Testes de consistência do modelo cosmológico padrão

Carlos Bengaly

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

Observatório Nacional

Outline

- The standard model of Cosmology (SCM) and its foundations
- Do we really understand the cosmos? How can we test these foundations?
- Consistency tests of the SCM:
  (i) Non-parametric reconstructions of cosmic curvature: current constraints and forecasts
  (ii) Measuring the speed of light with cosmological observations: current constraints and forecasts
- Concluding remarks

A little bit about myself..

- Carlos Bengaly (any pronouns are ok), B.Sc. in Physics (UFRJ, 2010), M.Sc. in Astronomy (ON-RJ, 2013), Ph.D in Astronomy (ON-RJ, 2016);

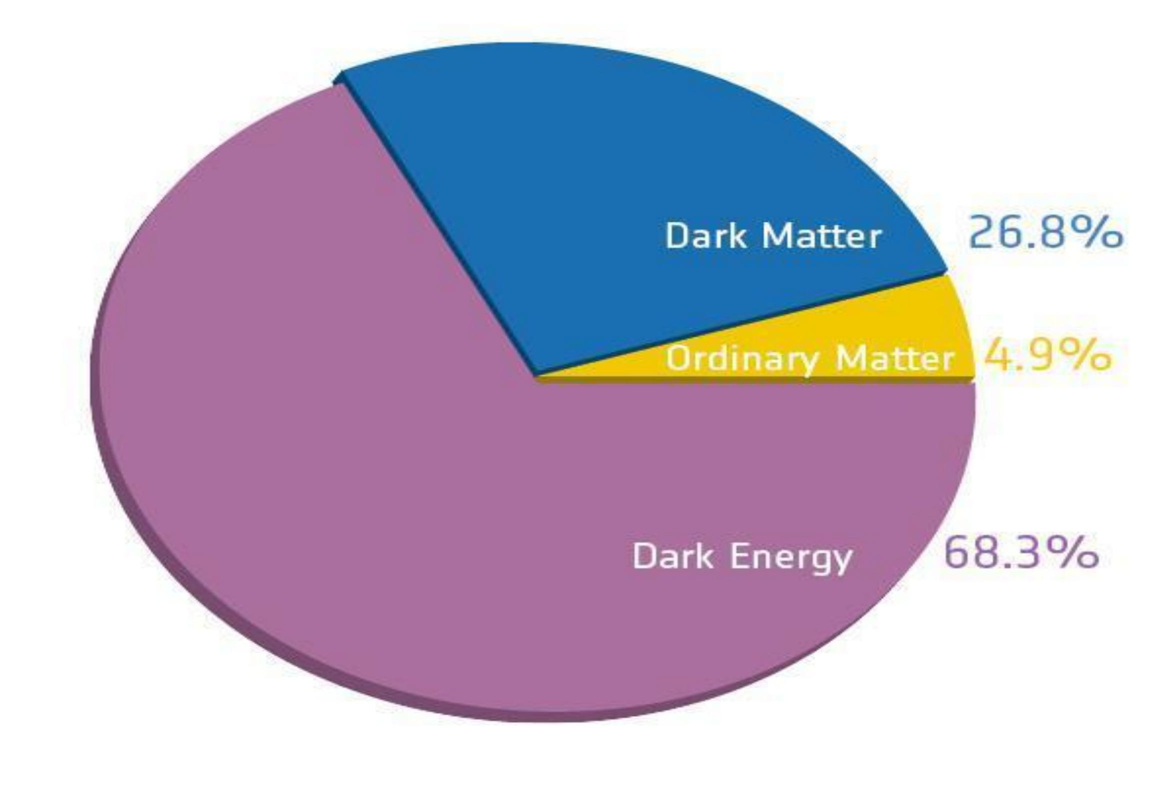
- Postdoc in University of the Western Cape, South Africa (2017-2019), Université de Genève (2019-2020), and ON-RJ (2020-2025). Working as an associate researcher at ON-RJ since late March 2025.

- Main interests: observational and theoretical cosmology, data analysis, philosophy of cosmology etc

Lattes http://lattes.cnpq.br/6562331419311591
Inspire https://inspirehep.net/authors/1703361
iD https://orcid.org/0000-0001-5731-3348

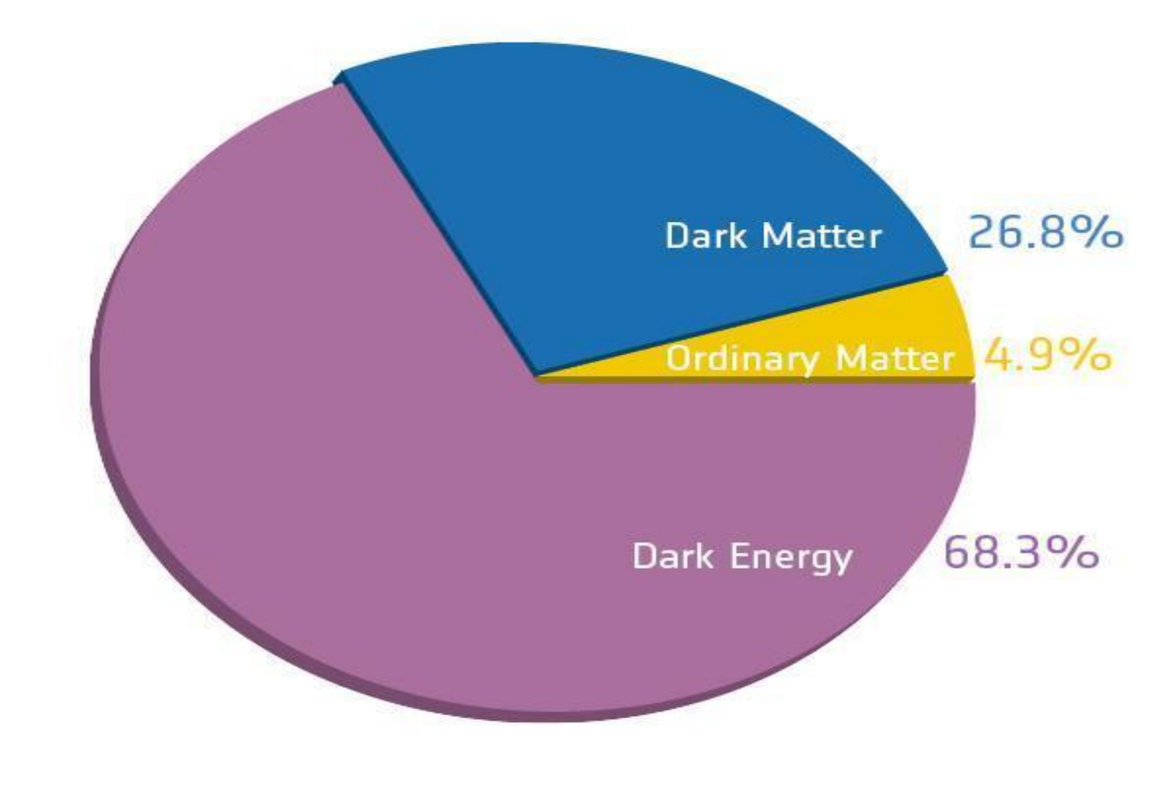
The standard model of Cosmology

The standard model of Cosmology



Credits: Planck Collaboration

The standard model of Cosmology

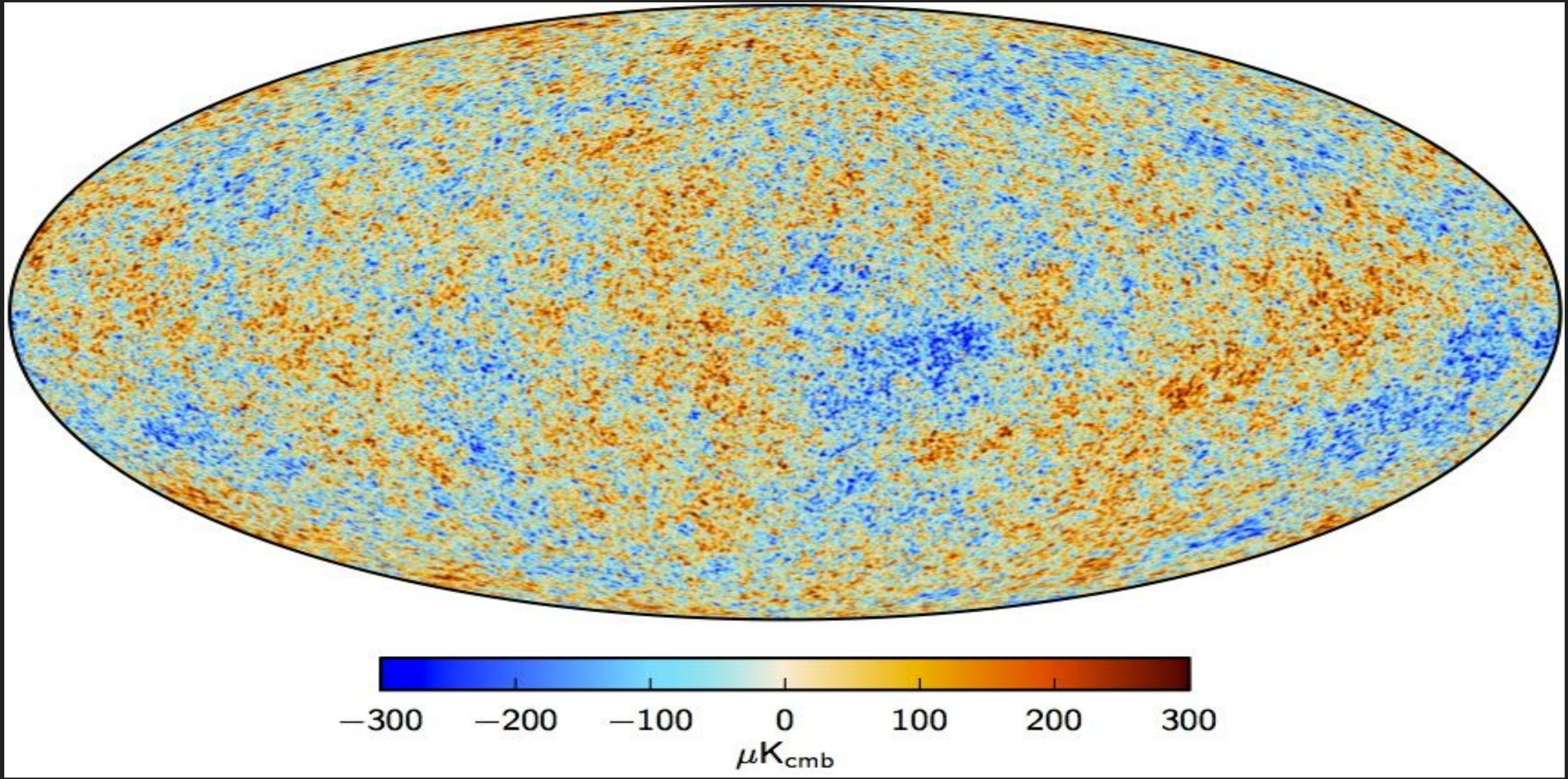


Credits: Planck Collaboration

What is dark matter?

