Model-independent tests of the standard cosmological model

Carlos Bengaly

FAPERJ
Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro

Observatório Nacional

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CNPq

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Outline

- The standard model of Cosmology (SCM)
- We have a SCM, but do we *really* understand the cosmos?
- Model-independent tests of the SCM:
  - A null test of Cosmological Principle with BAO measurements
  - A cosmological measurement of the speed of light in a model-independent way
  - Delta diagnostic: a null test of cosmic acceleration
- Concluding remarks and perspectives

The standard model of Cosmology

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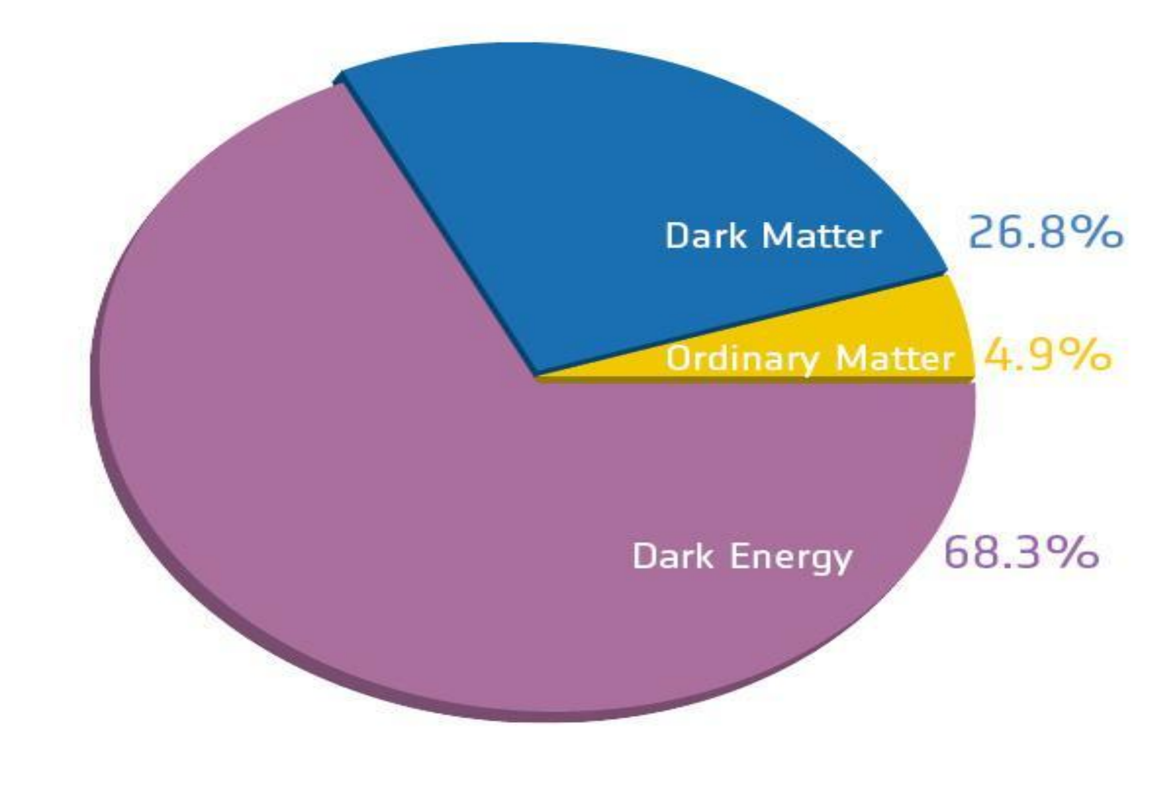
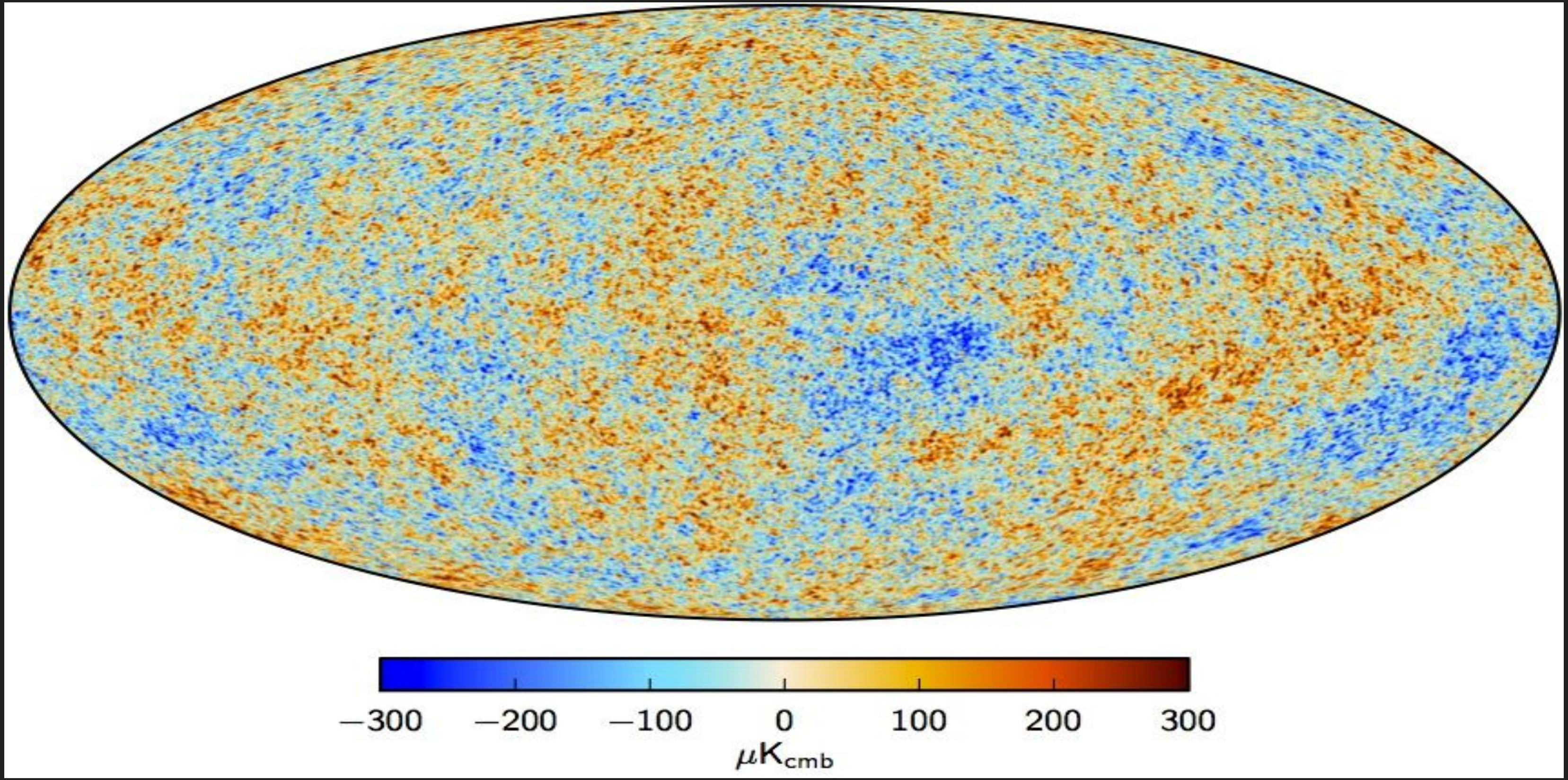


Credits: Planck Collaboration

What is dark matter?

