Probing the standard model of Cosmology and its fundamental hypothesis: state-of-art and forecasts

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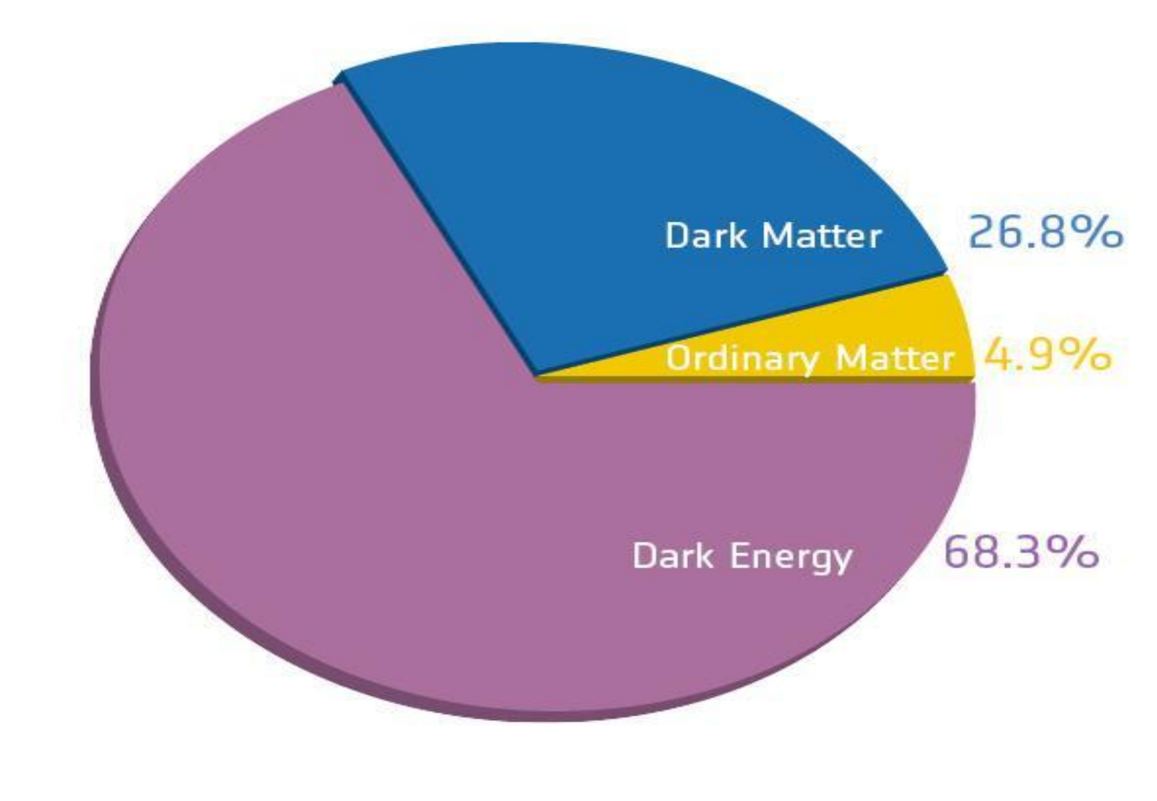
Outline

- The standard model of Cosmology (SCM)
- We have a SCM, but do we *really* understand the cosmos?
- Observational tests of the SCM foundations
  - Testing the cosmological Principle with observational data
  - Null tests of the standard model with current and future observations
  - Miscellaneous stuff
- Concluding remarks and perspectives

The standard model of Cosmology today

The standard model of Cosmology

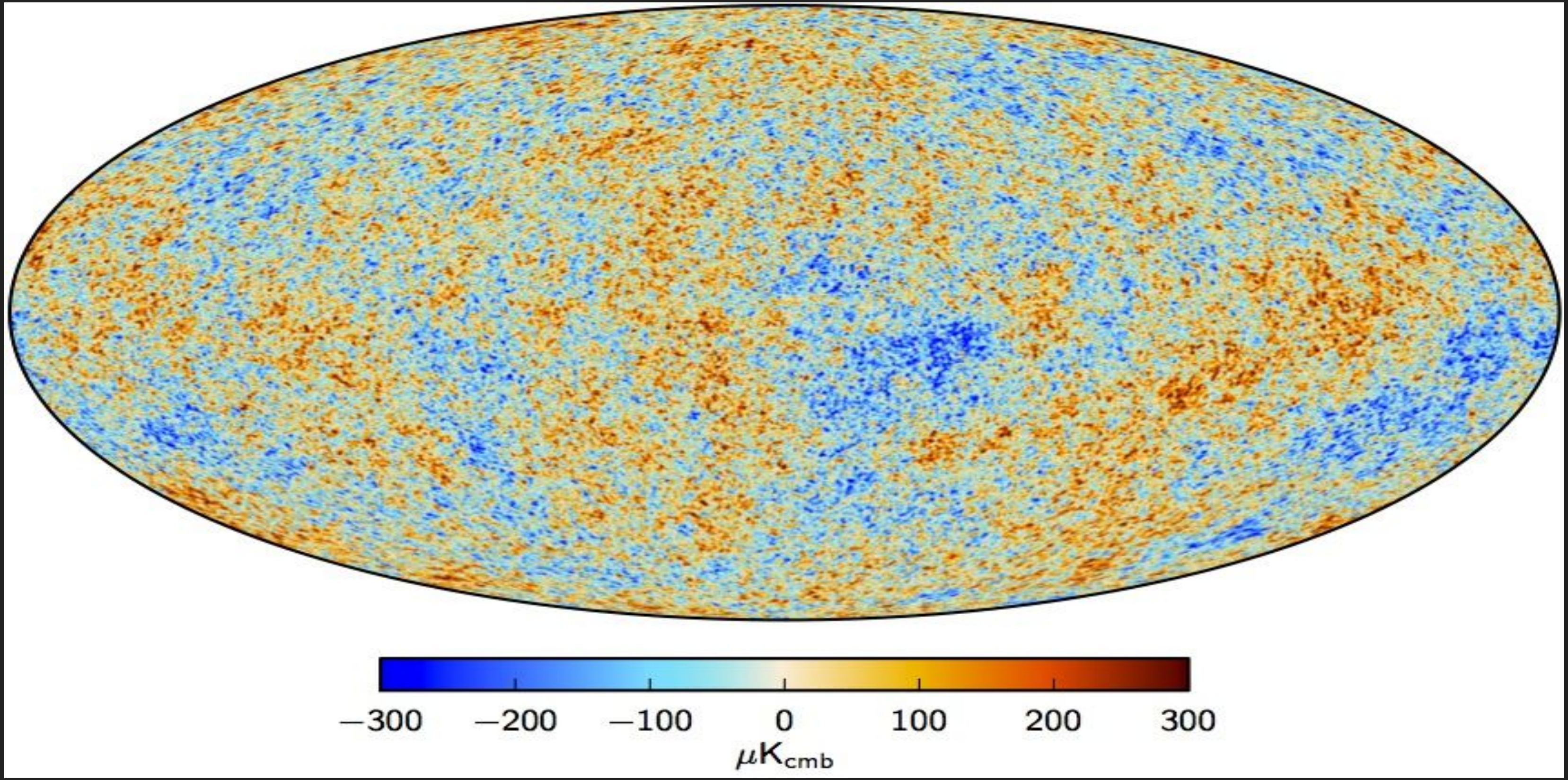


Credits: Planck Collaboration

What is dark matter?

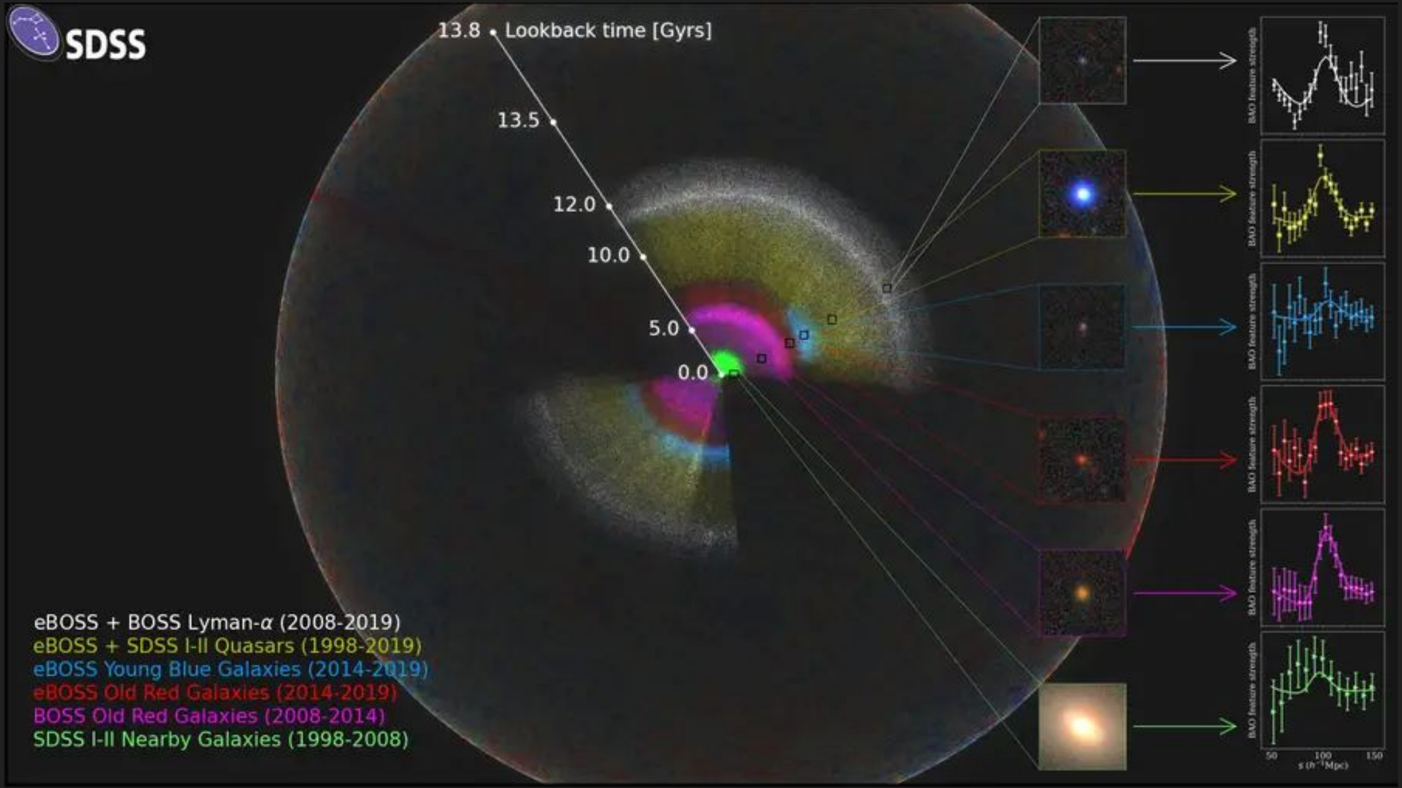
What is dark energy?

The Cosmic Microwave Background (CMB)



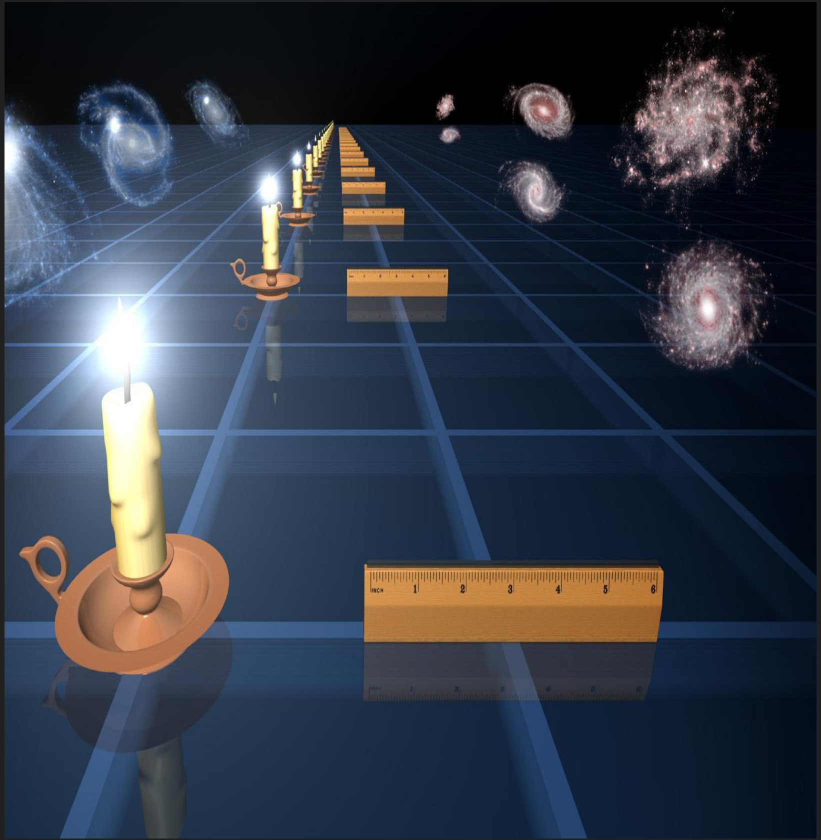
Credits: Planck Collaboration

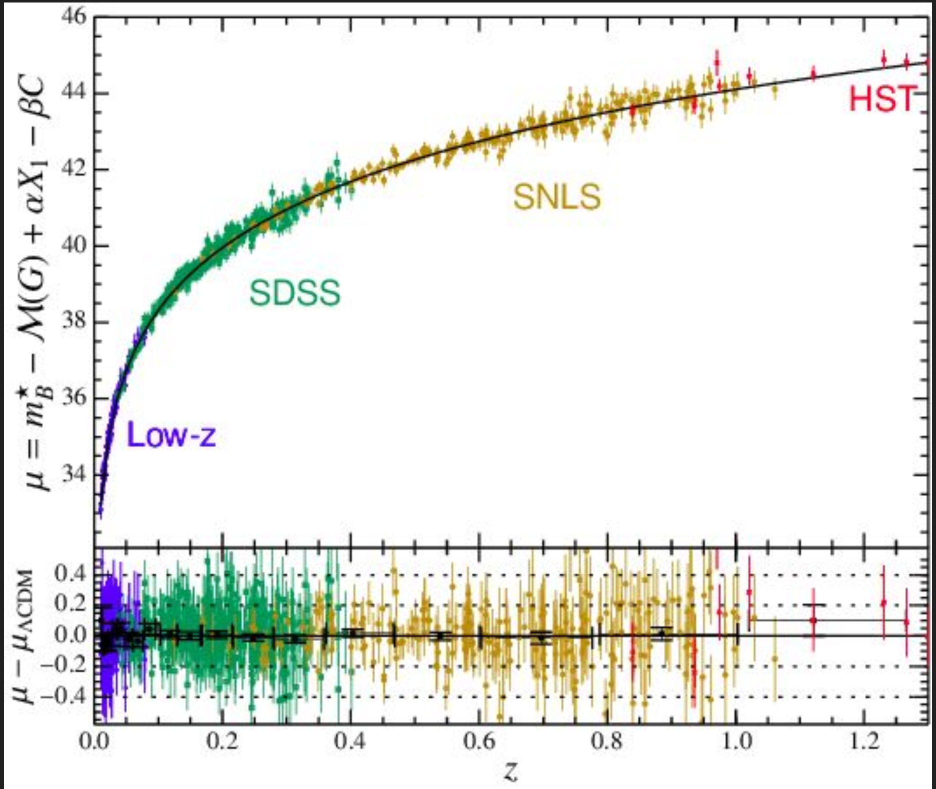
The galaxy distribution in the large-scale structure of the Universe



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

The distance to Type Ia Supernovae (SNe)





But what is the ΛCDM model *really* about?