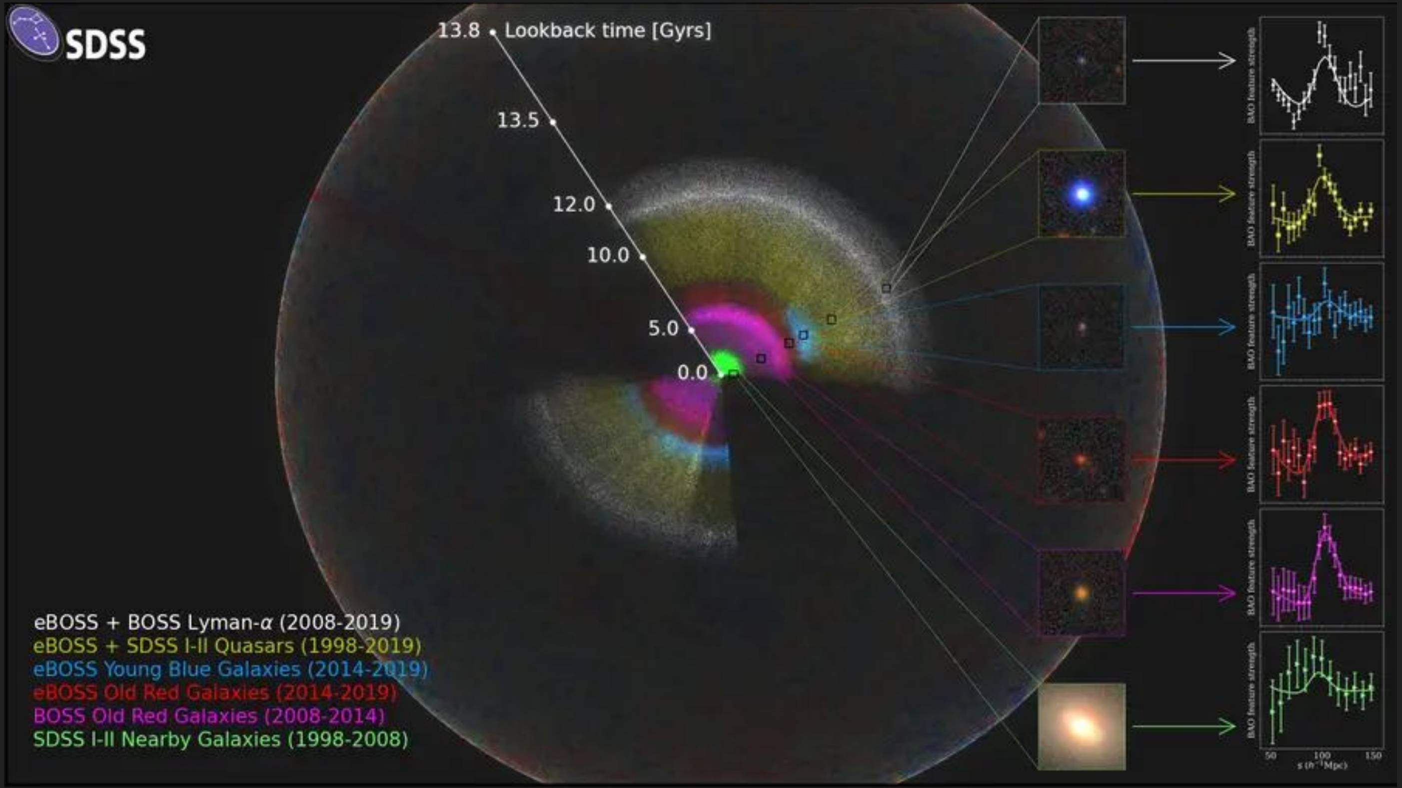
What is dark energy?

The Cosmic Microwave Background (CMB)



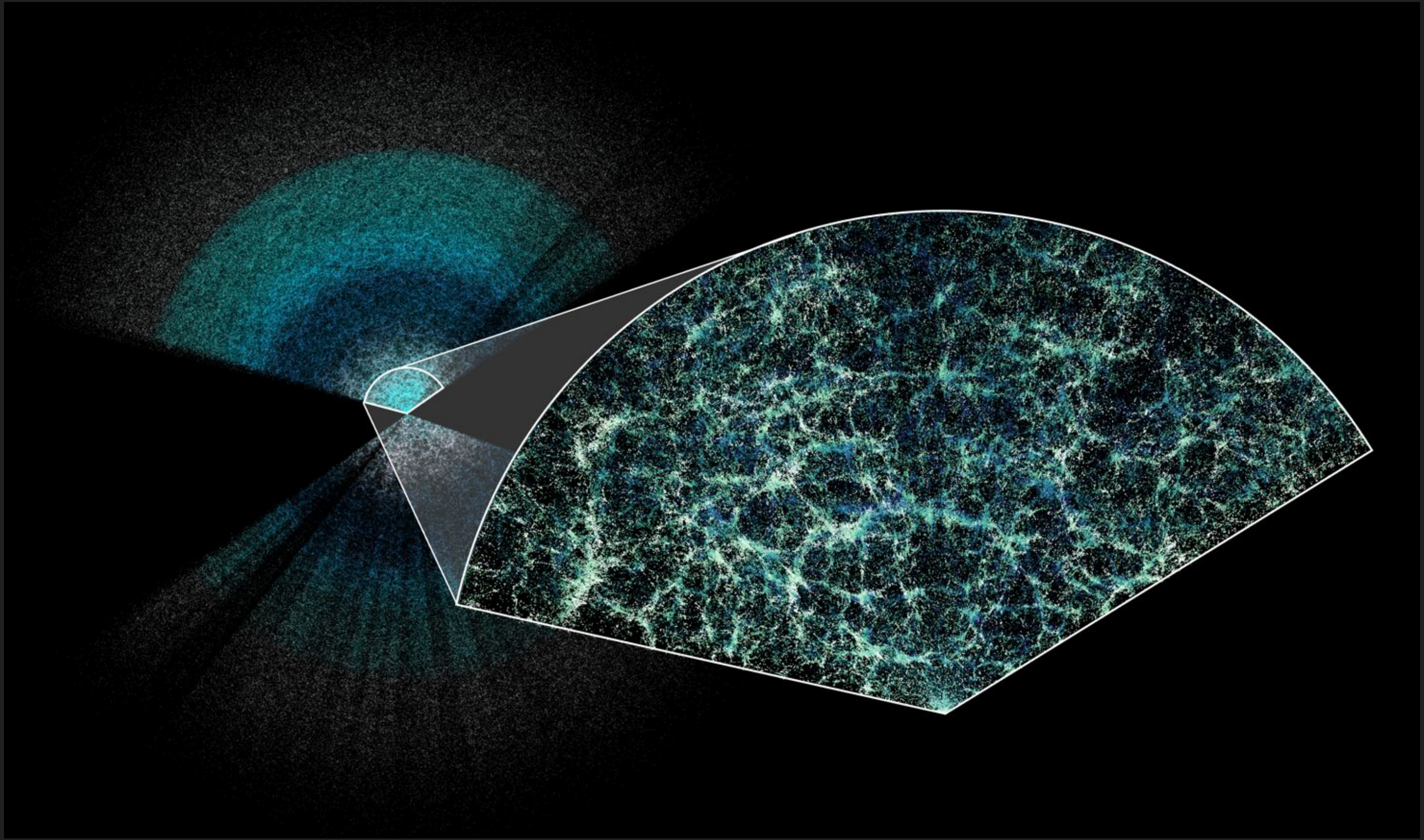
Credits: Planck Collaboration

The large-scale structure of the Universe



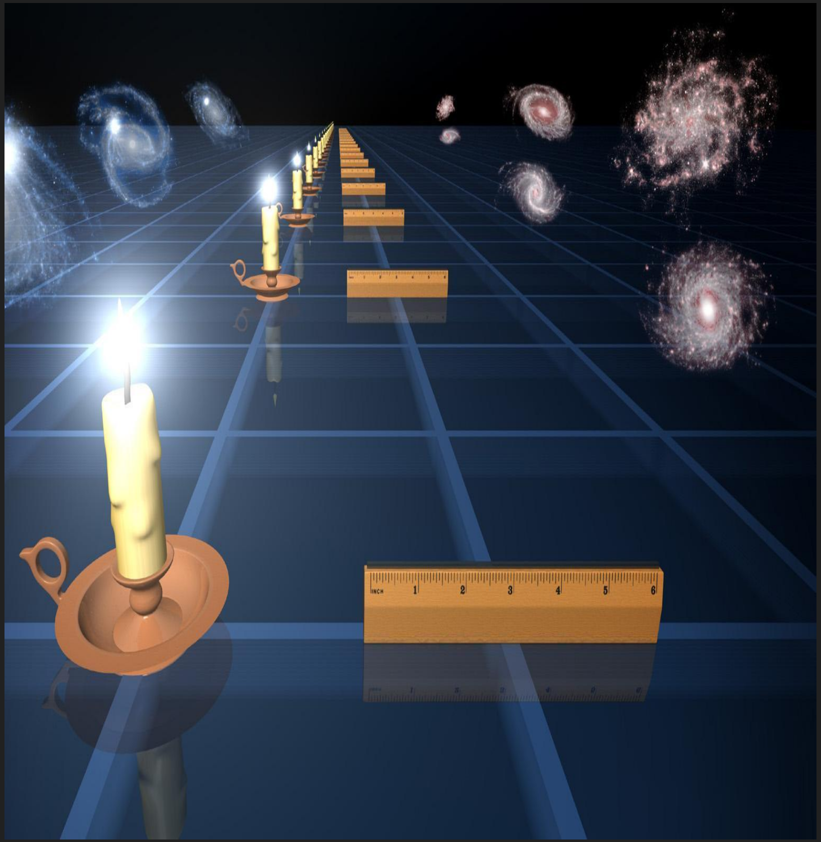
Credits: Anand Raichoor/EPFL, Ashley Ross/Ohio State University, and the SDSS Collaboration

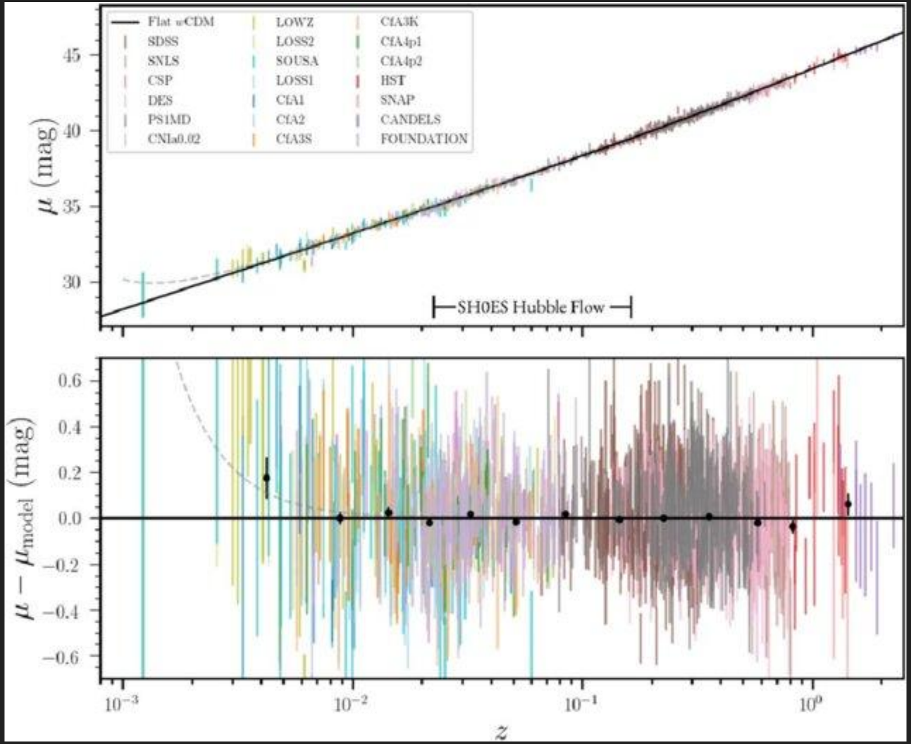
The large-scale structure of the Universe



Credits:
Claire Lamman/DESI collaboration; custom colormap package by cmastro.

The distance to Type Ia Supernovae (SNe)





Credits: Brout et al. 2022

Ok, we have a model which explains very well cosmological observations…

Ok, we have a model which explains very well cosmological observations…

but do we really understand the cosmos?

Ok, we have a model which explains very well cosmological observations…

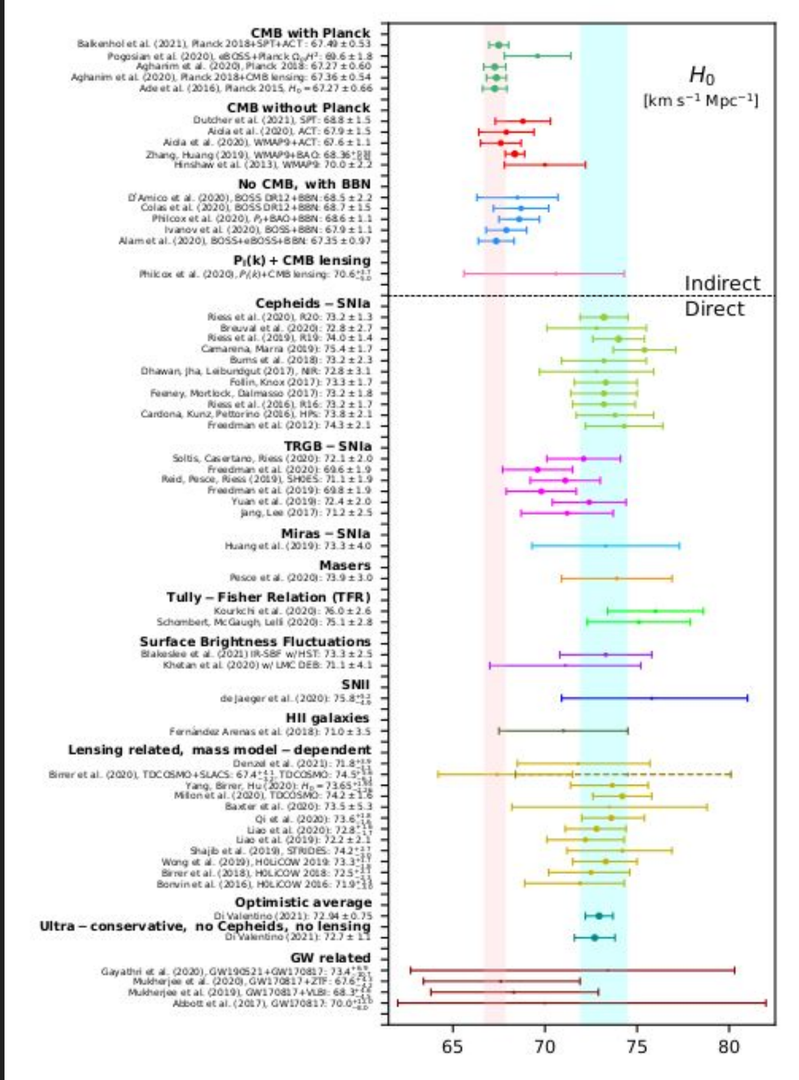
but do we really understand the cosmos?

