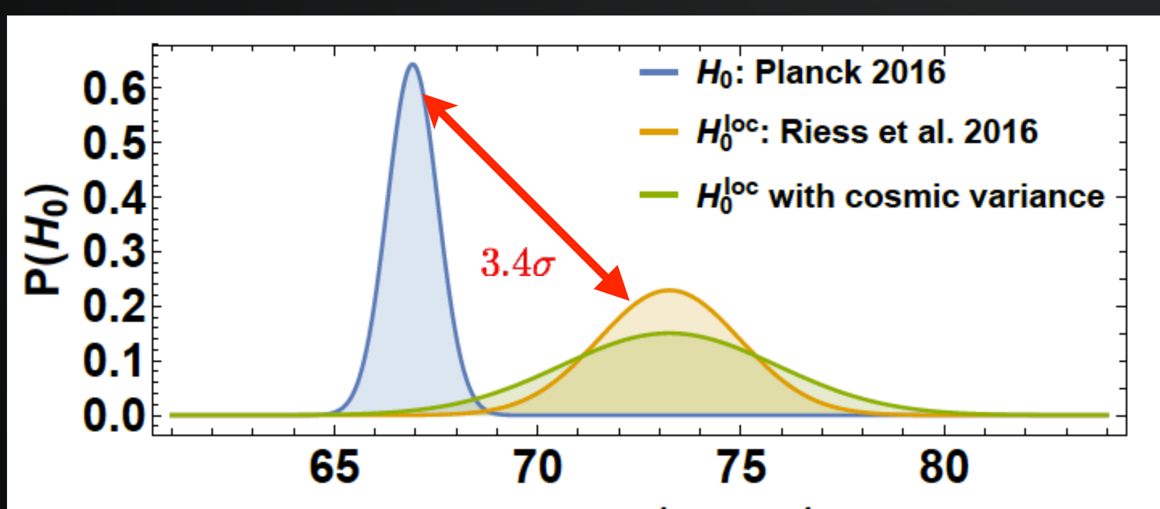
Cosmological constant problem: 10^{121} times larger than the observed value

Dark Energy

- Tensions ⟶ Evidence of a dynamical Dark Energy?

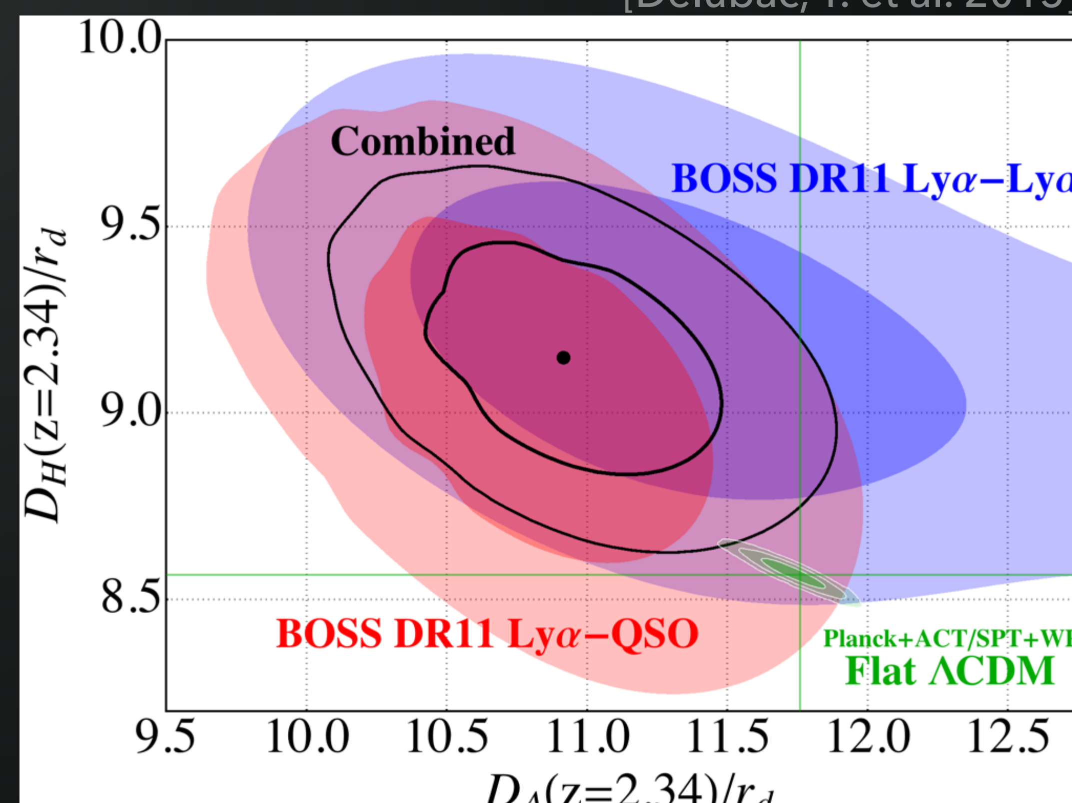


[Adapted from Fredman 2017]



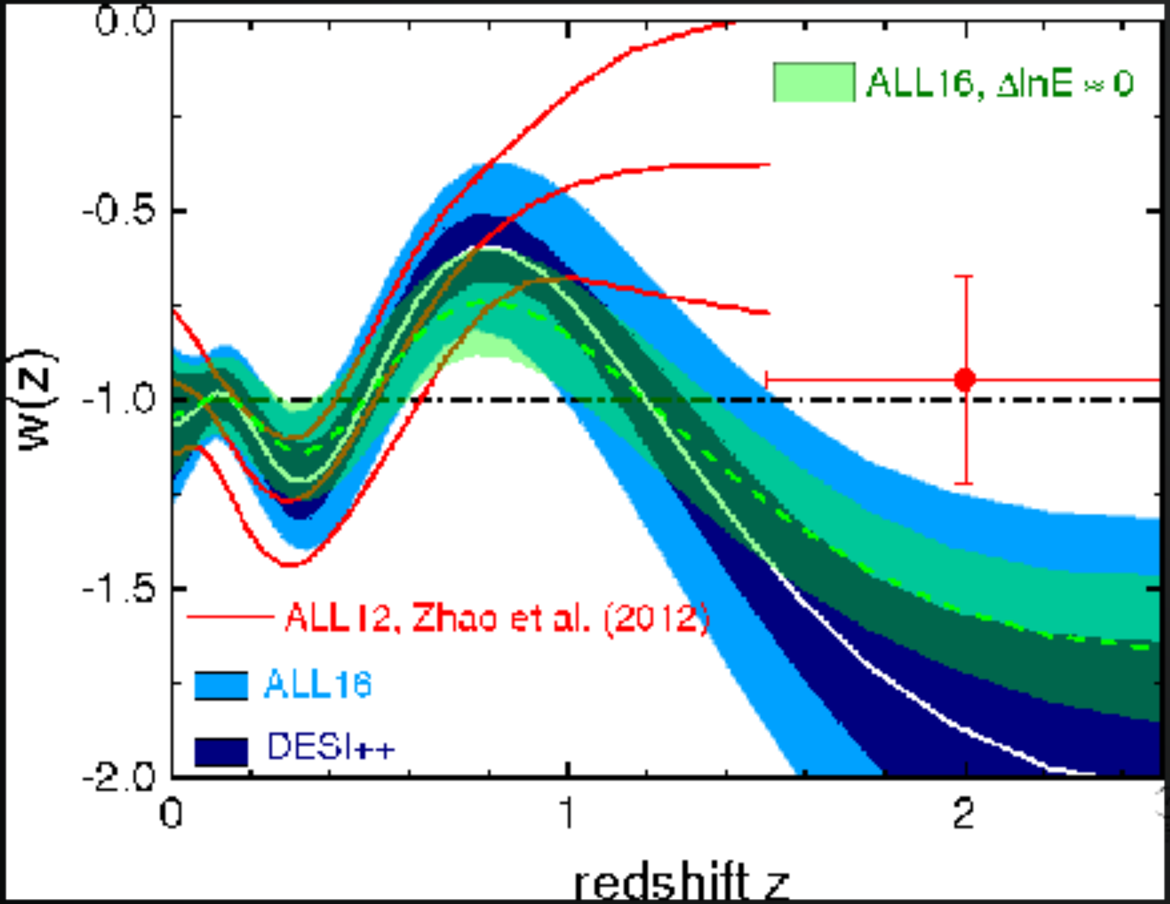
[Camarena, 2018]

[Delubac, T. et al. 2015]



Reconstruction of the de DE EoS

Recent reconstruction of w(z) from combined data points to an exciting profile for the Eos for DE.

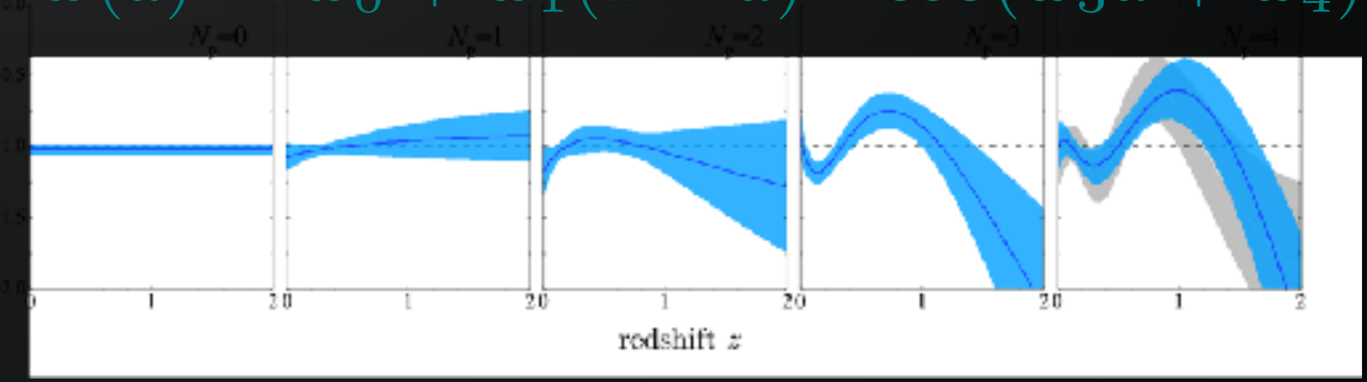


[Zhao+ 2017]

Inspired by these results, some proposals have appeared in the literature trying to model the behavior:

$$w(a) = \sum_{i=0}^{N_p} w_i (1-a)^i$$

$$w(a) = w_0 + w_1 (1-a)^{w_2} cos(w_3 a + w_4)$$



[Zhang +2017]

Dark energy models

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$G_{\mu\nu} \sim g, \partial g, \partial^2 g$

Modified gravity

f(R) theories

Scalar-tensor models

Braneworld models

Galileons

...

$T_{\mu\nu} \sim \rho, P$

Modified matter

Quintessence

K-essence

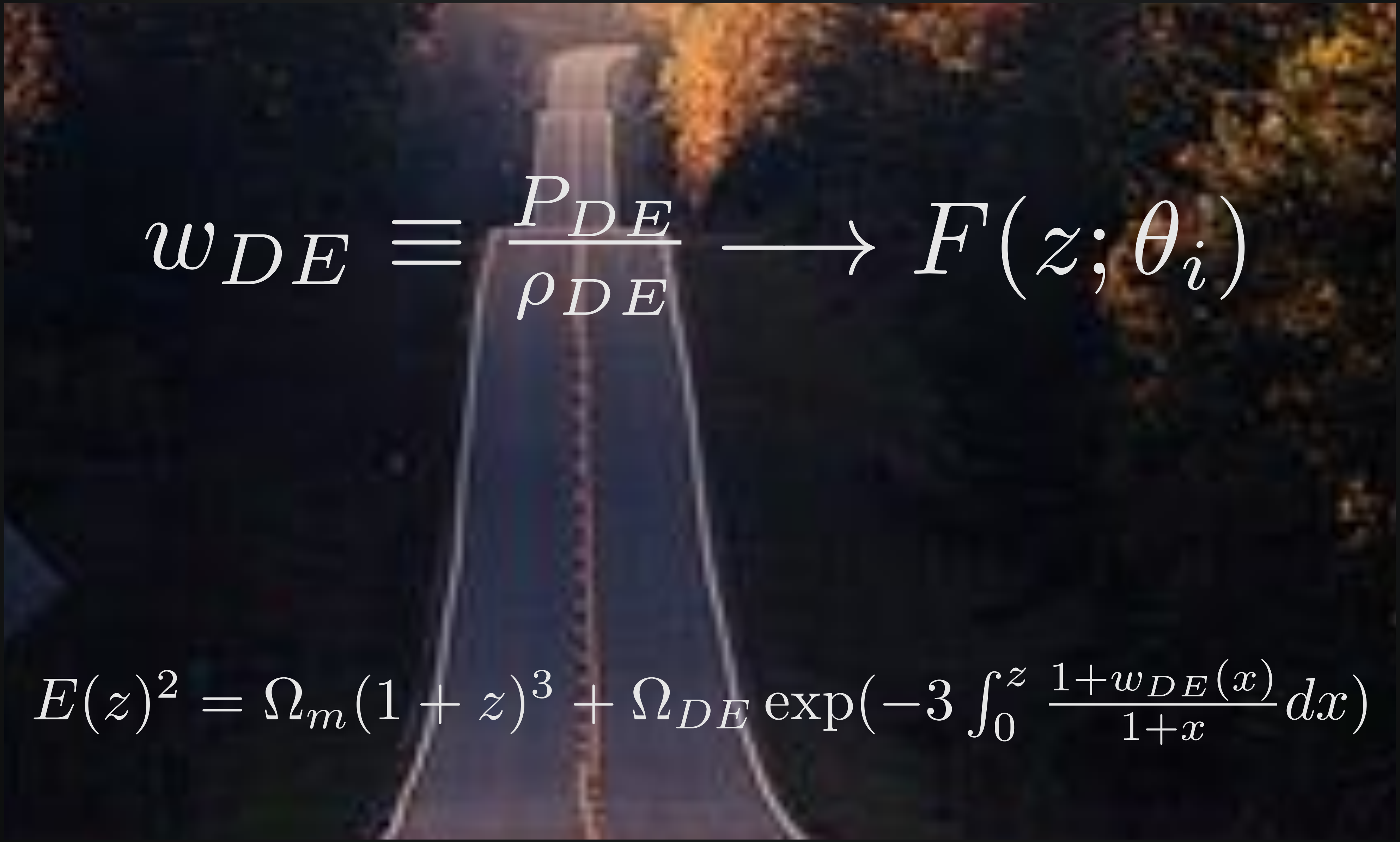
Tachyon

Chaplygin gas

...

Phenomenological modeling

- Instead of fixing specific model and testing against observations



$$w_{DE} \equiv \frac{P_{DE}}{\rho_{DE}} \longrightarrow F(z;\theta_i)$$

$$E(z)^2 = \Omega_m(1+z)^3 + \Omega_{DE}\exp\left(-3\int_0^z \frac{1+w_{DE}(x)}{1+x}dx\right)$$

Parametrization inspired in Quintessence

Parametrization inspired in Quintessence

Under the supervision of Dr. Axel de la Macorra
IF - UNAM

Quintessence

$$\mathcal{L}_\phi = \sqrt{-g}[g^{\mu\nu}\phi_{,\mu}\phi_{,\nu} + V(\phi)]$$

For sufficiently flat potential we can achieve acceleration.