ΛCDM model

- ΛCDM = Λ represents the Cosmological Constant, responsible for the late-time cosmic acceleration, whereas CDM = *cold dark matter*

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- Cold Dark Matter:
  - Only gravitational interaction
  - not directly seen, only indirect detection through light deviation - gravitational lensing phenomenon
  - Needed to explain spiral galaxy rotation curve, and large-scale structure
  - Main candidates: weakly interacting massive particles (WIMPs) like axions (not yet detected)
  - no evidence for neutrinos (hot dark matter, relativistic), alternative gravity models like Mond (modified newtonian dynamics) and MACHOs (massive compact halo objects)

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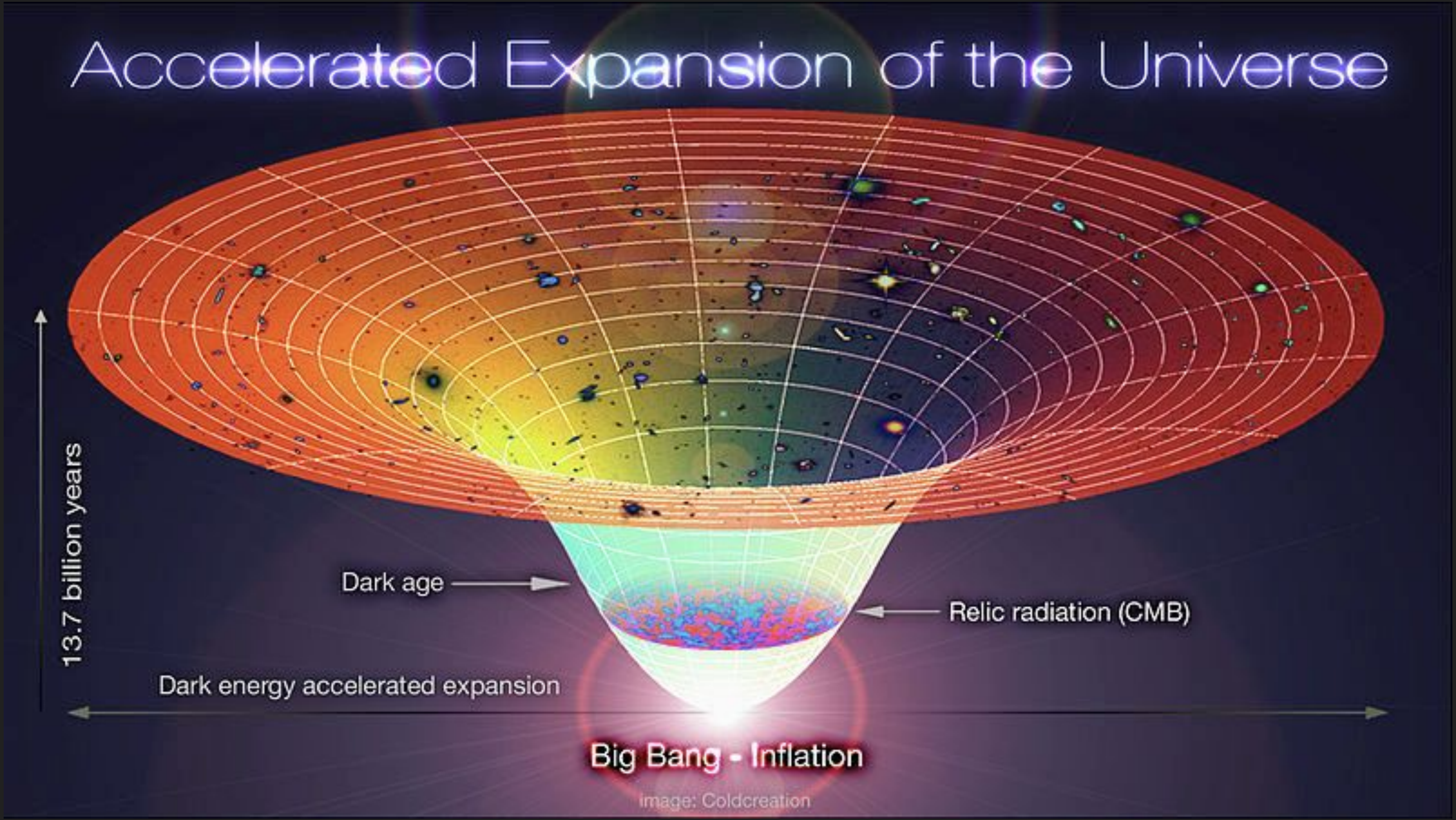
- Dark energy:
  - exotic component behaving like a perfect fluid with negative equation of state ($P = w\rho$, $w < 0$)
  - dominates the energy budget of the Universe in the last 3 billion years (why just now?? Cosmic coincidence problem)
  - Best candidate today: Cosmological Constant Λ, where $w=-1$
  - Λ associated with vacuum density energy. However, if Λ = vacuum, we have 120 orders of magnitude between cosmological observations and quantum field theory predictions (!!!)
  - main Λ alternatives: quintessence fields, dynamical dark energy, modified gravity models like f(R), Gauss-Bonnet etc.


Accelerated Expansion of the Universe
13.7 billion years
Dark age
Relic radiation (CMB)
Dark energy accelerated expansion
Big Bang - Inflation
image: Coldcreation

ΛCDM model

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- Inflation (?): developed independently by Alan Guth, Paul Steinhardt, Andrei Lide and Alexey Starobinsky, it comprises an early Universe mechanism aiming at solving the following problems
  - horizon problem: why do CMB temperature anisotropies exhibit such similar temperature if they are not in causal contact?
  - curvature problem: why does the Universe today seem flat?
  - homogeneity problem: why is the Universe today statistically homogeneous and isotropic?
  - topological defects and magnetic monopole: where are they??

  Alternative models: bouncing models, string gas etc

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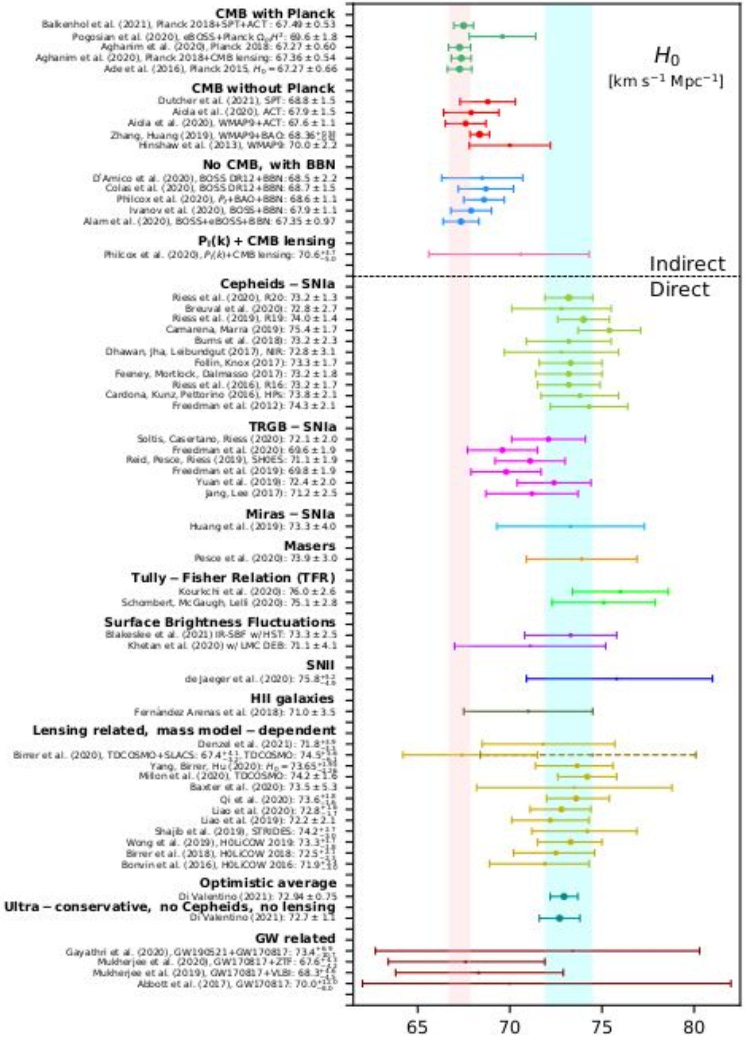
Moreover, there are some possible "cracks" on the CM, like the ~4.4σ H_0 tension and ~2.5σ σ_8 tension



Credits: Di Valentino+ 21

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 CM, like the ~4.4σ H0 tension and ~2.5σ σ8 tension

We shall revisit the fundamental pillars which the CM is based upon

The foundations of the concordance model

- **General Relativity (GR) as the theory of gravity**

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- The Cosmological Principle (CP)

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- 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

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

DOES THE CP REALLY DESCRIBE THE OBSERVED UNIVERSE?

The foundations of the concordance model

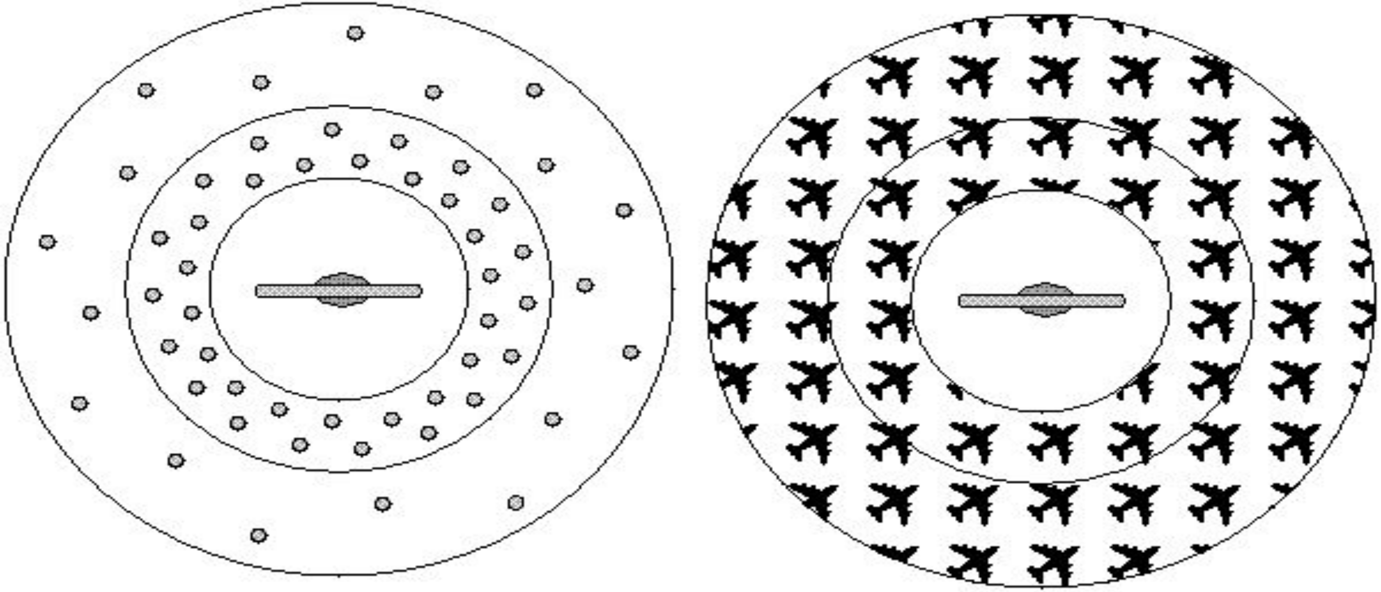
- General Relativity (GR) as the theory of gravity

- The Cosmological Principle (CP)

NO CP = NO FLRW UNIVERSE = NO CONCORDANCE MODEL!

Part I:
Testing the cosmological principle with cosmological observations

A cartoon vision of the CP



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?

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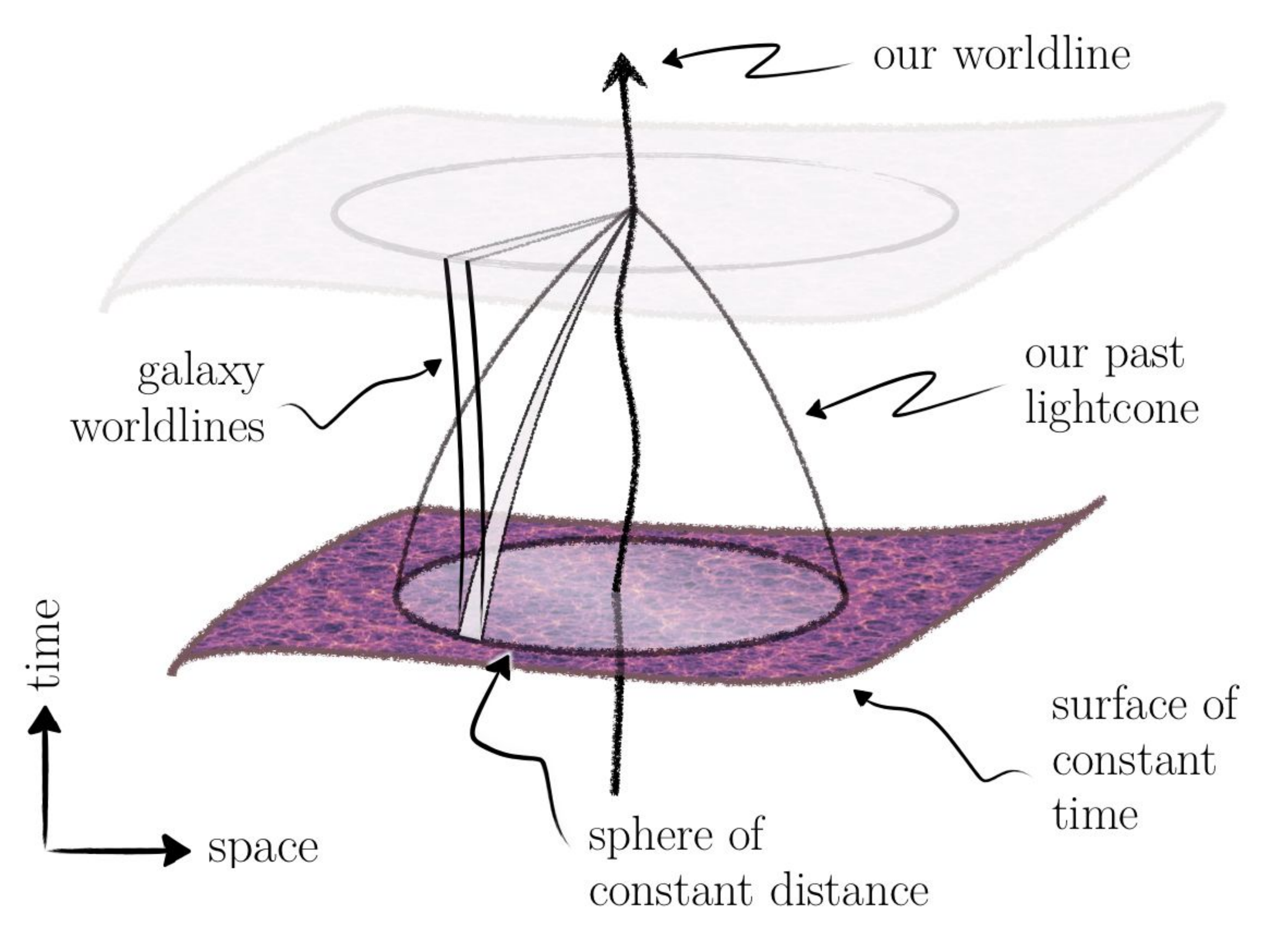
  Note: Consistency tests of statistical homogeneity are possible:
  * FLRW metric consistency relation (Clarkson, Bassett and Lu 2008)
  * Determination of a scale of homogeneity in source counts using fractal dimension (Pietronero 1987)



From: Clarkson 2012
arxiv:1204.5505

see also Clarkson & Maartens 2010;
arxiv:1005.2165

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Part I: Testing isotropy with source counts

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  CB, Santos, Maartens JCAP2018; CB, Maartens, Randriamiarinarivo, Baloyi JCAP2019; CB, Siewert, Schwarz, Maartens MNRAS2019;