Moreover, there are some possible “cracks” on the SCM, like the ~5σ H0 tension

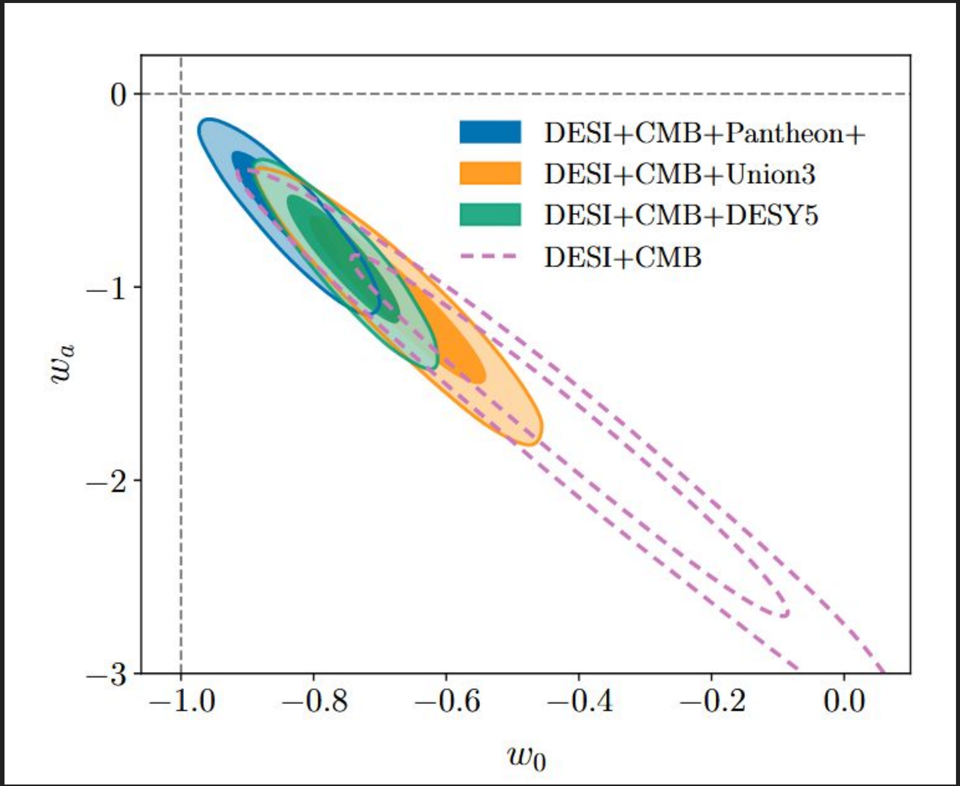
Ok, we have a model which explains very well cosmological observations…

but do we really understand the cosmos?

Moreover, there are some possible “cracks” on the SCM, like the ~5σ H0 tension – also, dark energy might be dynamical!



Credits: Di Valentino+ 21



Credits: DESI collaboration, arXiv:2503.14738

O modelo ΛCDM

Ok, mas como descrevemos essas quantidades na prática?

Eq. de Friedmann dita a dinâmica do Universo $\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{a^2}$

Derivação newtoniana: sendo a energia total do sistema gravitacional

$$E = \frac{m\dot{a}^2 x^2}{2} - Gm\,\frac{4\pi\rho a^2 x^2}{3}$$

Temos então $\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{a^2}$ onde $kc^2 = -\frac{2E}{mx^2}$

ρ representa a densidade de energia do conteúdo material do Universo

k denota o fator de curvatura, que pode ser k=-1,0,+1 para Universo aberto, plano e fechado, respectivamente

O modelo ΛCDM

Outra forma de escrever a Eq. de Friedman

$$H = H_0 \sqrt{\Omega_{r0} a^{-4} + \Omega_{m0} a^{-3} + \Omega_{k0} a^{-2} + \Omega_\Lambda}$$

Onde $\Omega_i \equiv \rho/\rho_c; \quad \rho_c \equiv 3H^2/(8\pi G)$

Podemos obter esses valores a partir da eq. de continuidade $\dot{\rho} = -3H(\rho + P)$

Sendo $P = w\rho$, temos então que $\rho \propto a^{-3(1+w)}$, onde w=⅓ para radiação, w=0 para matéria, w=-1 para constante cosmológica. Logo:

$$\rho_r \propto \rho_{r0} a^{-4}; \; \rho_m = \rho_{m0} a^{-3}; \; \rho_\Lambda = \rho_{\Lambda 0}$$

O modelo ΛCDM

Outra forma de escrever a Eq. de Friedman

$$H = H_0 \sqrt{\Omega_{\mathrm{r0}} a^{-4} + \Omega_{\mathrm{m0}} a^{-3} + \Omega_{\mathrm{k0}} a^{-2} + \Omega_\Lambda}$$

Onde $\Omega_i \equiv \rho/\rho_{\mathrm{c}}; \quad \rho_{\mathrm{c}} \equiv 3H^2/(8\pi G)$

H representa o parâmetro de Hubble, enquanto H0 é a Constante de Hubble, que ditam a taxa de expansão do Universo no passado e hoje, respectivamente

$$H_0 = (\dot{a}/a)|_{t=0}$$

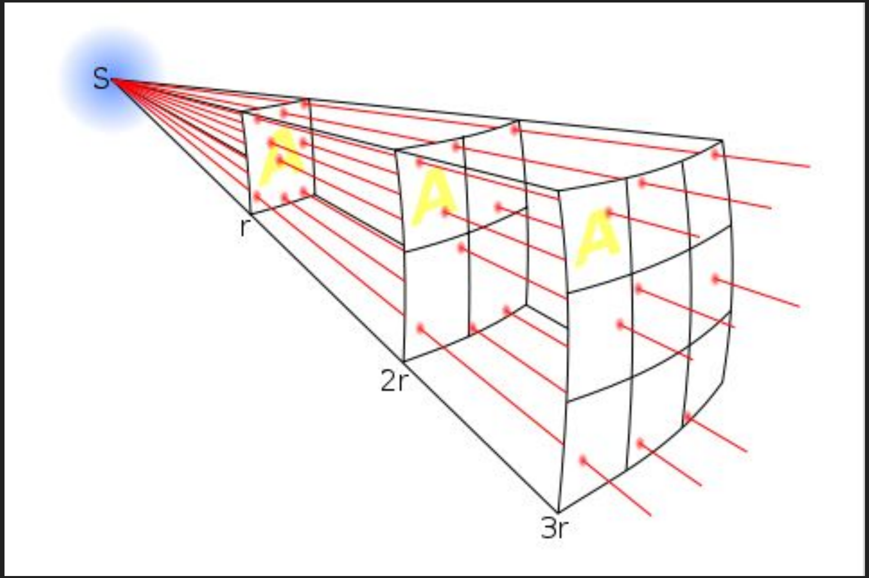
Medindo o Universo

- Em Astronomia, medimos sempre a luz que vem de objetos cósmicos até nós. Em outras palavras: sempre olhamos para imagens do passado quando medimos o Universo

- A luz que chega até nós não apresenta as mesmas características de quando foi emitida há milhões ou bilhões de ano => desvio pro vermelho (redshift) devido a expansão cosmológica

$$z = \frac{\lambda_o - \lambda_e}{\lambda_e} \qquad 1 + z = \frac{\lambda_o}{\lambda_e} = \frac{a_0}{a_e} = \frac{1}{a}$$

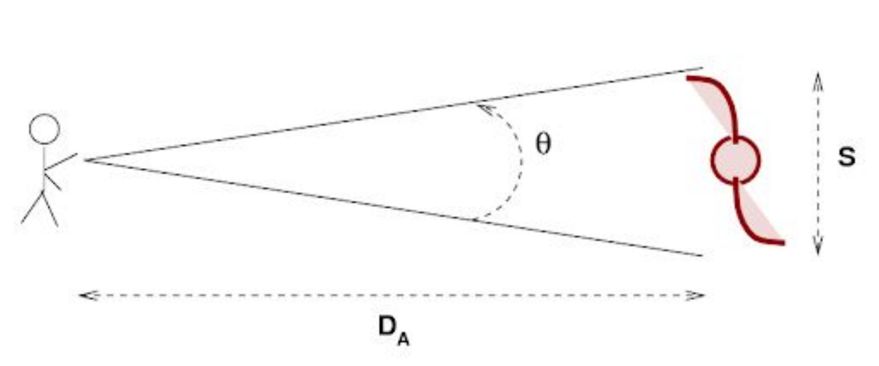
Medindo o Universo

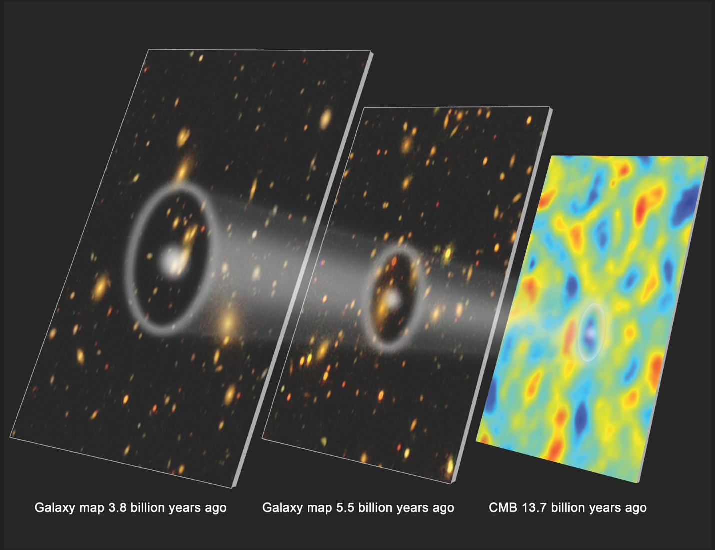


$$F_{\rm o} = L_{\rm o}/(4\pi r^2) = (1+z)^{-2} L_{\rm e}/(4\pi r^2)$$

$$D_{\rm L} = (1+z)r = (1+z)\int_0^z dz'/H(z')$$

Medindo o Universo





$$\theta_e \sim s/D_A; \quad \theta_o \sim s a(t_e)/r$$

$$D_A = r/a(t_e) = (1+z)^{-1} \int_0^z dz' / H(z)$$

Medindo o Universo

- Outra forma de medir o Universo vem da idade diferencial de galáxias

- Galáxias muito antigas que evoluem passivamente (sem formação estelar), então podemos datar sua idade por meio do estágio evolutivo das estrelas

- Isso nos fornece uma medida do parâmetro de Hubble

$$H(z) = \dot{a}/a = -(1+z)dz/dt$$

Note que podemos também obter medidas de H(z) de BAO, como dito anteriormente

The foundations of the standard model

The foundations of the standard model

- General Relativity (GR) as the theory of gravity

The foundations of the standard model

- General Relativity (GR) as the theory of gravity
- The Cosmological Principle (CP)

The foundations of the standard model

- General Relativity (GR) as the theory of gravity

- The Cosmological Principle (CP)
  - Universe is statistically homogeneous and isotropic (at large scales!)