We can get the equation of state:

$$w_{DE} \equiv \frac{p}{\rho} = \frac{\dot{\phi}/2 - V(\phi)}{\dot{\phi}/2 + V(\phi)}$$

$$w_{DE} < -1$$

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$G_{\mu\nu} \sim g, \partial g, \partial^2 g$

Modified gravity

f(R) theories

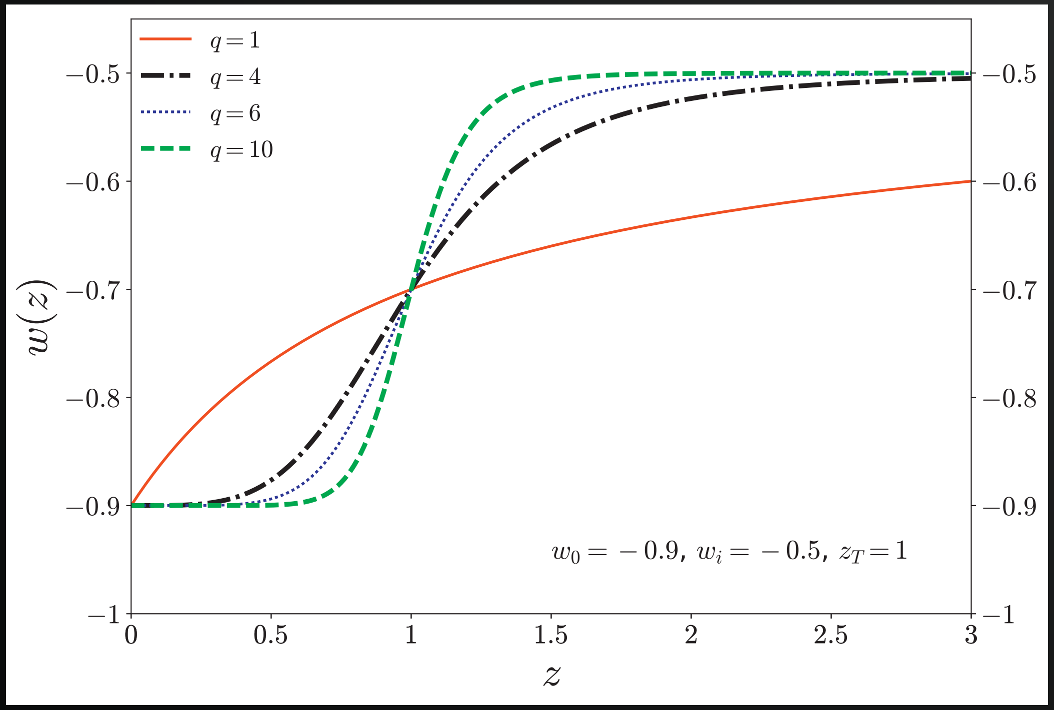
$T_{\mu\nu} \sim \rho, P$

Modified matter

Quintessence

SEoS model

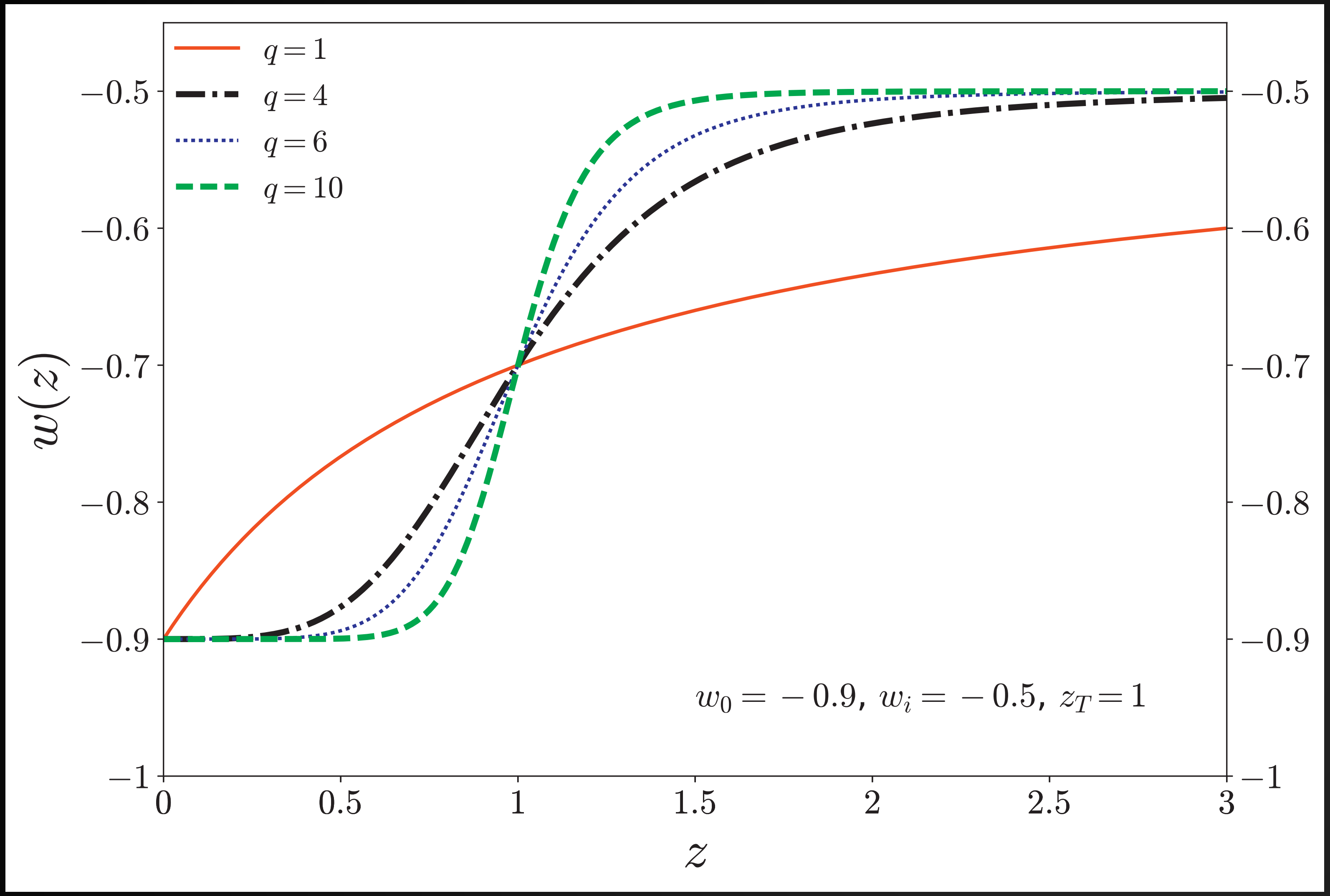
- DE parametrization based on scalar field dynamics, but the parametrization of w can be used without the connection to scalar fields
  - It may grow and later decrease or the reverse can happen, and it can have steep or smooth transition from an initial value of w_i to the present day w_0 value.



$w(z)$ instead of $V(\phi)$, ϕ_0, $\dot{\phi}_0$

[A. Macorra 2015 1511.04439]

SEoS model



[A. Macorra 2015 1511.04439]

[**MJ** & A. De la Macorra 1604.01442]

[**MJ** & A. De la Macorra 1708.08529]

Inspired by quintessence behavior at late times and allows for a more general behavior between the high redshift and present values

$$w(z) = w_0 + (w_i - w_0)\frac{(z/z_T)^q}{1+(z/z_T)^q}$$

Includes the CPL case when the transition time and the steepness are fixed to $q=z_T=1$

Implementation to observational data

For probing late time evolution we use

- BAO measurements from galaxies and LyA forest, as well as the latest determination of $H_0 = 73.21 \pm 1.74$km/s/Mpc. [Riess +16]
- CMB compressed likelihood [Planck '15 DE&MG paper]

We kept a flat geometry and the baryon density fixed.

Uniform priors on the free parameters:

$$\vec{\theta} = \{w_0, w_i, q, z_T, \Omega_c h^2, h\}$$

Isotropic BAO measurements:

$$D_V(z) = \left[(1+z)^2 D_A(z) c \frac{z}{H(z)}\right]^{1/3}$$

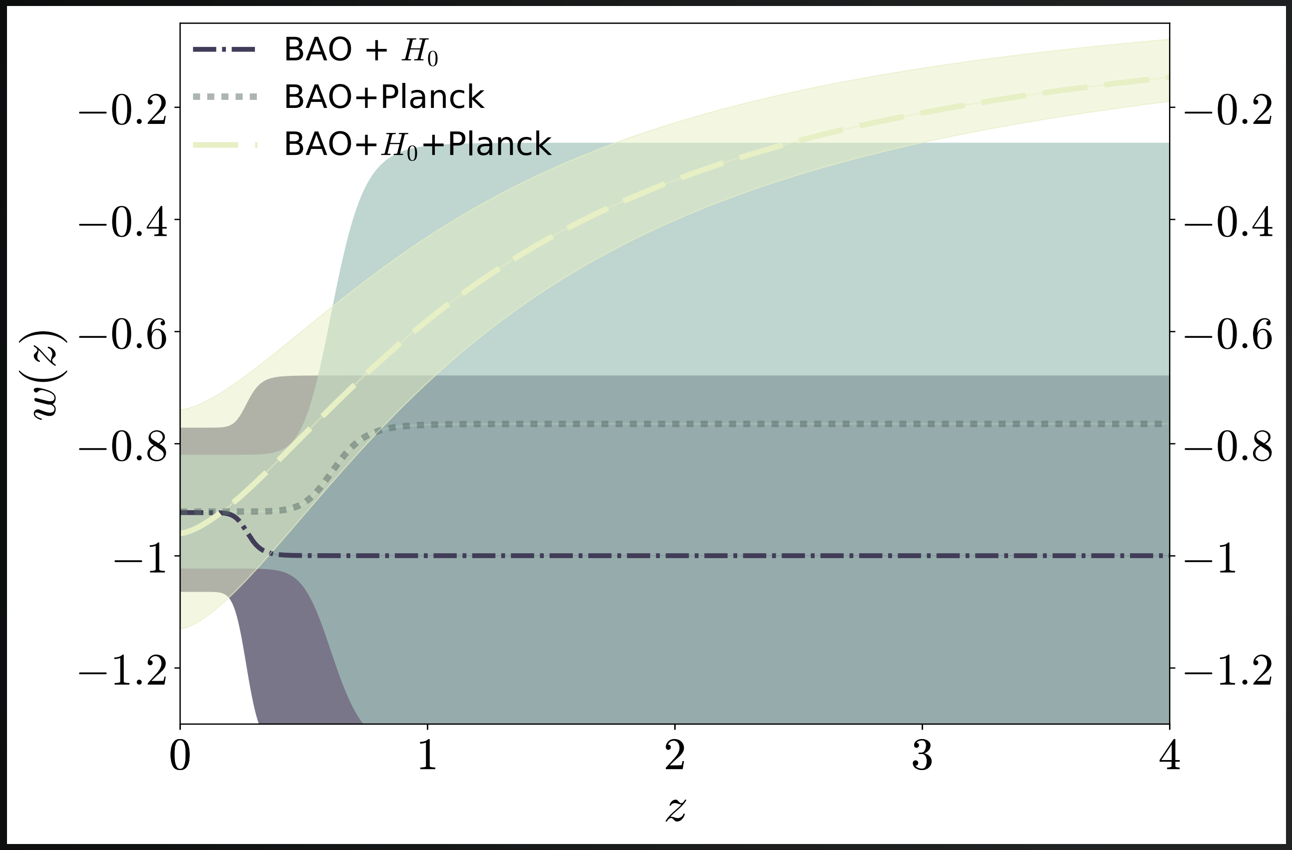
$$r_{BAO}(z) \equiv \frac{s(z_{drag})}{D_V(z)}$$

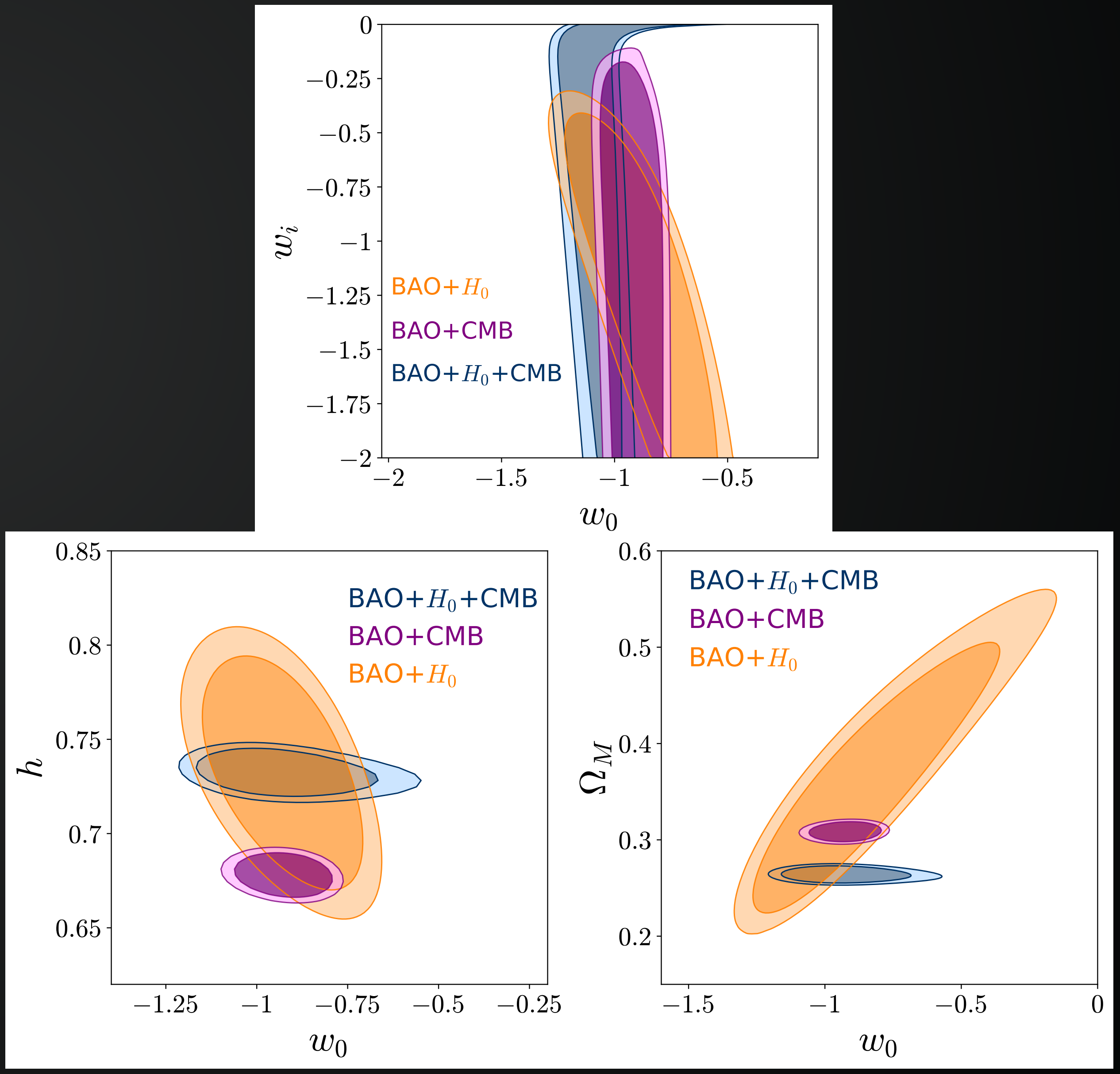
Data set	**Redshift**	$r_{BAO}(z)$
6dF	0.106 [27]	0.336 ± 0.015
SDSS DR7	0.15 [32]	0.2239 ± 0.0084
SDSS(R) DR7	0.35 [33]	0.1137 ± 0.0021
SDSS-III DR12	0.38 [30]	0.100 ± 0.0011
	0.61 [30]	0.0691 ± 0.0007
SDSS-III DR11	2.34 [35]	0.0320 ± 0.0013
	2.36 [34]	0.0329 ± 0.0009

*no WiggleZ

Implementation to observational data

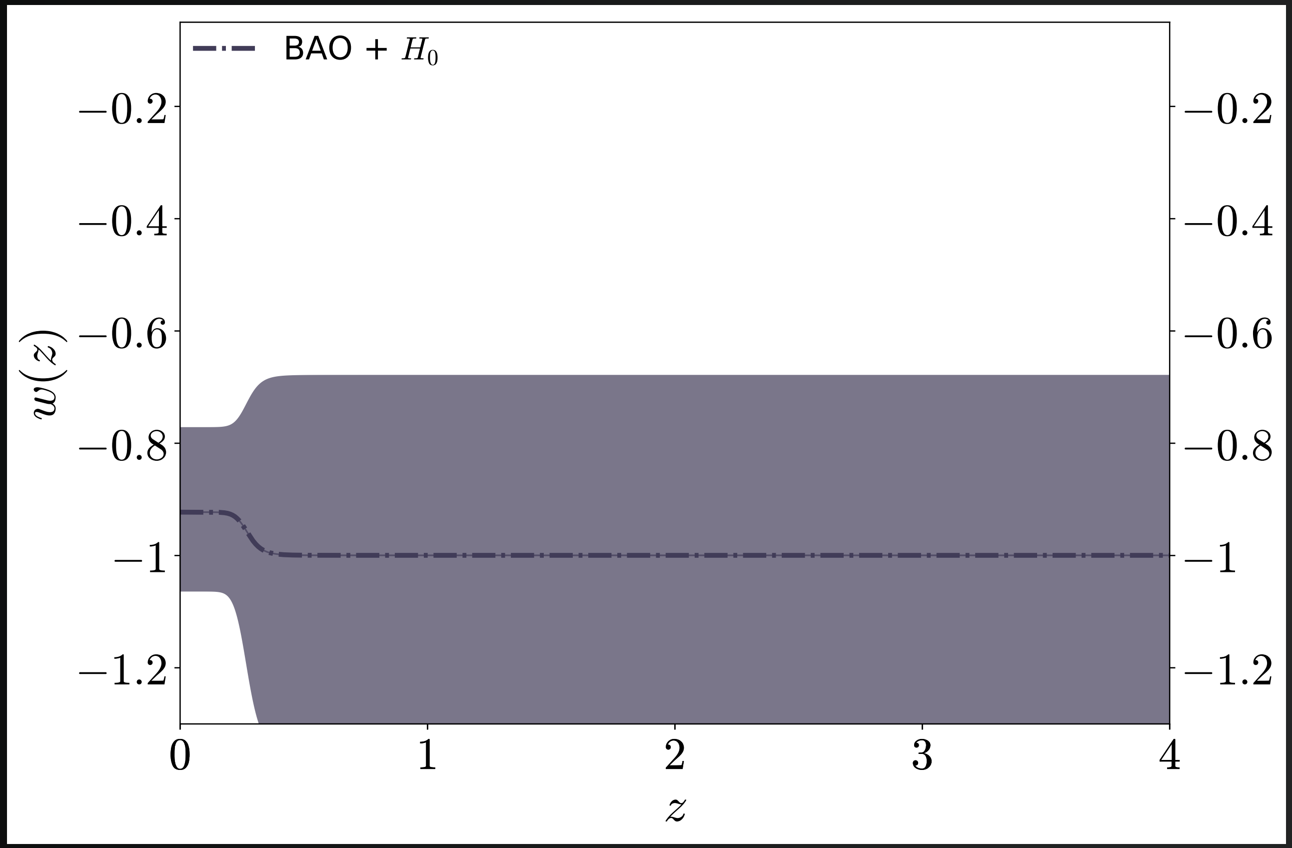
[**MJ** & A. De la Macorra 1708.08529]