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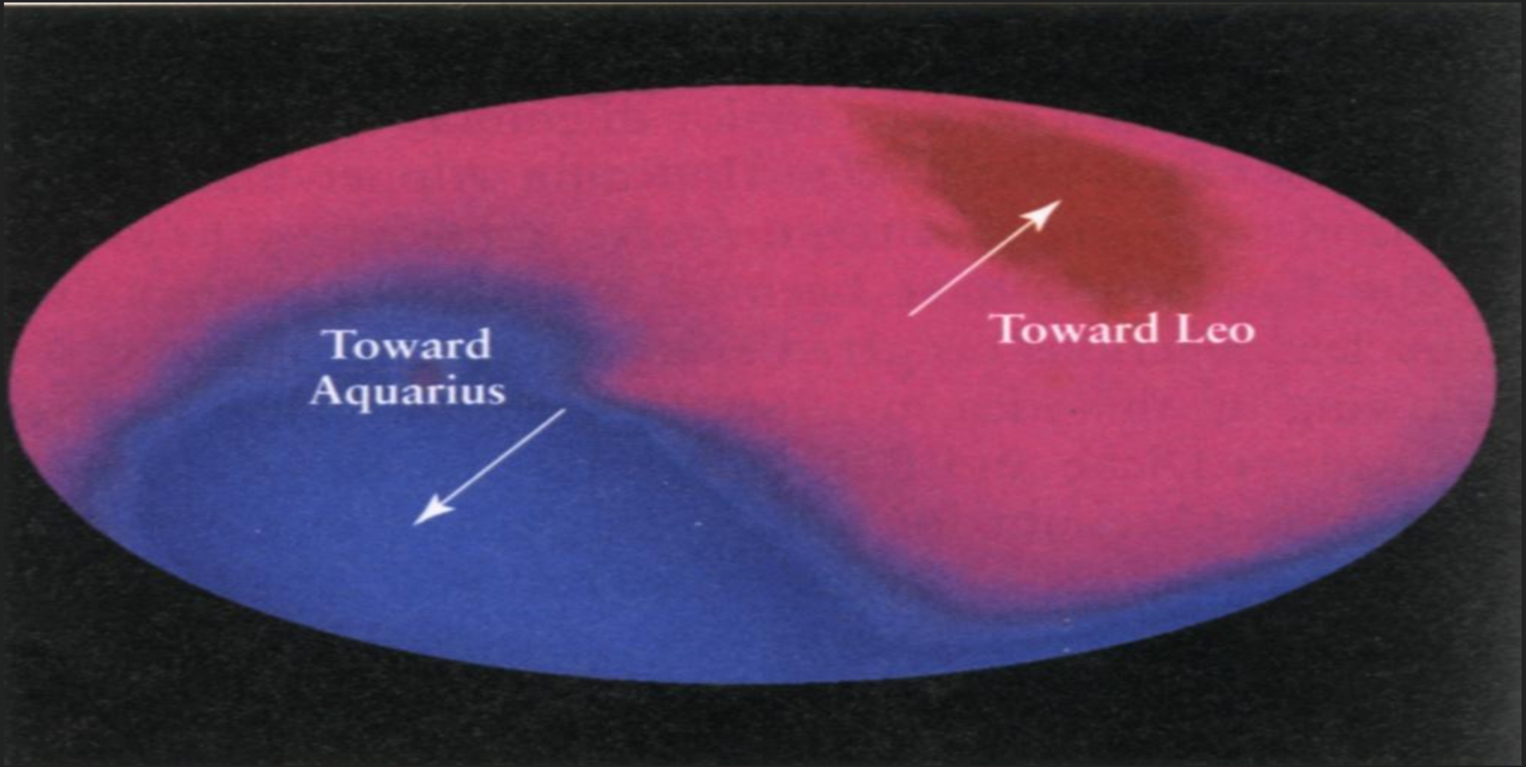
  See also CB+ MNRAS2017, MNRAS2018 for analysis using low-z galaxy counts in infrared, CB+ MNRAS2017b for galaxy clusters, CB+ ApJ2015, Andrade+ PRD2017, ApJ2018 for SNe, Andrade+ MNRAS2019 for GRBs

The dipole anisotropy of radio counts

CB, Santos, Maartens

JCAP 04 (2018) 031
e-Print: 1710.08804 [astro-ph.CO]

Is the Universe isotropic?



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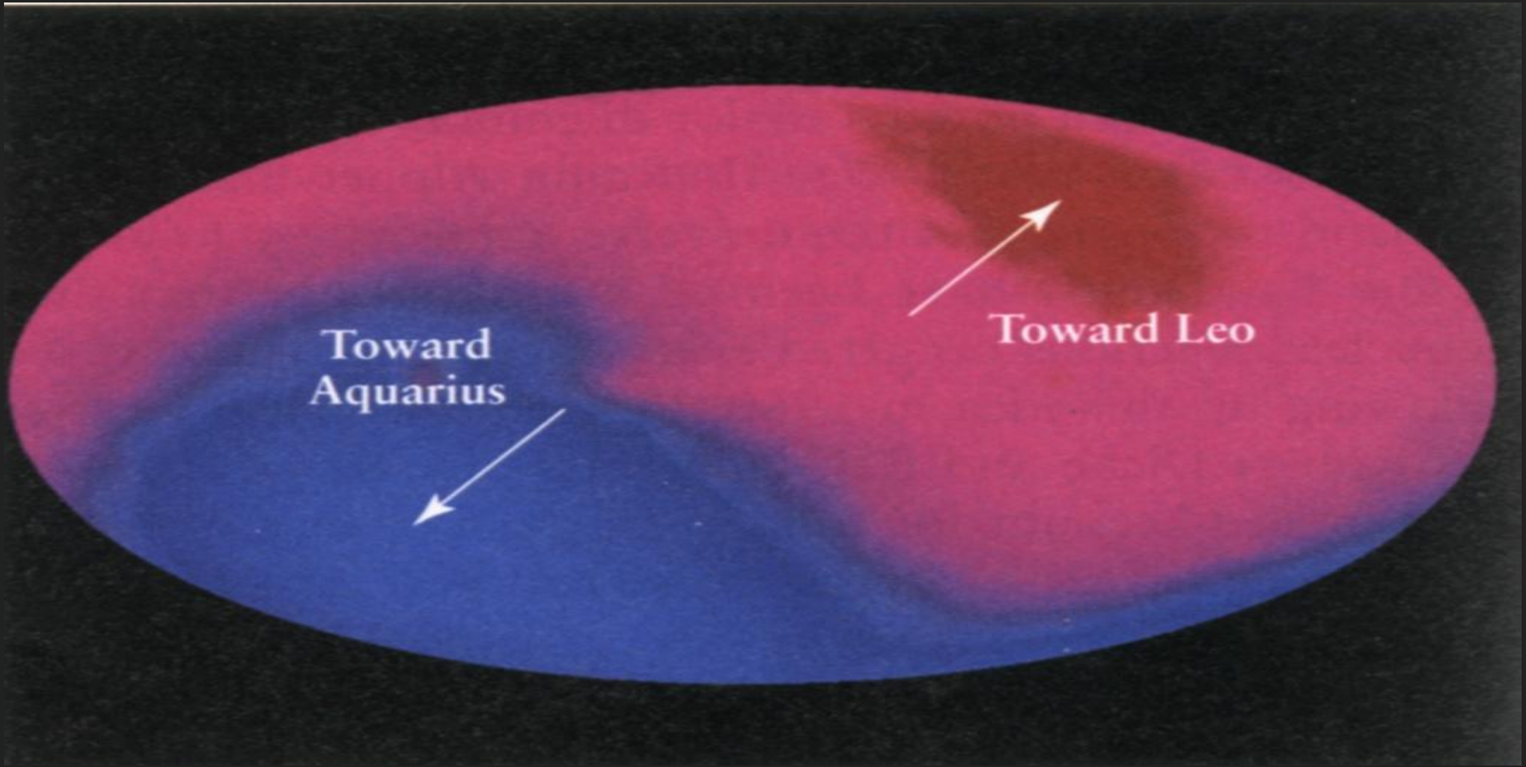

The dipole anisotropy in the CMB

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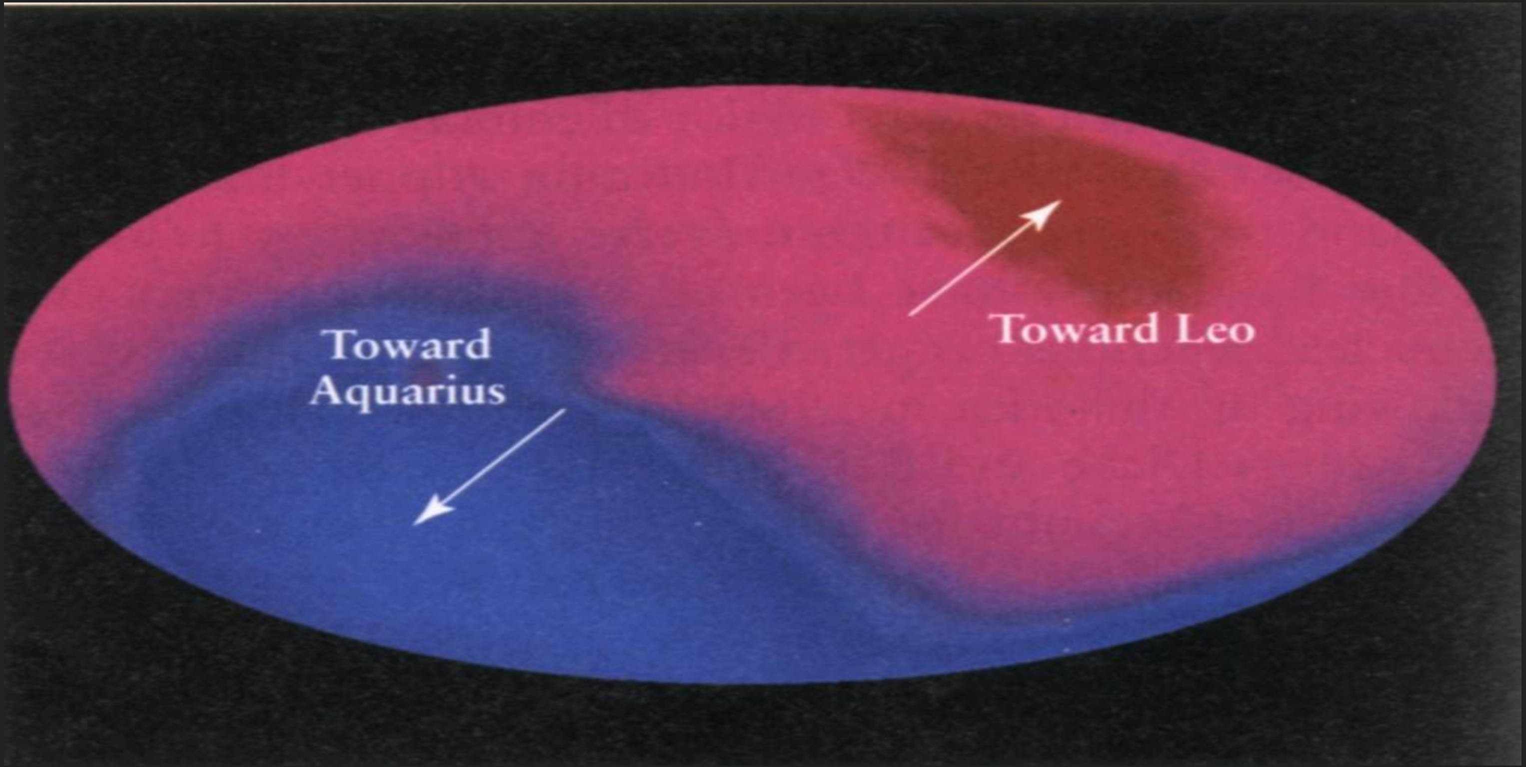

$$v \simeq 369 \ \mathrm{km/s}$$

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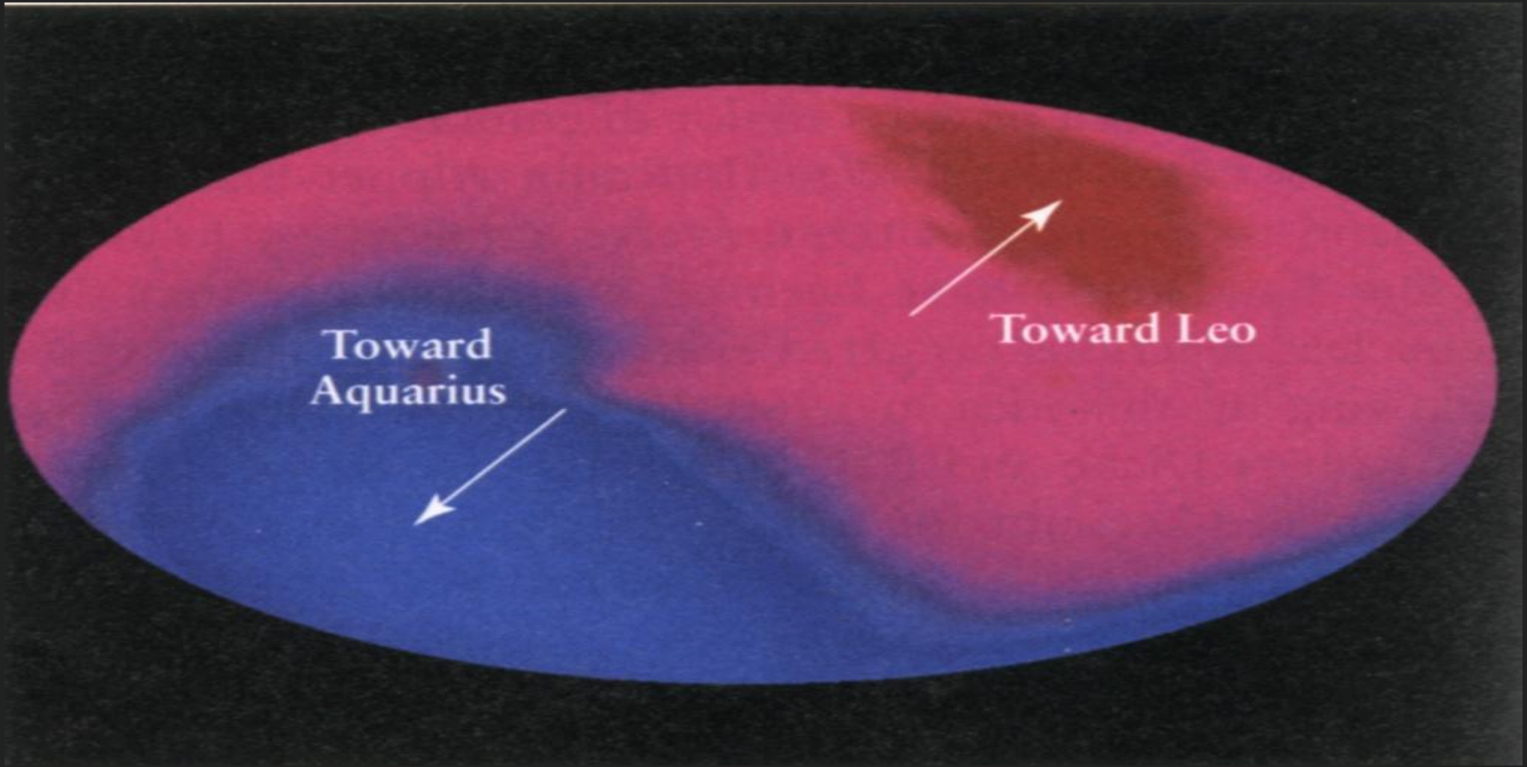

Can we detect this dipole in number counts?