The foundations of the standard model

- General Relativity (GR) as the theory of gravity

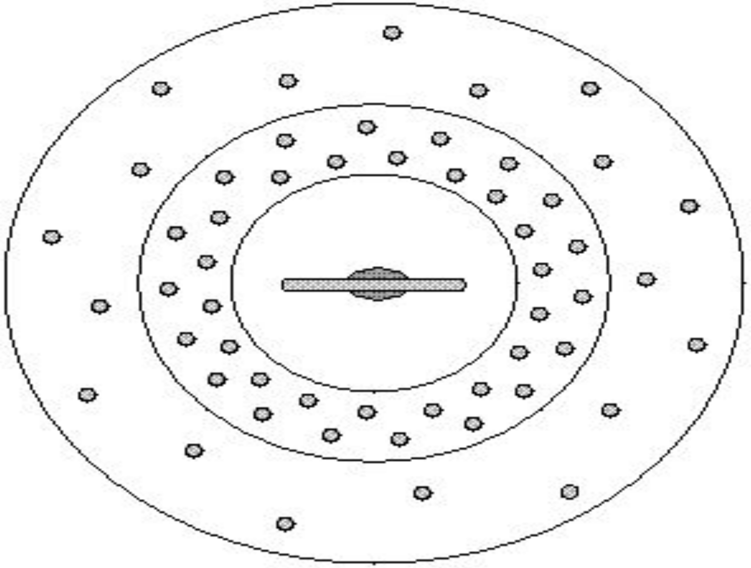
- The Cosmological Principle (CP)
  - Universe is statistically homogeneous and isotropic (at large scales!)
  - FLRW metric

The foundations of the standard model

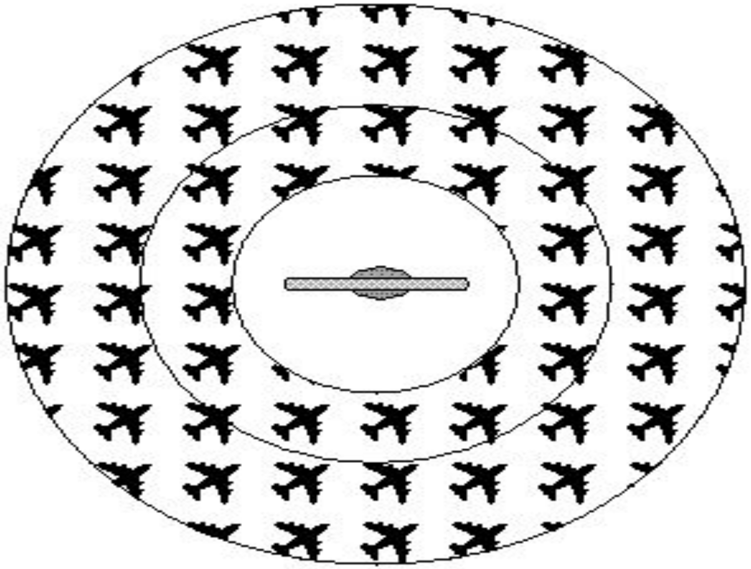
- General Relativity (GR) as the theory of gravity

- The Cosmological Principle (CP)
  - Universe is statistically homogeneous and isotropic (at large scales!)
  - FLRW metric
  - No preferred directions and positions in the large-scale Universe

The foundations of the standard model



Is this *homogeneous* and *isotropic*? Which aspect is it not?



Outside the central sphere, is this universe *homogeneous* and *isotropic*? Which aspect is it not?

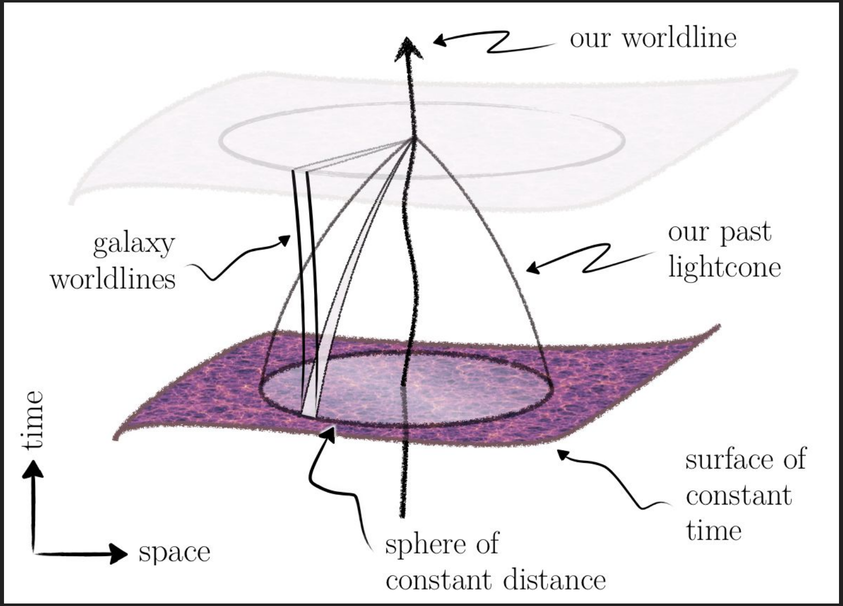
Ok, but… how can we test these assumptions?

Ok, but… how can we test these assumptions?

- **Testing isotropy directly is straightforward, but testing homogeneity is not – observations are performed along the past light-cone, not on time-constant hypersurfaces.**

Ok, but… how can we test these assumptions?

- **Testing isotropy directly is straightforward, but testing homogeneity is not – observations are performed along the past light-cone, not on time-constant hypersurfaces.**



Credits: Clarkson 2012
https://arxiv.org/abs/1204.5505

Ok, but… how can we test these assumptions?

- Testing isotropy directly is straightforward, but testing homogeneity is not – observations are performed along the past light-cone, not on time-constant hypersurfaces.
  (Consistency tests of the FLRW hypothesis are feasible!)

Ok, but… how can we test these assumptions?

- Testing isotropy directly is straightforward, but testing homogeneity is not – observations are performed along the past light-cone, not on time-constant hypersurfaces.
  (Consistency tests of the FLRW hypothesis are feasible!)

- Testing the variability of fundamental constants in high redshifts can be incredibly difficult – and observationally expensive

Ok, but… how can we test these assumptions?

- Testing isotropy directly is straightforward, but testing homogeneity is not – observations are performed along the past light-cone, not on time-constant hypersurfaces. (Consistency tests of the FLRW hypothesis are feasible!)

- Testing the variability of fundamental constants in high redshifts can be incredibly difficult – and observationally expensive

- How to develop theoretical models that violate FLRW, or the constancy of those fundamental constants, that are not unphysical – or ruled out by cosmological data?

Ok, but… how can we test these assumptions?

- There are two possible approaches to be followed

Ok, but… how can we test these assumptions?

- There are two possible approaches to be followed
  (i) Bottom-top approach: We develop physically well-motivated alternative models and confront them with data

Ok, but… how can we test these assumptions?

- There are two possible approaches to be followed
  (i) Bottom-top approach: We develop physically well-motivated alternative models and confront them with data
  (ii) Top-bottom approach: We develop “blind”, “data-driven” methods directly to the data and thus verify if those assumptions actually hold true

Ok, but… how can we test these assumptions?

- There are two possible approaches to be followed
  (i) Bottom-top approach: We develop physically well-motivated alternative models and confront them with data
  (ii) Top-bottom approach: We develop robust "blind", "data-driven" methods directly to the data and thus verify if those assumptions actually hold true

Ok, but… how can we test these assumptions?

- There are two possible approaches to be followed
  (i) Bottom-top approach: We develop physically well-motivated alternative models and confront them with data
  (ii) Top-bottom approach: We develop robust "blind", "data-driven" methods directly to the data and thus verify if those assumptions actually hold true

- Approach (ii): no need to assume cosmological models a priori.

Ok, but… how can we test these assumptions?

- There are two possible approaches to be followed
  (i) Bottom-top approach: We develop physically well-motivated alternative models and confront them with data
  (ii) Top-bottom approach: We develop robust "blind", "data-driven" methods directly to the data and thus verify if those assumptions actually hold true

- Approach (ii): no need to assume cosmological models a priori.

- If we still find consistency between the SCM and data, we can underpin its validity – or rule it out - in a robust, "model-agnostic" way!

Ok, but… how can we test these assumptions?

- There are two possible approaches to be followed
  (i) Bottom-top approach: We develop physically well-motivated alternative models and confront them with data
  (ii) Top-bottom approach: We develop robust "blind", "data-driven" methods directly to the data and thus verify if those assumptions actually hold true

- Approach (ii): no need to assume cosmological models a priori.

- If we still find consistency between the SCM and data, we can underpin its validity – or rule it out - in a robust, "model-agnostic" way!
  (ps: care must be taken in order to avoid human and/or machine biases)

(i) Non-parametric reconstructions of cosmic curvature: current constraints and forecasts

Mariana L.S. Dias, Antônio F.B. da Cunha, CB, Rodrigo S. Gonçalves, Jonathan Morais

e-print: 2411.19252 [astro-ph.CO]
Eur.Phys.J.C 85 (2025) 4, 432

Eur. Phys. J. C (2025) 85:432
https://doi.org/10.1140/epjc/s10052-025-14159-0

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Non-parametric reconstructions of cosmic curvature: current constraints and forecasts

Mariana L. S. Dias[1,a], **Antônio F. B. da Cunha**[1,2,b], **Carlos A. P. Bengaly**[1,c], **Rodrigo S. Gonçalves**[1,2,d], **Jonathan Morais**[1,2,e]

[1] Observatório Nacional, Rio de Janeiro, RJ 20921-400, Brazil
[2] Departamento de Física, Universidade Federal Rural do Rio de Janeiro, Seropédica, RJ 23897-000, Brazil

Received: 11 December 2024 / Accepted: 6 April 2025

Motivation

- The SCM relies on the assumption of the Cosmological Principle, so we can describe cosmic distances and ages through the FLRW metric

Motivation

- The SCM relies on the assumption of the Cosmological Principle, so we can describe cosmic distances and ages through the FLRW metric

- We can use the cosmic curvature as a means to perform a consistency test of FLRW – and hence the Cosmological Principle

Motivation

- The SCM relies on the assumption of the Cosmological Principle, so we can describe cosmic distances and ages through the FLRW metric

- We can use the cosmic curvature as a means to perform a consistency test of FLRW – and hence the Cosmological Principle

- In the FLRW scenario, the curvature can be positive (spherical), negative (hyperbolical) of null (flat). However, its value must not change over time. If it does, we have an immediate violation of the FLRW metric, and thus the Cosmological Principle is ruled out!

Motivation

- The SCM relies on the assumption of the Cosmological Principle, so we can describe cosmic distances and ages through the FLRW metric

- We can use the cosmic curvature as a means to perform a consistency test of FLRW – and hence the Cosmological Principle

- In the FLRW scenario, the curvature can be positive (spherical), negative (hyperbolical) of null (flat). However, its value must not change over time. If it does, we have an immediate violation of the FLRW metric, and thus the Cosmological Principle is ruled out!

- Goal: verify if the curvature is indeed constant as a function of cosmic time using observational data from SNe and cosmic chronometers.

Method

- The FLRW metric follows the definition

$$ds^2 = c^2 dt^2 - a^2(t)\left(\frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right),$$

c is the speed of light, a(t) is the scale factor, (r,θ,ϕ) are radial coordinates, k is the curvature sign.

Method

- The FLRW metric follows the definition

$$ds^2 = c^2 dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right),$$

c is the speed of light, a(t) is the scale factor, (r,θ,ϕ) are radial coordinates, k is the curvature sign.

- By combining the above metric with Einstein's Field Equations, we can arrive at the Friedmann equation, where the cosmic curvature parameter is defined as

$$\Omega_k(z) \equiv -\frac{kc^2}{a^2(z)H^2(z)},$$

$$\Omega_{k,0} = -\frac{kc^2}{H_0^2},$$

$$\Omega_{k,0}\begin{cases} > 0\ (open) \\ = 0\ (flat) \\ < 0\ (closed) \end{cases}$$

Method

- Still in the FLRW framework, we can define the luminosity distance as

$$d_L(z) = \frac{c(1+z)}{H_0\sqrt{|\Omega_{k,0}|}}\mathcal{F}\left(\sqrt{|\Omega_{k,0}|}\int_0^z \frac{dz'}{E(z')}\right),$$

$$\mathcal{F}(x) = \begin{cases} sinh(x), & \text{if } \Omega_{k,0} > 0 \\ x, & \text{if } \Omega_{k,0} = 0 \\ sin(x), & \text{if } \Omega_{k,0} < 0 \end{cases}$$

E(z) = H(z)/H0, H0 being the Hubble Constant, H(z) the Hubble parameter (as given by the Friedmann equation), and z the redshift, defined as (1+z) = 1/a(t)

Method

- Still in the FLRW framework, we can define the luminosity distance as

$$d_L(z) = \frac{c(1+z)}{H_0\sqrt{|\Omega_{k,0}|}}\mathcal{F}\left(\sqrt{|\Omega_{k,0}|}\int_0^z \frac{dz'}{E(z')}\right),$$

$$\mathcal{F}(x) = \begin{cases} sinh(x), & \text{if } \Omega_{k,0} > 0 \\ x, & \text{if } \Omega_{k,0} = 0 \\ sin(x), & \text{if } \Omega_{k,0} < 0 \end{cases}$$

E(z) = H(z)/H0, H0 being the Hubble Constant, H(z) the Hubble parameter (as given by the Friedmann equation), and z the redshift, defined as (1+z) = 1/a(t)

- We can invert the above relation and obtain (Clarkson, Bassett, Lu 2008):

$$\Omega_{k,0} = \frac{E^2(z)D'^2(z) - 1}{D^2(z)},$$

$$D(z) = \frac{H_0 d_L(z)}{c(1+z)}.$$

if $\Omega_{k,0} \neq \text{constant}$
then FLRW is ruled out!