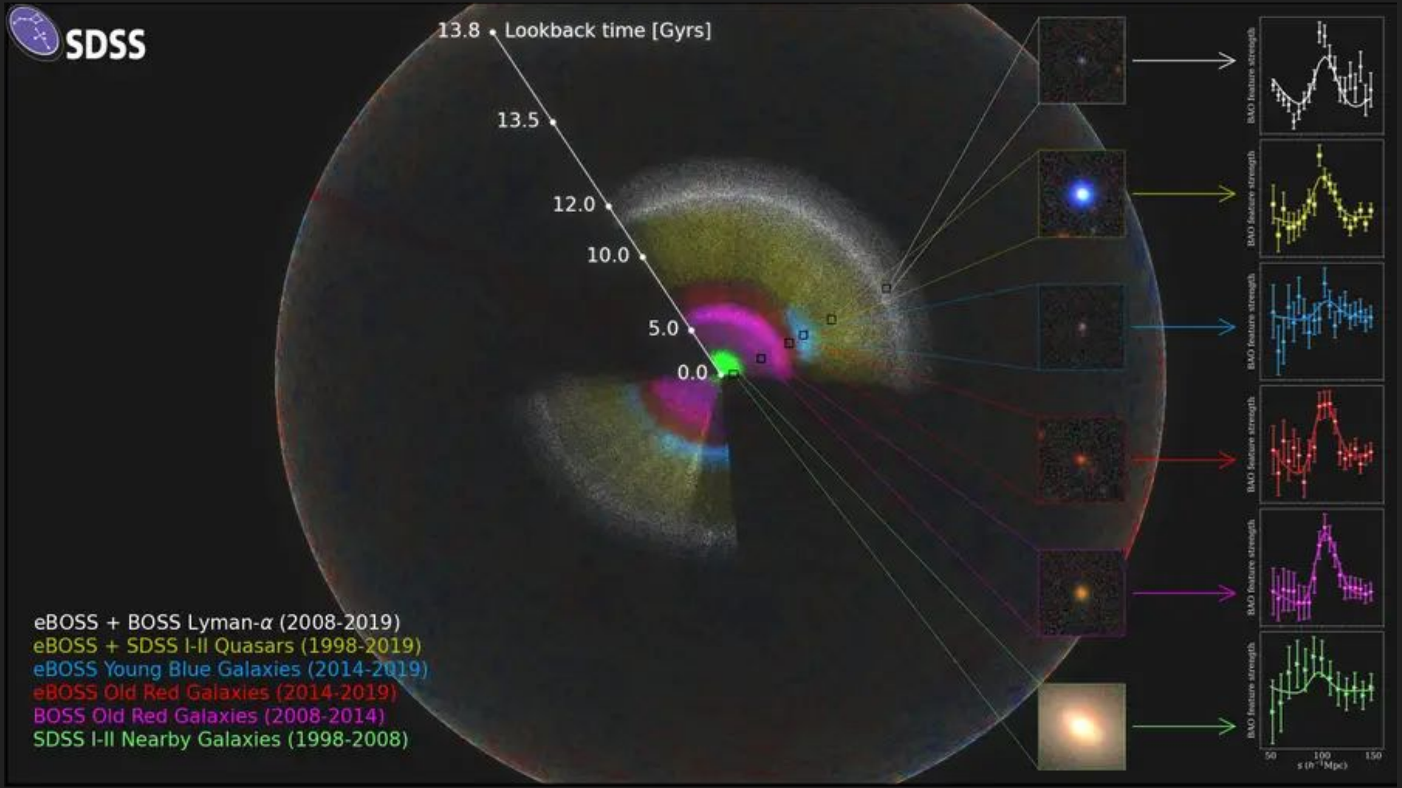
What is dark energy?

The Cosmic Microwave Background (CMB)