Mon. Not. R. astr. Soc. (1984) **206,** 377–381

On the expected anisotropy of radio source counts

G. F. R. Ellis* and J. E. Baldwin† *Orthodox Academy of Crete, Kolymbari, Crete*

Received 1983 May 31; in original form 1983 March 31

Summary. If the standard interpretation of the dipole anisotropy in the microwave background radiation as being due to our peculiar velocity in a homogeneous isotropic universe is correct, then radio-source number counts must show a similar anisotropy. Conversely, determination of a dipole anisotropy in those counts determines our velocity relative to their rest frame; this velocity must agree with that determined from the microwave background radiation anisotropy. Present limits show reasonable agreement between these velocities.

A TEST OF COSMOLOGICAL PRINCIPLE:
PROBING THE DIPOLE ANISOTROPY IN THE COUNTS OF RADIO CATALOGUES

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SYSTEMATICS?

The dipole anisotropy in radio number counts

- Given the spectral index $S \propto \nu^{-\alpha}$
- Given the scaling relation $N(>S) \propto S^{-x}$
- By combining Doppler boost with the aberration of angles, we have (Ellis & Baldwin 1984)

$$N_{\rm obs} = N_{\rm rest}\left[2 + x(1+\alpha)\right]\beta\cos\theta$$

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$$N_{\rm obs} \propto A\cos\theta$$

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$$A = 0.00462$$
$$\alpha = 0.76,\ x = 1.0,\ \beta = 0.00123$$

Observational data: sample construction I

- Two largest large-sky radio catalogues currently available:
  NVSS (NRAO VLA Sky Survey @ 1400 MHz) vs. TGSS (TIFR GMRT Sky Survey @ 150 MHz)

- Both survey probe the entire sky down to the southernmost declinations
  (DEC>-40deg for NVSS, DEC>-53deg for TGSS)

- Flux threshold selected

$$100 < S_{\rm TGSS} < 5500 \text{ mJy} \qquad f_{\rm sky} \simeq 0.687; \; N_{\rm tot} = 233,395$$

$$20 < S_{\rm NVSS} < 1000 \text{ mJy} \qquad f_{\rm sky} = 0.657; \; N_{\rm tot} = 253,313$$

Observational data: sample construction II

We further cleaned both catalogues as follows:

- Removal of large rms noise pixels (10mJy/beam) - only for TGSS sample

- Elimination of galactic plane ($|b|<10$deg)

- Elimination of pixels within 1deg of local radio sources and local clusters

- Regions whose radio galactic foreground emission exceeds T=50mK according to the Haslam map (Haslam et al. 1982)

Data Analysis

- Hemispherical comparison estimator to look for a preferred direction - assigned to the radio dipole

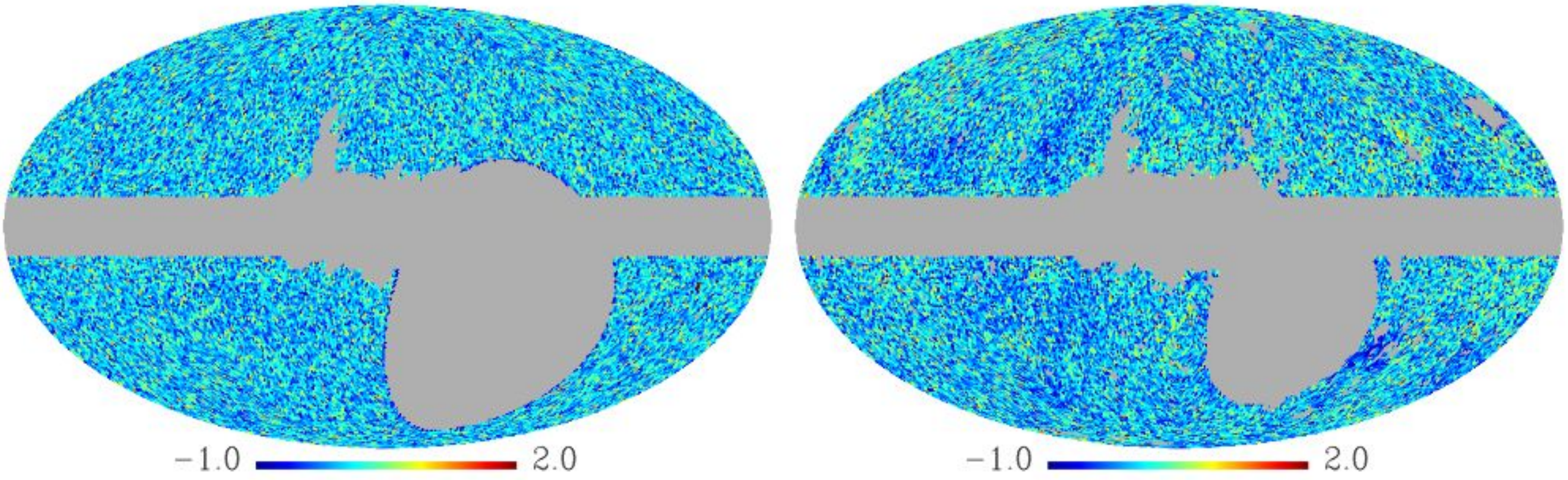
- Source count maps produced with HEALPix package as well (Nside=64)

- Compare real x mock count maps produced with flask code with a fiducial power spectrum from CAMB sources

- n(z) distribution for the radio sources following SKADS, b(z) follows Nusser & Tiwari 2016: $b(z) = 1.6 + 0.7z + 0.35z^2$

- Also verified how do flux density errors and flux calibration affect the dipole

Observational data: number counts



NVSS (left) versus TGSS (right)

Results

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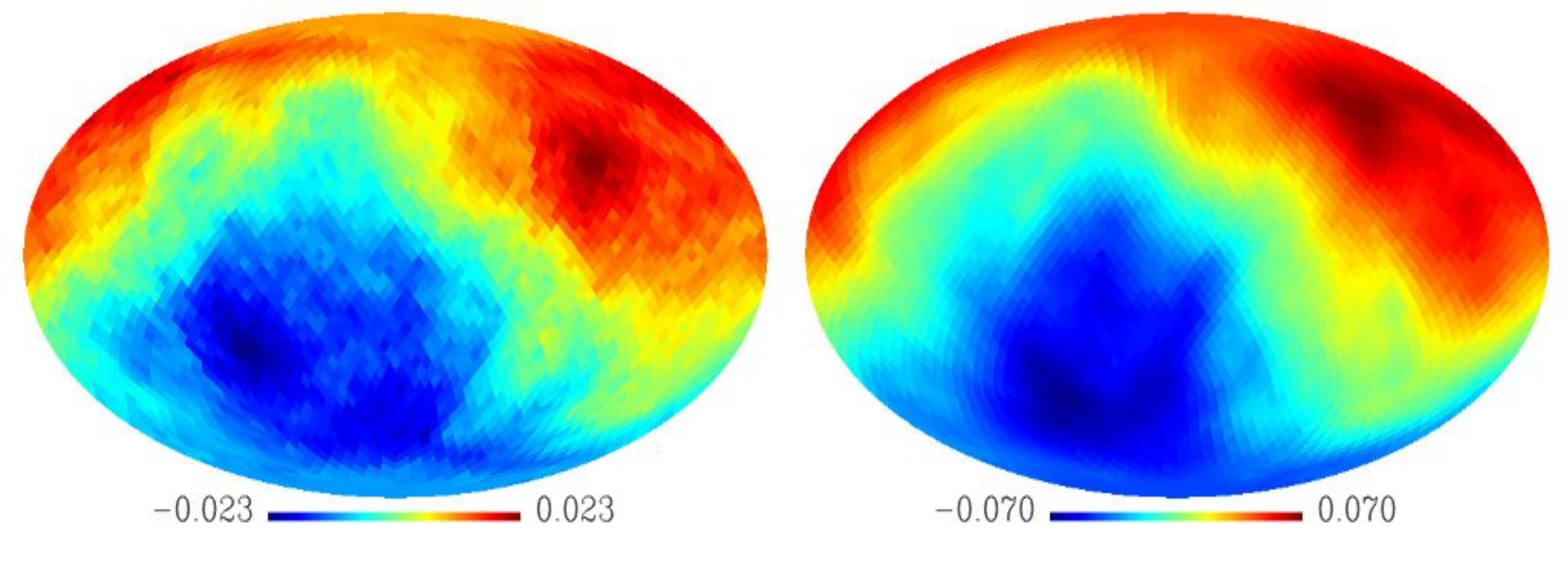


NVSS (left) versus TGSS (right) dipole

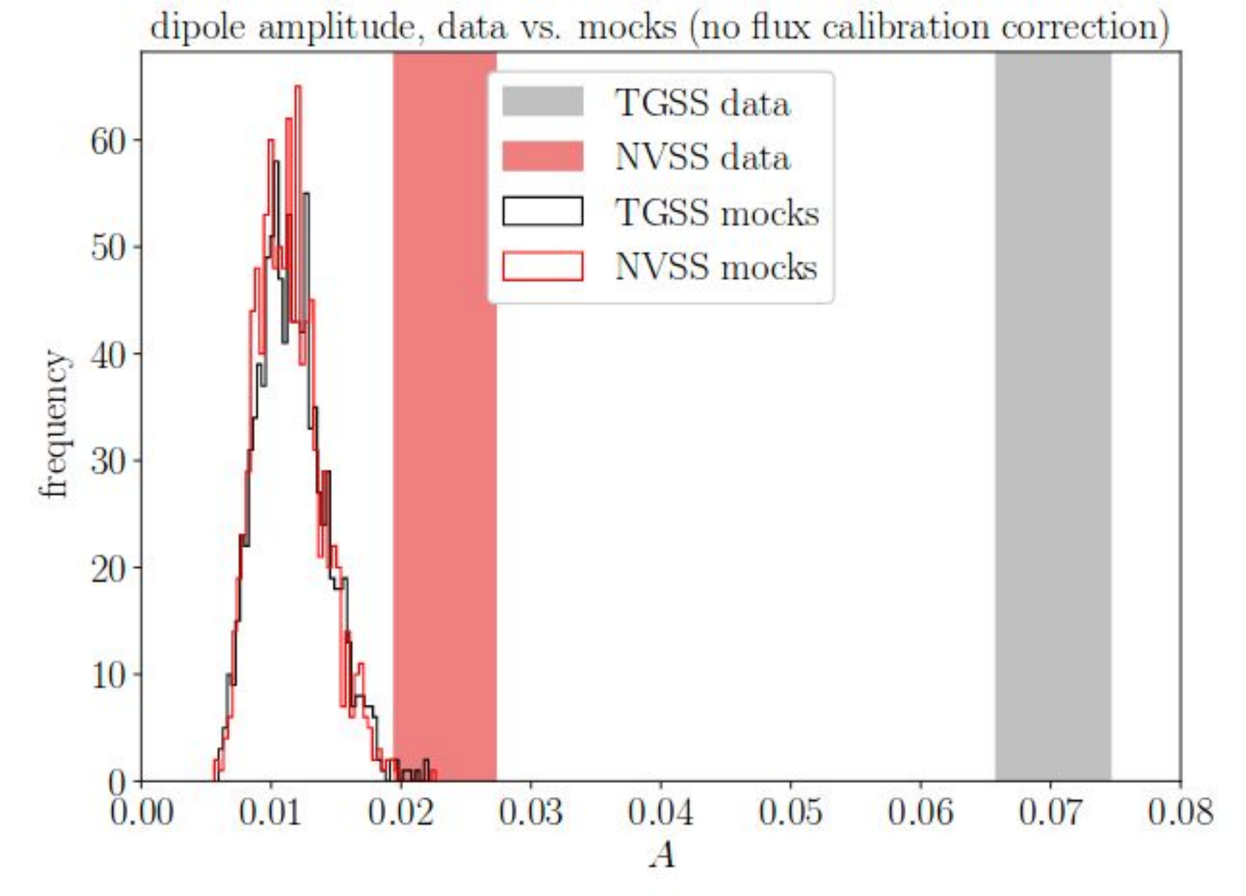
Direction is consistent with CMB, amplitude is much higher!

Results

Survey	Flux range (mJy)	A_{obs}	(l, b)	ref.
TGSS	$100 < S < 5000$	0.070 ± 0.004	$(243.00° \pm 12.00°, 45.00° \pm 3.00°)$	This work
NVSS	$20 < S < 1000$	0.023 ± 0.004	$(253.12° \pm 11.00°, 27.28° \pm 3.00°)$	This work
NVSS (other work)	$S > 20$	0.021 ± 0.006	$(244.69° \pm 27.00°, 41.18° \pm 29.00°)$	[9]
	$20 < S < 1000$	0.021 ± 0.005	$(252.22° \pm 10.00°, 42.74° \pm 9.00°)$	[10]
	$S > 15$	0.027 ± 0.005	$(213.99° \pm 20.00°, 15.30° \pm 14.00°)$	[11]
	$S > 25$	0.019 ± 0.005	$(248.47° \pm 19.00°, 45.56° \pm 9.00°)$	[12]
	$S > 20$	0.010 ± 0.005	$(256.49° \pm 9.00°, 36.25° \pm 11.00°)$	[13]
	$S > 20$	0.012 ± 0.005	$(253.00°, 32.00°)$	[17]
	$S > 10$	0.019 ± 0.002	$(253.00° \pm 2.00°, 28.71° \pm 12.00°)$	[16]

Direction is quite right, but the amplitude is much higher!

Results: mock data performance



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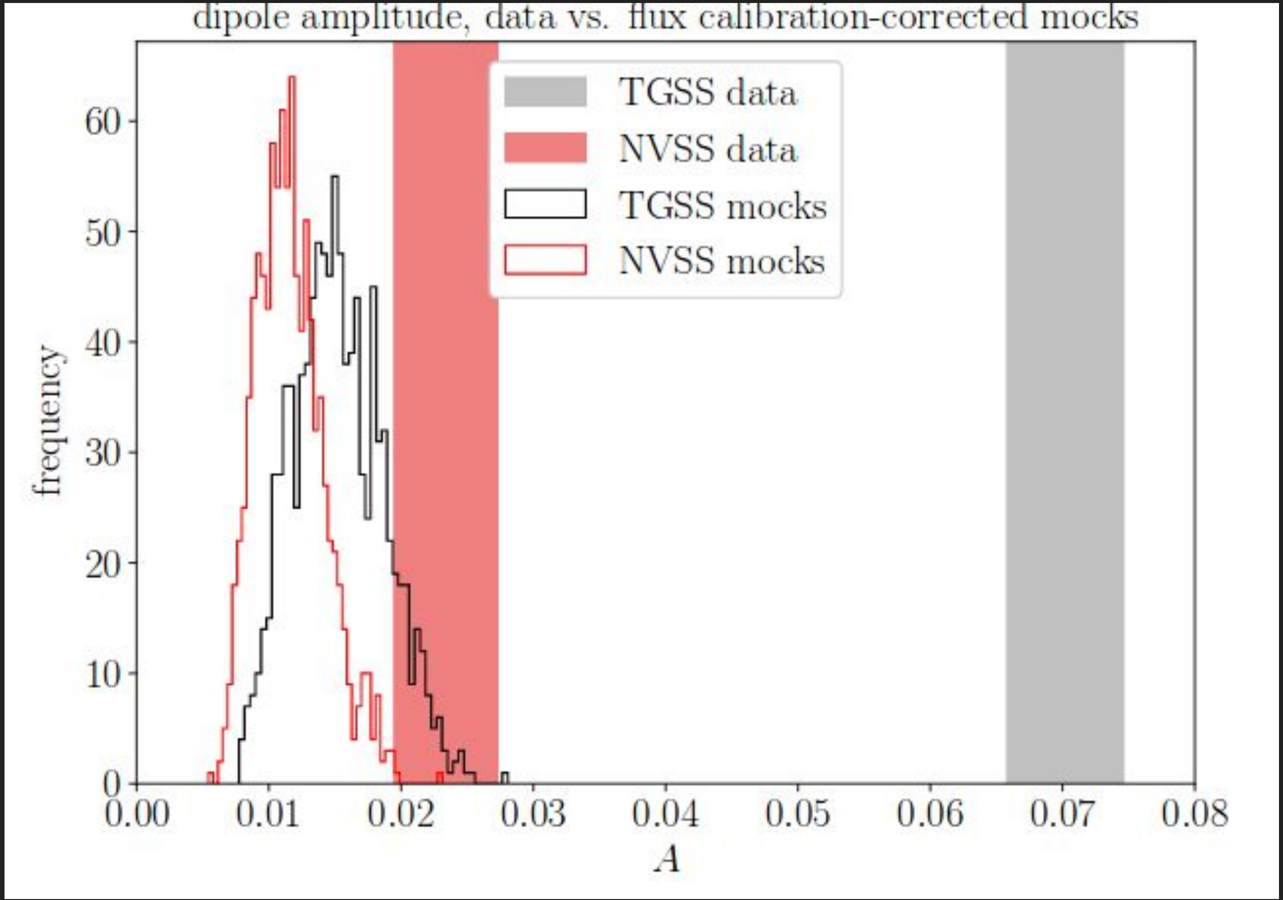


What happens in smaller angular scales?