Method

- We can also rewrite the previous expression as

$$\frac{\Omega_{k,0} D^2(z)}{E(z)D'(z)+1} = E(z)D'(z) - 1,$$ so that $$\mathcal{O}_k(z) \equiv E(z)D'(z) - 1.$$

- Hence, if the right-hand side of Ok(z) is different from zero at any non-zero redshift, we have null curvature ruled out!

Method

- We can also rewrite the previous expression as

$$\frac{\Omega_{k,0} D^2(z)}{E(z)D'(z)+1} = E(z)D'(z) - 1,$$ so that $$\mathcal{O}_k(z) \equiv E(z)D'(z) - 1.$$

- Hence, if the right-hand side of Ok(z) is different from zero at any non-zero redshift, we have null curvature ruled out!

- In order to avoid prior assumptions on a cosmological model, we carry out a non-parametric analysis (model-independent) by reconstructing the D(z) and E(z) curves from data (see next slide!) using a method called Gaussian Processes (GP) – assumes a gaussian distribution over functions that best describes the patterns of the data.

(

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 12 Apr 2012 (v1), last revised 31 May 2012 (this version, v2)]

Reconstruction of dark energy and expansion dynamics using Gaussian processes

Marina Seikel, Chris Clarkson, Mathew Smith

An important issue in cosmology is reconstructing the effective dark energy equation of state directly from observations. With few physically motivated models, future dark energy studies cannot only be based on constraining a dark energy parameter space, as the errors found depend strongly on the parameterisation considered. We present a new non-parametric approach to reconstructing the history of the expansion rate and dark energy using Gaussian Processes, which is a fully Bayesian approach for smoothing data. We present a pedagogical introduction to Gaussian Processes, and discuss how it can be used to robustly differentiate data in a suitable way. Using this method we show that the Dark Energy Survey - Supernova Survey (DES) can accurately recover a slowly evolving equation of state to sigma_w = +-0.04 (95% CL) at z=0 and +-0.2 at z=0.7, with a minimum error of +-0.015 at the sweet-spot at z~0.14, provided the other parameters of the model are known. Errors on the expansion history are an order of magnitude smaller, yet make no assumptions about dark energy whatsoever. A code for calculating functions and their first three derivatives using Gaussian processes has been developed and is available for download at this http URL .

Comments:	20 pages, 9 figures, improved analysis, GaPP code available at this http URL
Subjects:	**Cosmology and Nongalactic Astrophysics (astro-ph.CO)**
Cite as:	arXiv:1204.2832 **[astro-ph.CO]**
	(or arXiv:1204.2832v2 **[astro-ph.CO]** for this version)
	https://doi.org/10.48550/arXiv.1204.2832
Journal reference:	JCAP06(2012)036
Related DOI:	https://doi.org/10.1088/1475-7516/2012/06/036

A Gaussian process is the generalisation of a Gaussian distribution. While the latter is the distribution of a random variable, the Gaussian process describes a distribution over functions. Consider a function f formed from a Gaussian process. The value of f when evaluated at a point x is a Gaussian random variable with mean $\mu(x)$ and variance $\mathrm{Var}(x)$. The function value at x is not independent of the function value at some other point $\tilde{x}$ (especially when x and $\tilde{x}$ are close to each other), but is related by a covariance function $\mathrm{cov}\left(f(x), f(\tilde{x})\right) = k(x, \tilde{x})$. Thus, the distribution of functions can be described by the following quantities:

$$\mu(x) = \mathbb{E}[f(x)]\,, \tag{2.2}$$

$$k(x, \tilde{x}) = \mathbb{E}[(f(x) - \mu(x))(f(\tilde{x}) - \mu(\tilde{x}))]\,, \tag{2.3}$$

$$\mathrm{Var}(x) = k(x, x)\,. \tag{2.4}$$

The Gaussian process is written as

$$f(x) \sim \mathcal{GP}\left(\mu(x), k(x, \tilde{x})\right)\ . \tag{2.5}$$

There is a wide range of possible covariance functions. While one will often chose covariance functions that only depend on the distance between the input points $|x - \tilde{x}|$, this is not a necessary requirement. Throughout this work, we use the squared exponential covariance function:

$$k(x, \tilde{x}) = \sigma_f^2 \exp\left(-\frac{(x - \tilde{x})^2}{2\ell^2}\right)\ . \tag{2.6}$$

)

Data

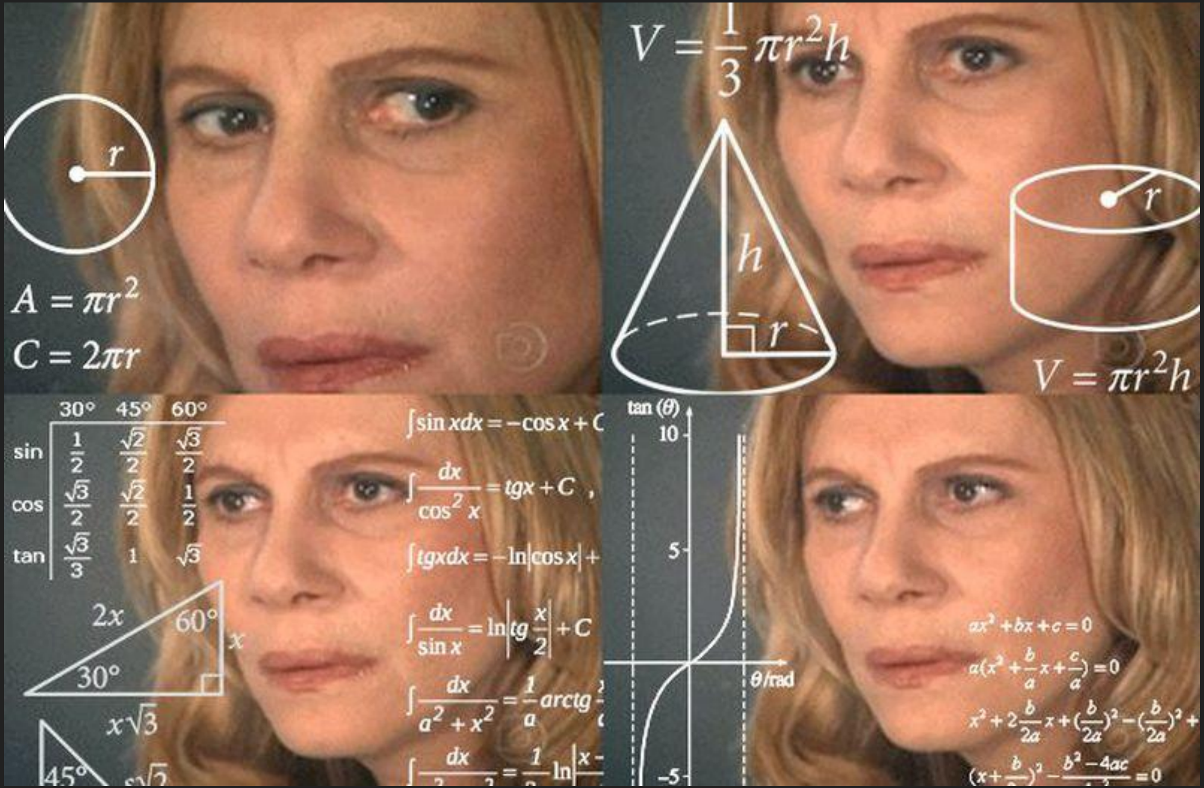
- Initially, we use the Pantheon+ and SH0ES compilation of SNe as our D(z) data, comprising 1701 distance measurements of 1550 distinct objects, along with 31 differential galaxy age measurements (cosmic chronometers) as our E(z) data, in order to compute Ωk0 and Ok as a function of redshift using the GP method. The Hubble Constant H0 is taken from SH0ES measurement, H0 = 73.6 \pm 1.1 km/s/Mpc.

Data

- Initially, we use the Pantheon+ and SH0ES compilation of SNe as our D(z) data, comprising 1701 distance measurements of 1550 distinct objects, along with 31 differential galaxy age measurements (cosmic chronometers) as our E(z) data, in order to compute Ωk0 and Ok as a function of redshift using the GP method. The Hubble Constant H0 is taken from SH0ES measurement, H0 = 73.6 \pm 1.1 km/s/Mpc

- We also perform forecasts of the Ωk0 and Ok consistency tests by simulating 1000 D(z) measurements expected from gravitational wave events by LIGO, and 23 E(z) data points expected from radial BAO measurements by redshift surveys like J-PAS, again using GP, assuming a fiducial cosmological model consistent with Pantheon+ and SH0ES SCM best-fit

Results



r
$A = \pi r^2$
$C = 2\pi r$
$V = \frac{1}{3}\pi r^2 h$
h
r
r
$V = \pi r^2 h$
30° 45° 60°
sin
cos
tan
2x
60°
x
30°
$x\sqrt{3}$
45°
$\int \sin x dx = -\cos x + C$
$\int \frac{dx}{\cos^2 x} = tgx + C$
tan (θ)
10
5
-5
θ/rad
$ax^2 + bx + c = 0$

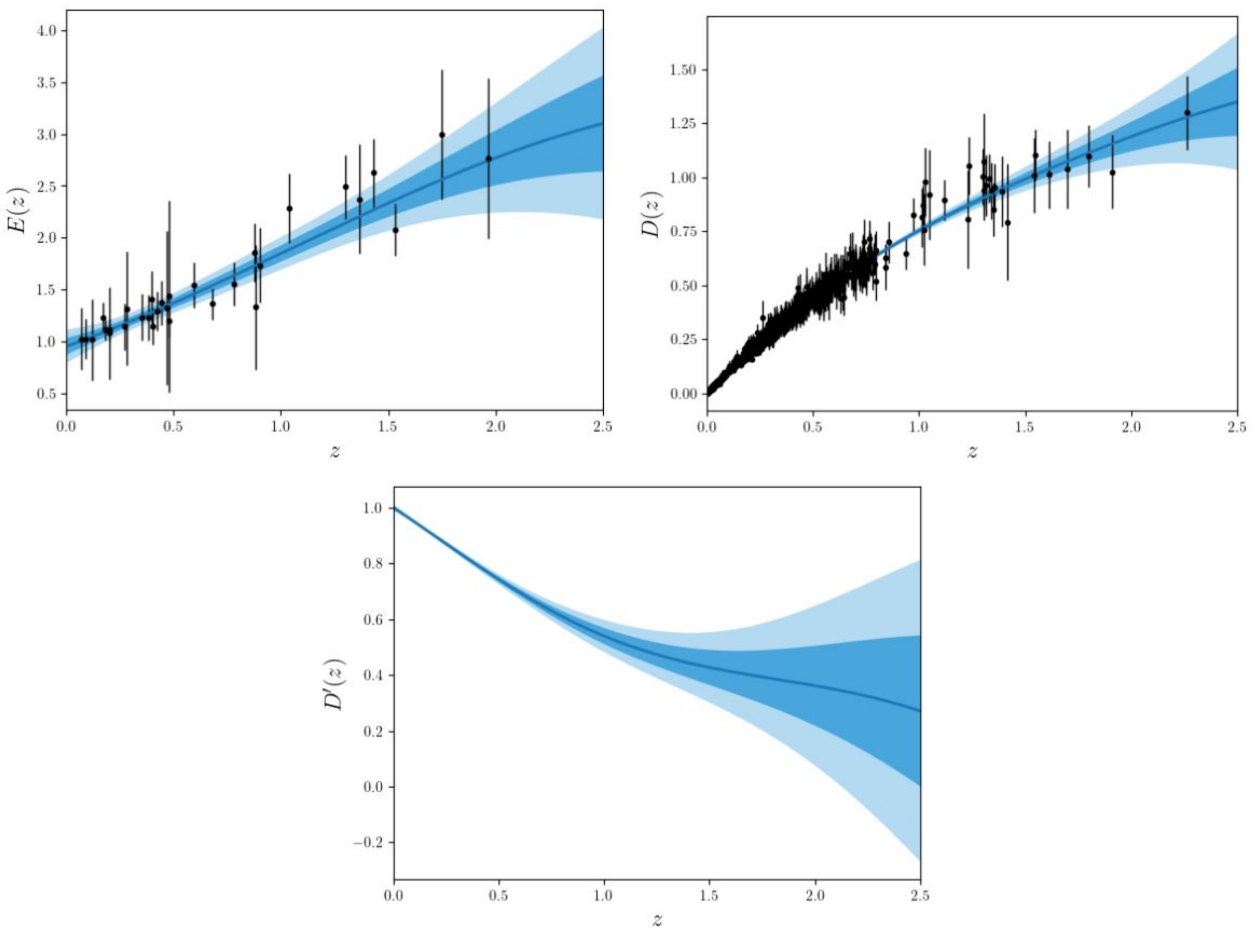


FIG. 4: Reconstructions of $E(z)$ (cosmic chronometers), $D(z)$ (SNe) and $D'(z)$ functions for the observational data.