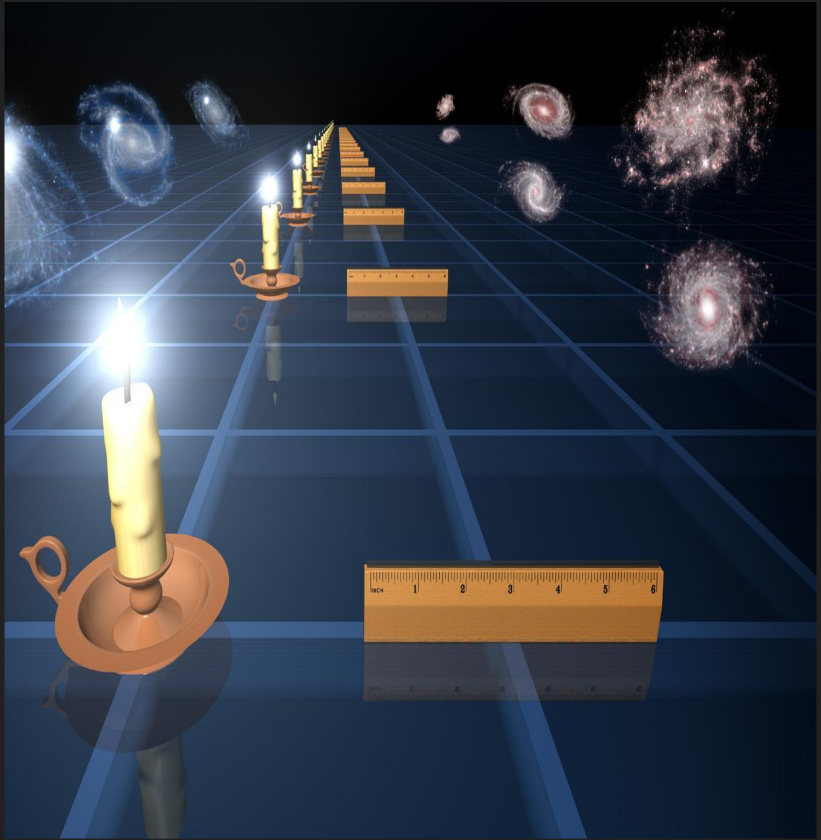
Credits: Planck Collaboration

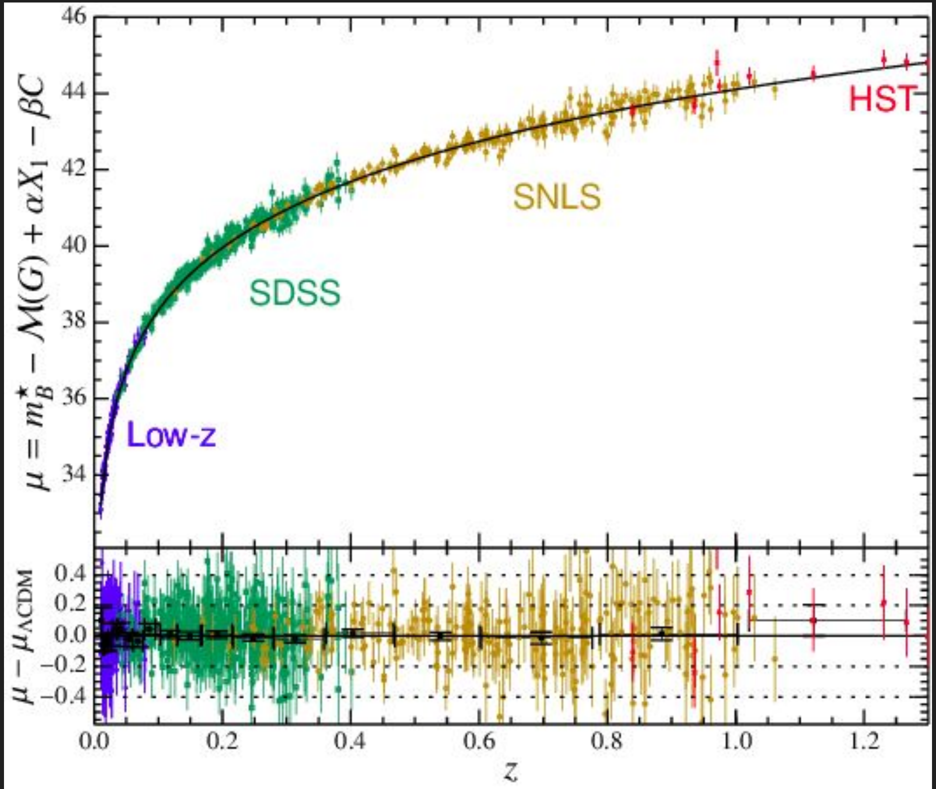
The galaxy distribution in the large-scale structure of the Universe



Credits: Anand Raichoor/EPFL, Ashley Ross/Ohio State University, and the SDSS Collaboration

The distance to Type Ia Supernovae (SNe)





Ok, we have a model which explains very well cosmological observations… but do we really understand the cosmos?

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Moreover, there are some possible “cracks” on the CM, like the ~4.4σ H_0 tension and ~2.5σ σ_8 tension

We shall revisit the fundamental assumptions which the SCM is based upon

A null test of the Cosmological Principle with BAO measurements

CB

e-print: 2111.06869 [gr-qc]

Phys.Dark Univ. 35 (2022) 100966

Data and method

- We use angular diameter distance measurements from the **transverse BAO mode (DAz)** (Carvalho+15,20; Alcaniz+17; de Carvalho+18; Avila+19), along with cosmic chronometers from **radial BAO mode (Hz)**

- These modes should be consistent along the redshift, so that (Maartens11)

$$\zeta(z) = 1 - \frac{L_{\parallel}}{L_{\perp}} = 1 - \frac{(1+z)D_{\rm A}(z)}{D_{\rm C}(z)}$$

$$\zeta(z) \neq 0 \ \text{ implies FLRW ruled out.}$$

Data and method

- We reconstruct both distance measurement samples with **GaPP** (https://github.com/astrobengaly/GaPP), which performs non-parametric reconstructions using **Gaussian Processes**

- We assume the sound horizon scale measured by Carvalho+ 20 (C20) and Verde+ 17 (VBHJ17) and two H0 priors

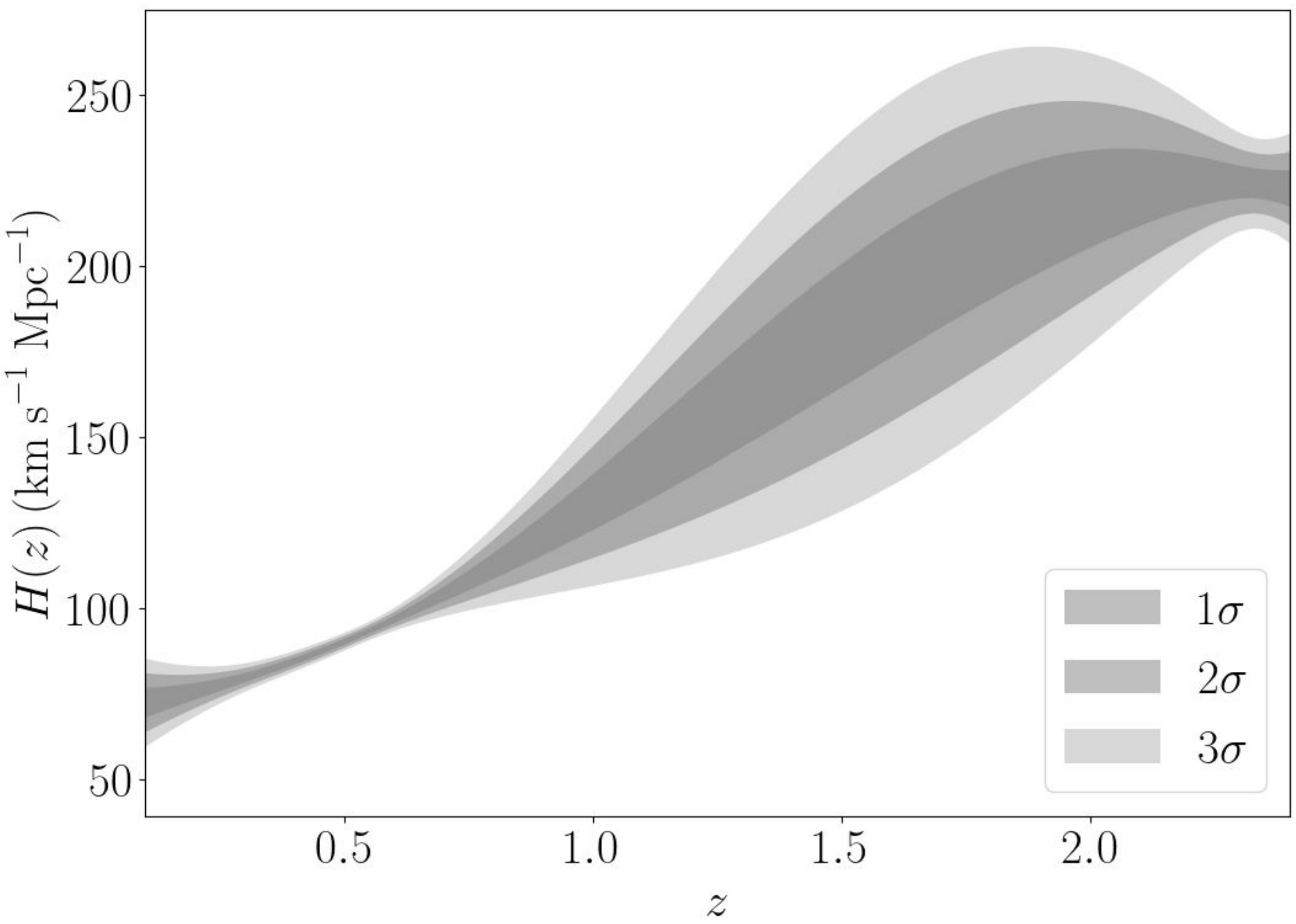
$$r_s^{C20} = 107.4 \pm 1.7\,\mathrm{Mpc\,h^{-1}} \qquad H_0^{P18} = 67.50 \pm 0.50\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