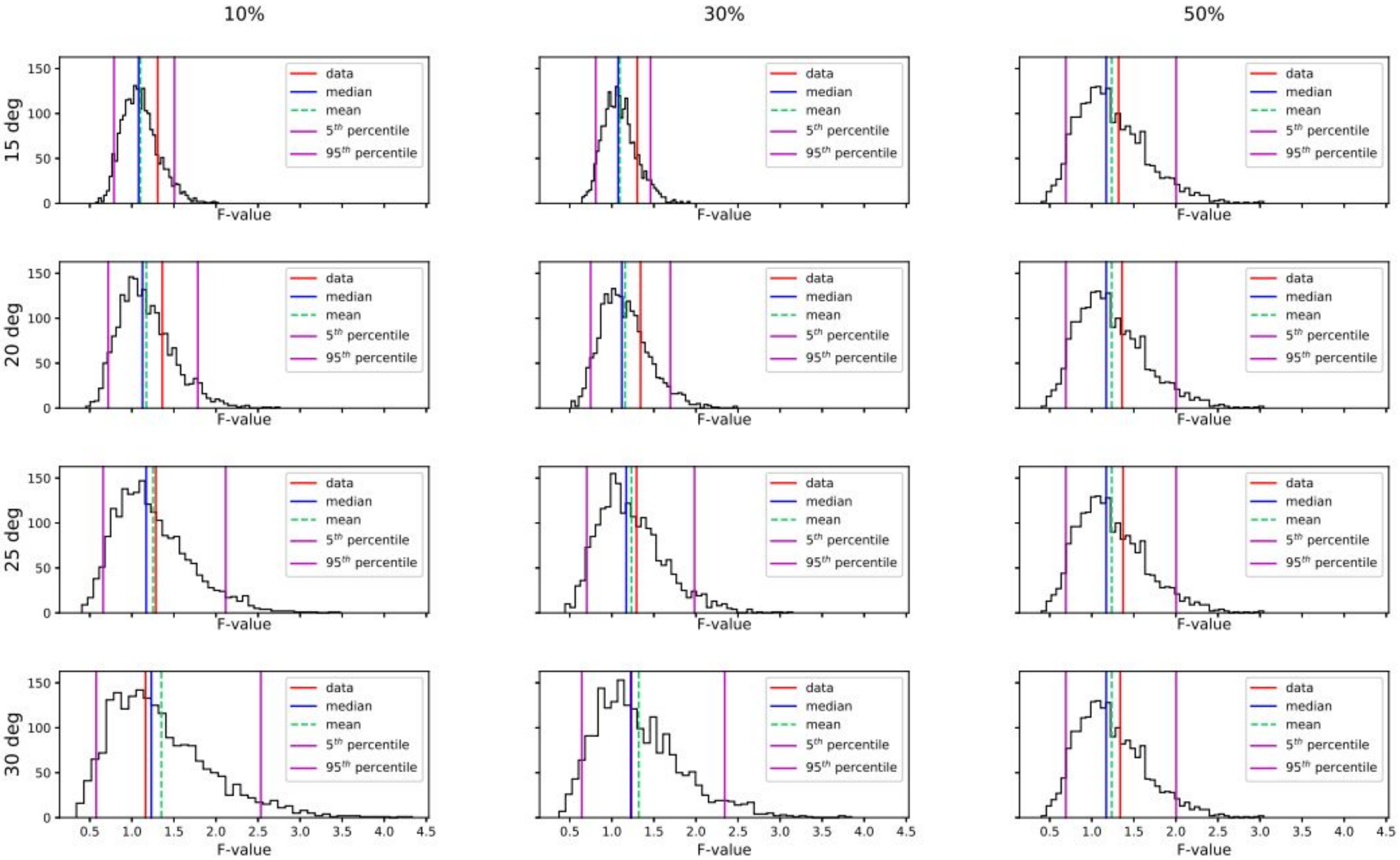
CB, Maartens, Randriamiarinarivo, Baloyi

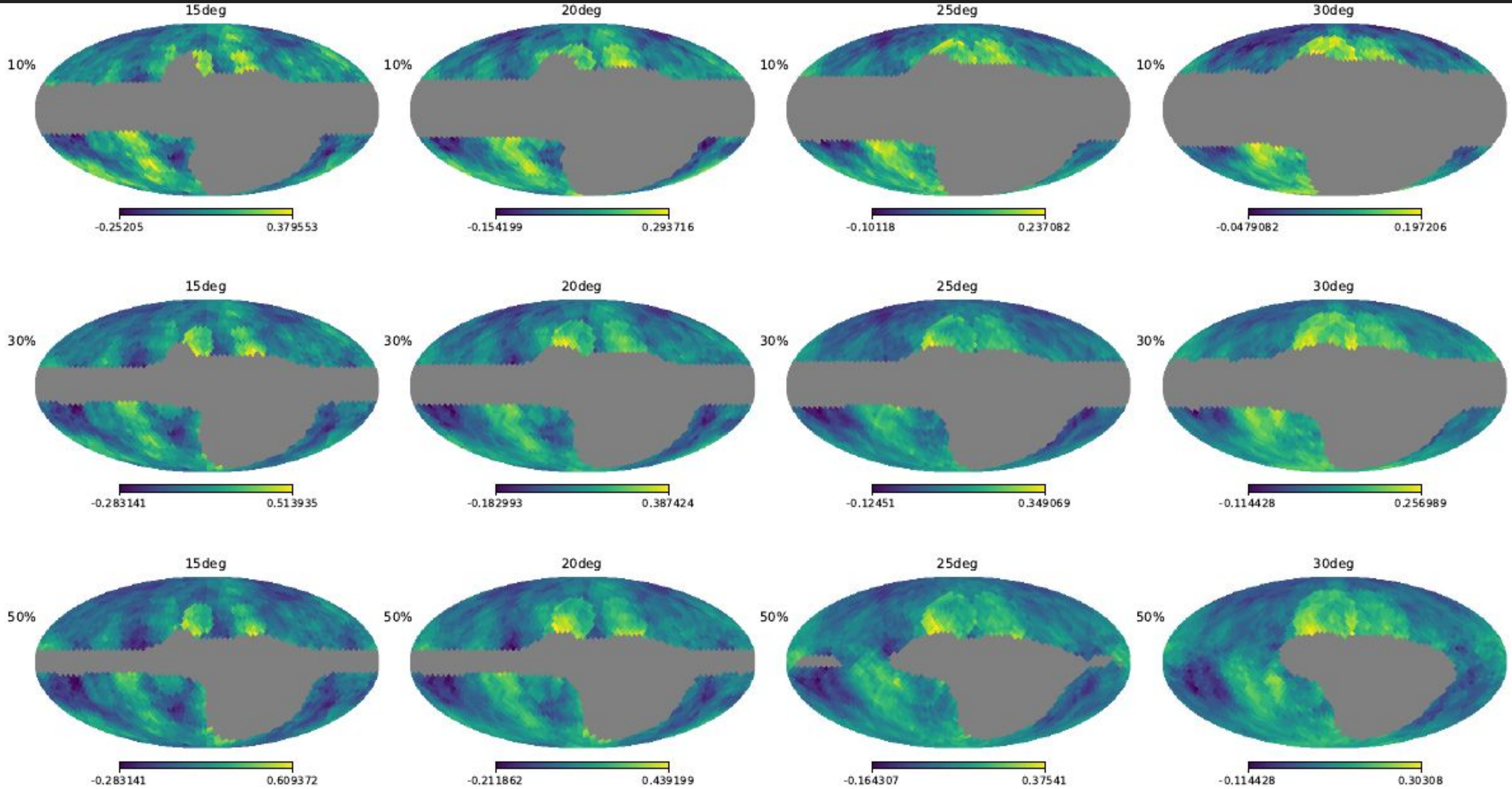
JCAP 09 (2019) 025
e-Print:1905.12378 [astro-ph.CO]

Observational data and estimator

- **Data:** Again we use the NVSS sample at 20<S<1000mJy, the mask built in Bengaly et al 2018 - minus an anomalous region within 5deg of (l,b)=(207.13,-17.84) - and mock realisations following the same prespection as well

- **Estimator:**
  - we draw patches in the sky of 15,20,25,30 deg size and compute the source count variance inside it;
  - patches with 10, 20 or 30% masked pixels are eliminated
  - ANOVA test - variance between patches/variance within patches > 1 indicates exact isotropy
  - a local variance map comparing variance of data x variance of mocks (see Alonso et al. 2014; Akrami et al. 2014)


10%
30%
50%
15 deg
20 deg
25 deg
30 deg
F-value
data
median
mean
5th percentile
95th percentile
0
50
100
150
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5


15deg
20deg
25deg
30deg
10%
-0.25205
0.379553
-0.154199
0.293716
-0.10118
0.237082
-0.0479082
0.197206
30%
-0.283141
0.513935
-0.182993
0.387424
-0.12451
0.349069
-0.114428
0.256989
50%
-0.283141
0.609372
-0.211862
0.439199
-0.164307
0.37541
-0.114428
0.30308

Conclusions

- No evidence against statistical isotropy in NVSS source counts at scales smaller than 25 degree
- Only the NVSS dipole seems to be anomalous, not smaller scales. This was confirmed in later analysis (Dolfi+ 2019; Ghosh+ 2019, Siewert+ 2020)
- In contrast with TGSS counts that are anomalous at >10deg. Flux calibration seems to be the main issue in TGSS (Ghosh+ 2019)
- Large dipole anisotropy also seen in mid-IR AGNs (Secrest+ 21, Singal 21)
- SKA will be able to perform a precision test of cosmic isotropy (CB+ 19)

The scale of cosmic homogeneity with SDSS-IV DR16 QSOs

Gonçalves, G. Carvalho, Andrade, CB, J. Carvalho, Alcaniz

JCAP 03 (2021) 029

e-Print: 2010.06635 [astro-ph.CO]

How can we probe the homogeneity scale?

- Homogeneity cannot be directly tested - consistency tests are possible

- A practical test: compute the fractal dimension of the spatial distribution of cosmic objects (Pietronero 1987, Coleman & Pietronero 1992)

- We expect $D2 \rightarrow 3$ if the Universe is statistically homogeneous - thus indistinguishable from a random distribution. In smaller scales, the Universe is lumpier, thus $D2 < 3$

- The scale where $D2 \simeq 3$ is considered the scale of cosmic homogeneity. Absence of such transition scale would hint at a departure of the CP

THE FRACTAL STRUCTURE OF THE UNIVERSE - CORRELATIONS OF GALAXIES AND CLUSTERS AND THE AVERAGE MASS DENSITY

L PIETRONERO*

*Corresponding author for this work

University of Groningen

Research output: Contribution to journal › Article › Academic › peer-review

Method and data analysis

- We use the latest release (DR16) of SDSS-IV QSOs

- We bin the data into two ranges: [2.2,2.4] and [2.5,3.2], comprising ~19k objects each

- We compute the integral correlation and fractal dimension of QSOs spatial distribution following

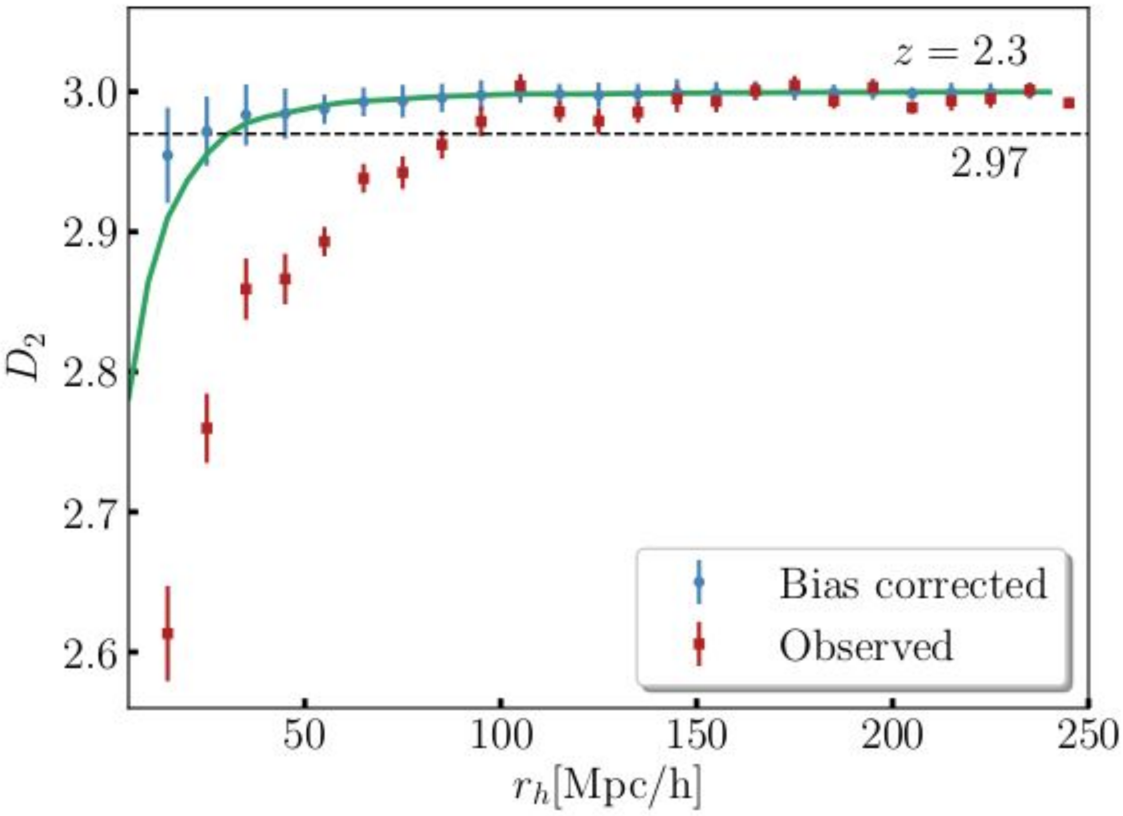
$$\mathcal{N}(<r) \equiv \frac{\sum_{\rho=0}^{r} DD(\rho)}{\sum_{\rho=0}^{r} RR(\rho)} \qquad D_2(r) \equiv \frac{d \ln \mathcal{N}(<r)}{d \ln r} + 3 \,.$$

  where $DD(\rho)$ and $RR(\rho)$ stand for the 2pcf of the data and the random catalogues