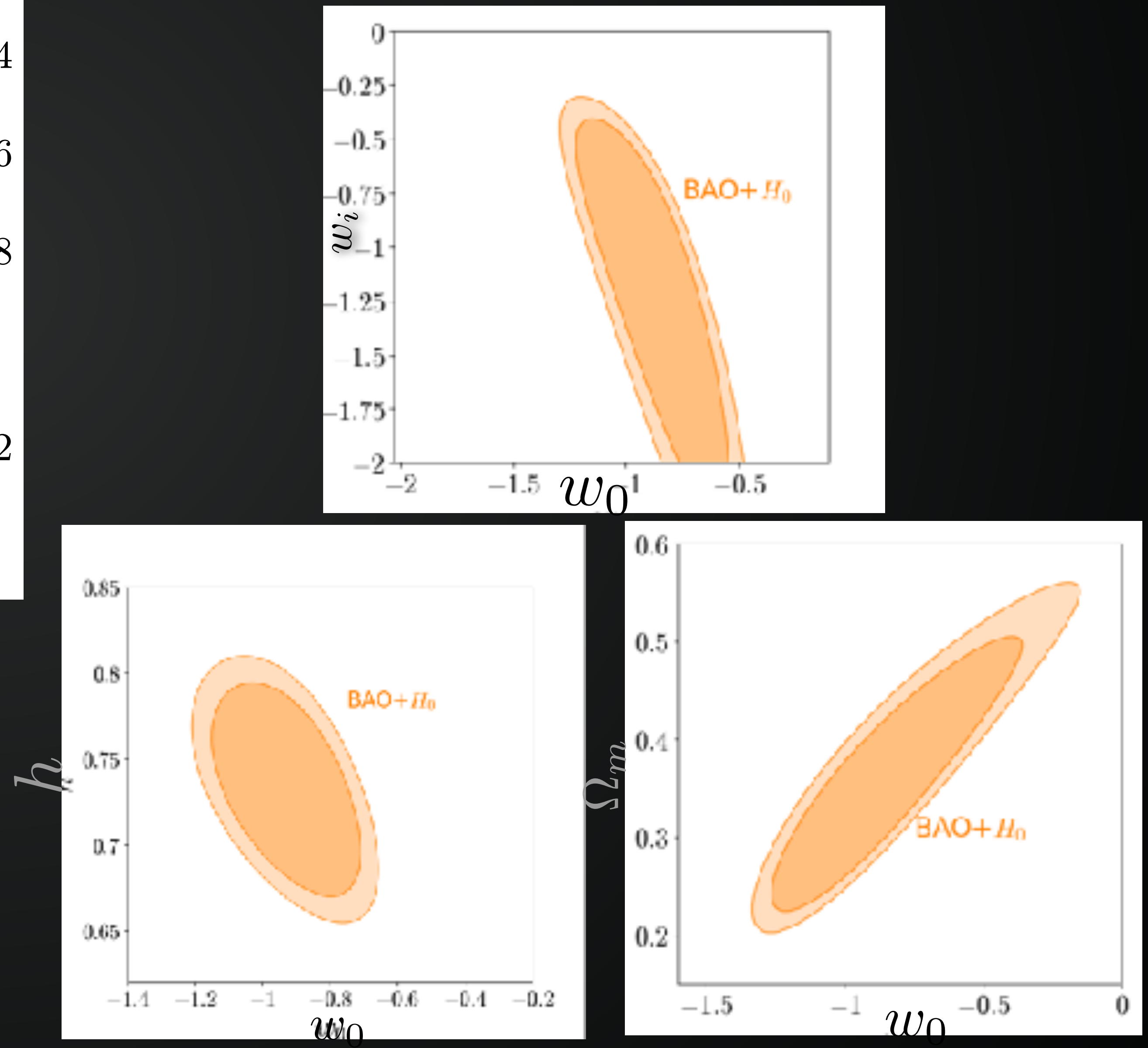




[**MJ** & A. De la Macorra 1708.08529]

- BAO + H0



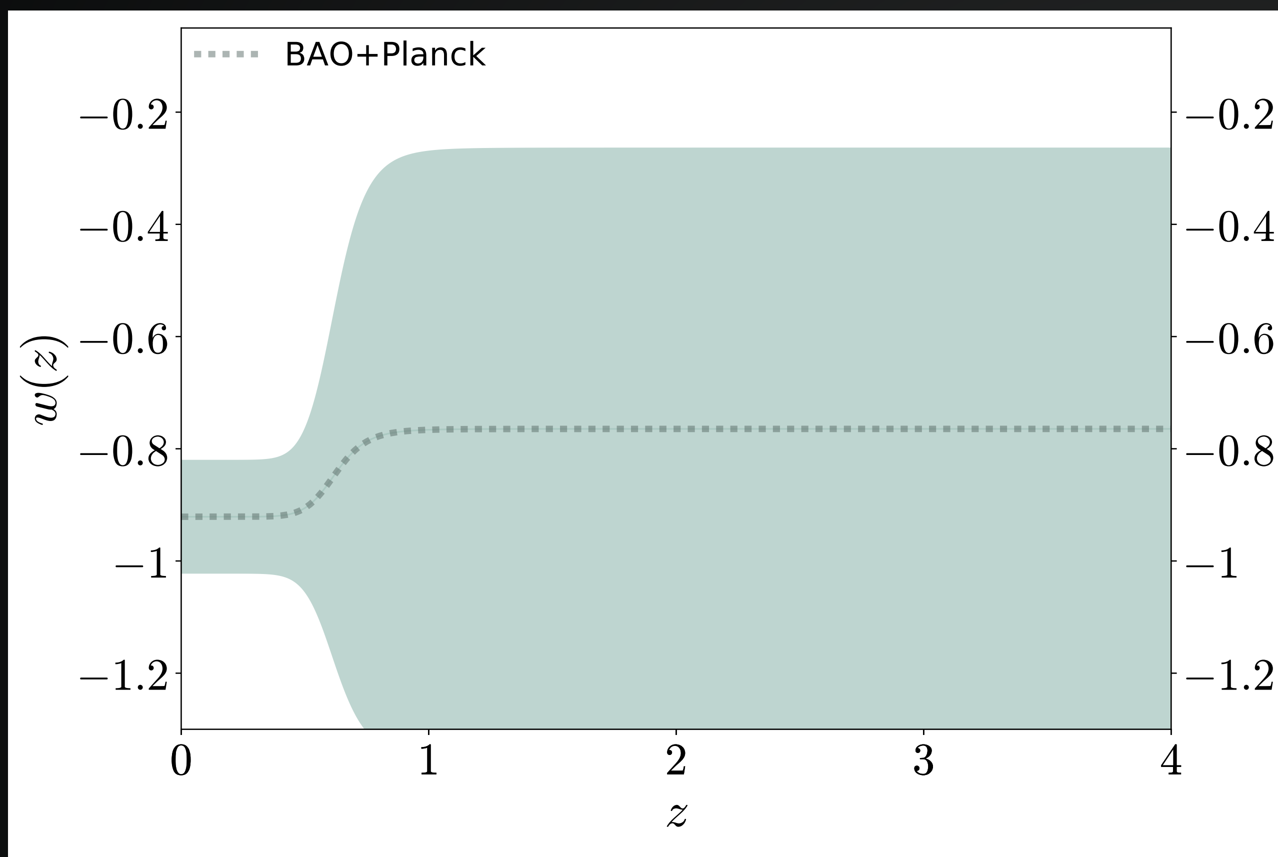


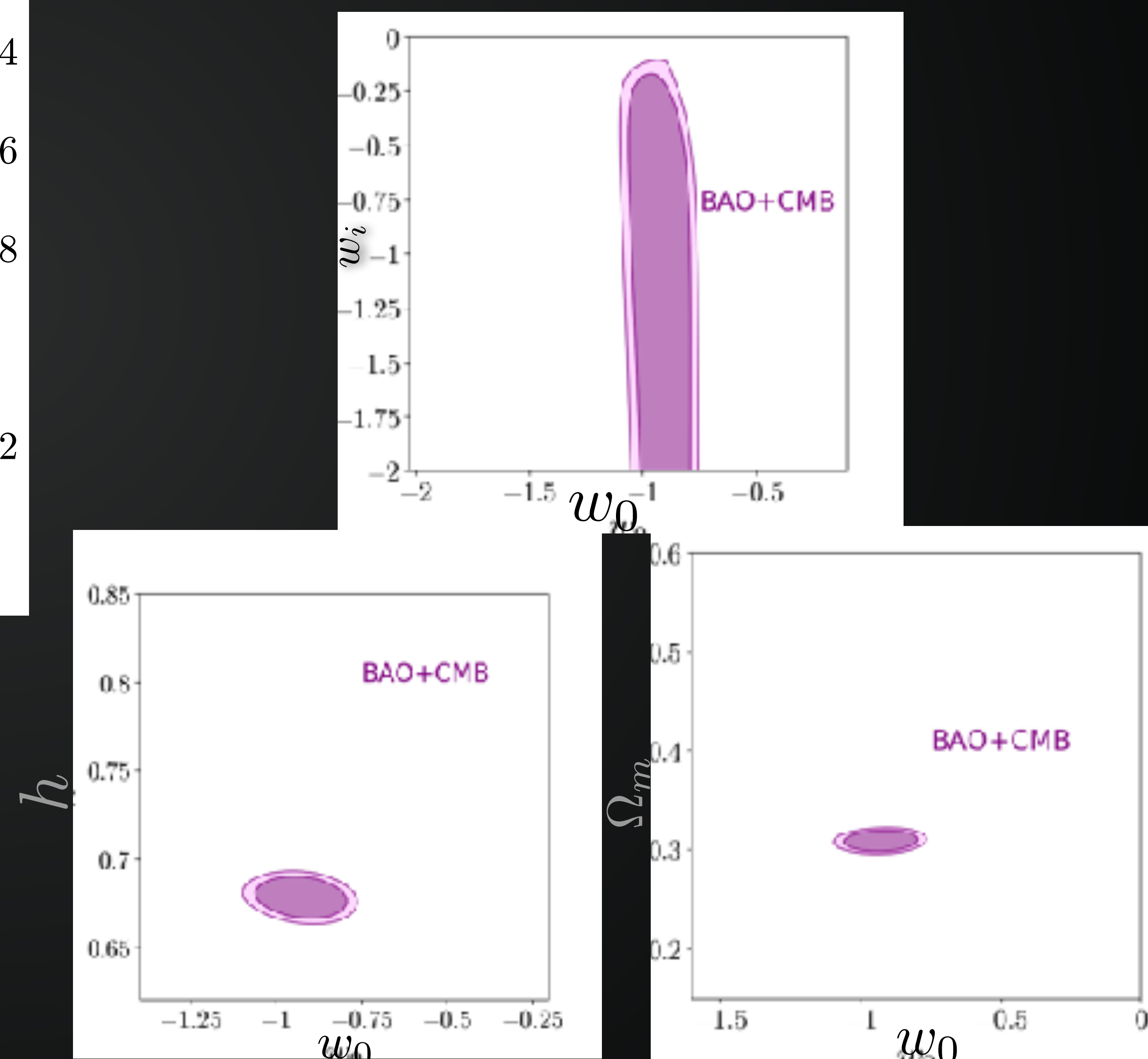
$$w_0 = -0.92^{+0.15}_{-0.14}$$

$$w_i = -0.99(\leq -0.67)$$
$$q = 9.97(\geq 7.19)$$
$$z_T = 0.28(\leq 1.08)$$

[**MJ** & A. De la Macorra 1708.08529]

- BAO + Planck



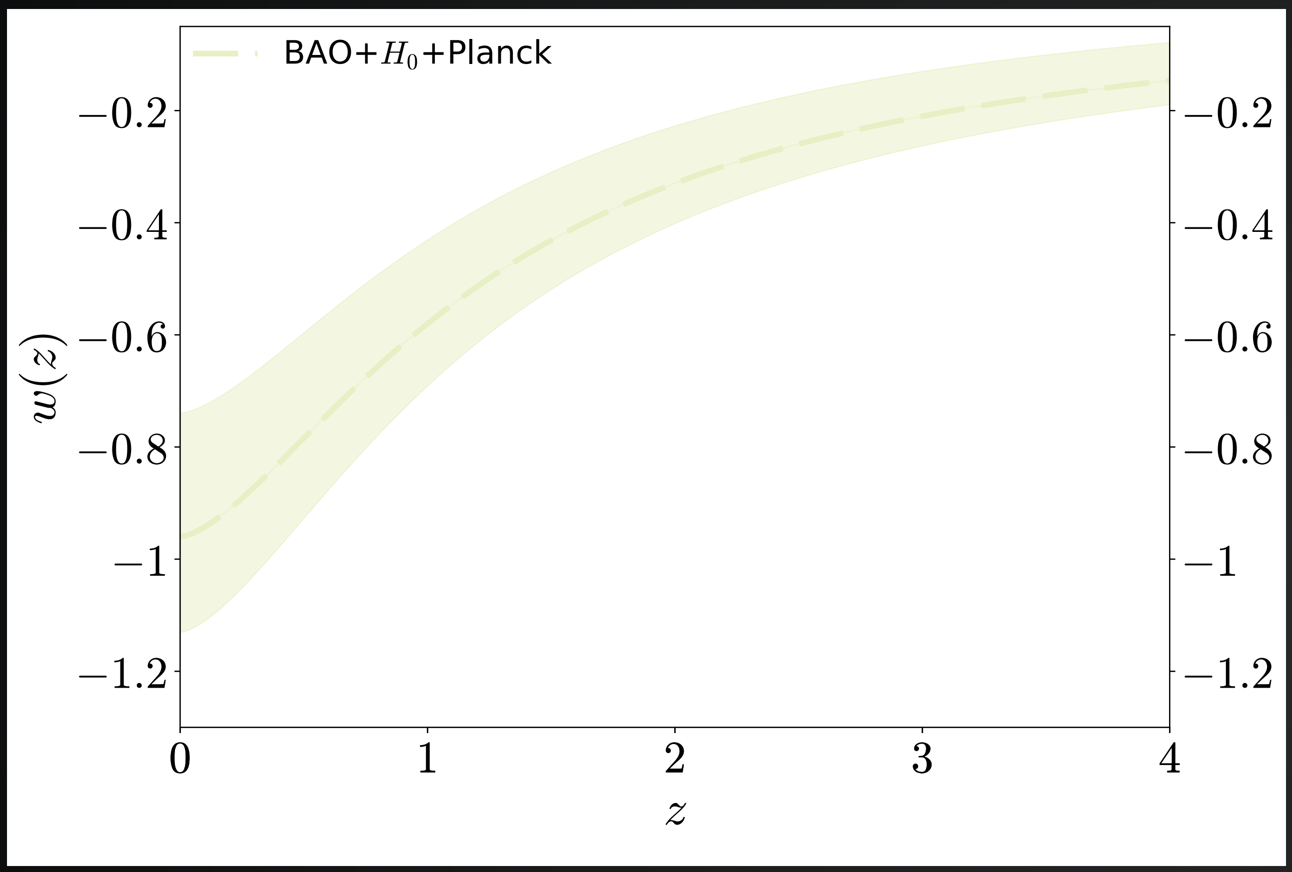


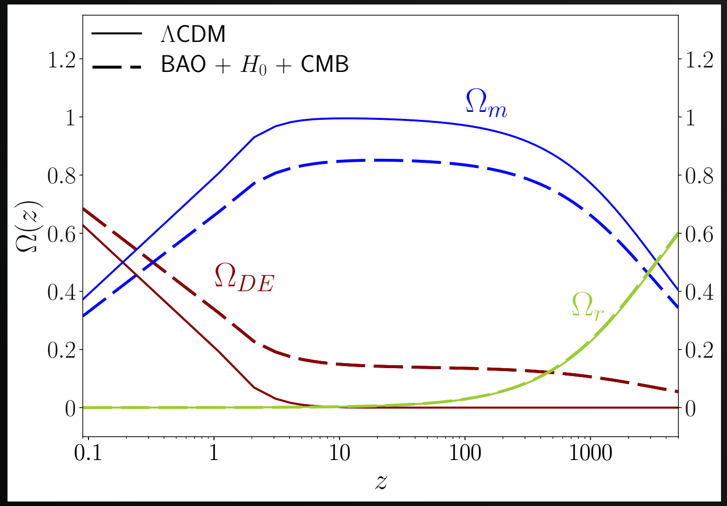
$w_0 = -0.92 \pm 0.10$
$w_i = -0.77(\leq -0.27)$
$q = 9.8(\geq 6.9)$
$z_T = 0.63(\geq 0.10)$

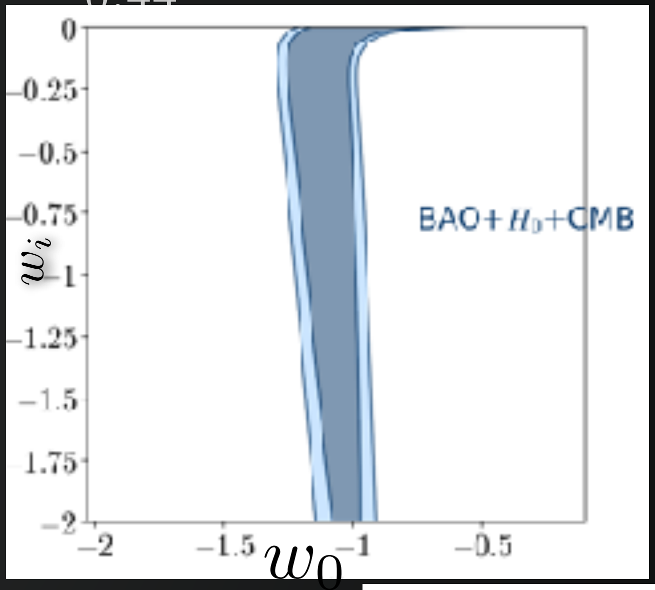
[**MJ** & A. De la Macorra 1708.08529]