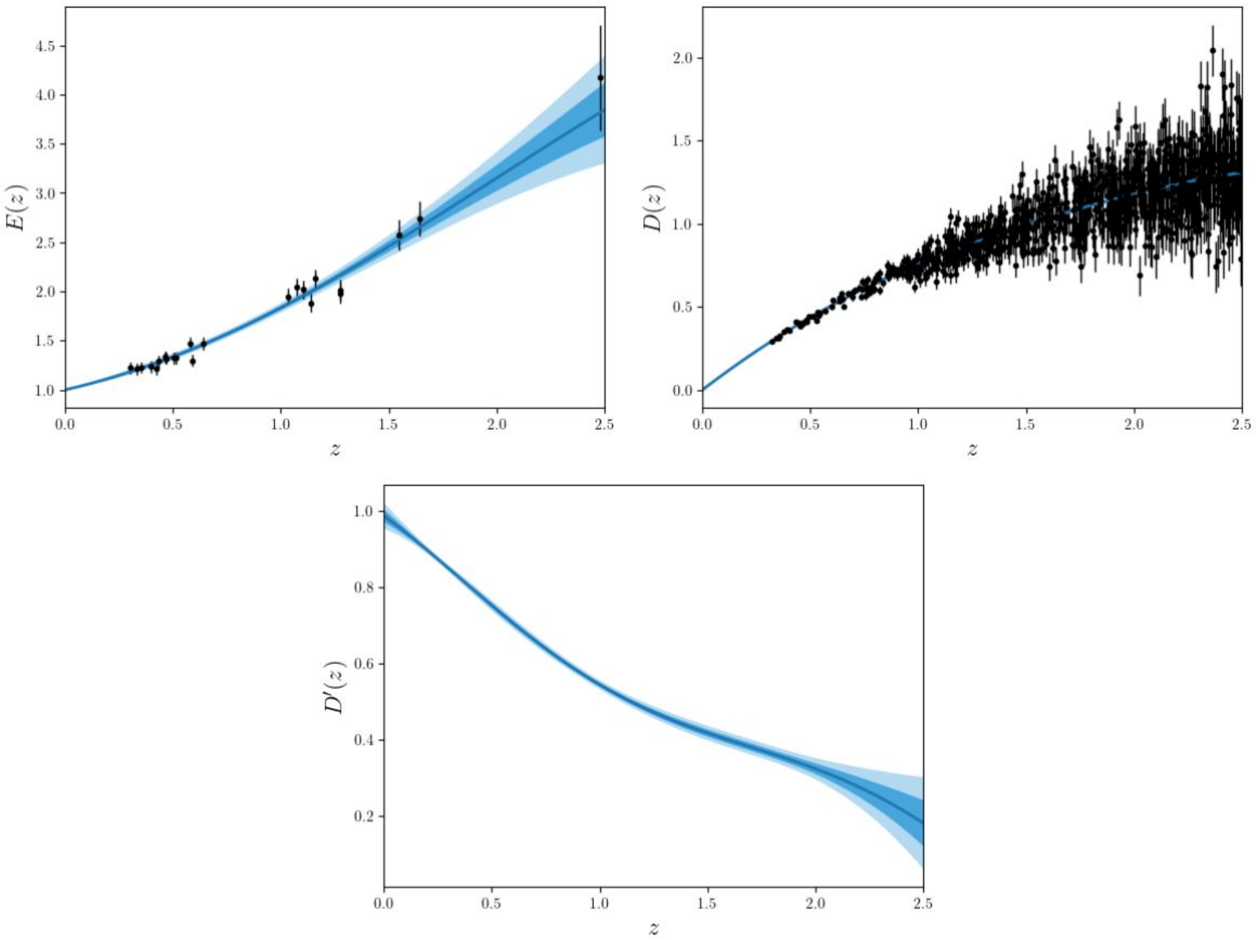
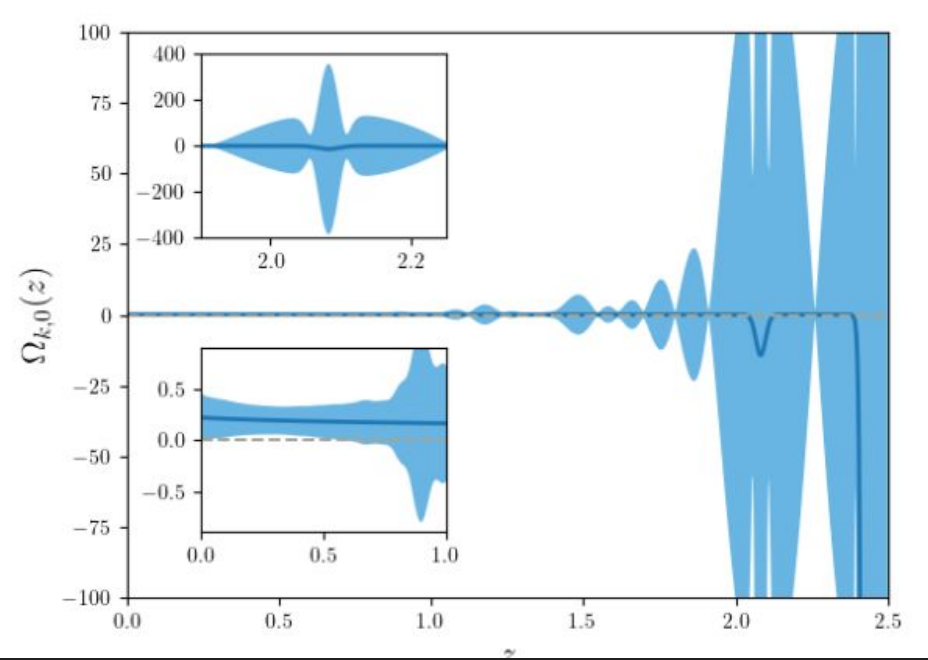
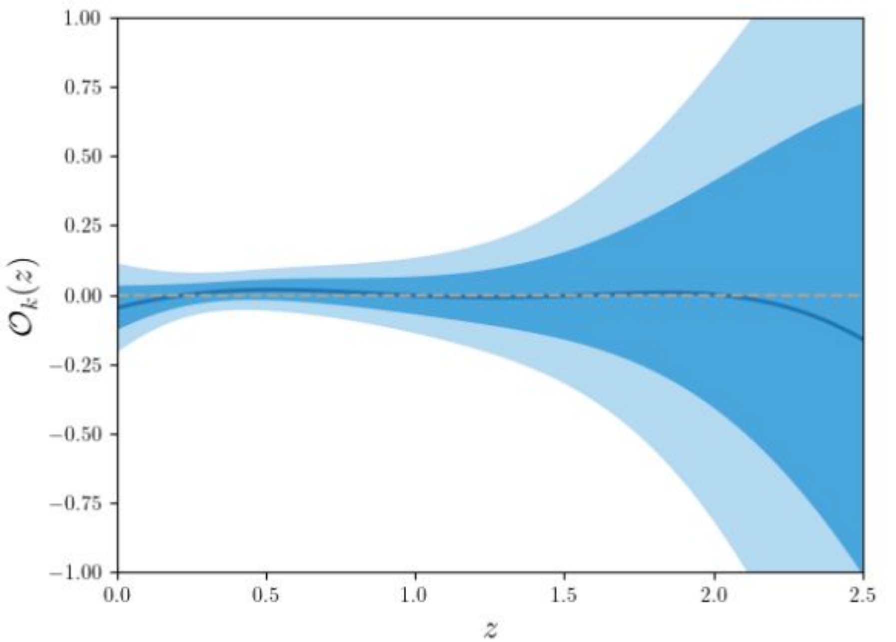
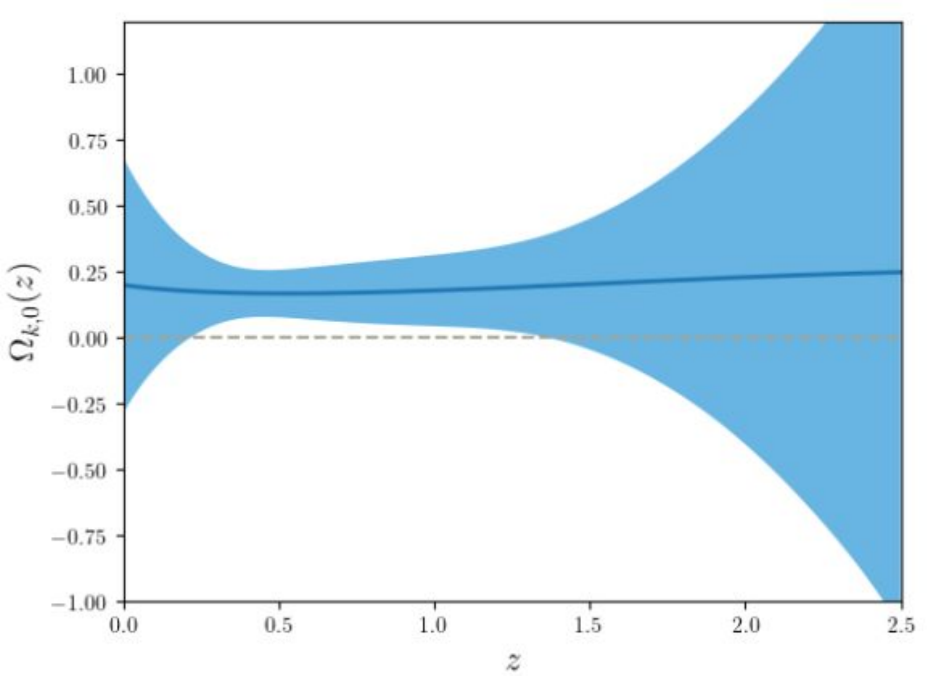


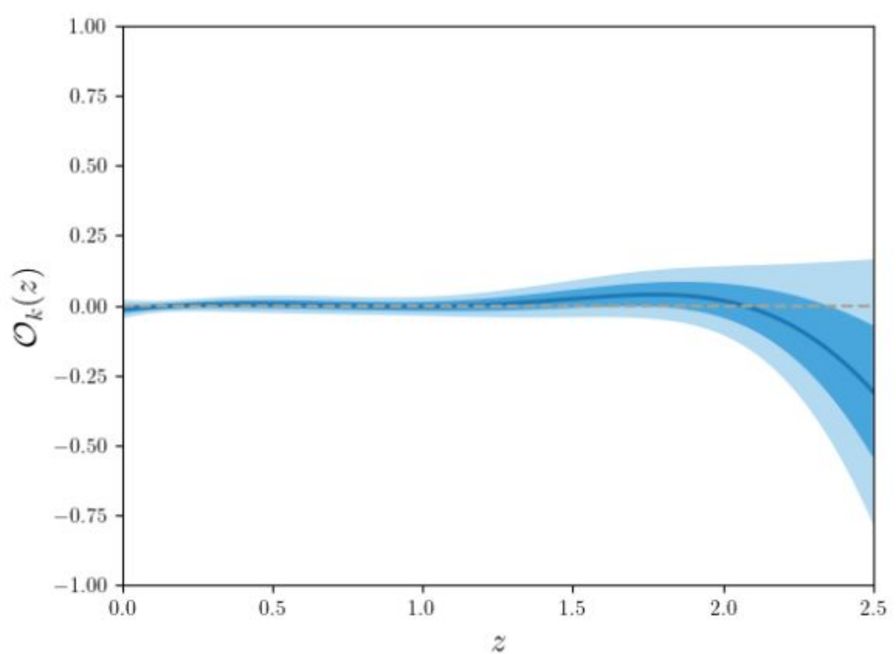
FIG. 5: Reconstructions of $E(z)$ (redshift surveys), $D(z)$ (GW) and $D'(z)$ functions for the simulated data.