$$r_s^{VBHJ17} = 101.0 \pm 2.3\,\mathrm{Mpc\,h^{-1}} \qquad H_0^{R21} = 73.04 \pm 1.04\ \mathrm{km\ s^{-1}\ Mpc^{-1}}\,.$$

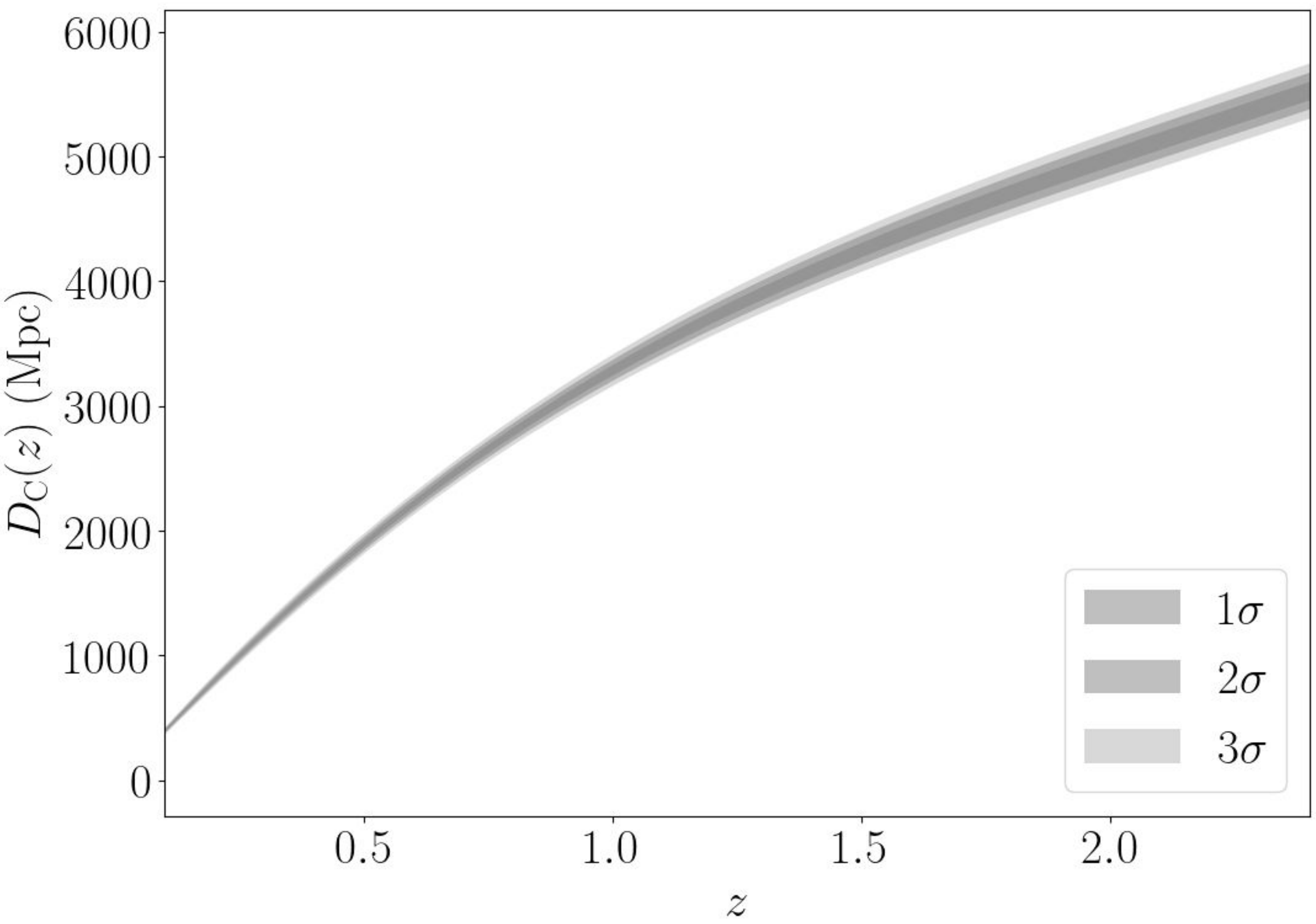
- The radial comoving distance is obtained by integrating the reconstructed H(z)