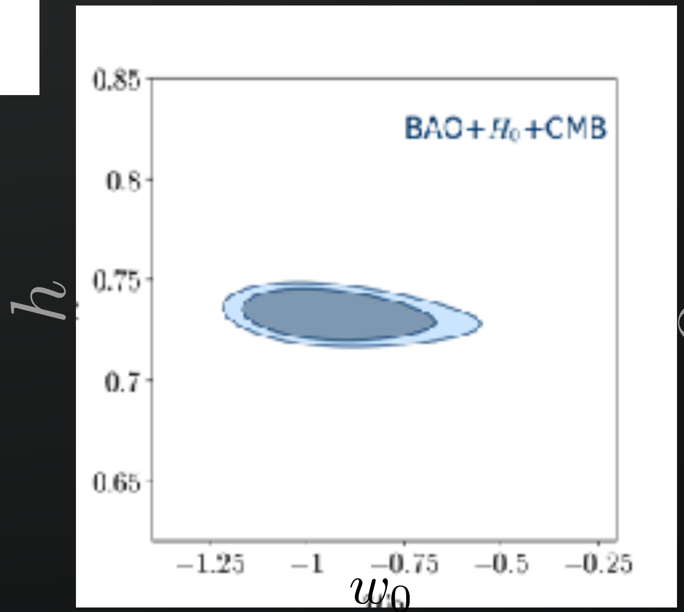
- BAO + H0 + Planck

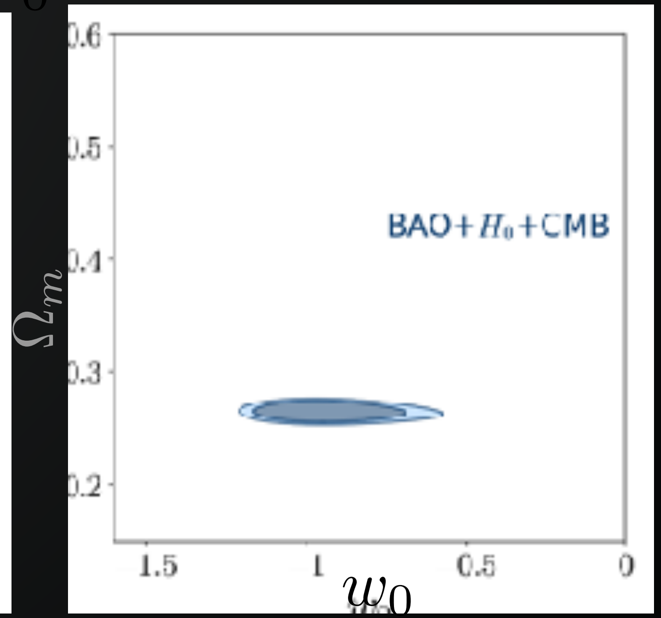
$$w_0 = -0.96^{+0.22}_{-0.17}$$
$$w_i = 0^{+0.04}_{-0.02}$$
$$q = 1.5^{+1.3}_{-0.5}$$
$$z_T = 1.31^{+1.42}_{-0.44}$$











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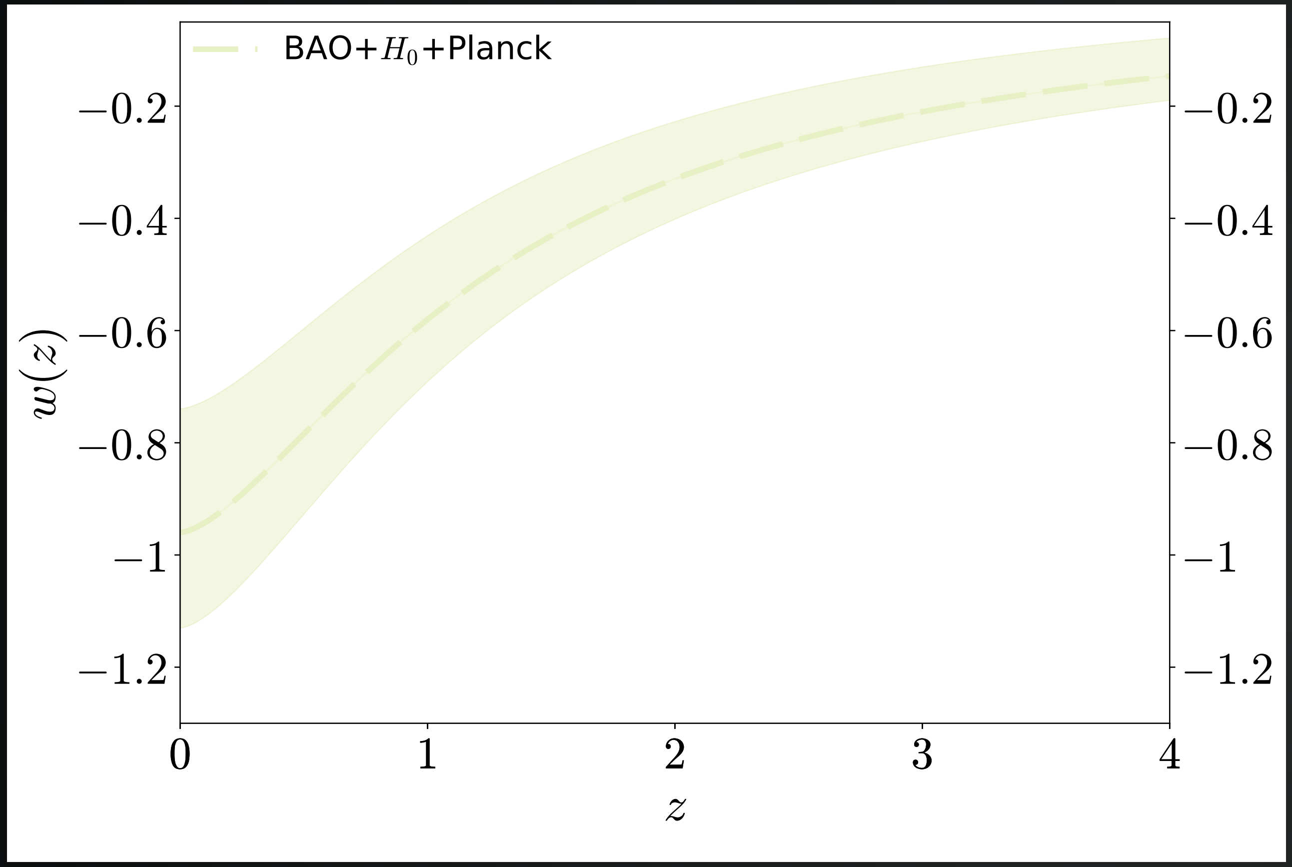

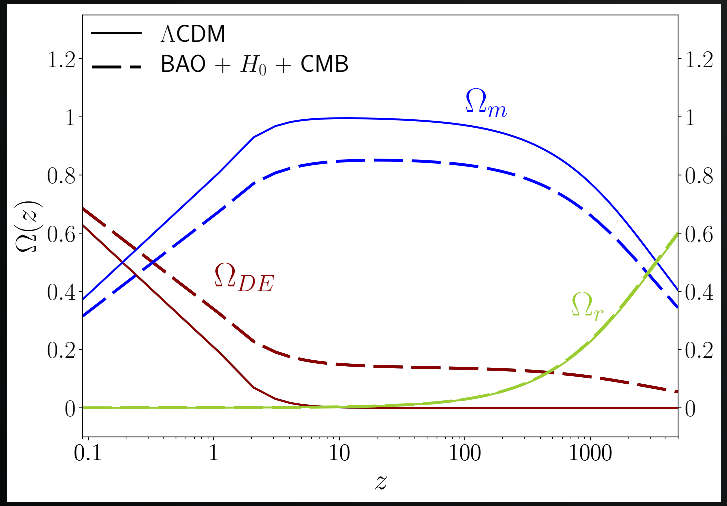

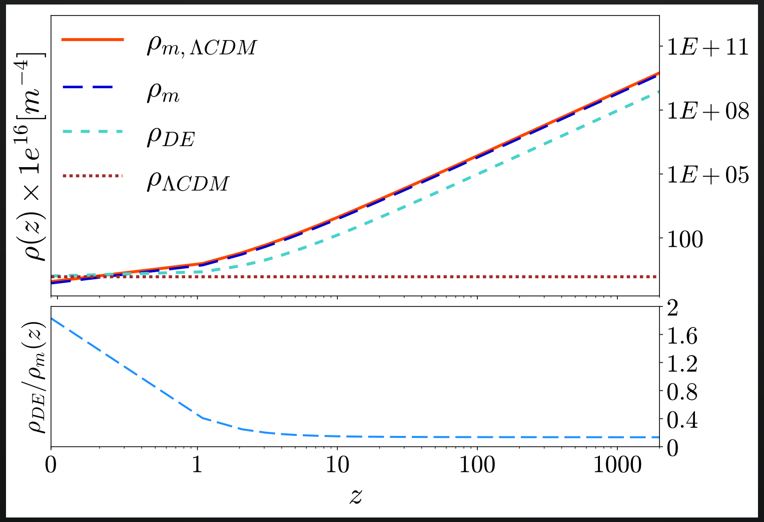

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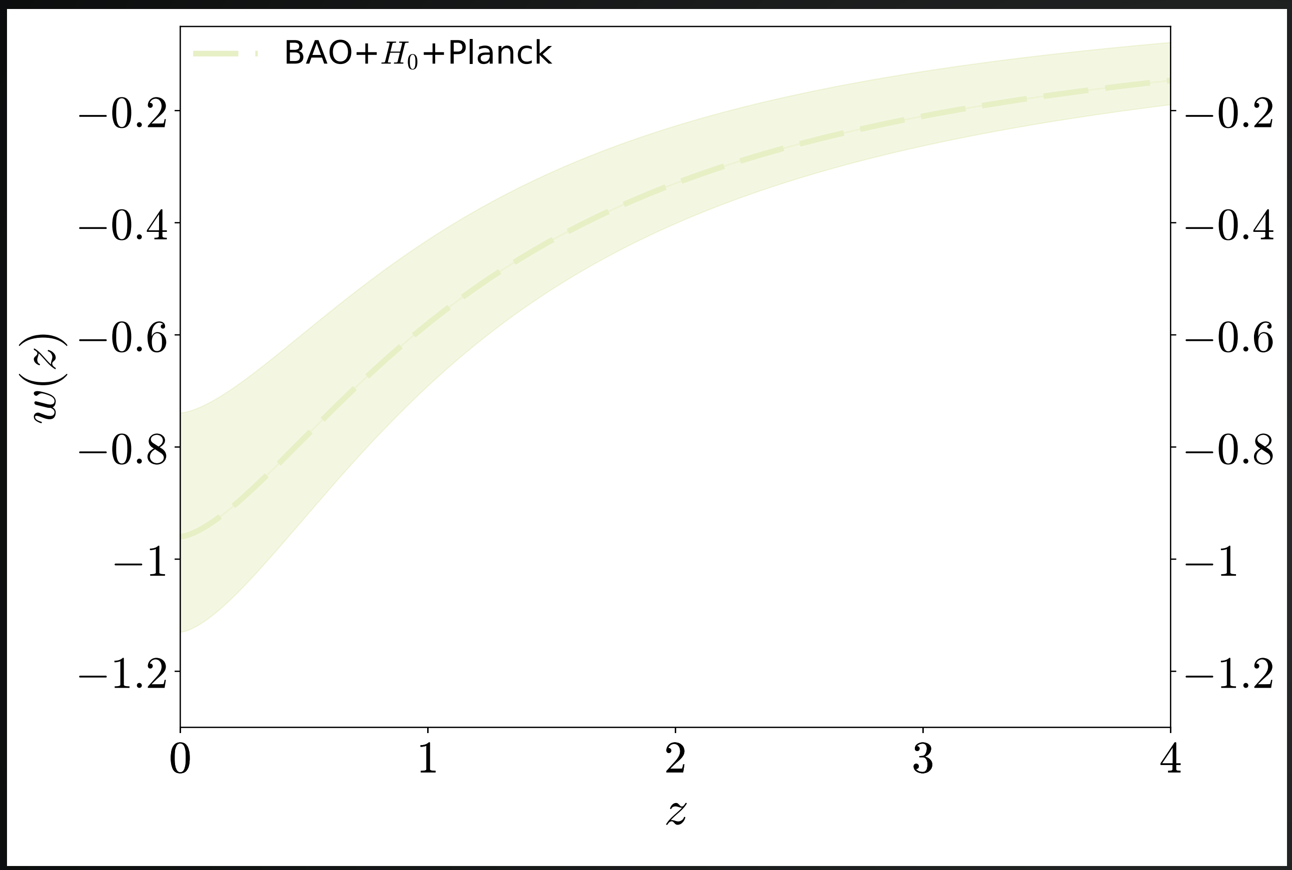
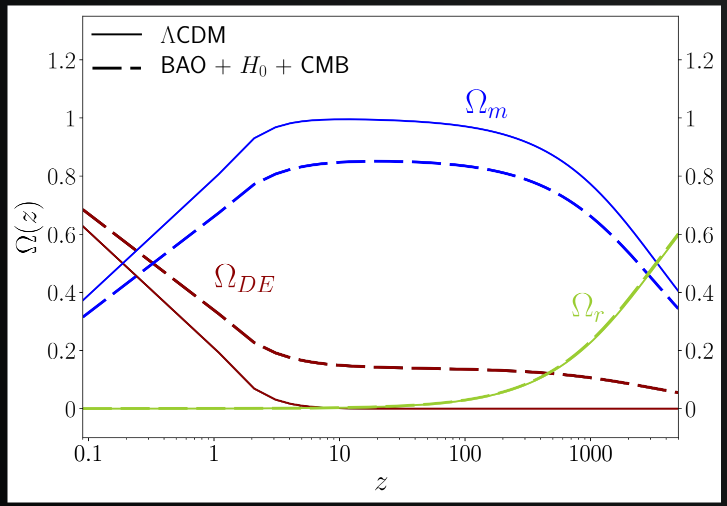
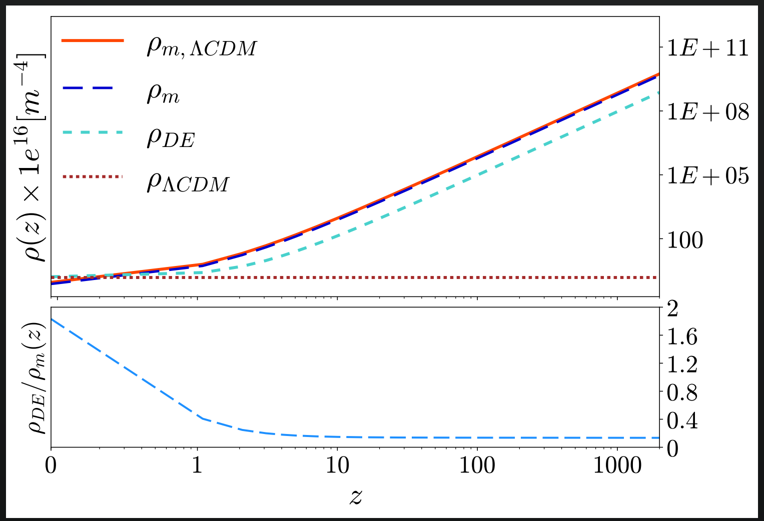
DE density at early times is not negligible since it has $w_i = 0$.

$\Omega DE(z^*) = 10\%$

Adding an extra component that behaves like dust ($\sim a^{-3}$) at large redshifts.