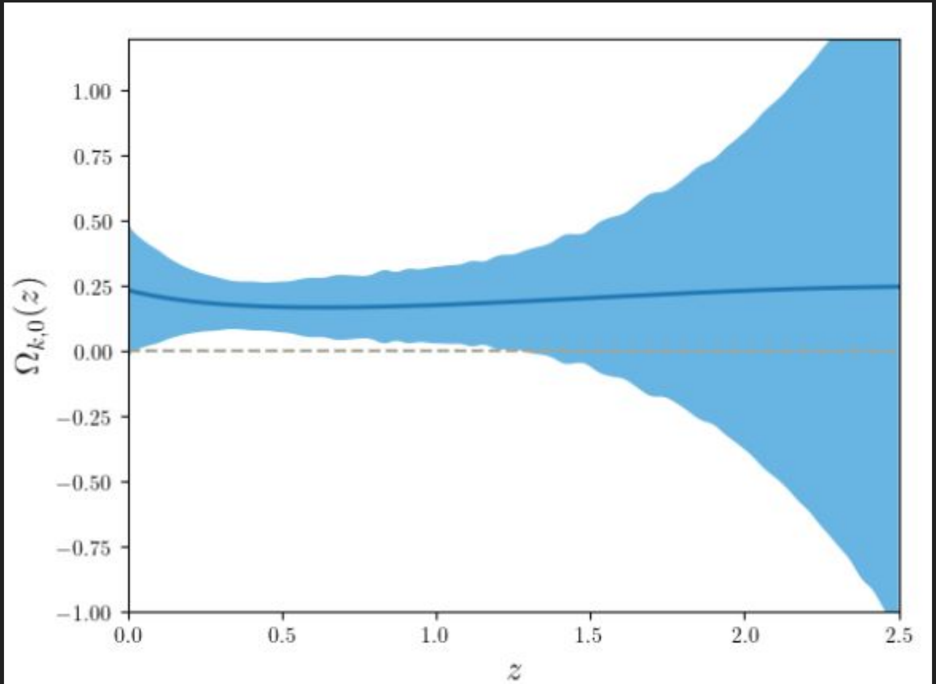


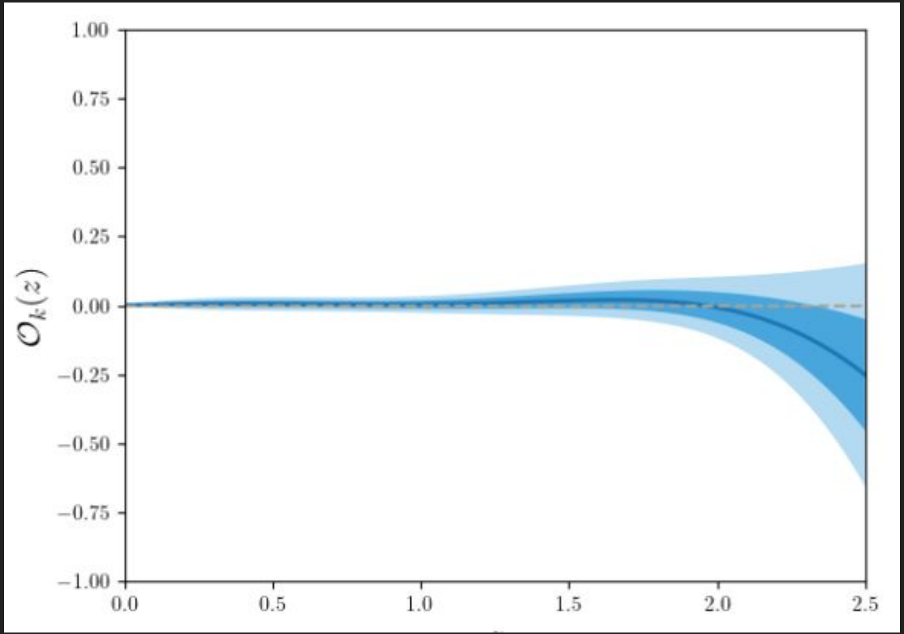
Ωk0 results (left plot) versus Ok(z) results (right plot) using Pantheon+ and SH0ES SNe combined with Cosmic Chronometers.





Ωk0 results (left plot) versus Ok(z) results (right plot) forecasts using simulated LIGO GW events combined with J-PAS





Ωk0 results (left plot) versus Ok(z) results (right plot) forecasts using Pantheon+ and GW combined with Cosmic Chronometers and J-PAS

Conclusions

- By using currently available observations, our results for $\Omega k0$ indicate no deviation from the FLRW hypothesis at 1σ confidence level, but the uncertainties are very large at higher redshifts ($z>1$) due to the lack of data. Likewise, our results for Ok(z) are consistent with a null curvature hypothesis at 1σ confidence level.

- The uncertainties of both tests can be significantly reduced, especially for the $\Omega k0$ test, with the advent of next-generation GW and redshift survey measurements.

- Our results show that the FLRW assumption for a flat (null curvature) universe is consistent with current cosmological data, and that we will be able to perform these tests with much higher precision in the future.

(ii) Measuring the speed of light with cosmological observations: current constraints and forecasts

Jaiane Santos, CB, Jonathan Morais, Rodrigo S. Gonçalves,

e-print: 2409.05838 [astro-ph.CO]
JCAP 11 (2024) 062

Motivation

- The speed of light “c” is one of the most fundamental constants in Physics. It is defined as the speed at which light travels in a vacuum, approximately c = 2.998 x 10^5 km/s

Motivation

- The speed of light "c" is one of the most fundamental constants in Physics. It is defined as the speed at which light travels in a vacuum, approximately c = 2.998 x 10^5 km/s

- Although it can be measured very precisely in local (Earth) laboratories, as well as in the Solar System, cosmological measurements of the speed of light are still scarce, and much less precise

Motivation

- The speed of light "c" is one of the most fundamental constants in Physics. It is defined as the speed at which light travels in a vacuum, approximately $c = 2.998 \times 10^5$ km/s

- Although it can be measured very precisely in local (Earth) laboratories, as well as in the Solar System, cosmological measurements of the speed of light are still scarce, and much less precise

- Goal: measure the speed of light with cosmological observations at high redshifts, to check if it agrees with local experiments, and also forecast the precision that can be achieved with future observational data – again using simulations of GW (LIGO) and redshift survey (J-PAS) measurements

Method

- Again in the FLRW framework, we can write the angular diameter distance as

$$D_A(z) = \frac{1}{(1+z)} \int_0^z \frac{c dz}{H(z)} ,$$

Method

- Again in the FLRW framework, we can write the angular diameter distance as

$$D_A(z) = \frac{1}{(1+z)} \int_0^z \frac{c dz}{H(z)} \,,$$

- We can differentiate both hands of the above equation, so that we get

$$\frac{\partial}{\partial z}[(1+z)D_A(z)] = \frac{c(z)}{H(z)} \,, \quad \Rightarrow \quad c(z) = H(z)[(1+z)D'_A(z) + D_A(z)] \,,$$

Method

- Again in the FLRW framework, we can write the angular diameter distance as

$$D_A(z) = \frac{1}{(1+z)} \int_0^z \frac{c\,dz}{H(z)} ,$$

- We can differentiate both hands of the above equation, so that we get

$$\frac{\partial}{\partial z}[(1+z)D_A(z)] = \frac{c(z)}{H(z)} ,$$ => $$c(z) = H(z)[(1+z)D'_A(z) + D_A(z)] ,$$

- In the SCM, DA is expected to reach a maximum at around zm ~ 1.5, so we can simplify the previous expression as

$$c(z_m) = D_A(z_m)H(z_m) ,$$

$$\sigma^2_{c(z_m)} = \left(H(z)\sigma_{D_A(z)}\right)^2 + \left(D_A(z)\sigma_{H(z)}\right)^2 .$$

Data

- We use the same Pantheon+ SN dataset, where we get DA(z) from the luminosity distances DL(z) via the cosmic distance duality relation: DL = DA*(1+z)^2, so we have 1701 DA(z) data points – note that this relation may not be valid for varying speed of light models, but we're not considering such a case here

Data

- We use the same Pantheon+ SN dataset, where we get DA(z) from the luminosity distances DL(z) via the cosmic distance duality relation: DL = DA*(1+z)^2, so we have 1701 DA(z) data points – note that this relation may not be valid for varying speed of light models, but we're not considering such a case here

- We also use the 31 cosmic chronometer measurements, but this time around combined with 18 radial BAO measurements, comprising 48 H(z) data points in total

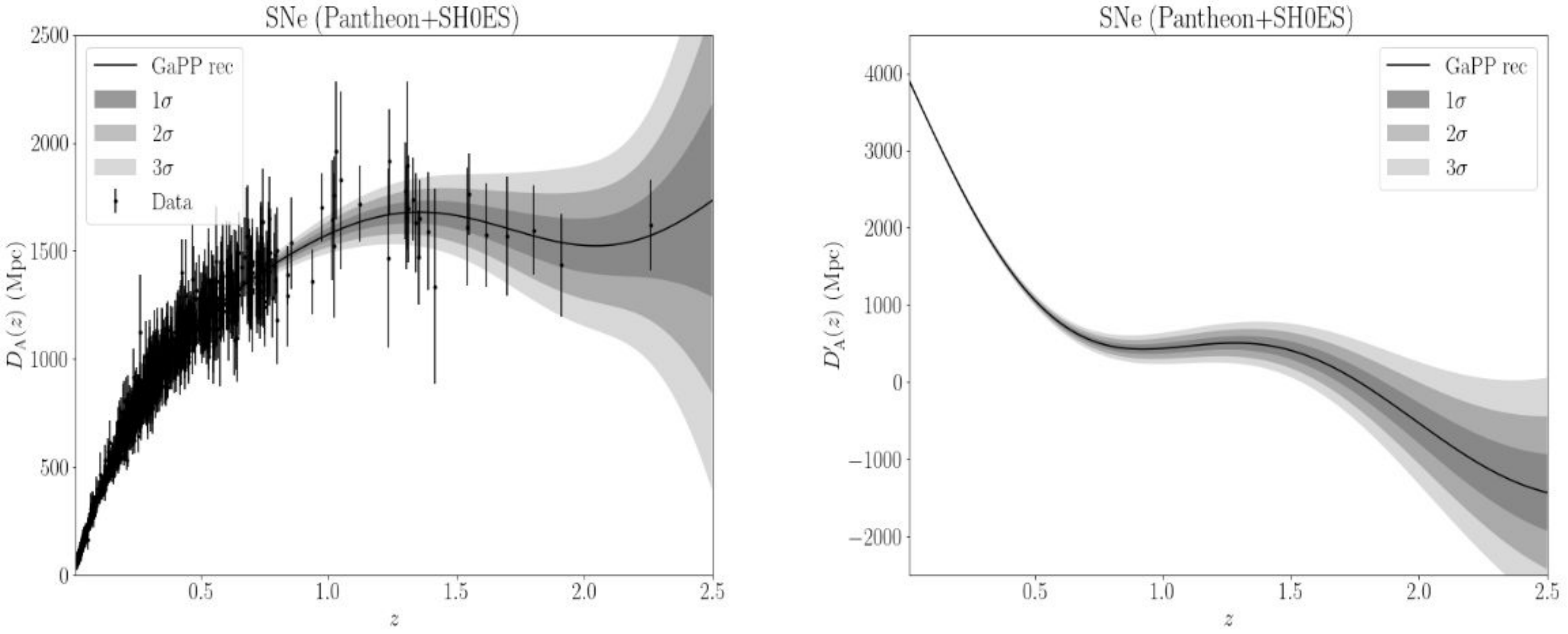
Data

- We use the same Pantheon+ SN dataset, where we get DA(z) from the luminosity distances DL(z) via the cosmic distance duality relation: DL = DA*(1+z)^2, so we have 1701 DA(z) data points – note that this relation may not be valid for varying speed of light models, but we're not considering such a case here

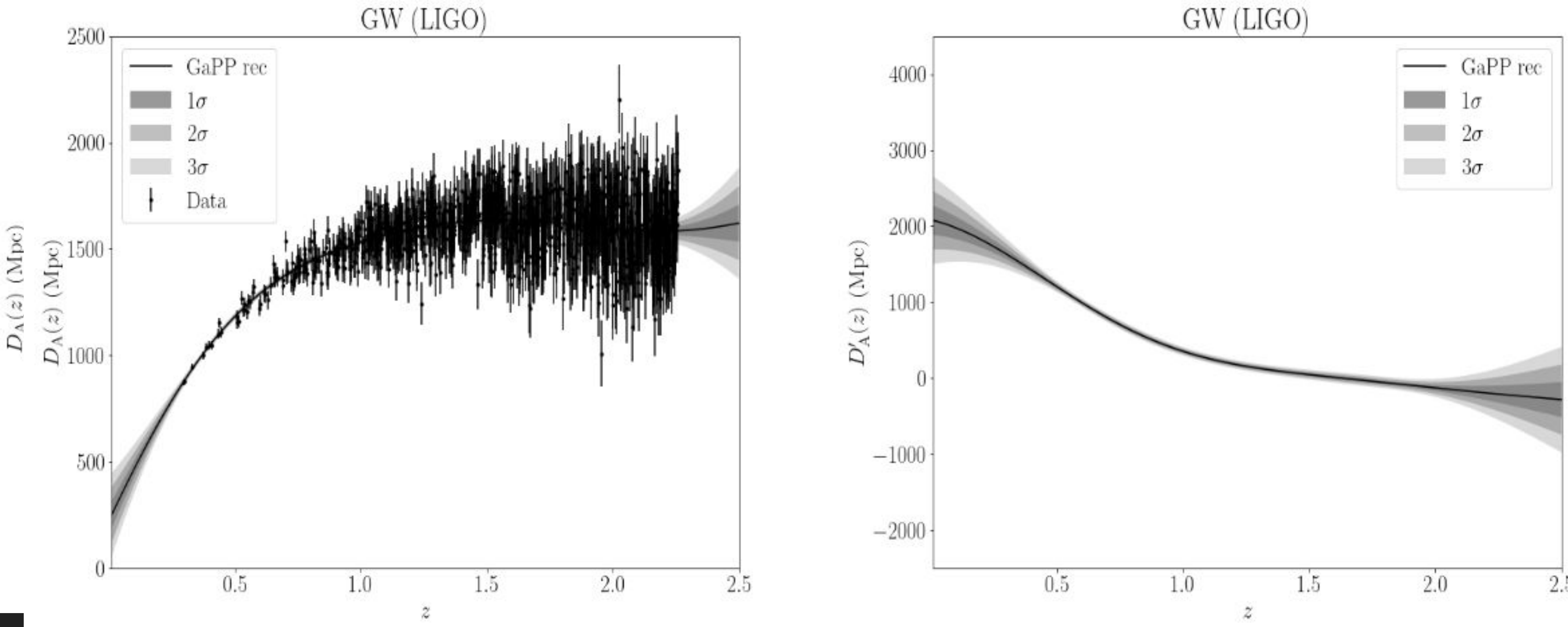
- We also use the 31 cosmic chronometer measurements, but this time around combined with 18 radial BAO measurements, comprising 48 H(z) data points in total

- We reconstruct DA(z) and H(z) using GP once more, where we identify the zm (where DA(z) is maximum) and then compute c(zm). We repeat the same procedure with next-generation cosmological simulations – 1000 DL(z) measurements by LIGO/ET GW and 23 H(z) measurements by J-PAS.