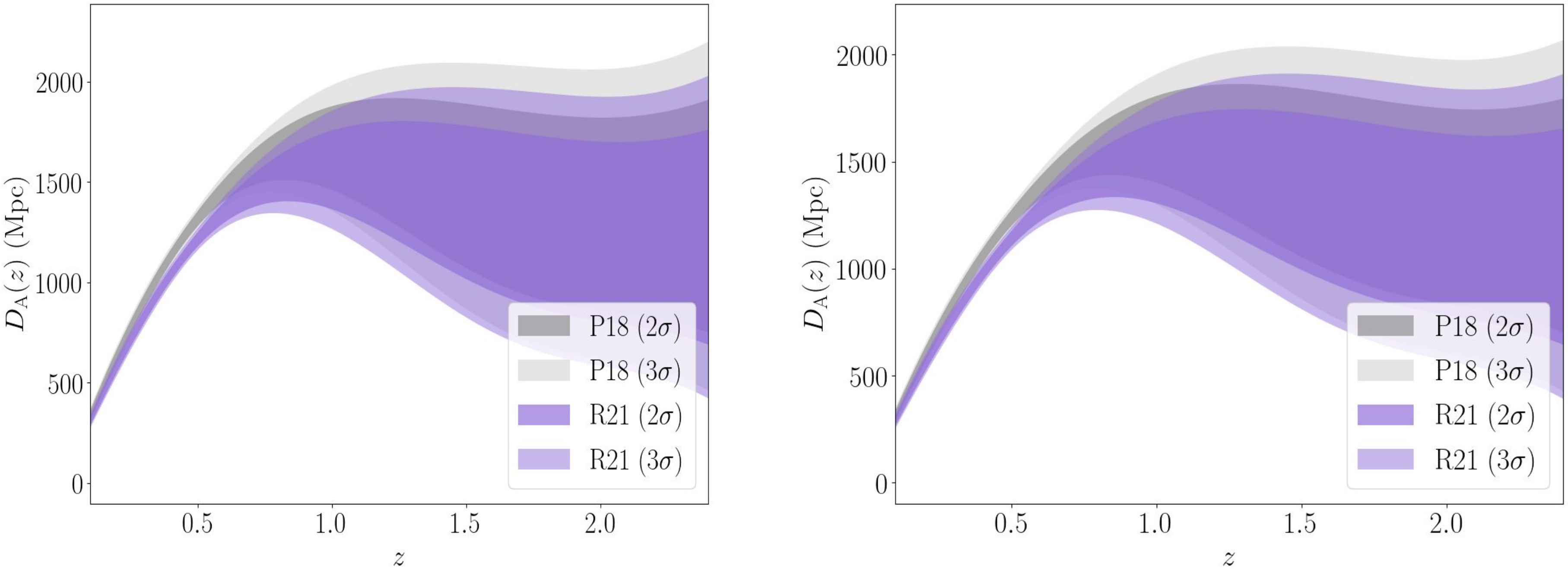
$$D_C(z) = \int_0^z \frac{c\,dz'}{H(z')} \approx \frac{c}{2} \sum_{i=1}^{N} (z_{i+1} - z_i) \left[\frac{1}{H(z_{i+1})} + \frac{1}{H(z_i)} \right]$$

Results

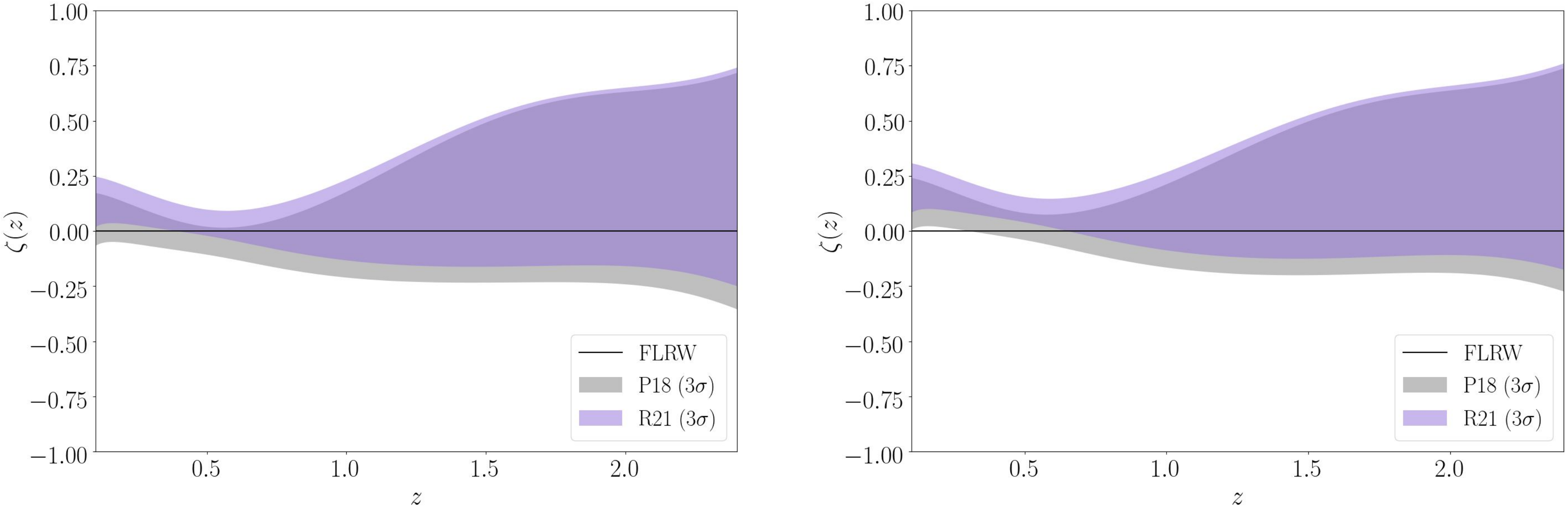


250
200
150
100
50
0.5
1.0
1.5
2.0
z
$H(z)$ (km s^{-1} Mpc^{-1})
1σ
2σ
3σ


6000
5000
4000
3000
2000
1000
0
$D_{\rm C}(z)$ (Mpc)
0.5
1.0
1.5
2.0
z
1σ
2σ
3σ



C20 (left panel) vs VBHJ17 (right panel)



C20 (left panel) vs VBHJ17 (right panel)

A model-independent test of speed of light variability with cosmological observations

Gabriel Rodrigues, CB

e-Print: 2112.01963 [astro-ph.CO]