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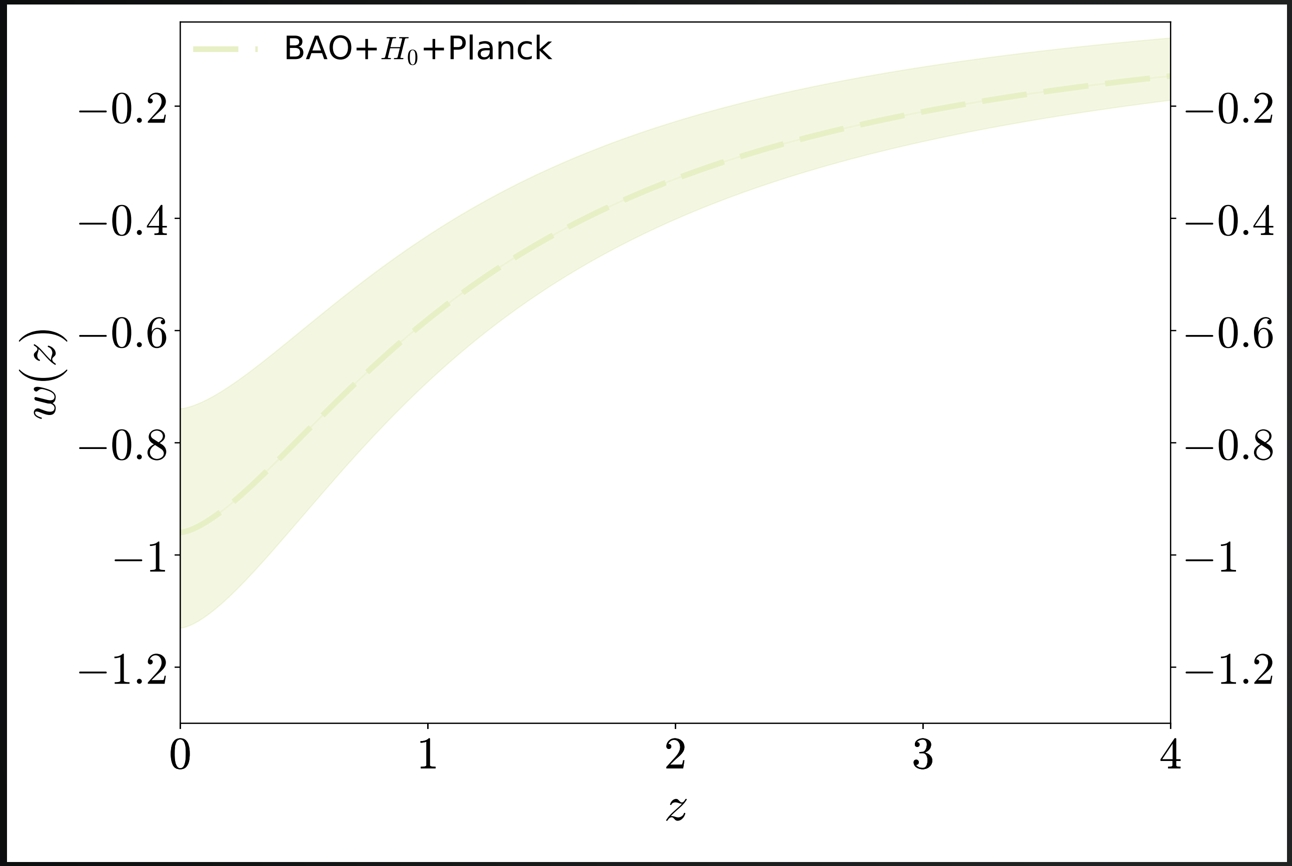

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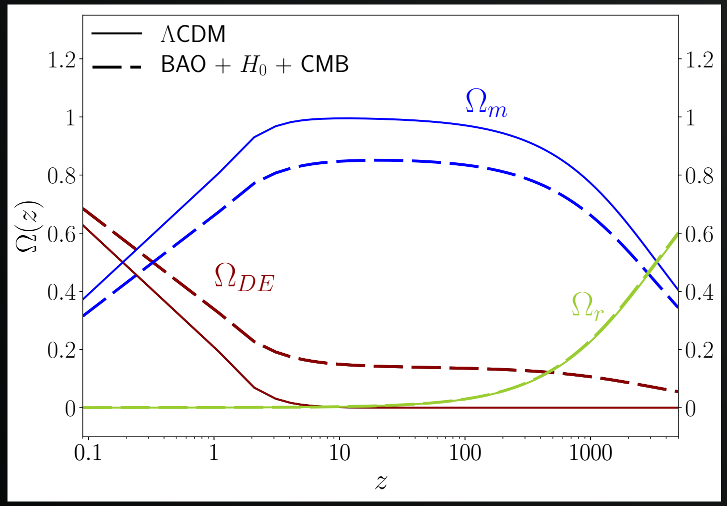
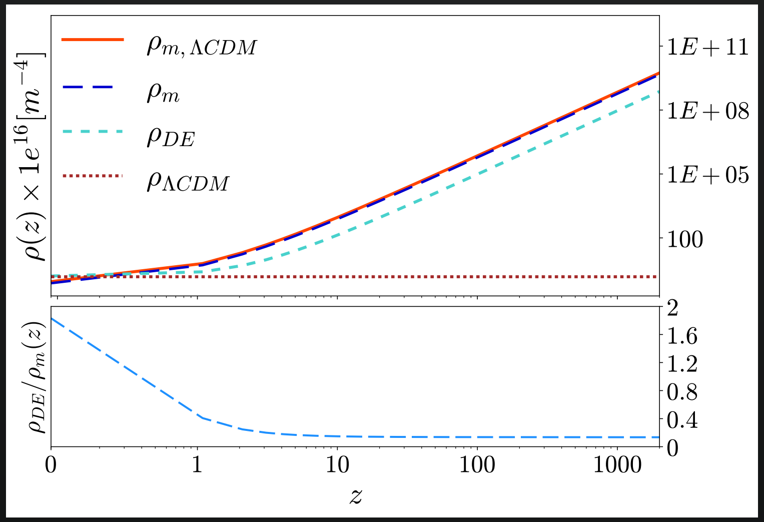
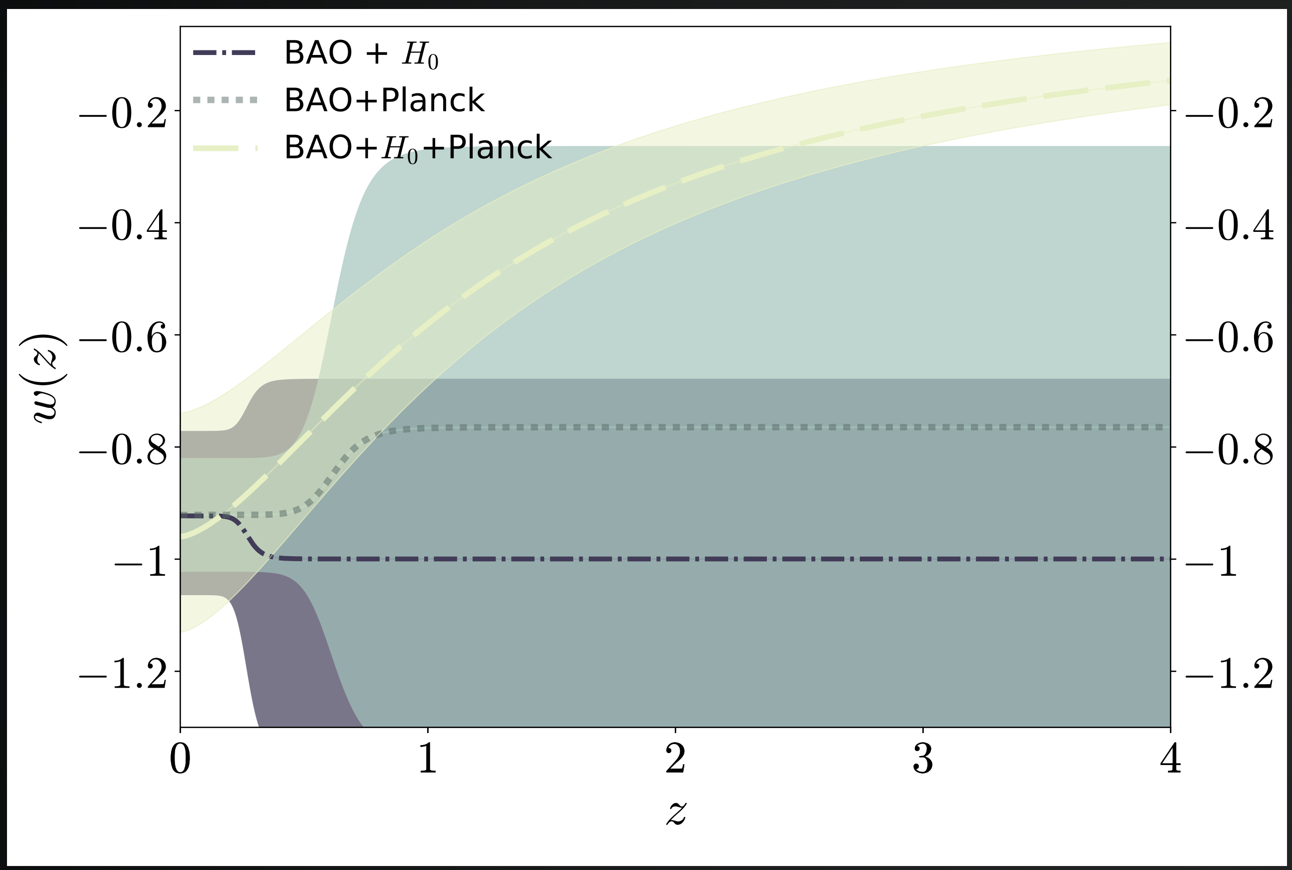
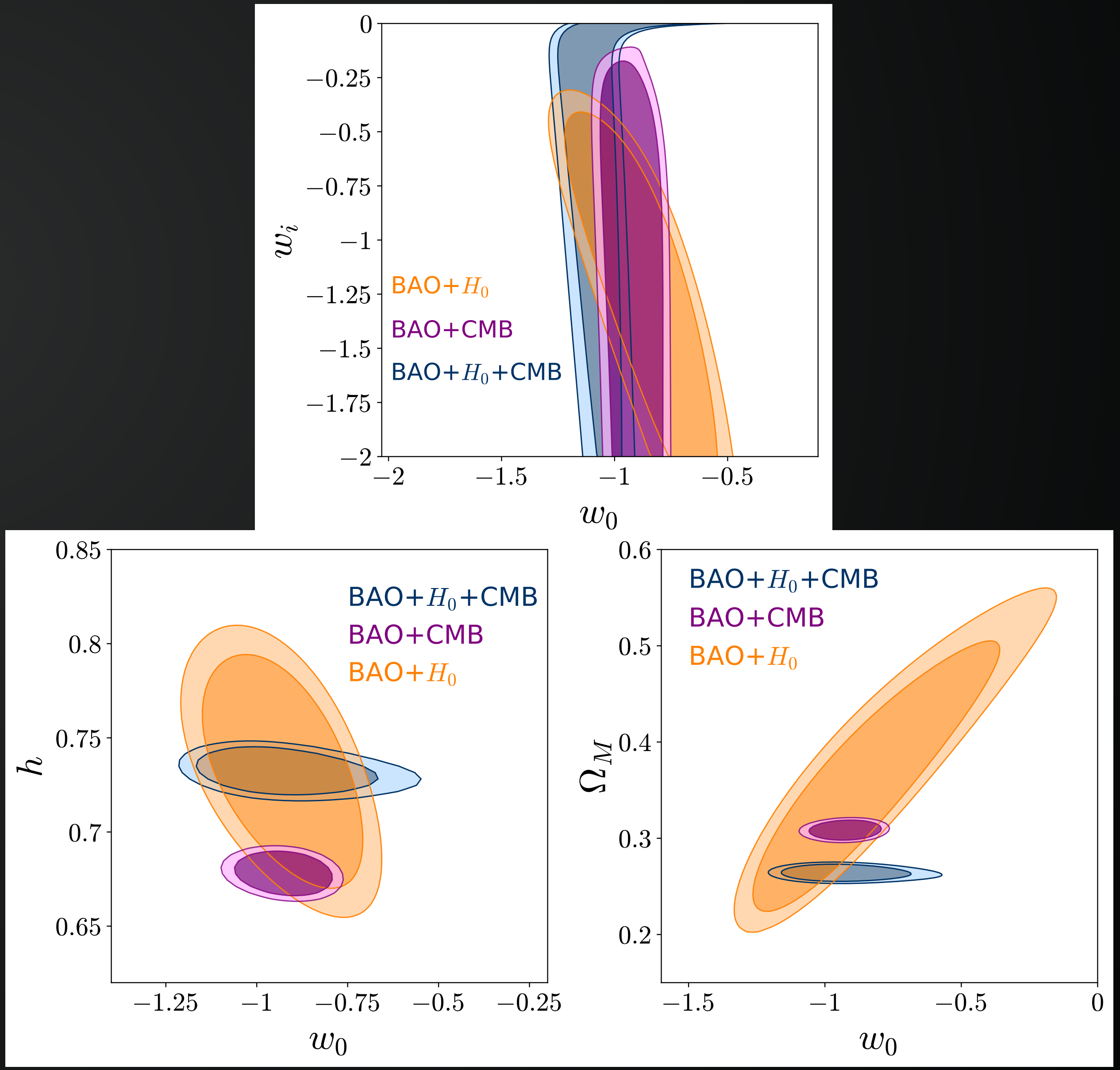




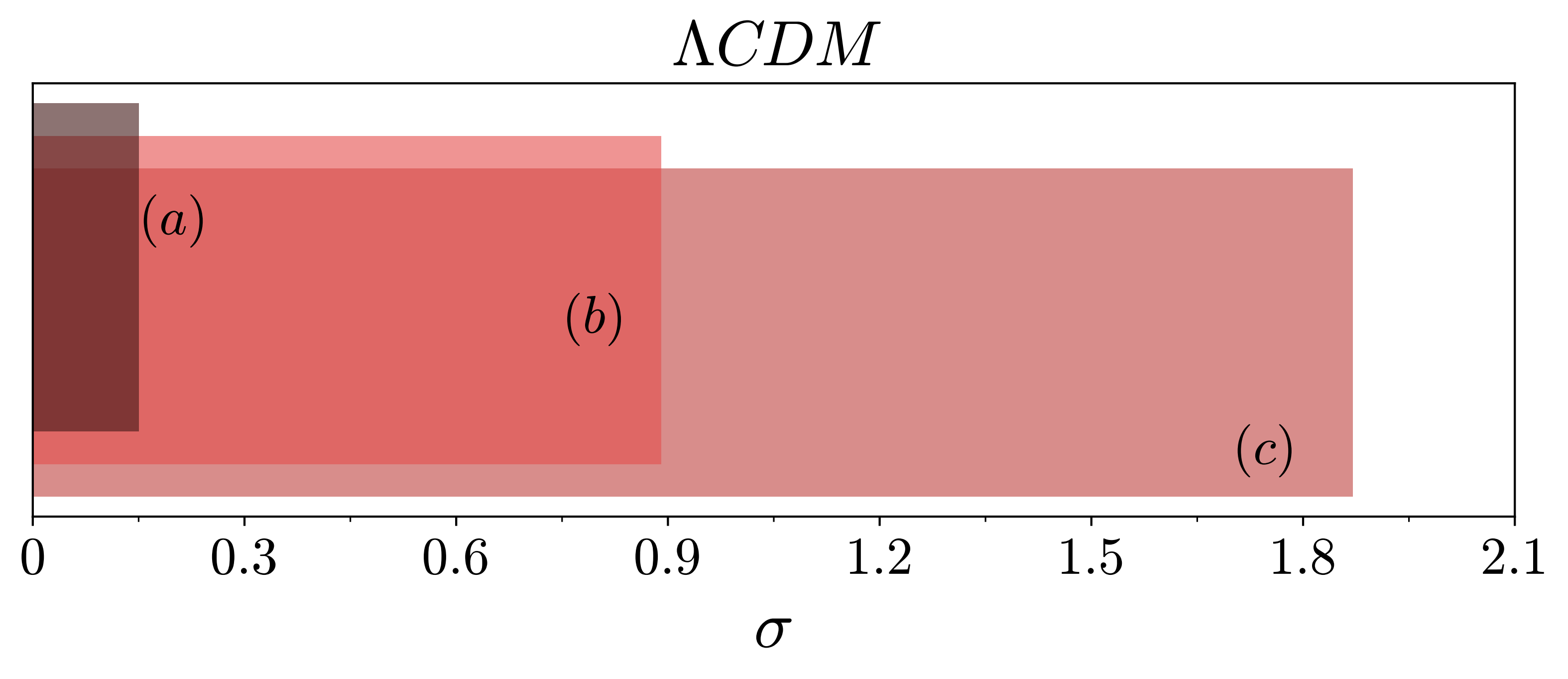
Precisely this non negligible DE at early times is what allows to put better constraints on the parameters for the EoS.

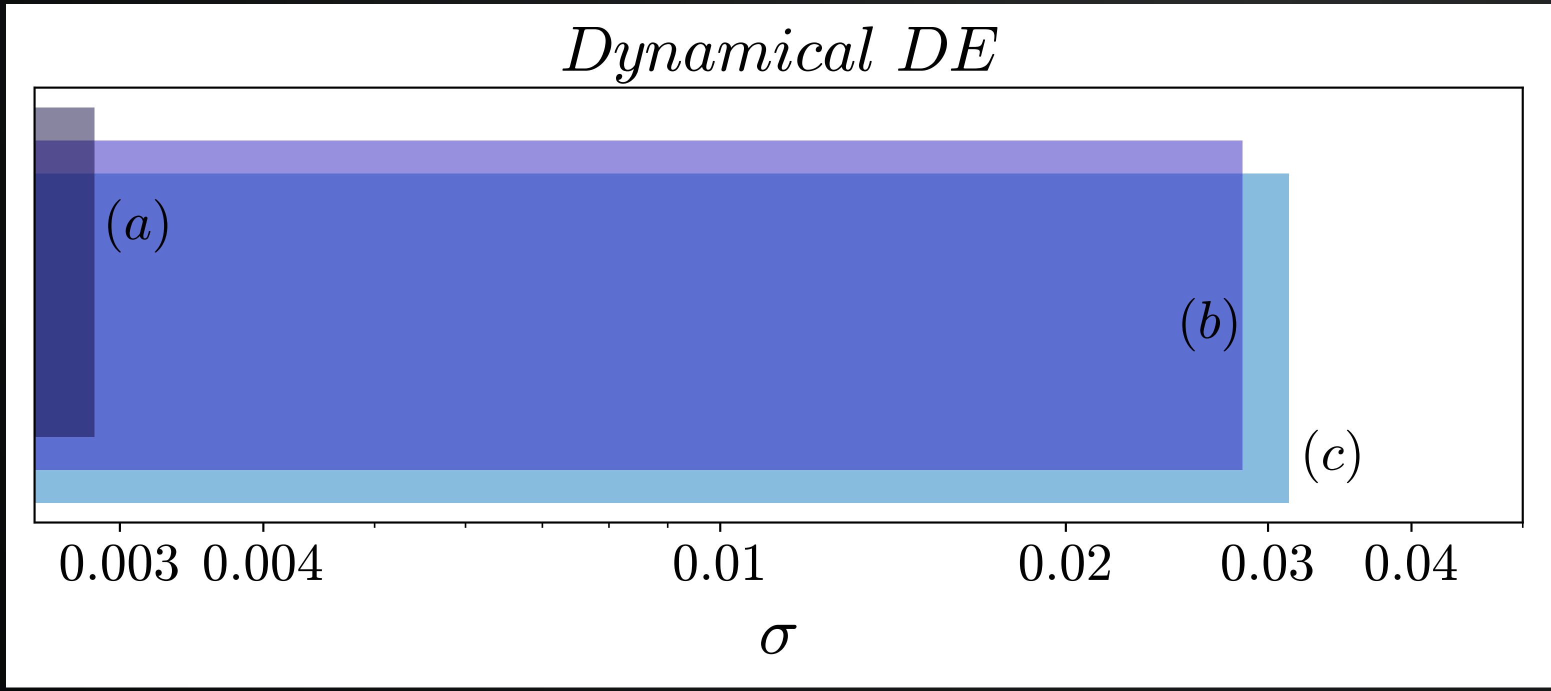
[**MJ** & A. De la Macorra 1708.08529]