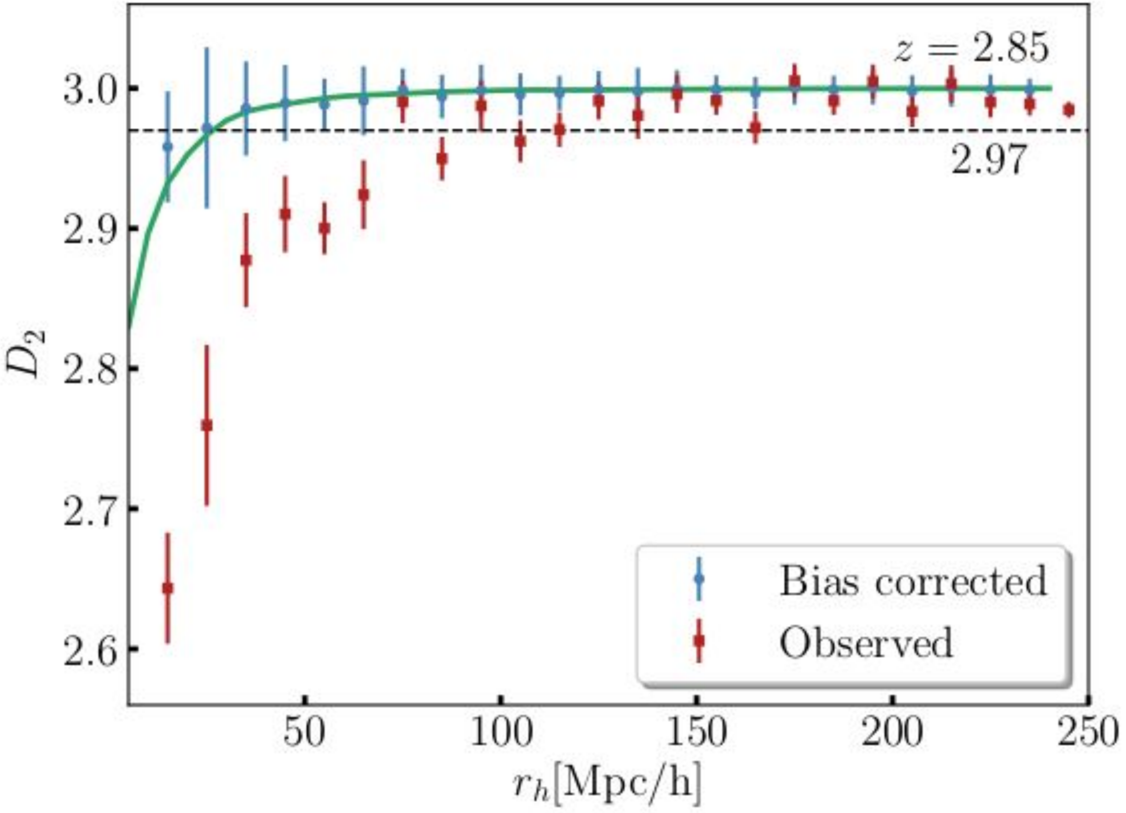
- We compare the observational results with theoretical predictions of the SCM

$$\mathcal{N}_{\rm th}(<r, \bar{z}) = \frac{3}{4\pi r^3} \int_0^r (1 + \xi(s, \bar{z})) 4\pi s^2 ds \qquad D_2^{\rm th}(r) \equiv \frac{d \ln \mathcal{N}_{\rm th}(<r)}{d \ln r} + 3$$

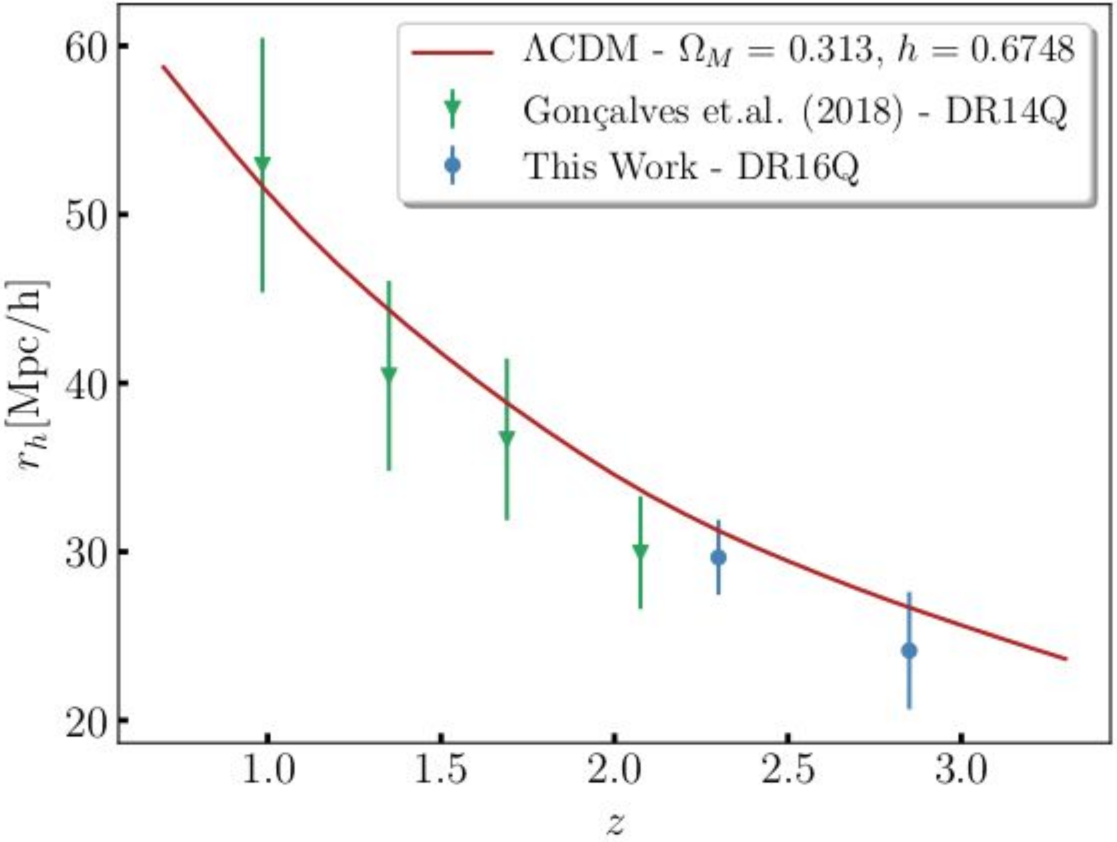
Obs: we de-bias the observational D2 according to $D_2^{\rm m}(r) = \frac{D_2^{\rm q}(r) - 3}{b^2} + 3 \,,$



$z = 2.3$
2.97
D_2
r_h[Mpc/h]
3.0
2.9
2.8
2.7
2.6
50
100
150
200
250
Bias corrected
Observed



$z = 2.85$
2.97
D_2
r_h[Mpc/h]
Bias corrected
Observed
3.0
2.9
2.8
2.7
2.6
50
100
150
200
250


ΛCDM - $\Omega_M = 0.313$, $h = 0.6748$
Gonçalves et.al. (2018) - DR14Q
This Work - DR16Q
60
50
40
30
20
r_h[Mpc/h]
1.0
1.5
2.0
2.5
3.0
z

Part II:
Null tests of the standard model with current and future observations

Om diagnostic: a null test of the flat LCDM

CB, Clarkson, Kunz, Maartens

Phys. Dark Univ. 33 (2021) 100856,
e-Print: 2007.04879 [astro-ph.CO]

Work outline

- We produce H(z) simulations following next-gen surveys specs: Euclid, DESI, SKA intensity mapping band 1 and 2 (SKA B1 and B2)

- Null tests of the flat LCDM model - violations of these conditions rule out the SCM

$$E(z) = H(z)/H_0 \qquad \mathcal{O}_{\rm m}(z) \equiv \frac{E(z)^2 - 1}{(1+z)^3 - 1} = \Omega_{\rm m}$$

$$\mathcal{L}_{\rm m}(z) \equiv 3(1+z)^2\left[1 - E(z)^2\right] + 2z(3 + 3z + z^2)E(z)E'(z) = 0$$

- We reconstruct E(z) using a non-parametric method called Gaussian Processes, as available the GaPP code (Seikel+ 12, https://github.com/astrobengaly/GaPP)

- We also simulate H(z) assuming other models to assess the test performance

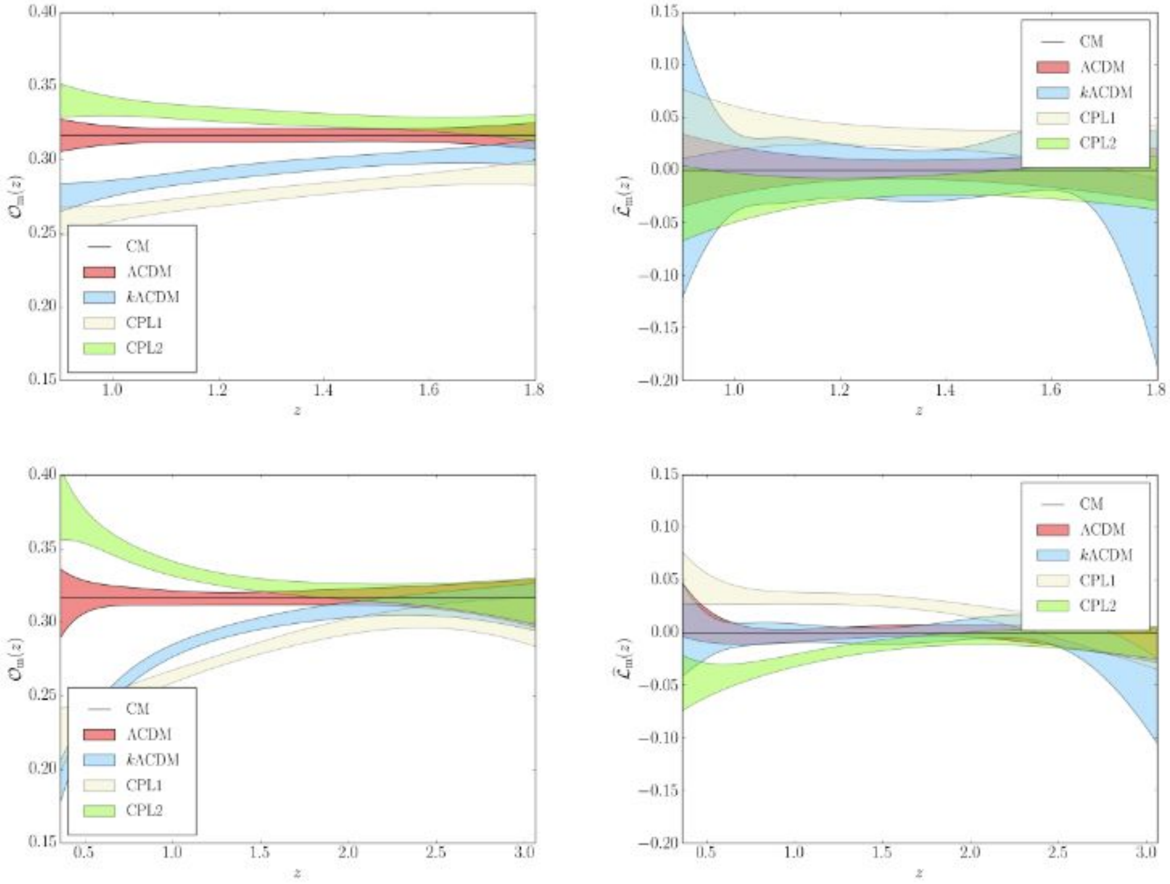


FIG. 1. $\mathcal{O}_{\rm m}$ (left) and $\mathcal{L}_{\rm m}$ (right) null tests, for Euclid-like (top) and SKA-like B1 (bottom) surveys. Shaded regions show 5σ ($\mathcal{O}_{\rm m}$) and 3σ ($\mathcal{L}_{\rm m}$) CL for the reconstructed mean. $\widehat{\mathcal{L}}_{\rm m}(z) \equiv \mathcal{L}_{\rm m}(1+z)^{-6}$ is used rather than $\mathcal{L}_{\rm m}$ to improve visualisation.

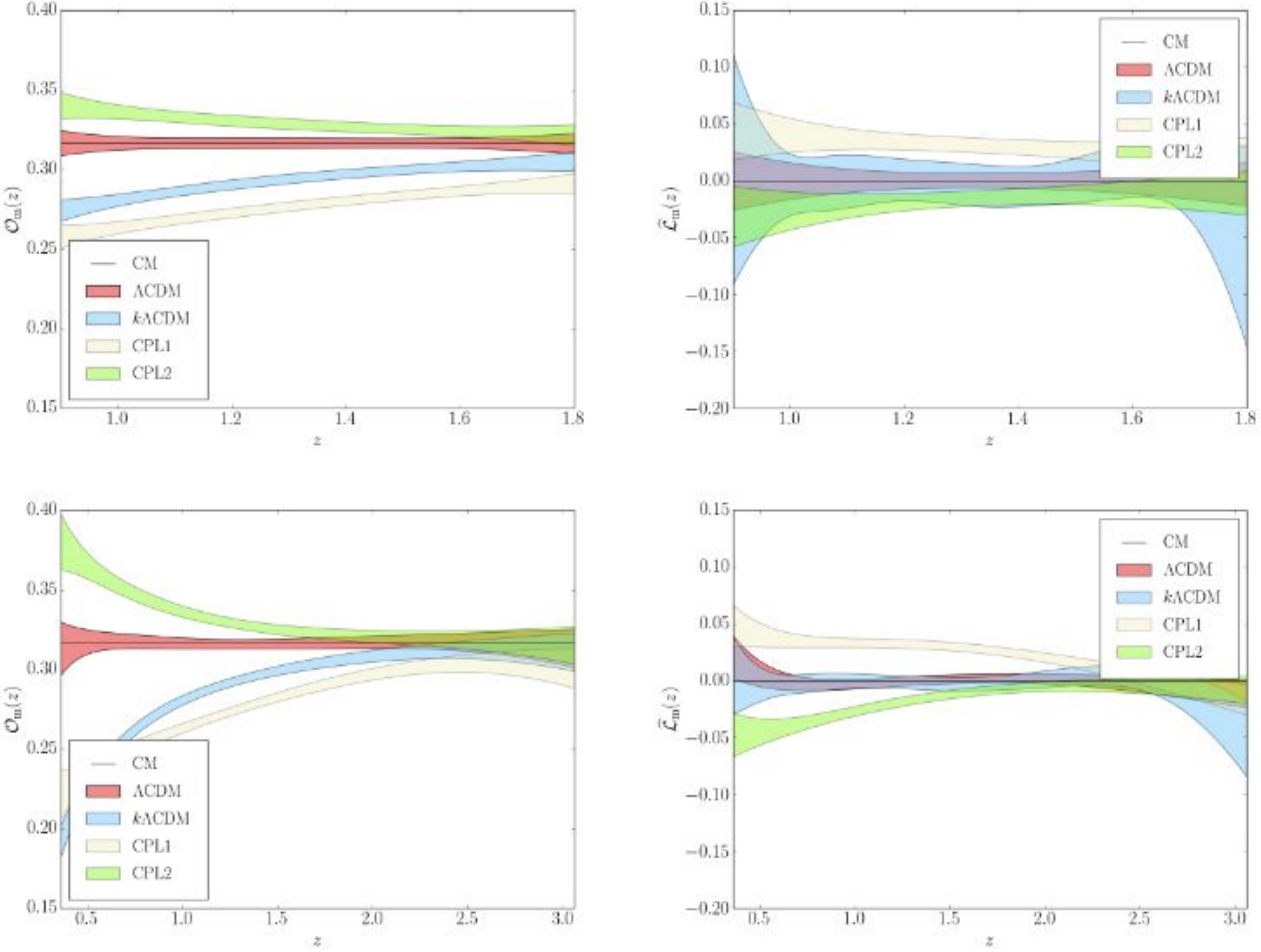


FIG. 2. Same as Fig. 1, but with $H(z)$ measurement uncertainties reduced by 30%.