JCAP 07 (2022) 07, 029

Data and method

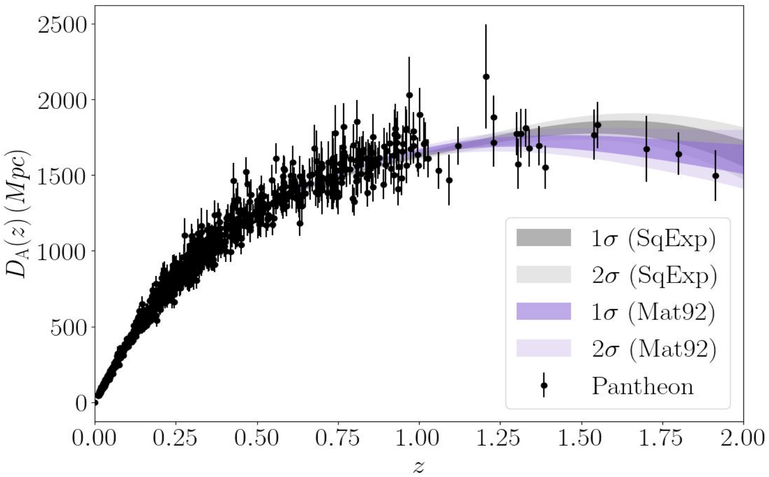
- The angular diameter distance is given by $D_A(z) = \frac{1}{(1+z)} \int_0^z \frac{cdz}{H(z)}$
- Differentiating the equation above w.r.t the redshift reads

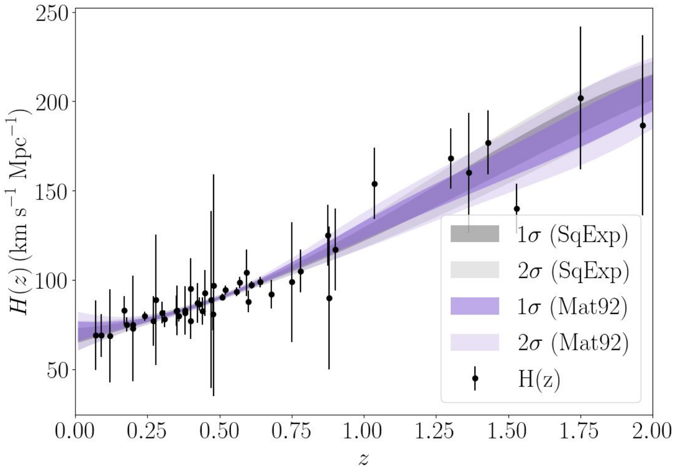
$$c(z) = H(z)[(1+z)D'_{\rm A}(z) + D_{\rm A}(z)]$$

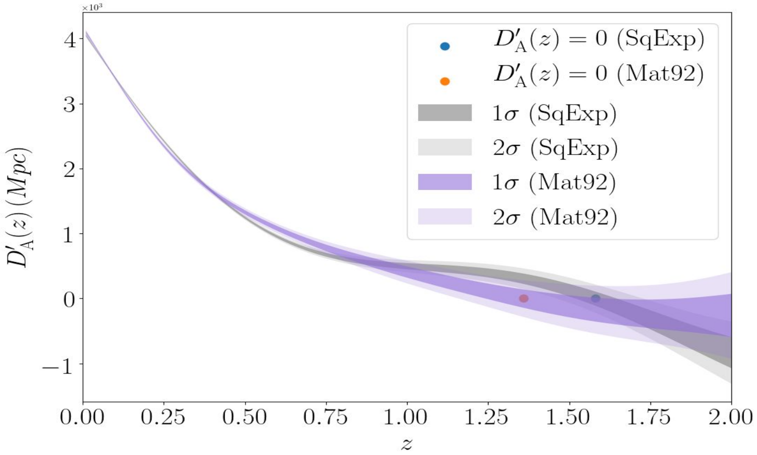
- We can obtain c(z) where the angular diameter distance reaches a maximum, so that

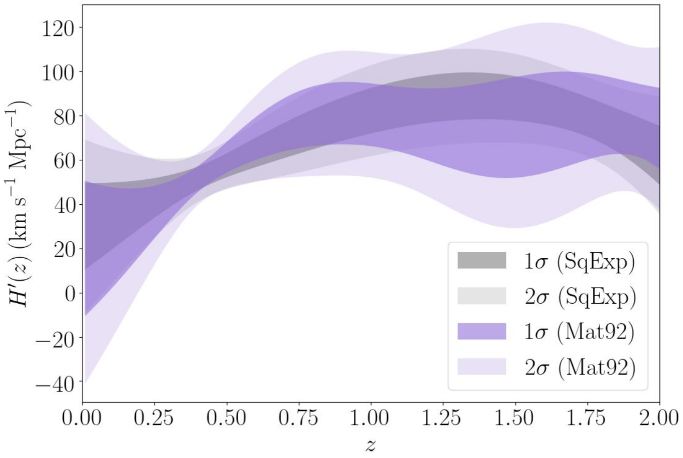
$$c(z_M) = D_A(z_M)H(z_M)$$

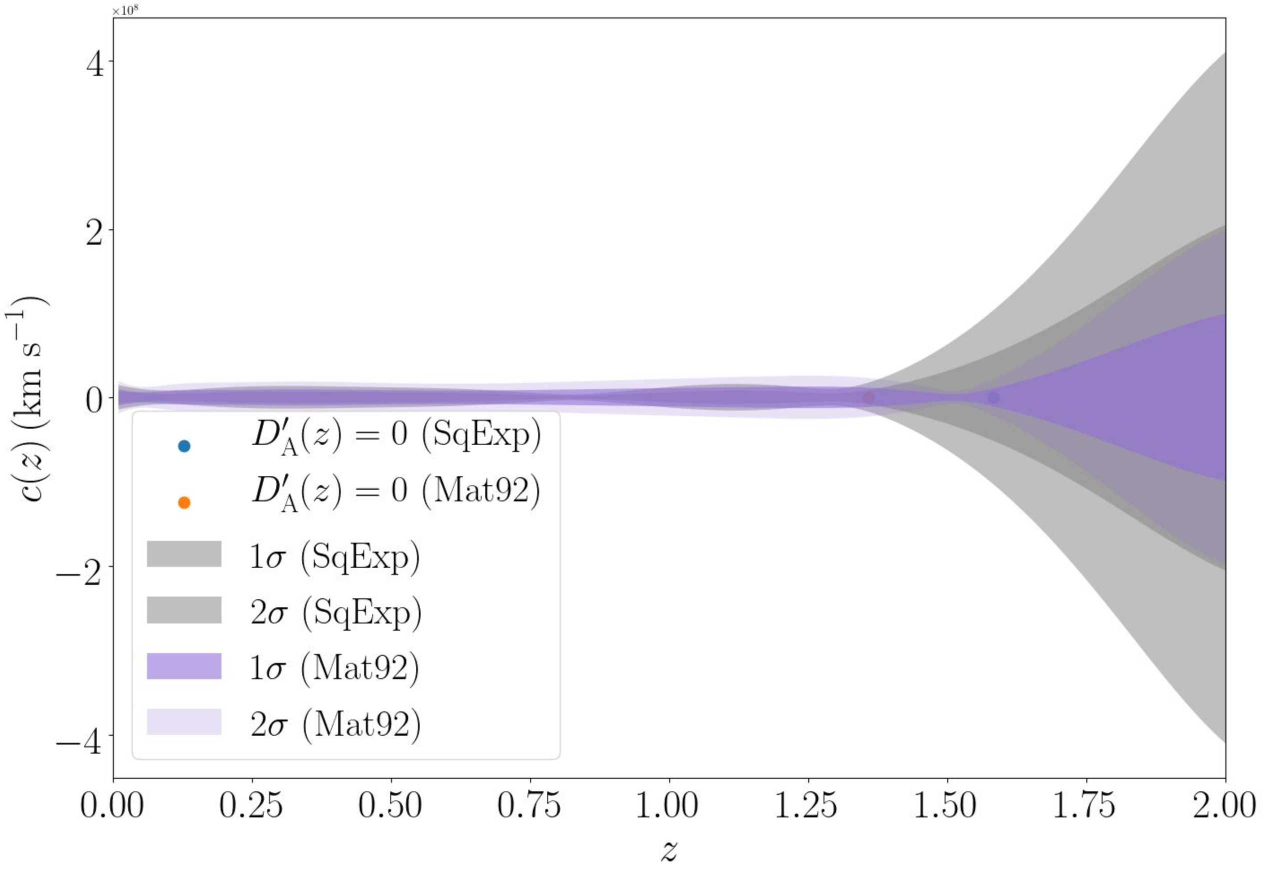
- We will measure **c(z)** using Pantheon SNe (converting DL(z) into DA(z) via distance duality relation), and cosmic clocks H(z) measurements from galaxy age and radial bao measurements. **Gaussian Processes** will be deployed for numerical reconstruction again