Tensions





(a) $\chi^2_{BAO+H_0}$

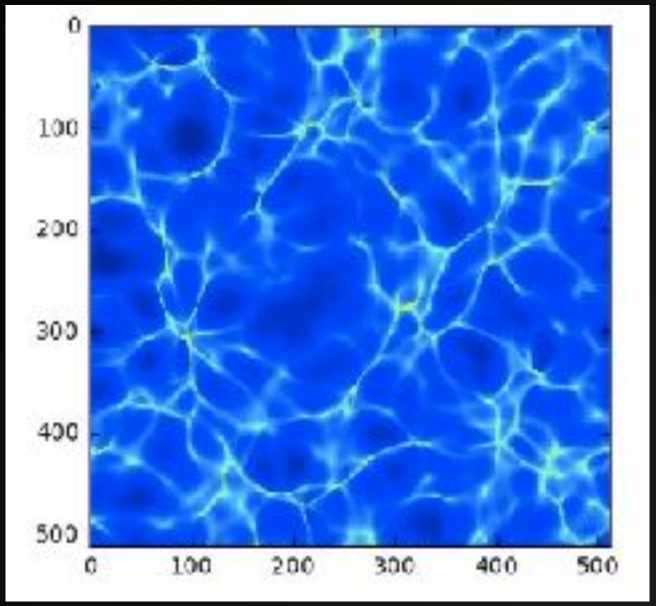
(b) $\chi^2_{BAO+Planck}$

(c) $\chi^2_{BAO+H_0+Planck}$

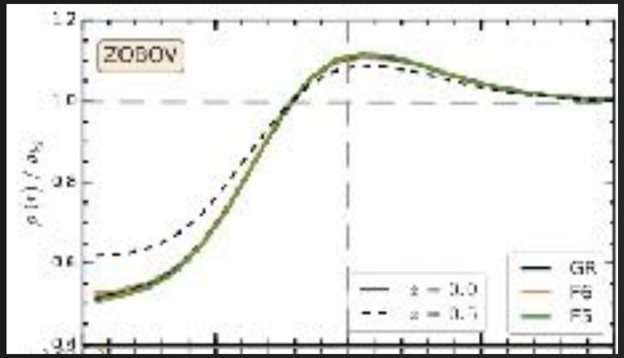
To take away

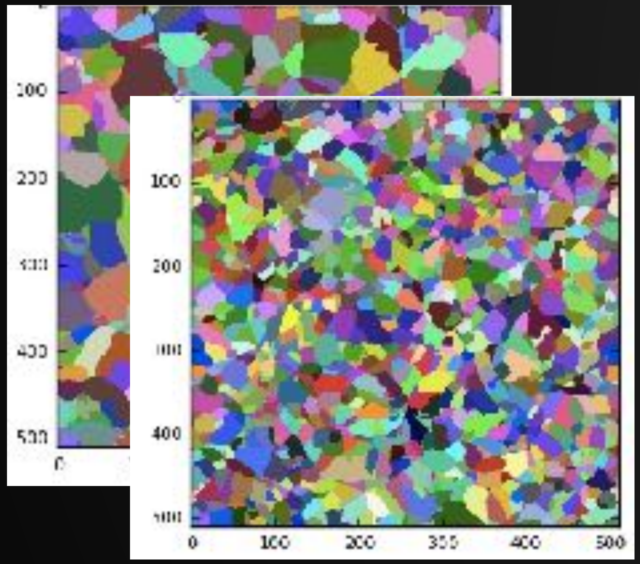
- Tension is reduced in a dynamical DE a model coming from a single scalar field and which does not cross the phantom dividing line.

Work in progress



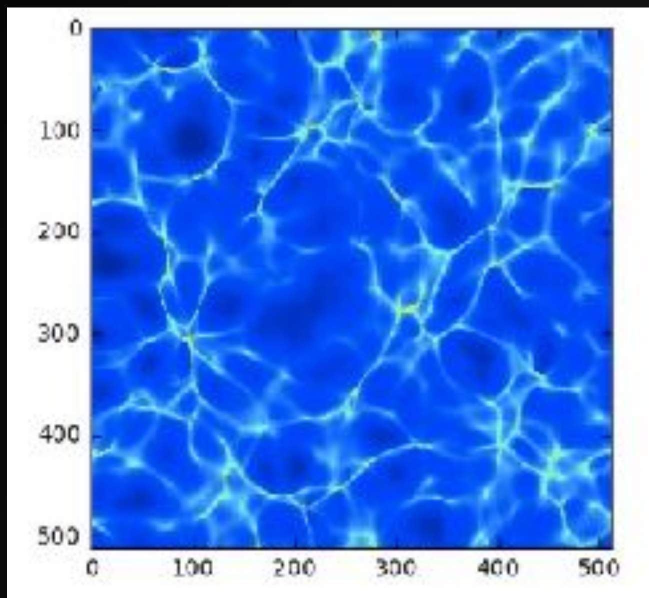
[Cautun+17]





Using SPINE method from
[Aragón-Calvo, 0809.5104]

Work in progress



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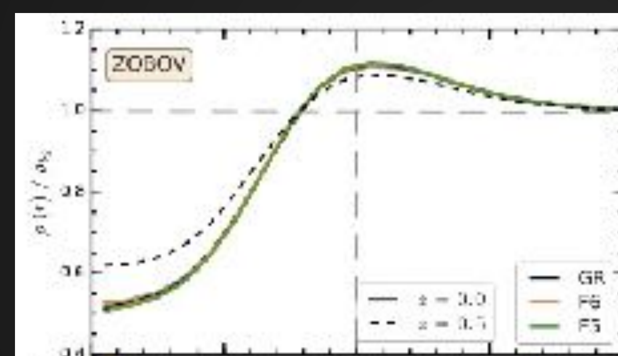

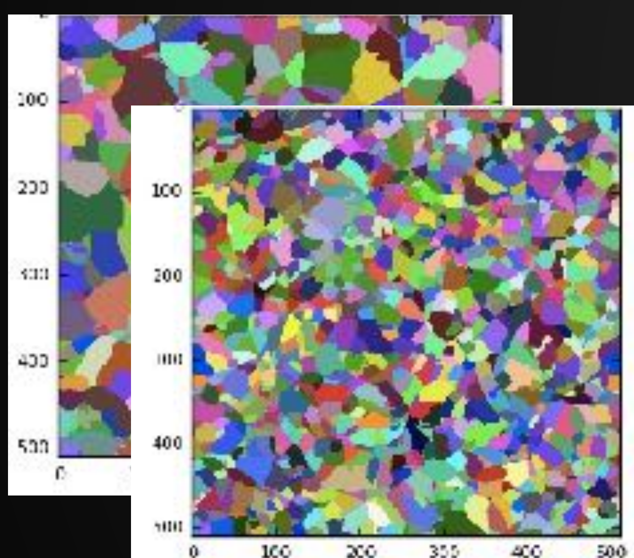

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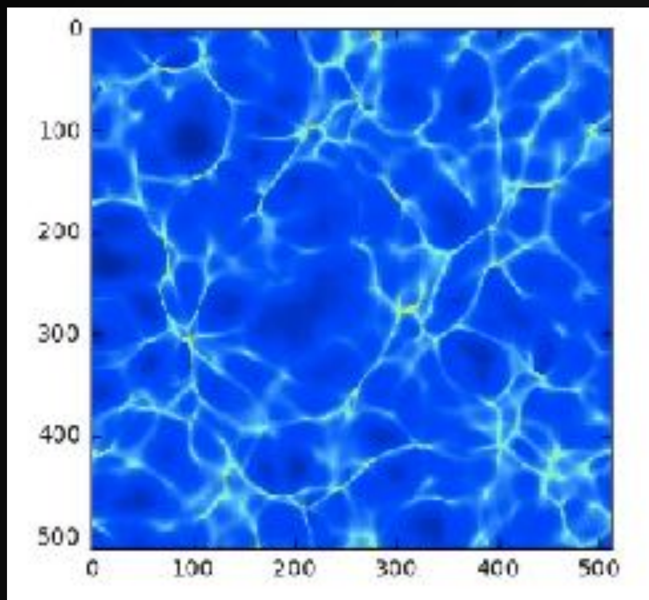

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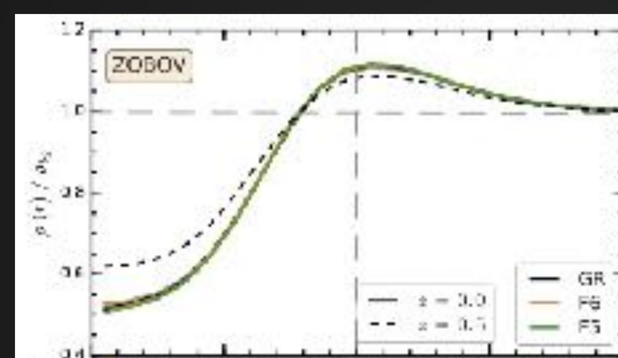
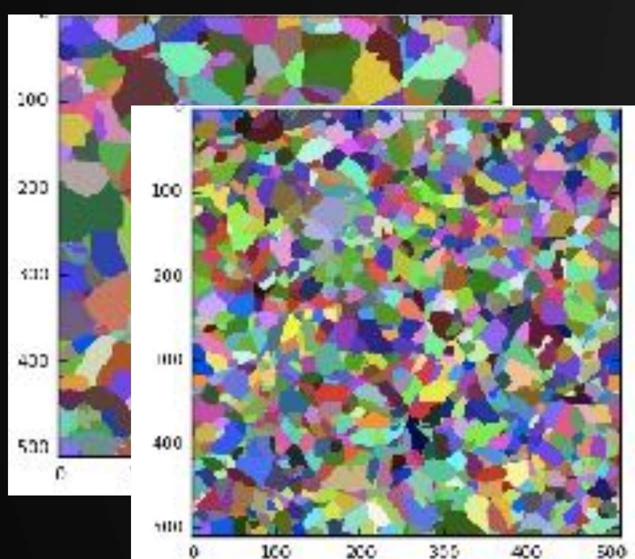
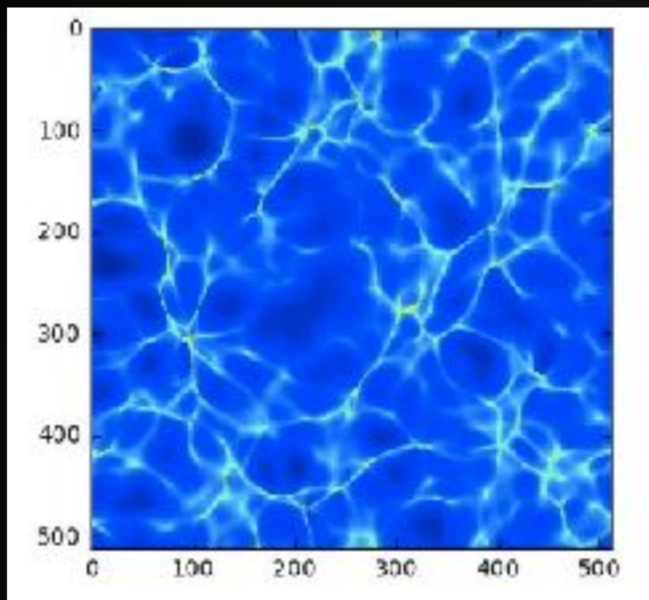




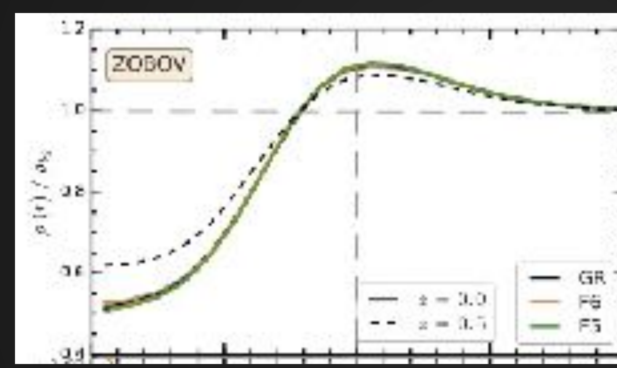
Using SPINE method from
[Aragón-Calvo, 0809.5104]

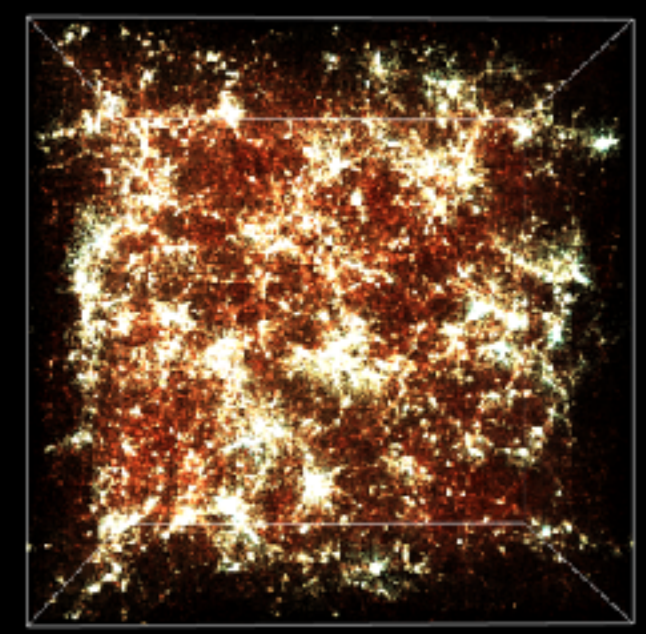
Under the supervision of Dr.Octavio Valenzuela (IA-UNAM)
Collaboration with Dr. Miguel Aragón (IA-UNAM) and Dra. Chandrachani Ningombam (IA-UNAM)

Work in progress

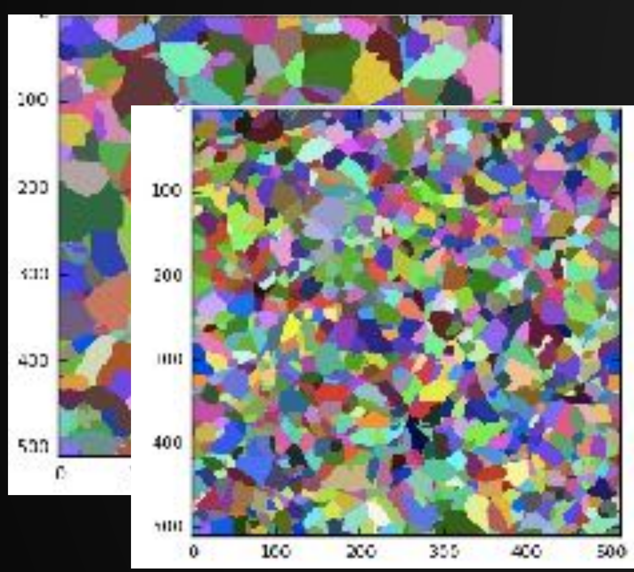


[Cautun+17]

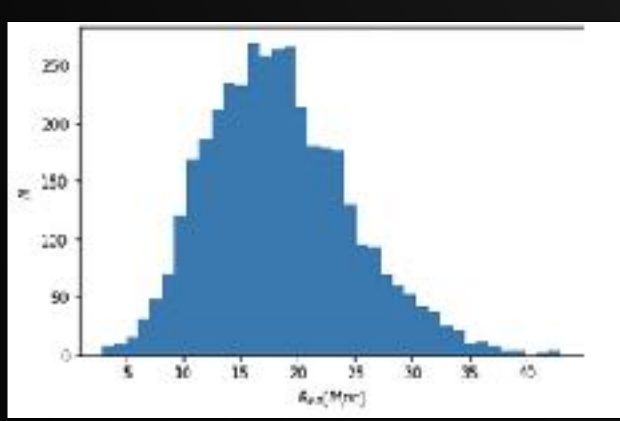


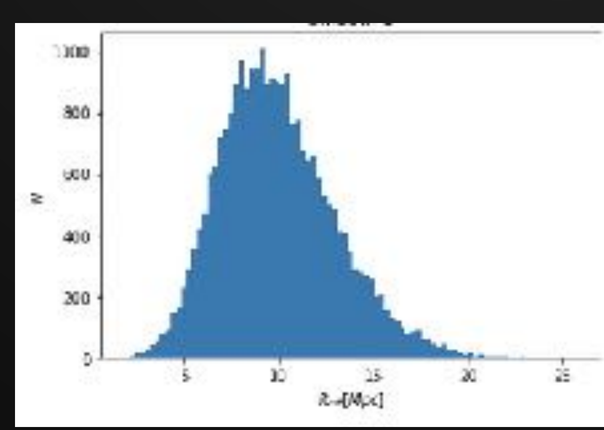


Credit: Chandrachani Ningombam



Using SPINE method from [Aragón-Calvo, 0809.5104]





Under the supervision of Dr.Octavio Valenzuela (IA-UNAM)
Collaboration with Dr. Miguel Aragón (IA-UNAM) and Dra. Chandrachani Ningombam (IA-UNAM)