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

Gabriel Rodrigues, CB

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

Data and method

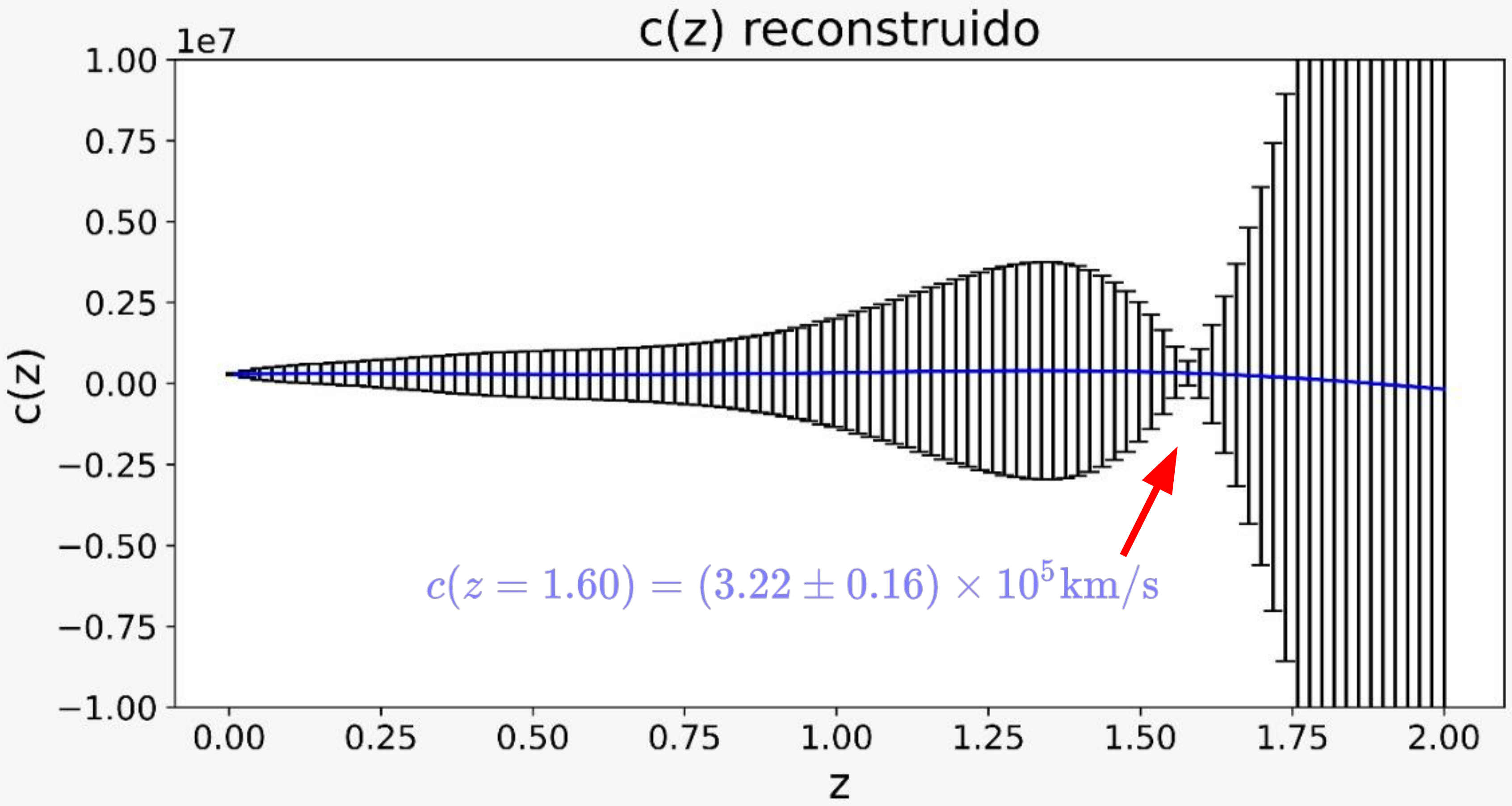
- The angular diameter distance is given by $D_A(z) = \frac{1}{(1+z)} \int_0^z \frac{cdz}{H(z)}$
- Therefore, differentiating the equation above w.r.t the redshift reads

$$\frac{\partial}{\partial z}[(1+z)D_A(z)] = \frac{c(z)}{H(z)}$$

- 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



c(z) reconstruido
1e7
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
c(z)
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
z
$c(z = 1.60) = (3.22 \pm 0.16) \times 10^5 \mathrm{km/s}$

Miscellaneous stuff

- We found that Euclid and SKA will be able to measure H0 at almost percent-level precision, and probe cosmic acceleration with (5-7)σ cl in a model-independent way (CB, Clarkson, Maartens JCAP 2020; CB MNRAS 2020)

- We found no evidence for a hotter Universe that could solve cosmological tensions using T(z) measurements from clusters (CB, Gonzalez, Alcaniz EPJC 2020), and no evidence for SN absolute magnitude evolution (Sapone, Nesseris, CB PDU 2021)

- Measurements of the angular scale of homogeneity (model-independent!) with SDSS-IV DR16 LRG in good agreement with predictions from the SCM (Andrade+ in prep.)

Concluding remarks and perspectives

Concluding remarks and perspectives

- Current radio continuum observations can only probe the Cosmological Principle, with limited precision. Surveys like EMU, LOFAR, SKA shall enormously improve these results

- The spatial distribution of SDSS-IV DR16 QSOs exhibits a characteristic scale of cosmic homogeneity in agreement with the foundations of the standard model

- Future redshift surveys such as Euclid and SKA can perform null tests of the standard model with unprecedented precision without any prior assumption about the underlying Cosmology

- As for data available today, we are able to measure the speed of light with 5% precision at z=1.58, and confirm the FLRW assumption at a 2

Take-home message:

We are living an exciting and transformational era in Cosmology, where we can determine cosmological parameters and the fundamental assumptions of Cosmology with percent-level precision!

Obrigado!

Complimentary slides

Delta diagnostic: a null test of the cosmic acceleration

CB, Gonzalez, Von Marttens, Alcaniz

(In prep - ALL RESULTS ARE PRELIMINARY!)

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

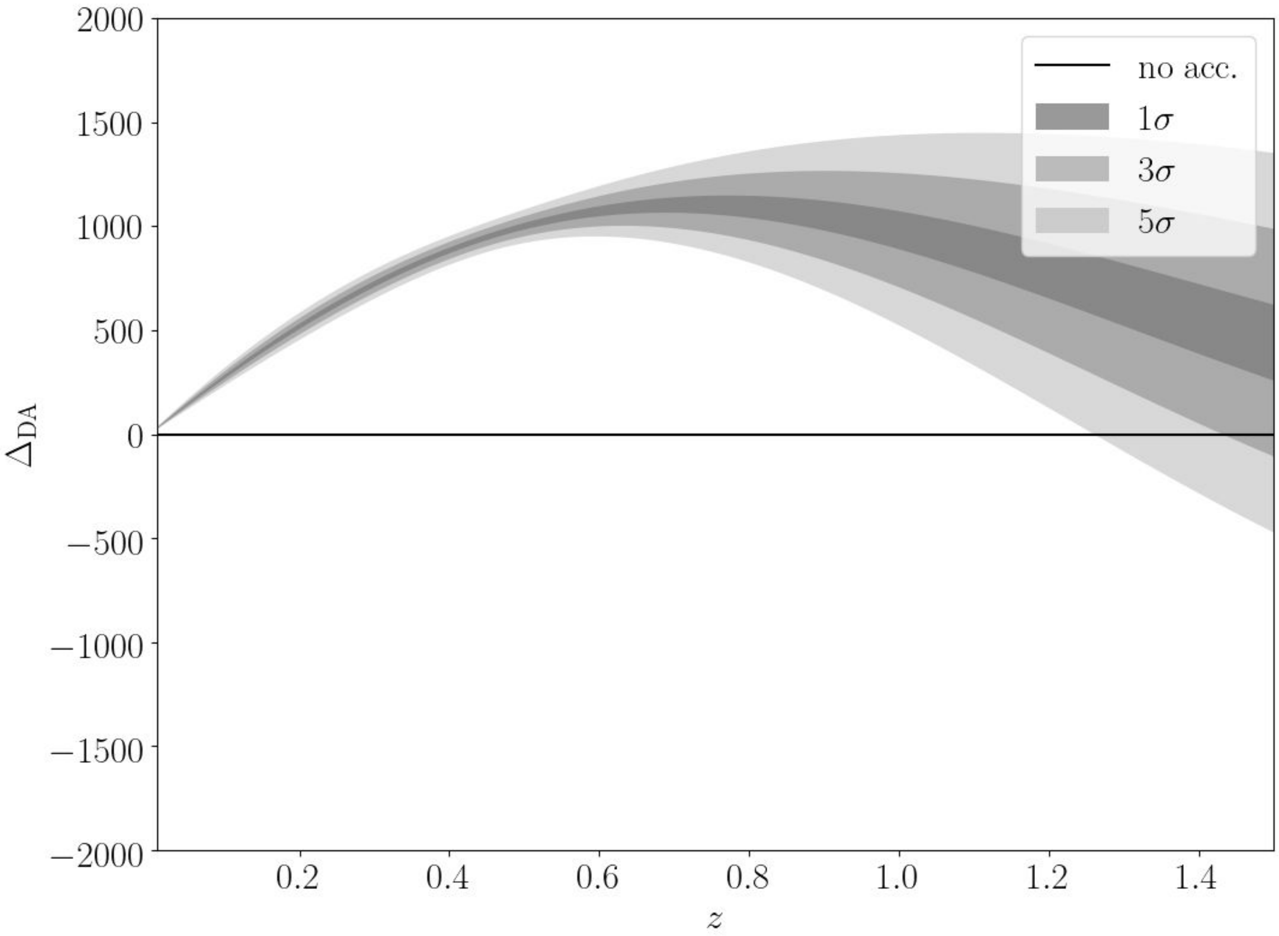
- A null test for cosmic acceleration (Seikel & Schwarz 08)

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

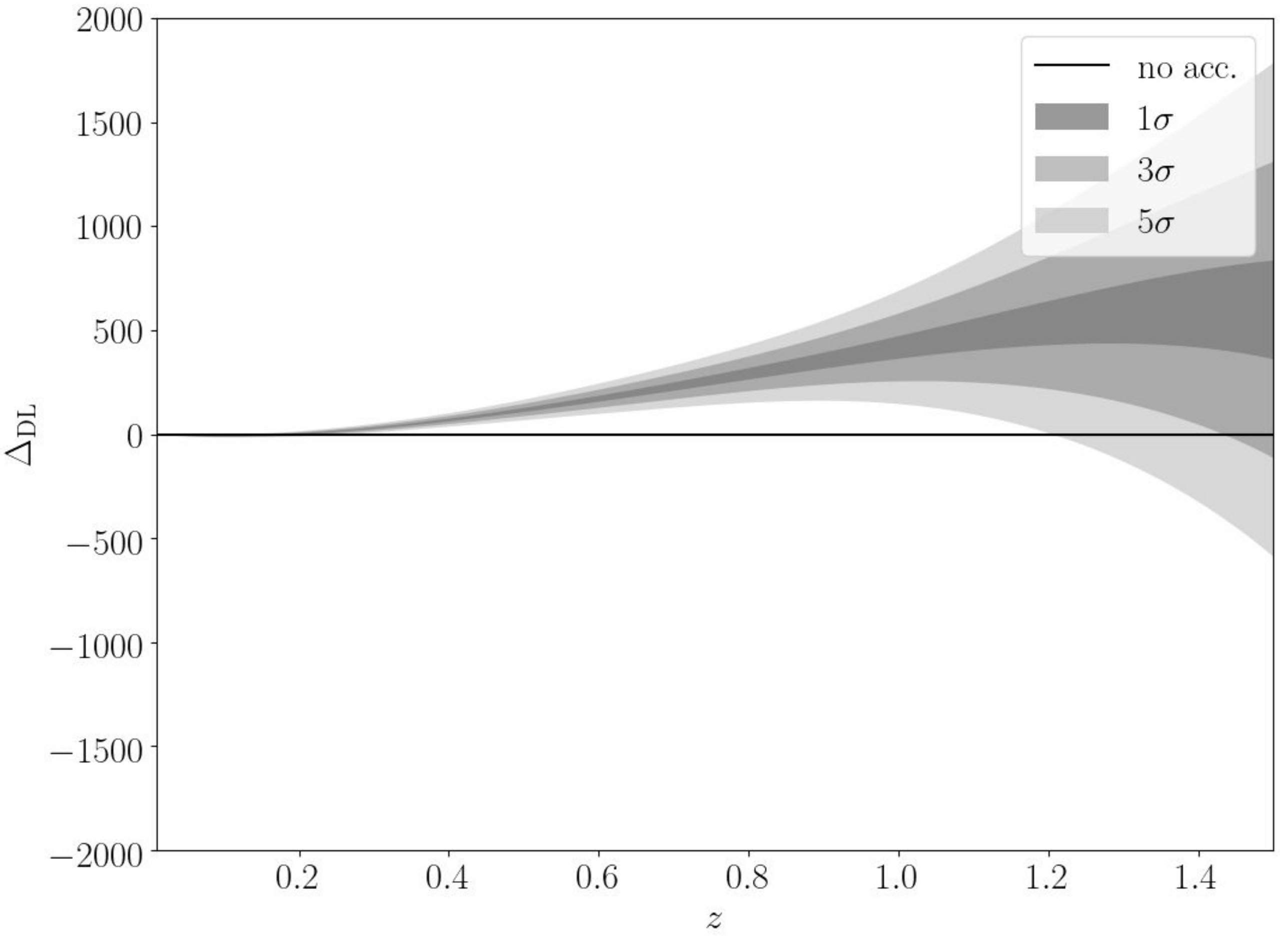
Therefore $D_C(z) \leq (c/H_0) \log(1+z)$ if the Universe never accelerated

- Delta diagnostic: $\Delta \equiv O_{\rm obs}(z) - O_{q\geq 0}(z) \geq 0$ (O_obs = DA, DL, H(z) etc)

- We perform this test with SNe and transversal BAO mode using the GP reconstruction from GaPP



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

Part II:

Probing the current temperature of the CMB and the absolute magnitude of SNe

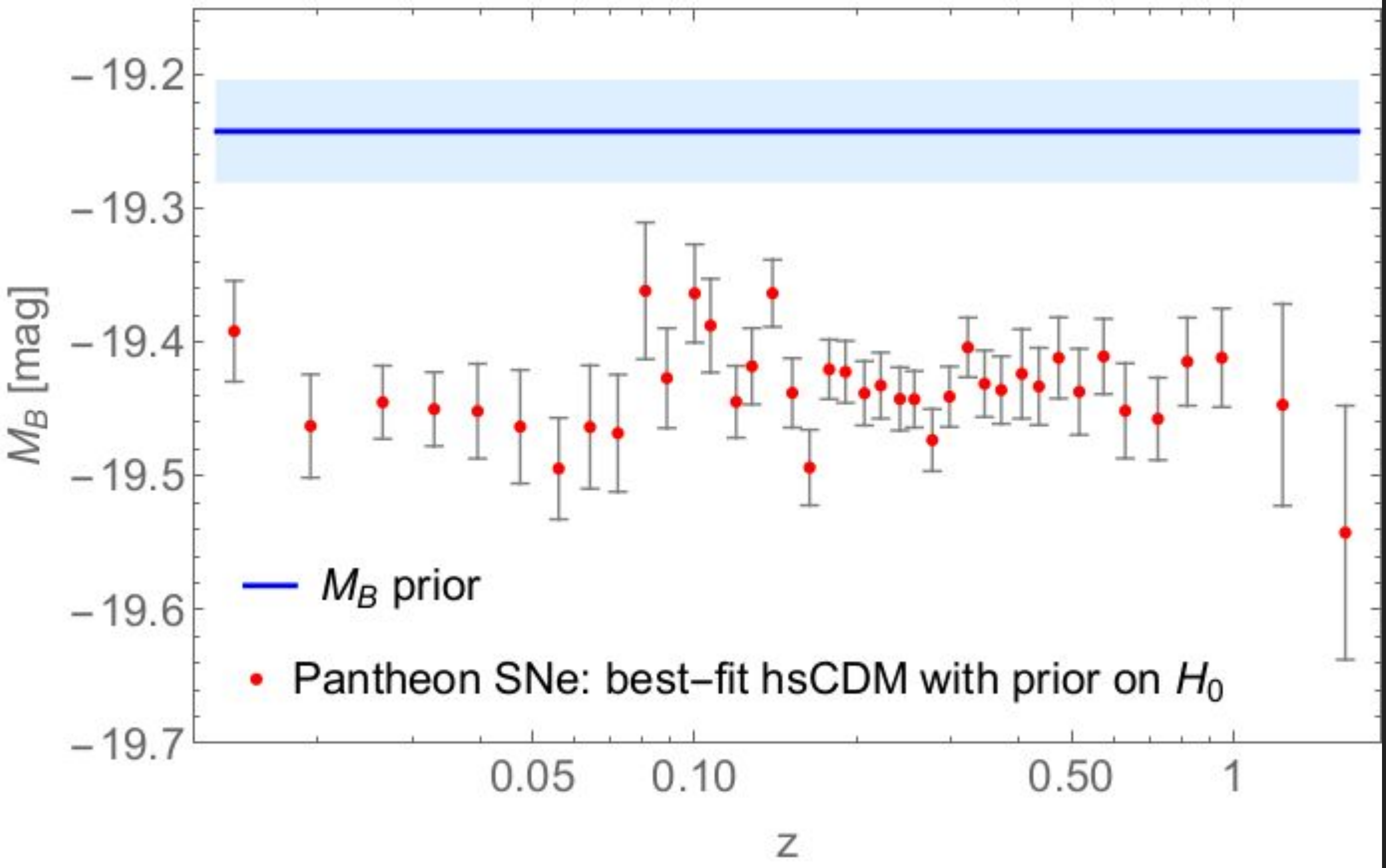
Motivation

- We know that the CMB behaves as a nearly perfect black body with T0 = 2.73K. FIRAS measured this value with extremely high precision 3 decades ago: T0 = 2.72548 +- 0.00057 (1σ)