2500
2000
1500
1000
500
0
$D_A(z)\,(Mpc)$
0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00
z
1σ (SqExp)
2σ (SqExp)
1σ (Mat92)
2σ (Mat92)
Pantheon


250
200
150
100
50
$H(z)\,(\mathrm{km\,s^{-1}\,Mpc^{-1}})$
0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00
z
1σ (SqExp)
2σ (SqExp)
1σ (Mat92)
2σ (Mat92)
H(z)


$\times 10^3$
4
3
2
1
0
-1
$D'_A(z)\,(Mpc)$
0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00
z
$D'_A(z) = 0$ (SqExp)
$D'_A(z) = 0$ (Mat92)
1σ (SqExp)
2σ (SqExp)
1σ (Mat92)
2σ (Mat92)


120
100
80
60
40
20
0
-20
-40
$H'(z)\,(\mathrm{km\,s^{-1}\,Mpc^{-1}})$
0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00
z
1σ (SqExp)
2σ (SqExp)
1σ (Mat92)
2σ (Mat92)



c(zm) = (3.20 +- 0.16) km/s (SqExp)
At z=1.58

c(zm) = (2.67 +- 0.14) km/s (Mat92)
At z = 1.36

Delta diagnostic: a null test of cosmic acceleration

CB, Rodrigo Von Marttens, Javier Gonzalez, Jailson Alcaniz

(In prep)

Work outline

Although LCDM provides a good fit for observations, **it is crucial to assess the evidence for cosmic acceleration in a model-independent way** - regardless assumptions on DE/MG

A null test for cosmic acceleration (Seikel & Schwarz 08)

$$\log E(z) = \int_0^z \frac{(1+q(z'))}{(1+z')} \qquad E(z) \geq (1+z)\ \forall q(z) \geq 0$$