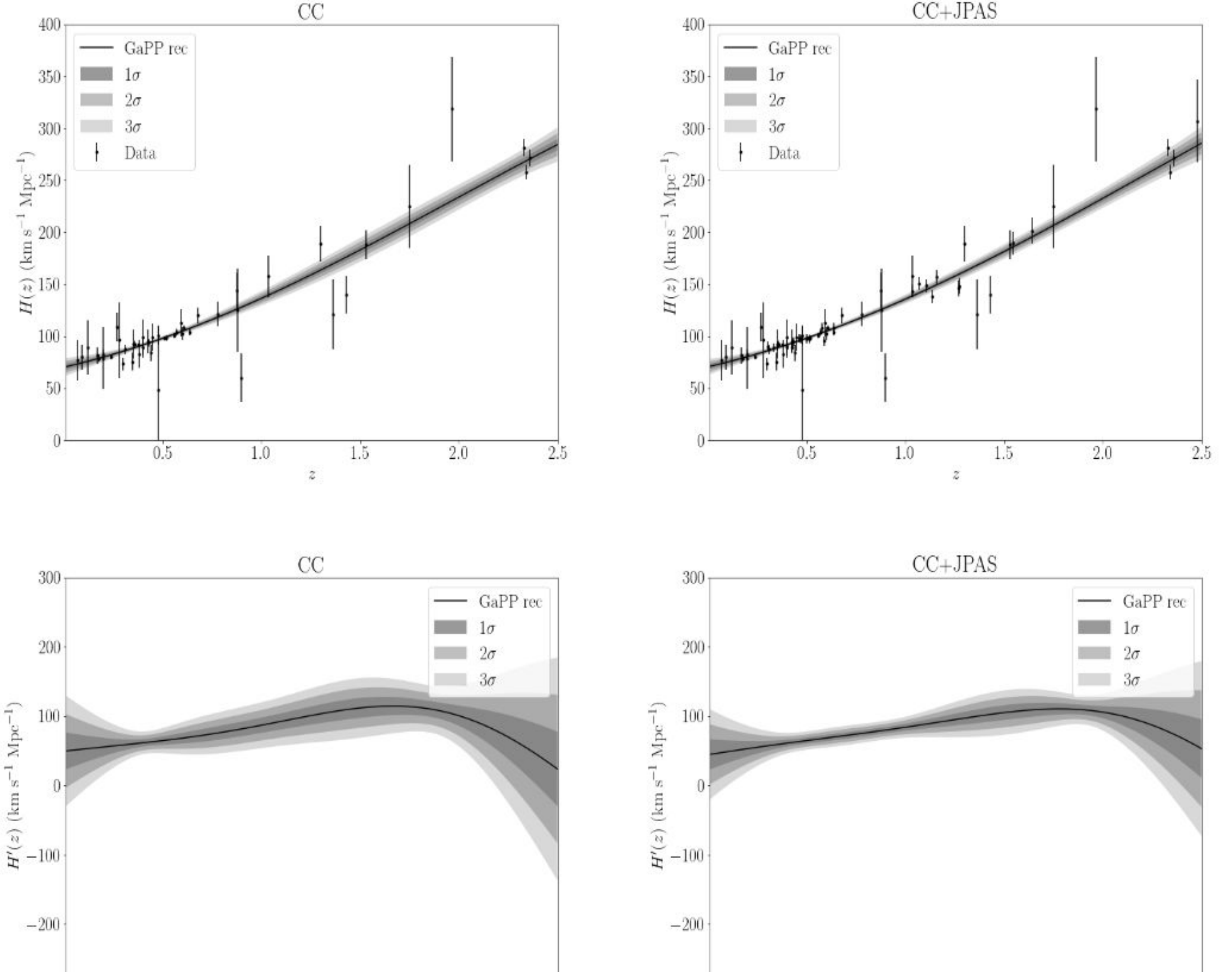
Results



SNe (Pantheon+SH0ES)
GaPP rec
1σ
2σ
3σ
Data
$D_A(z)$ (Mpc)
2500
2000
1500
1000
500
0
0.5
1.0
1.5
2.0
2.5
z
SNe (Pantheon+SH0ES)
GaPP rec
1σ
2σ
3σ
$D'_A(z)$ (Mpc)
4000
3000
2000
1000
0
−1000
−2000
0.5
1.0
1.5
2.0
2.5
z

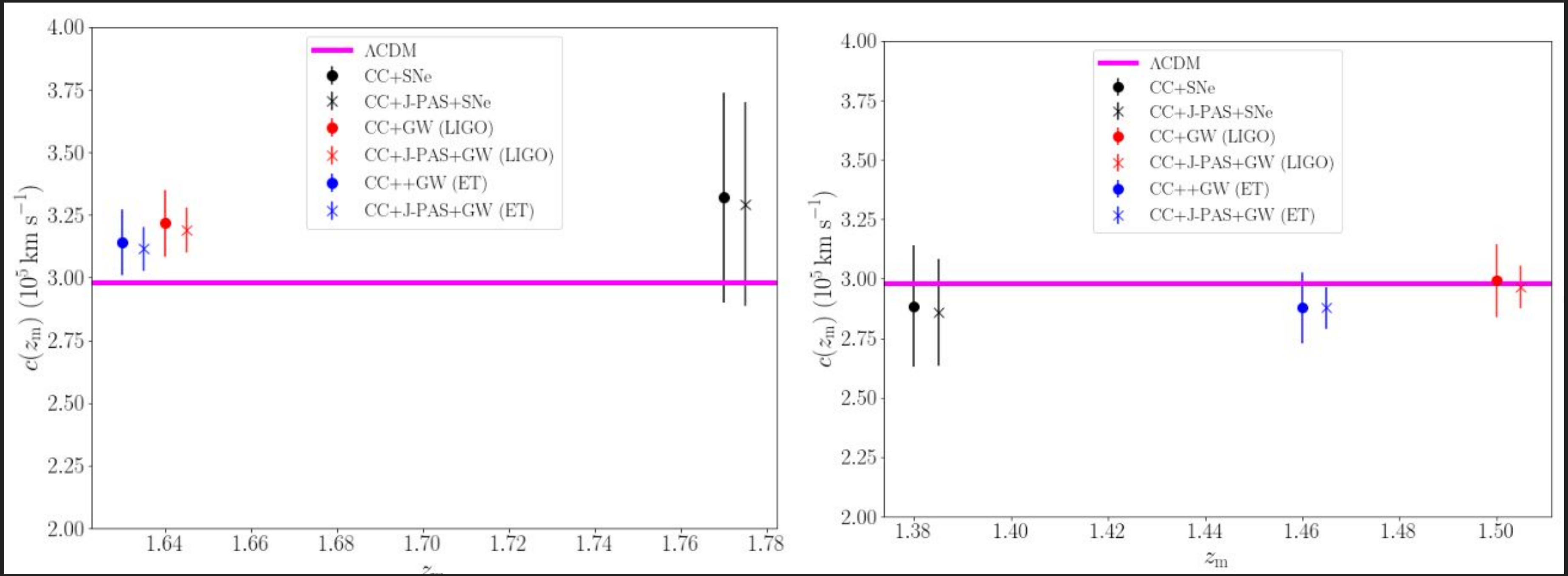


GW (LIGO)
GaPP rec
1σ
2σ
3σ
Data
$D_A(z)$ (Mpc)
z
GW (LIGO)
GaPP rec
1σ
2σ
3σ
$D'_A(z)$ (Mpc)
z



CC
CC+JPAS
GaPP rec
1σ
2σ
3σ
Data
$H(z)$ (km s^{-1} Mpc^{-1})
$H'(z)$ (km s^{-1} Mpc^{-1})
z

Results



c(zm) results obtained using the GP squared exponential kernel (left plot) and the Matern(7/2) kernel (right plot) – 2σ confidence intervals

TABLE I. Results for the $c(z_m)$ measurements assuming the Squared Exponential GP kernel. The first column displays the combination of data-sets, the second column shows the reconstructed z_m value, the third column provides the $c(z_m)$ measurements and their uncertainties in 1σ CL, in units of $10^5\,\mathrm{km\,s^{-1}}$, and the fourth column gives their relative uncertainty, in percent.

data-sets (CC+)	z_m	$c(z_m) \pm \sigma_{c(z_m)}$	uncertainty (%)
+SNe (Pantheon+SH0ES)	1.77	3.319 ± 0.210	6.25
+GW (LIGO)	1.64	3.217 ± 0.067	2.08
+GW (ET)	1.63	3.140 ± 0.066	2.10
data-sets (CC+JPAS+)	z_m	$c(z_m) \pm \sigma_{c(z_m)}$	uncertainty (%)
+SNe (Pantheon+SH0ES)	1.77	3.293 ± 0.203	6.16
+GW (LIGO)	1.64	3.190 ± 0.044	1.38
+GW (ET)	1.63	3.114 ± 0.043	1.38

TABLE II. Same as Table I, but rather assuming the Matérn(7/2) kernel.

data-sets (CC+)	z_m	$c(z_m) \pm \sigma_{c(z_m)}$	uncertainty (%)
+SNe (Pantheon+SH0ES)	1.38	2.884 ± 0.128	4.45
+GW (LIGO)	1.50	2.992 ± 0.077	2.59
+GW (ET)	1.46	2.877 ± 0.074	2.58
data-sets (CC+JPAS+)	z_m	$c(z_m) \pm \sigma_{c(z_m)}$	uncertainty (%)
+SNe (Pantheon+SH0ES)	1.38	2.859 ± 0.112	3.91
+GW (LIGO)	1.50	2.965 ± 0.045	1.52
+GW (ET)	1.46	2.851 ± 0.043	1.51

Conclusions

- Current observations are able to provide a 4-6% precision measurement of the speed of light at about $z \sim 1.4$-1.8, depending on the kernel adopted for the reconstructions, whose values agree with local experiments at $\sim 2\sigma$ confidence level

- In addition, we found that future experiments of GW can improve these figures to about ~2-2.5%, and down to ~1.5% when redshift surveys are also considered

- We will be able to carry out nearly percent-level measurements of the speed of light in the future, so we can test if its value is really consistent with local measurements at redshifts that correspond to an Universe age of 3.2-4.0 Gyr

Concluding remarks

Concluding remarks

- The SCM has been extremely successful in describing cosmological observations for over 2 decades. Still, it is plagued with several caveats, both theoretical and observational. So it is crucial to test its foundations in light of available data – and forecast the precision that can be achieved with future observations.

- In this presentation, we showed that there is no evidence for departures of some of the SCM fundamental assumptions – such as the FLRW metric, and the speed of light as a physical constant

- Our results are robust with respect to possible biases due to implicit assumptions on the cosmological model, which we avoided by using Gaussian Processes, model-independent reconstructions of the data

- Future observations of GW events, and redshift surveys, will be able to significantly improve the precision of such tests (and many others!), and hence underpin the validity (or unsoundness) of the SCM

Thank you!
Obrigado!

Contact: carlosbengaly@on.br
GaPP code: https://github.com/astrobengaly/GaPP