Parametrization inspired in $f(R)$ theories

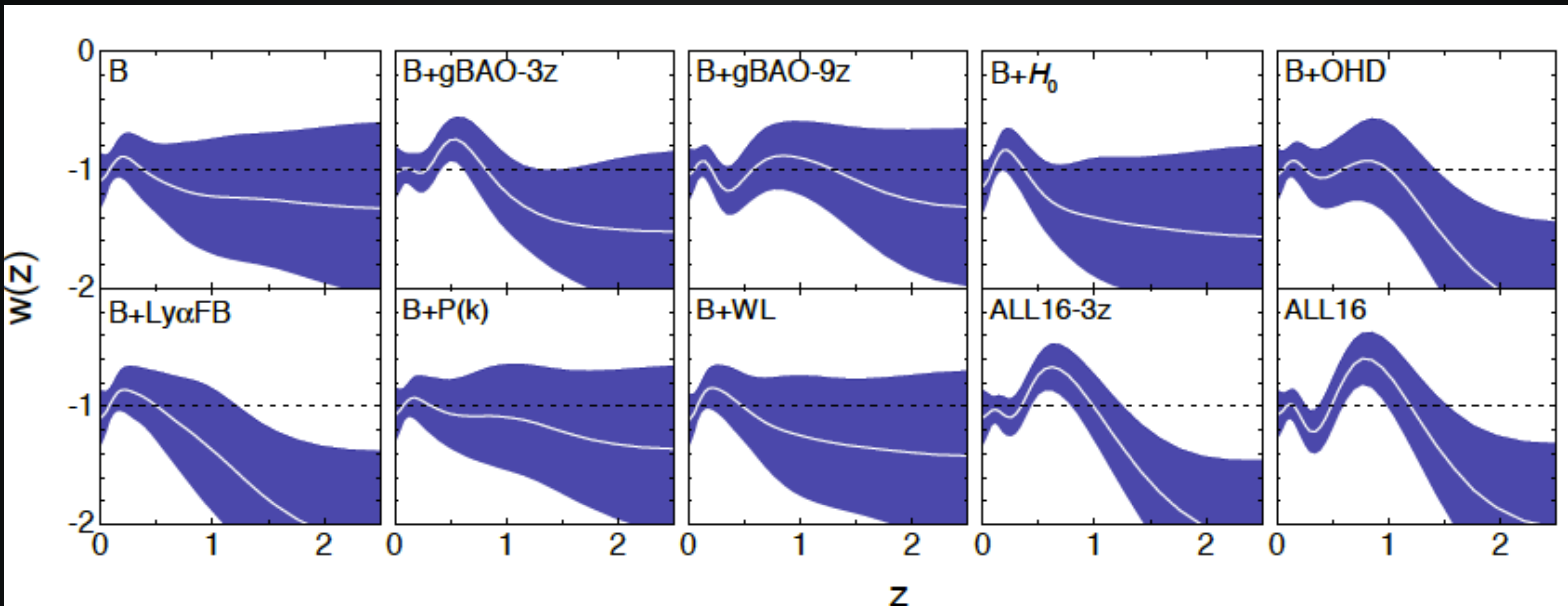
Parametrization inspired in $f(R)$ theories

Work in collaboration with

Dra. Luisa Jaime (Nuclear Physics Institute UNAM)

Dra. Celia Escamilla (MCTP/UNACH)

Reconstructed EoS for DE



[Zhao+ 2017]

- This profile cannot be reproduced by a single scalar field but it can be generated by modify gravity theories!

Cosmic acceleration may be originated from some geometric modification of Einstein theory.

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$G_{\mu\nu} \sim g, \partial g, \partial^2 g$

Modified gravity

f(R) theories

Scalar-tensor models

Braneworld models

Galileons

...

$T_{\mu\nu} \sim \rho, P$

Modified matter

Quintessence

K-essence

Tachyon

Chaplygin gas

...

f(R) theories of gravity

f(R) theories are constructed by replacing the usual Ricci scalar $\mathcal{R}$ in the Einstein-Hilbert action with an algebraic function of $\mathcal{R}$

$$S = \int d^4x\sqrt{-g}\left[\frac{f(R)}{2} + \mathcal{L}_m\right]$$

- Viable candidates after GW170817

The choice of the f(R) function must be such that :

- we obtain a late-time acceleration
- and have stable high-curvature limits and well behaved cosmological solutions with a proper era of matter domination.
- We also need to pass solar system and equivalence principle constraints.

[Amendola, L. + 083504]

[Sawicki, I. + 0702278]

f(R) theories of gravity

This leaves us with three cosmologically viable models:

- Hu & Sawicki

  [Hu + 0705.1158]

$$f(R) = R - R_{\rm HS}\frac{c_1\left(\frac{R}{R_{\rm HS}}\right)^n}{c_2\left(\frac{R}{R_{\rm HS}}\right)^n + 1}$$

- Starobinsky

  [Starobinsky 0706.2041]

$$f(R) = R + \lambda R_S\left[\left(1+\frac{R^2}{R_S^2}\right)^{-q} - 1\right]$$

- Exponential

  [Linder 0905.2962]

$$f(R) = R + \beta R_*(1 - e^{-R/R_*})$$

Geometric EoS for DE in f(R) gravity

We can extremise the action w.r.t. g_{ab} to get the field equations:

$$f_R R_{ab} - \frac{1}{2} f g_{ab} - (\nabla_a \nabla_b - g_{ab}\Box) f_R = \kappa T_{ab}$$

Using a flat FLRW metric we find the modified evolution equations:

$$\begin{aligned}
\ddot{R} = &\quad -3H\dot{R} - \frac{1}{3f_{RR}}\left[3f_{RRR}\dot{R}^2 + 2f - f_R R + \kappa T\right] \\
H^2 = &\quad -\frac{1}{f_{RR}}\left[f_{RR}H\dot{R} - \frac{1}{6}(Rf_R - f)\right] - \frac{\kappa T^t_t}{3f_R}, \\
\dot{H} = &\quad -H^2 - \frac{1}{f_R}\left[f_{RR}H\dot{R} + \frac{f}{6} + \frac{\kappa T^t_t}{3}\right]
\end{aligned}$$

Directly from the metric we can get

$$R = 6(\dot{H} + 2H^2)$$

And defining $T^x_{ab} = T^{tot}_{ab} - T_{ab}$ we can write the geometric equation of state

$$w_x = \frac{3H^2 - 3\kappa P - R}{3(3H^2 - \kappa\rho)}$$

which comes from a T_{ab} which strictly conserves energy and momentum and which is free of singularities [Jaime, L. + 1312.5428]

JJE parametrization

We need to integrate the field equations from the past to the future and, given the attractor behavior of this kind of gravity, its implementation into the pipeline of surveys, or in N-body, and Boltzmann codes is complex and requires many assumptions.

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$$\omega(z) = -1 + \frac{w_0}{1+w_1 z^{w_2}} cos(w_3 + z)$$

[Jaime, L., MJ, Escamilla, C. 1804.04284]

JJE parametrization

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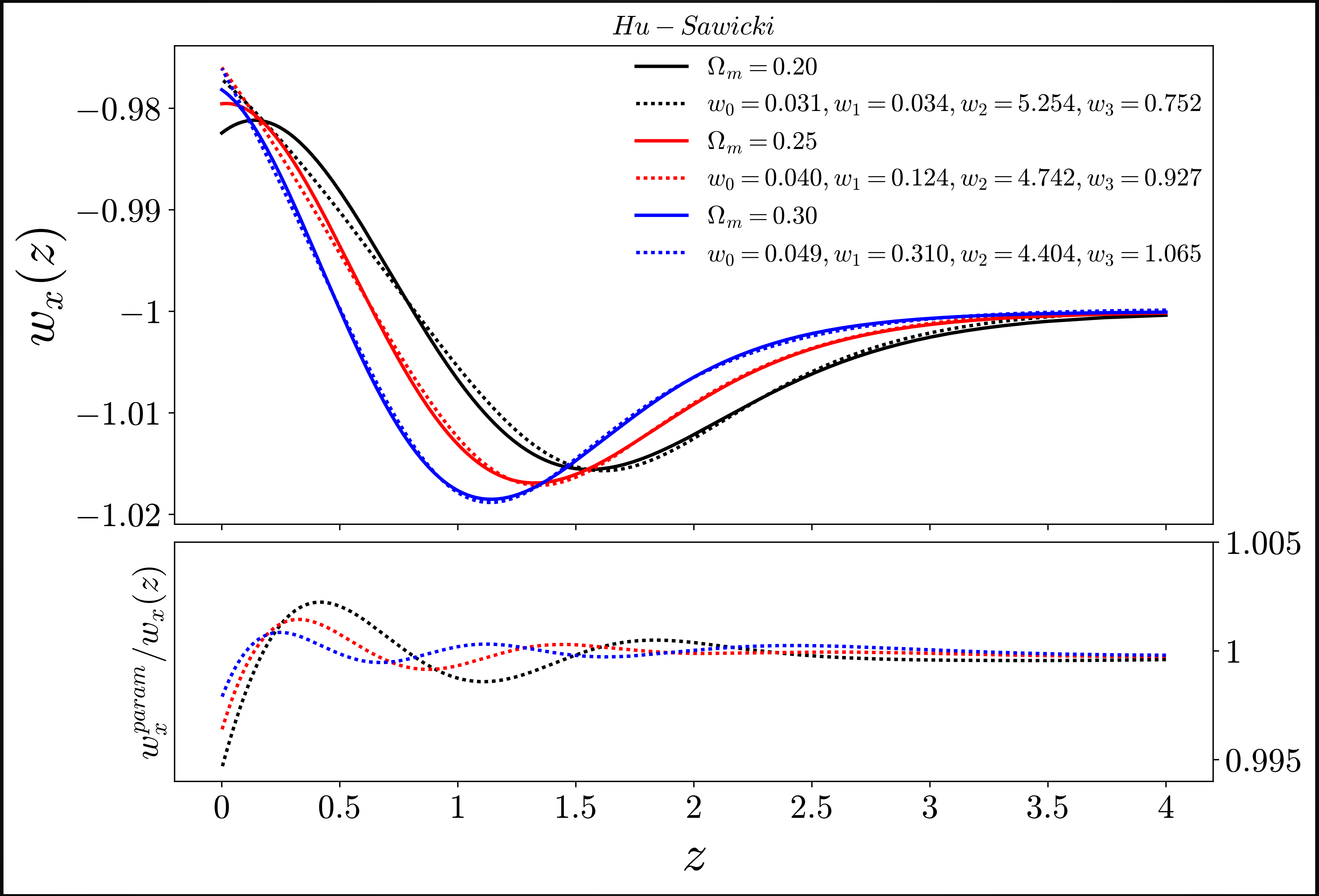
$$\omega(z) = -1 + \frac{w_0}{1+w_1 z^{w_2}} cos(w_3 + z)$$

- Has $w(z=0) = w_0 cos(w_3) - 1$
- Recovers $w=-1$ at large redshifts
- And allow oscillations in the range of interest of observations

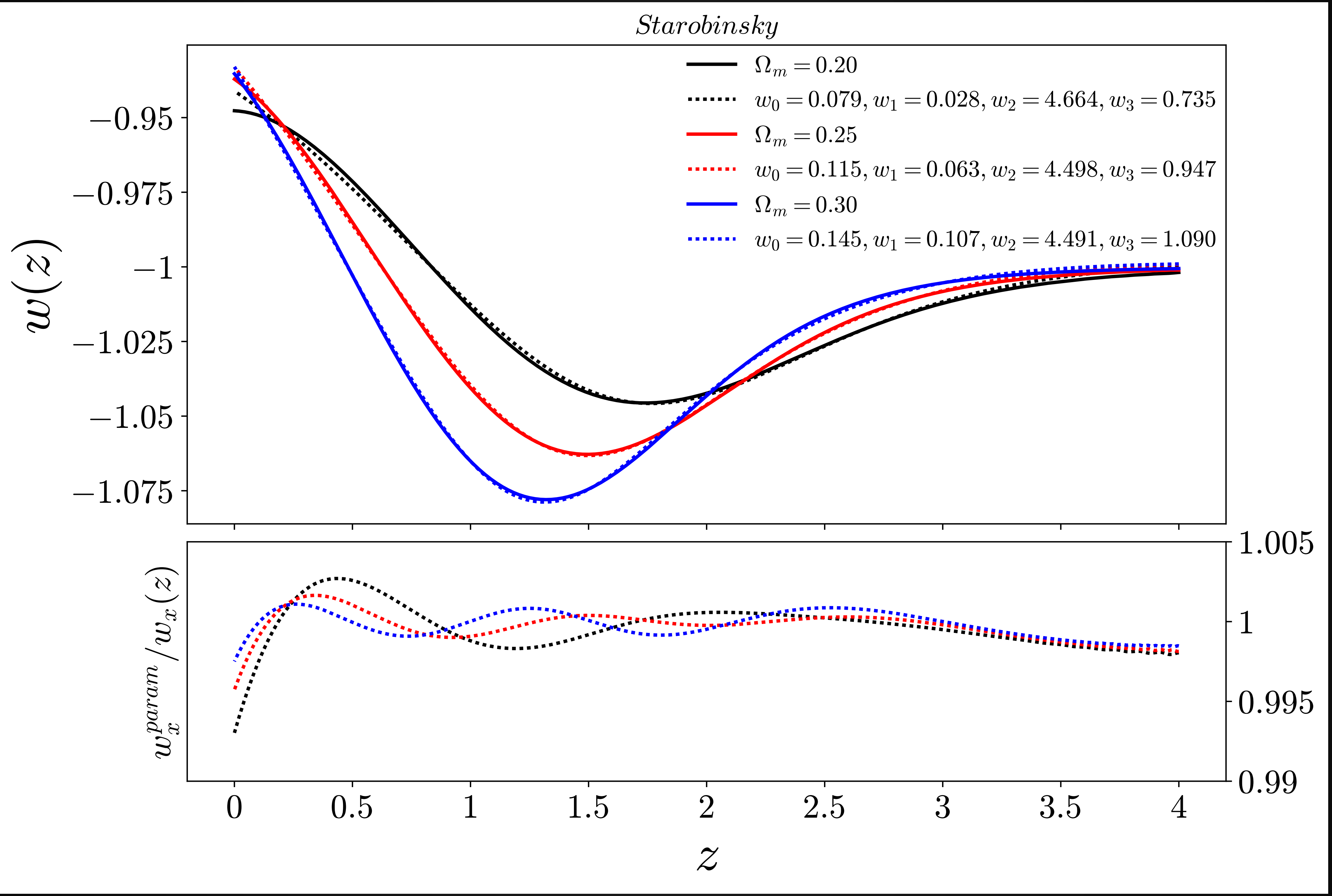
[Jaime, L., MJ, Escamilla, C. 1804.04284]

JJE parametrization



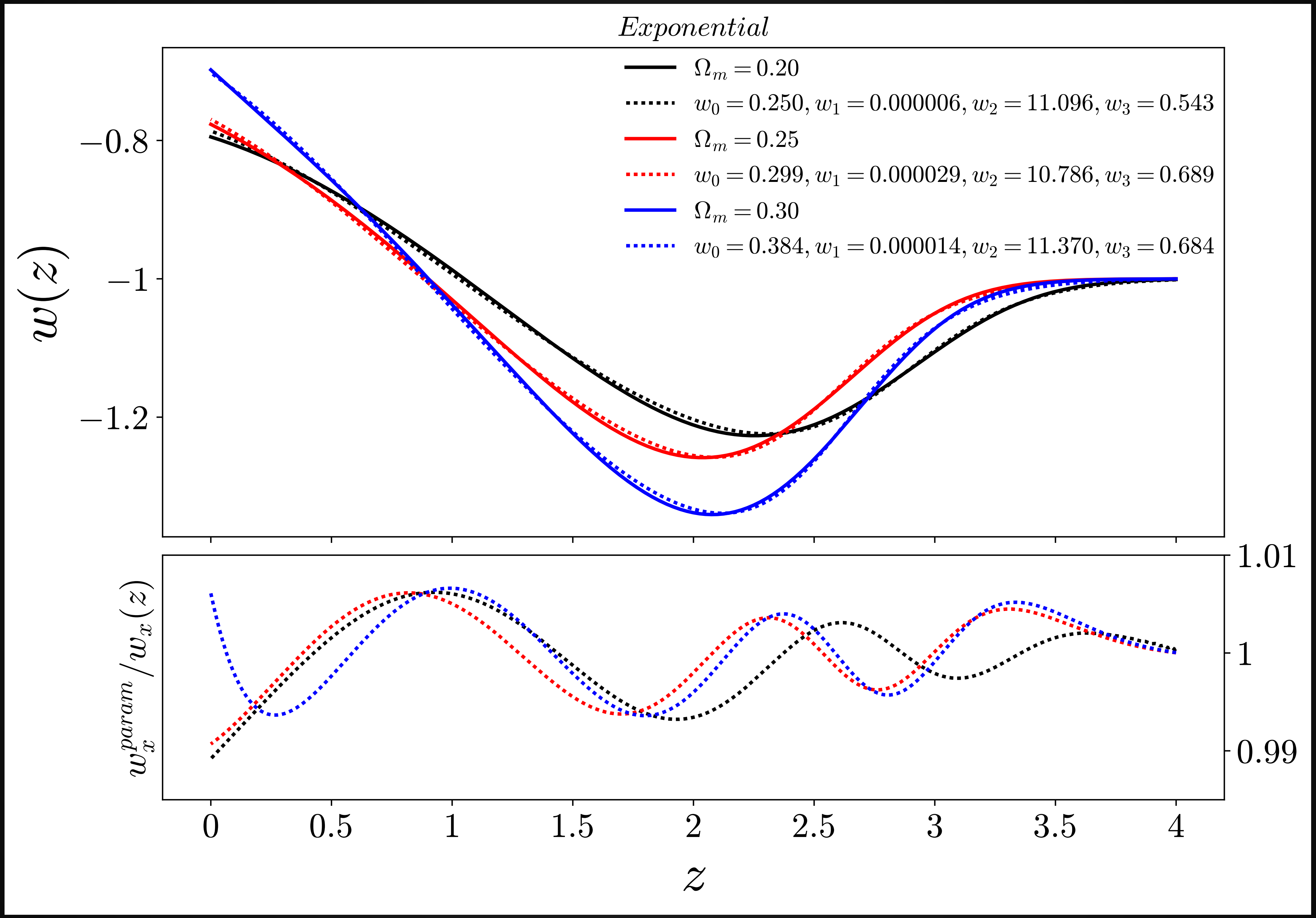
[Jaime, L., **MJ**, Escamilla, C. 1804.04284]