If the Universe **has never accelerated**, we have the **null condition**

$$D_C(z) = \int_0^z \frac{c\,dz}{H(z)} \leq (c/H_0)\log(1+z)$$

We can test this condition using the **delta estimator**

$$\Delta = D(z) - D(z; \forall q(z) \geq 0) > 0$$

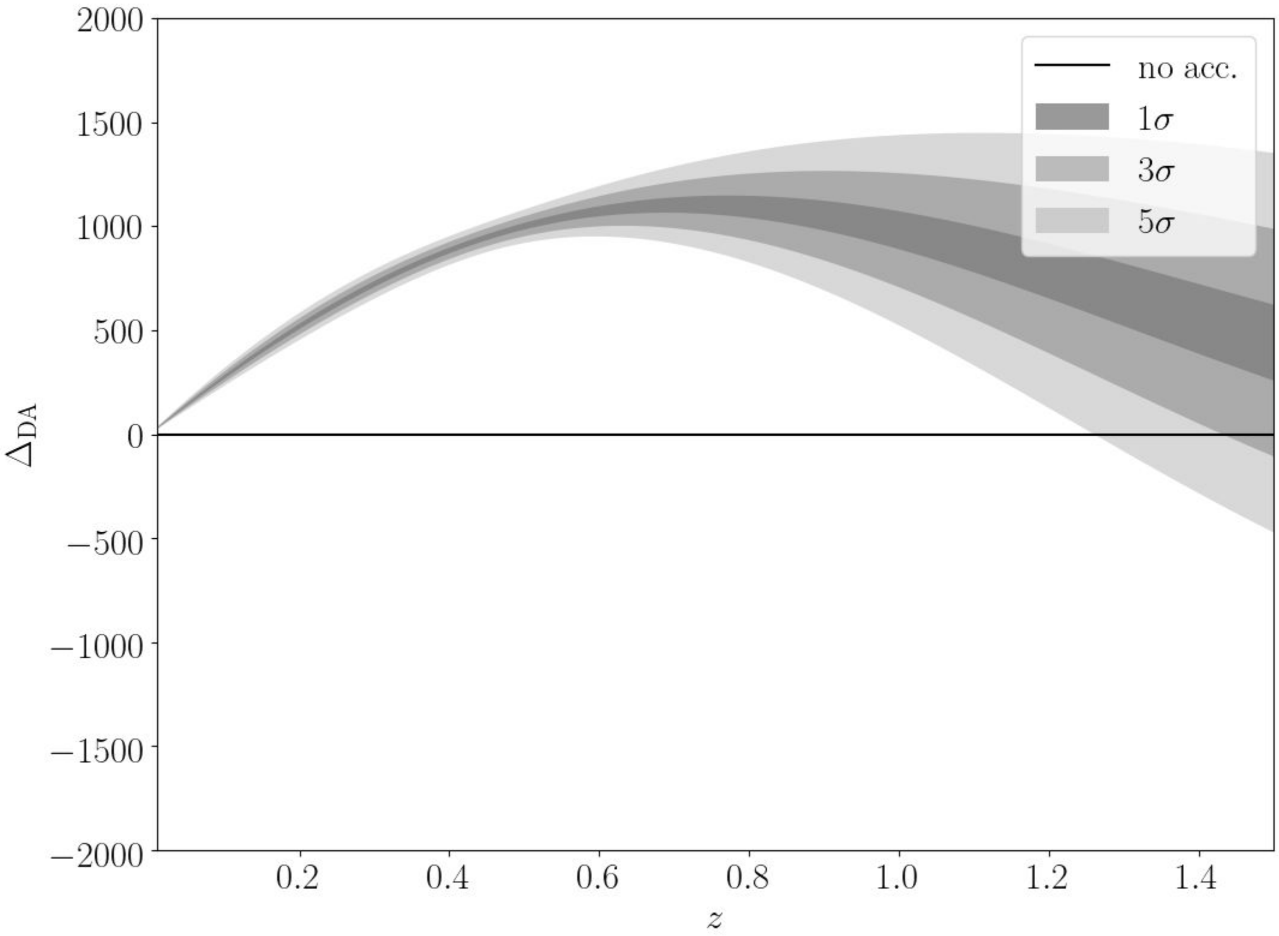
$$\text{if } q(z) < 0$$

Data and method

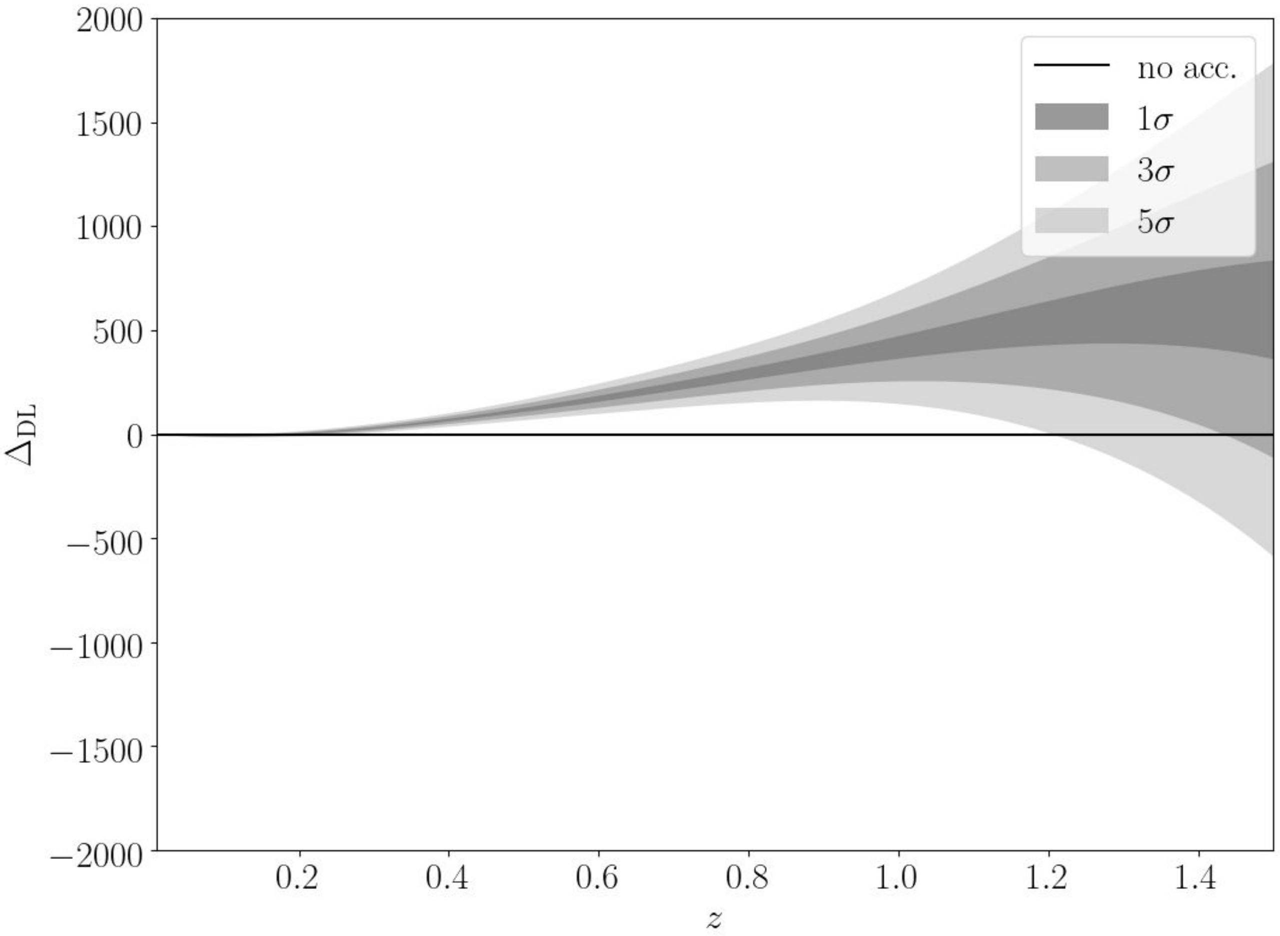
- We use Pantheon compilation of **SN luminosity distance (DL)** measurements (Scolnic+ 18), along with angular diameter distance data from the **transverse BAO mode (DA)** (Carvalho+15,20; Alcaniz+17; de Carvalho+18; Avila+19)

- Both observational samples do not depend on the assumption of a fiducial cosmological model

- We reconstruct both distance measurement samples with **GaPP** once more, so our analysis is **independent of any assumption on dark energy** a priori



no acc.
1σ
3σ
5σ
2000
1500
1000
500
0
−500
−1000
−1500
−2000
$\Delta_{\rm DA}$
0.2
0.4
0.6
0.8
1.0
1.2
1.4
z



2000
1500
1000
500
0
−500
−1000
−1500
−2000
$\Delta_{\rm DL}$
0.2
0.4
0.6
0.8
1.0
1.2
1.4
z
no acc.
1σ
3σ
5σ

Conclusions

- We perform **model-independent tests of the SCM** with SNe, BAO and cosmic clocks data. We find evidence for
  - **cosmic acceleration (~5sigma at z<1.2)**
  - **FLRW assumption (~3sigma at 0.3<z<2.4)**,
  - **null speed of light variability in 0<z<2, plus a ~5% measurement of c at z~1.60**

- How can next-gen surveys like J-PAS, Euclid, SKA improve these figures?

Thank you!
Obrigado!