JJE parametrization



[Jaime, L., **MJ**, Escamilla, C. 1804.04284]

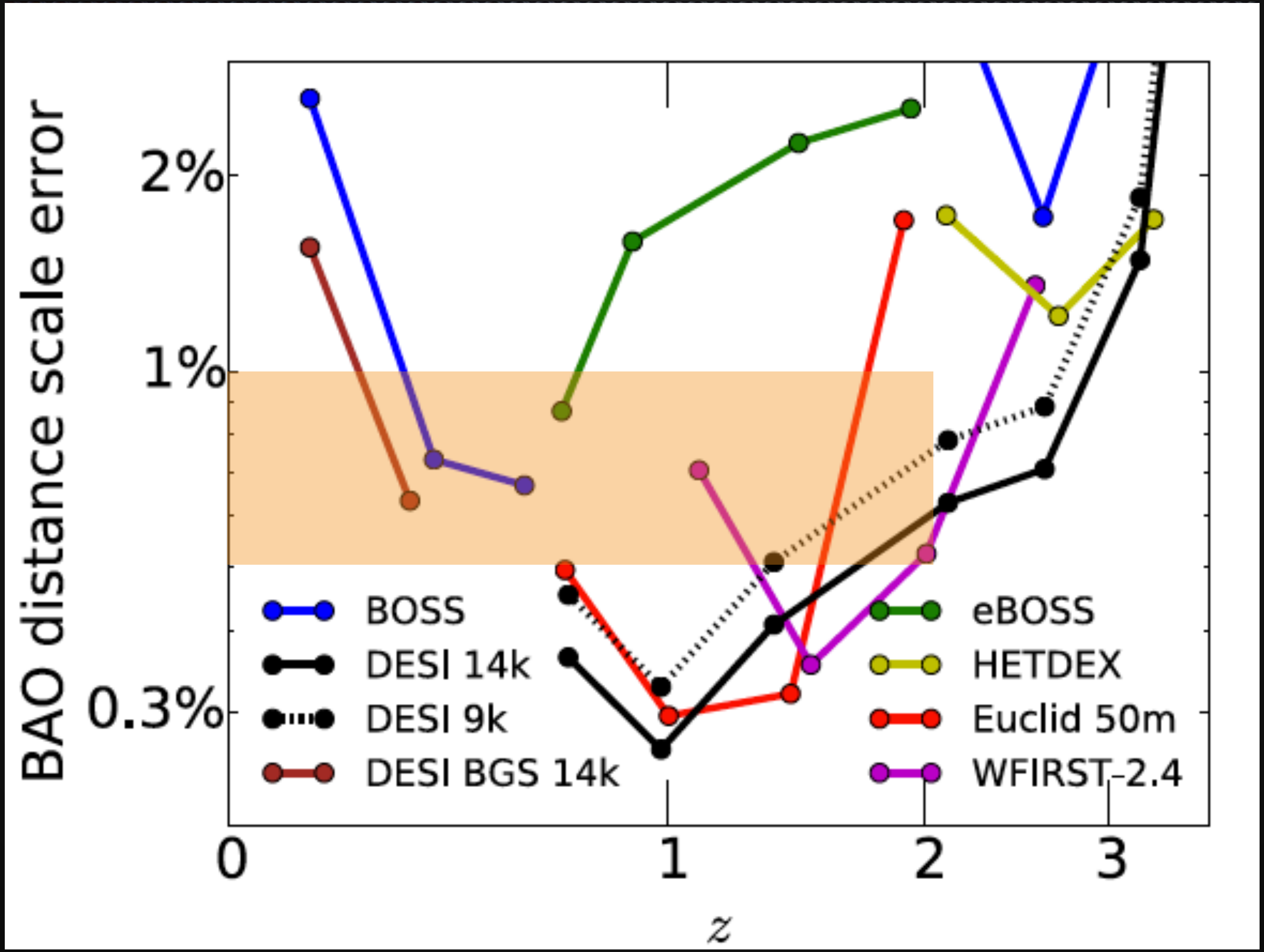
JJE parametrization



[Jaime, L., **MJ**, Escamilla, C. 1804.04284]

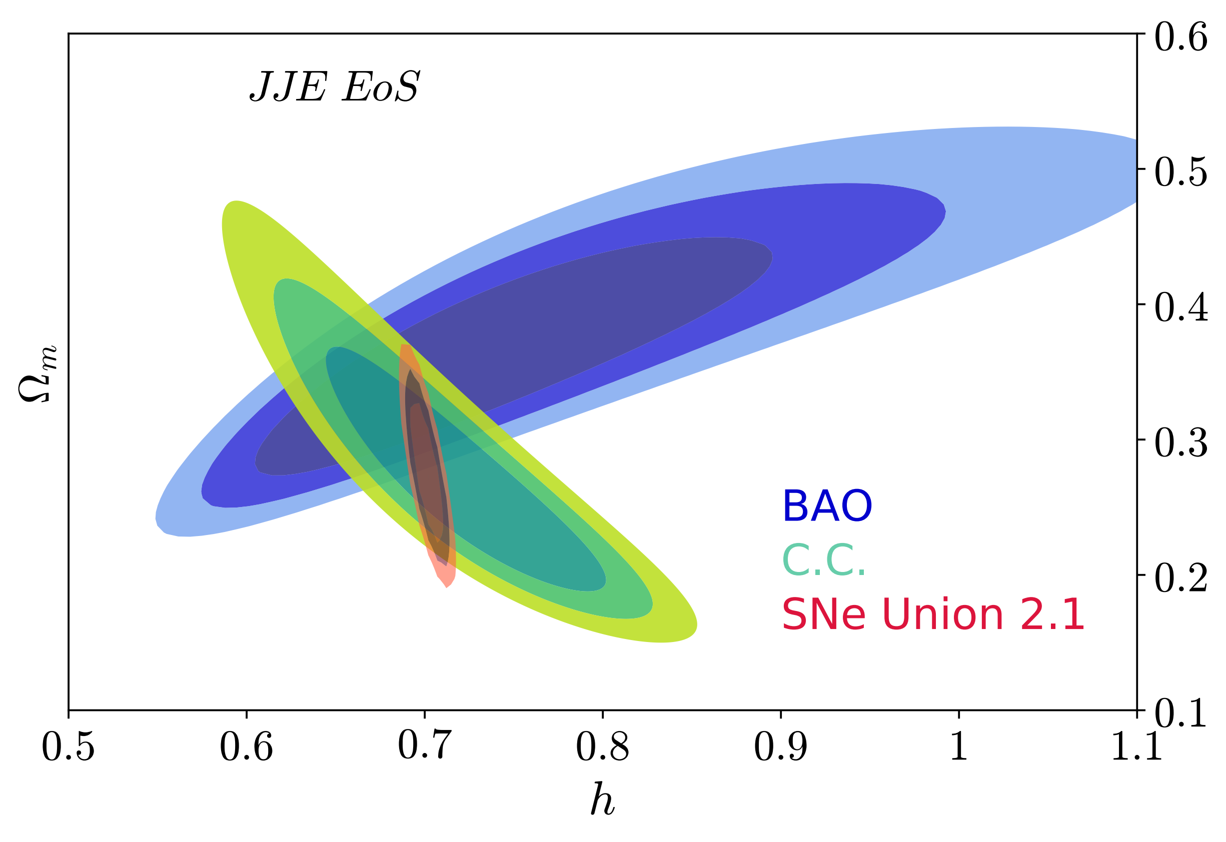
JJE parametrization

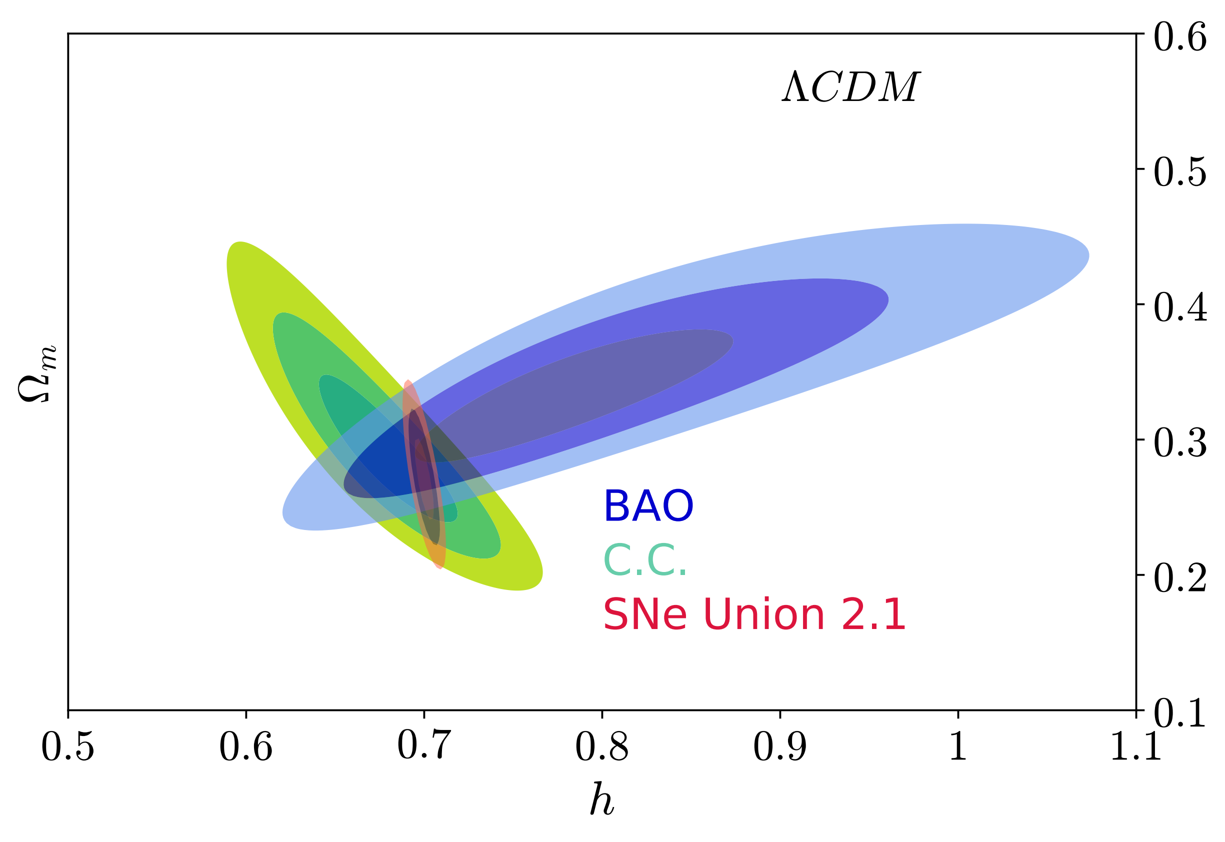
- Competitive precision in the region relevant for Dark Energy experiments



JJE parametrization: implementation to data

- BAO determination from galaxies and Ly-a measurements
- SNeIa
- Measurement of H(z) from cosmic clocks





[Jaime, L., **MJ**, Escamilla, C. 1804.04284]

JJE parameterization: Statistical inference

[Akaike, 1974]

$$T_{H_0} = \frac{|H_0 - H_0^{R16}|}{\sigma_{H_0}}$$

T_{H0}	Qualitative interpretation
< 1.4	No significant tension
$1.4 - 2.2$	Weak tension
$2.2 - 3.1$	Moderate tension
> 3.1	Strong tension

BAO ($N = 7$)	$-2\ln\mathcal{L}_{max} = \chi^2_{min}$	AIC	BIC	ΔAIC	ΔBIC	T_{H_0}
JJE GEoS ($m = 6$)	9.5501	21.5501	21.2255	7.8543	7.6379	0.145188
LCDM ($m = 2$)	9.6958	13.6958	13.5876	0	0	3.10425

CC ($N = 28$)	$-2\ln\mathcal{L}_{max} = \chi^2_{min}$	AIC	BIC	ΔAIC	ΔBIC	T_{H_0}
JJE GEoS ($m = 6$)	15.92685	27.9269	35.9201	7.5467	12.8755	0.0465561
LCDM ($m = 2$)	16.3802	20.3802	23.0446	0	0	0.957746

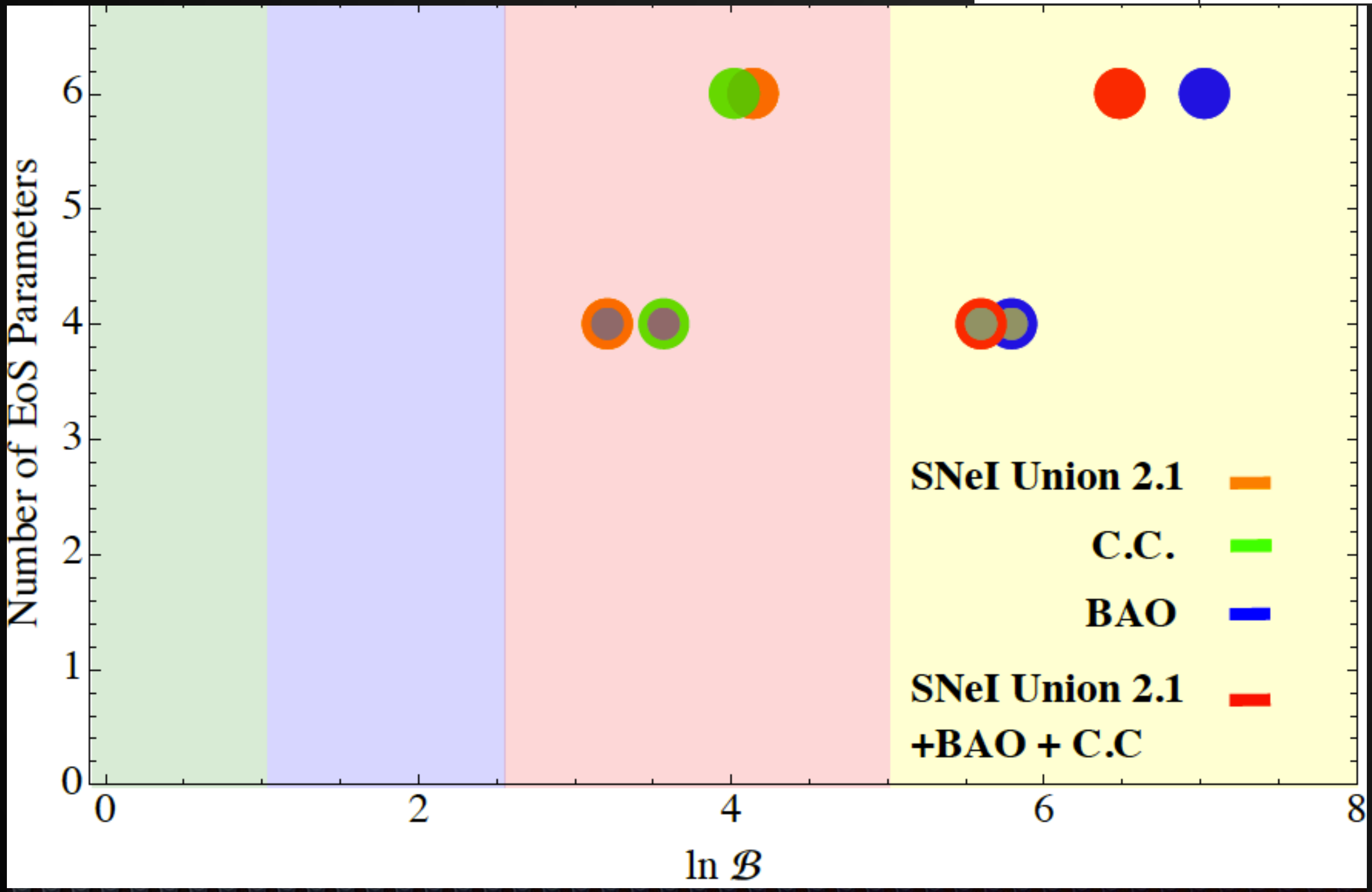
SNe U 2.1 ($N = 557$)	$-2\ln\mathcal{L}_{max} = \chi^2_{min}$	AIC	BIC	ΔAIC	ΔBIC	T_{H_0}
JJE GEoS ($m = 6$)	542.7686	554.7686	580.7039	8.0866	25.3768	0.191964
LCDM ($m = 2$)	542.6820	546.682	555.3271	0	0	2.81337

[Escamilla, C., Jaime, L, **MJ**, 2018]

[Escamilla, C. + 2018]

JJE parameterization: Statistical inference

$\ln B_{i0}$	Strength of evidence	color code
> 5	Strong evidence for model i	
$[2.5, 5]$	Moderate evidence for model i	
$[1, 2.5]$	Weak evidence for model i	
$[-1, 1]$	Inconclusive	



JJE EoS

CPL, BA

[Escamilla, C; Jaime, L, **MJ** 2018]

To take away

- We present a new parameterisation that can reproduce a f(R)-like cosmology with precision <0.8% in the range z = [0, 4]
- Each parameter in this 4-dim f(R)-like cosmology parameterisation have a closely physical meaning with the free parameters in the f(R) models considered.
- The implementation of this parameterisation to observational data shows enough statistical significance for current and future experiments.
- This parameterisation (based on physically motivated theory) can be used: as a fiducial model in surveys and to implement (easily) in Boltzmann codes [Jaime, Jaber, Escamilla. In process 2018]

THANK YOU FOR YOU TIME