- We also know that the SNe can be used as reliable standardisable candles

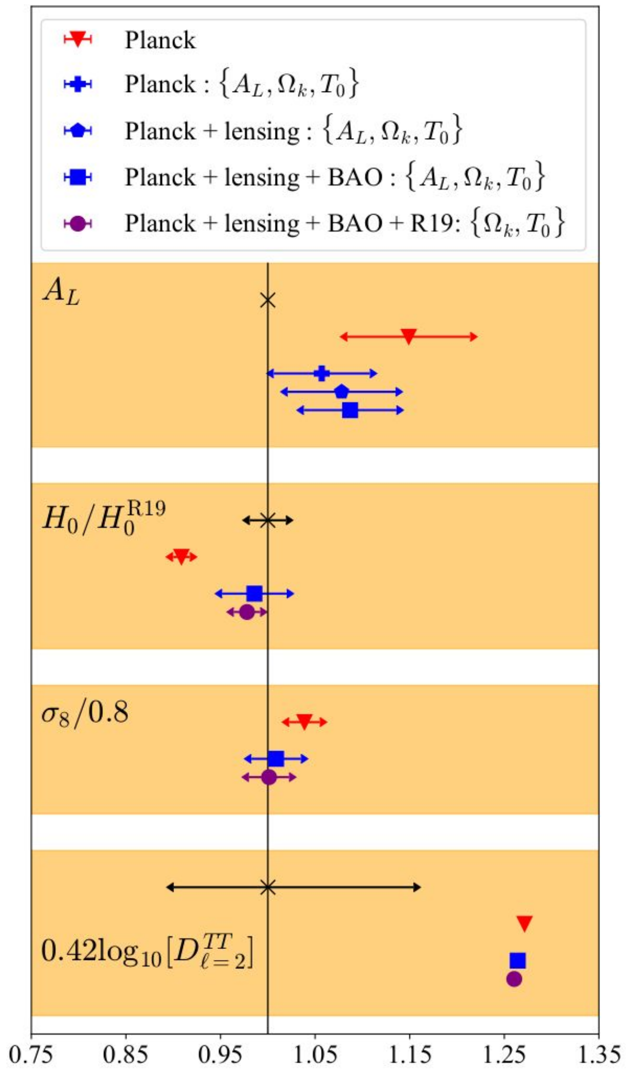
- However…
  - A hotter and open Universe is able to solve the H0 and σ8 tension, besides some CMB features i.e. the low quadrupole power (Bose and Lombriser 2021)
  - Pantheon SNe absolute magnitude is not compatible with SH0ES measurement (3.8σ-4.4σ) - strongly related to the H0 tension. (Camarena and Marra 2021)

- We shall revisit the T0 measurements and the constancy of Mabs - departures from standard values may hint at new physics!



Credits: Camarena and Marra

MNRAS 504 (4), 5164-5171 (2021)



Credits: Bose and Lombriser
Phys. Rev. D 103, 081304 (2021)

Is there evidence for a hotter Universe?

- We use measurements of $T(z)$ to obtain $T0$ using parametric and non-parametric approaches

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- We use measurements of T(z) to obtain T0 using parametric and non-parametric approaches

- Data:
  - primary: 103 SZ measurements within the redshift interval $0.01 < z < 0.97$
  - comb1: 12 T(z) measurements within the range $0.13 < z < 1.02$ along with 18 T(z) measurements in the interval $0.03 < z < 0.97$
  - comb2: 13T(z) measurements in the range $0.02 < z < 0.55$ combined with the 18 T(z) measurements mentioned above

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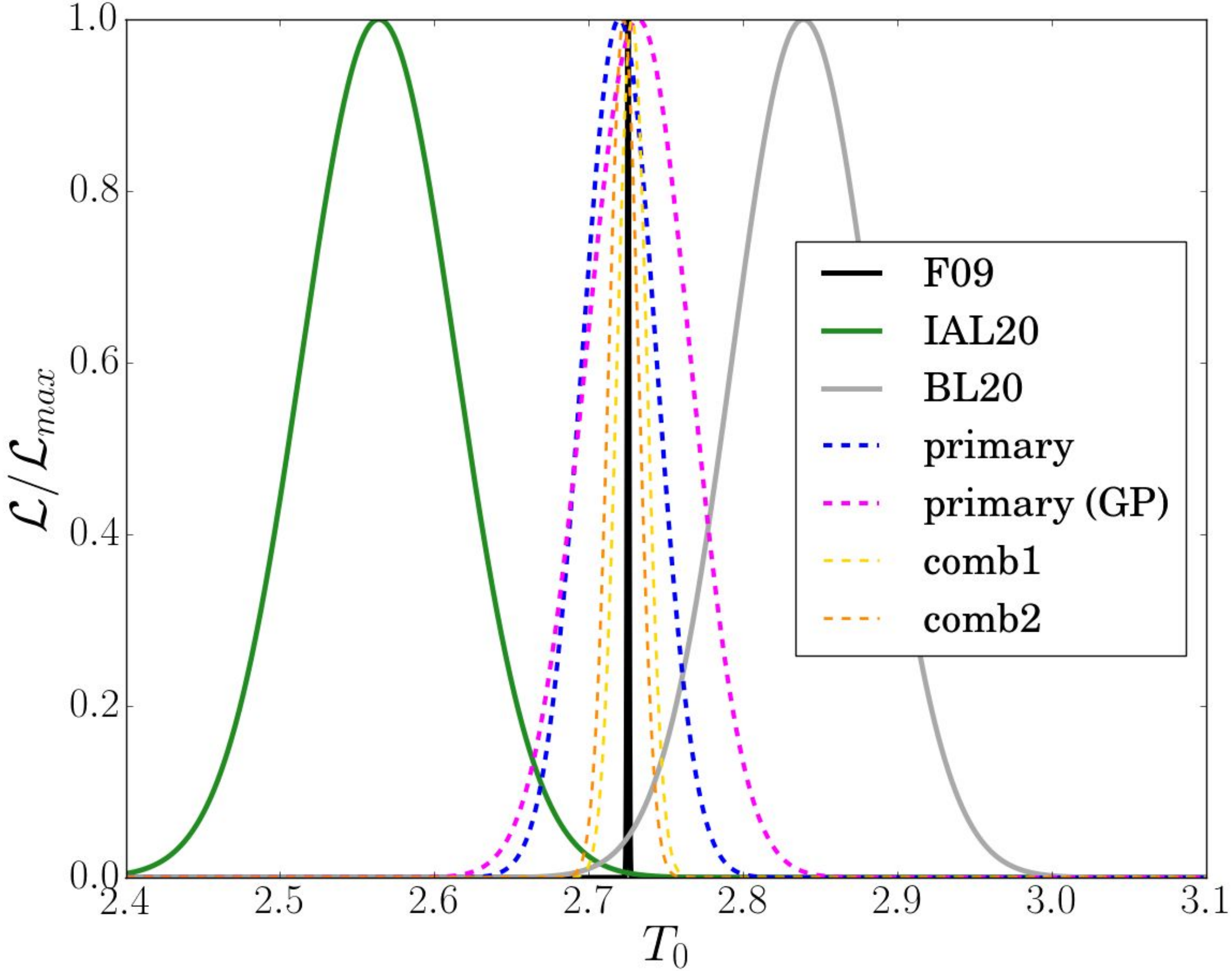
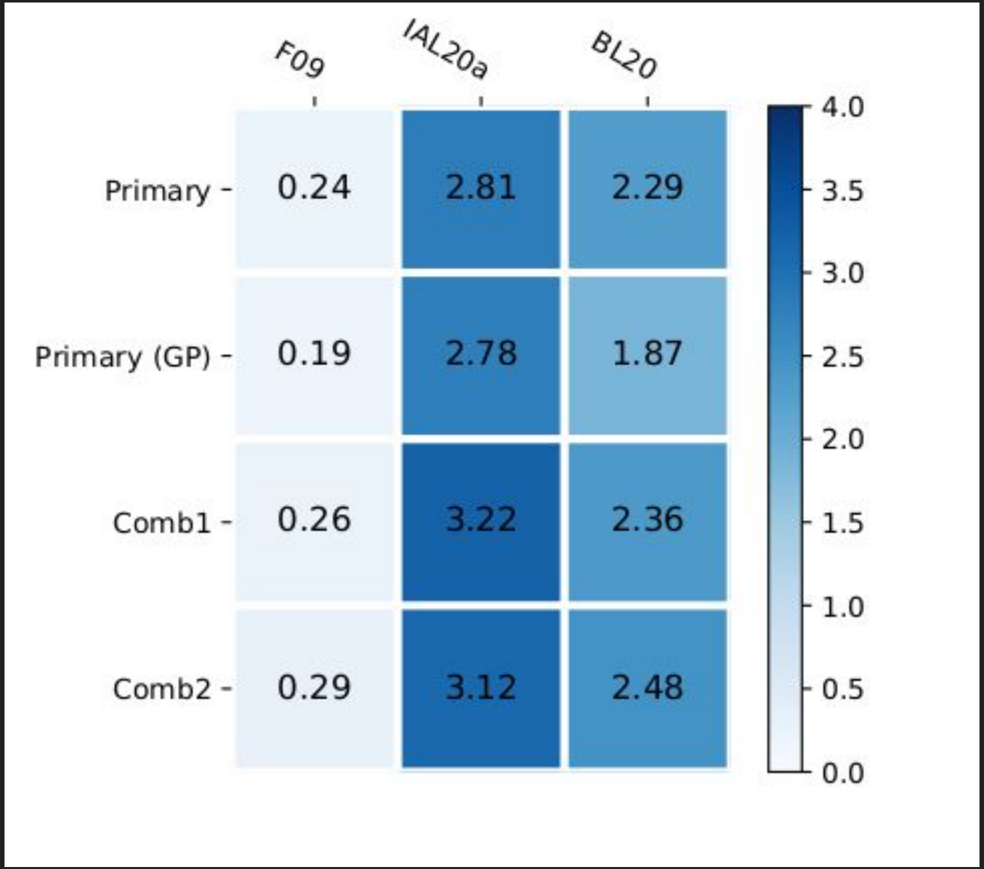
  - comb2: 13T(z) measurements in the range 0.02<z<0.55 combined with the 18 T(z) measurements mentioned above

- We compare our measurements with those in the literature
  T0 = 2.72548 +- 0.00057 (F09)
  T0 = 2.564 +- 0.050 (IAL20)
  T0 = 2.839 =- 0.046 (BL20)

$$\mathcal{T} = \frac{|T_{0,exp1} - T_{0,exp2}|}{\sqrt{\sigma^2_{exp1} + \sigma^2_{exp2}}}$$



CB, Gonzalez, Alcaniz
EPJC 80 (2020) 10, 936



Discrepancy between different T0 measurements

CB, Gonzalez, Alcaniz

EPJC 80 (2020) 10, 936

Is there any measurable redshift dependence on the SN Ia absolute magnitude?

- There are recent claims that SNe Mabs may exhibit redshift evolution due to host galaxy mass and morphology, besides stellar population age (Kang+ ApJ 2020; Lee+ 2020)

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- Such Mabs evolution could mimic dark energy. If this is true, SNe would not be able to underpin the evidence for late-time cosmic acceleration! (see Mohayee, Rameez, Sarkar (e-Print: 2106.03119)

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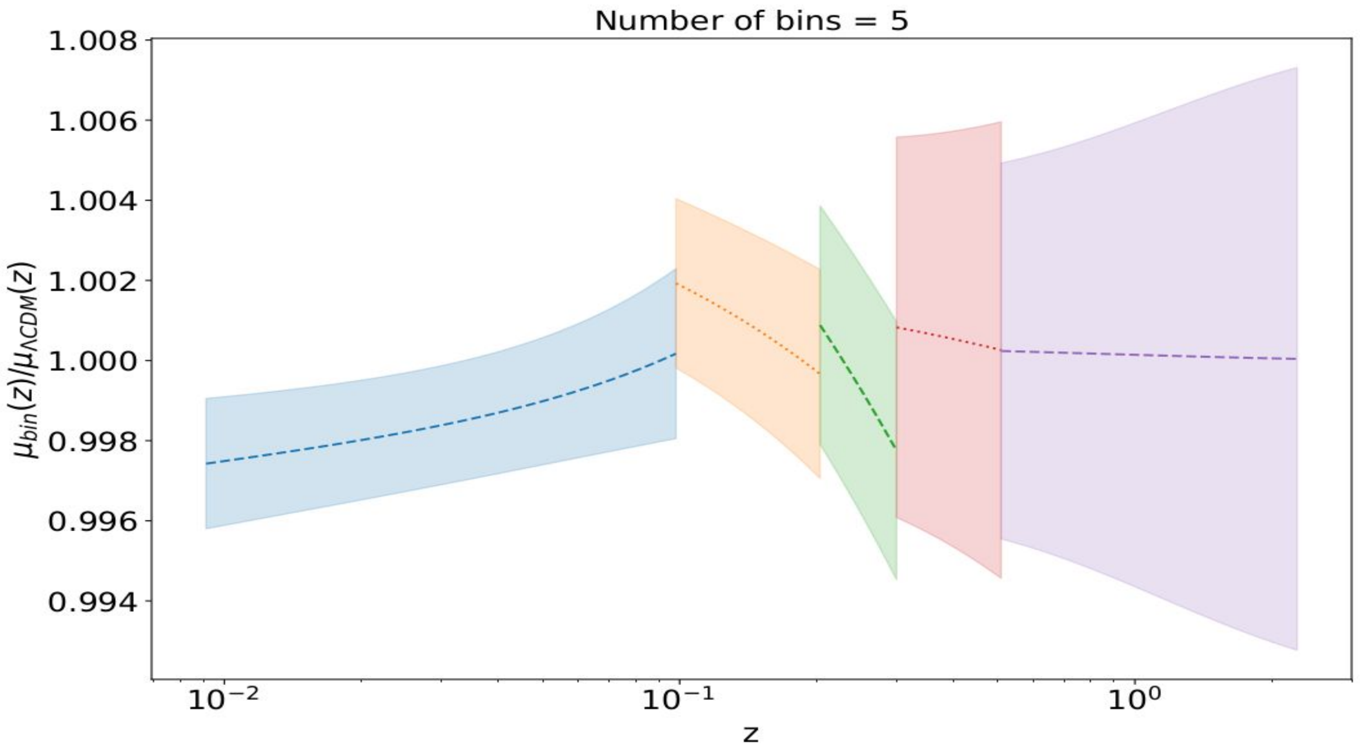
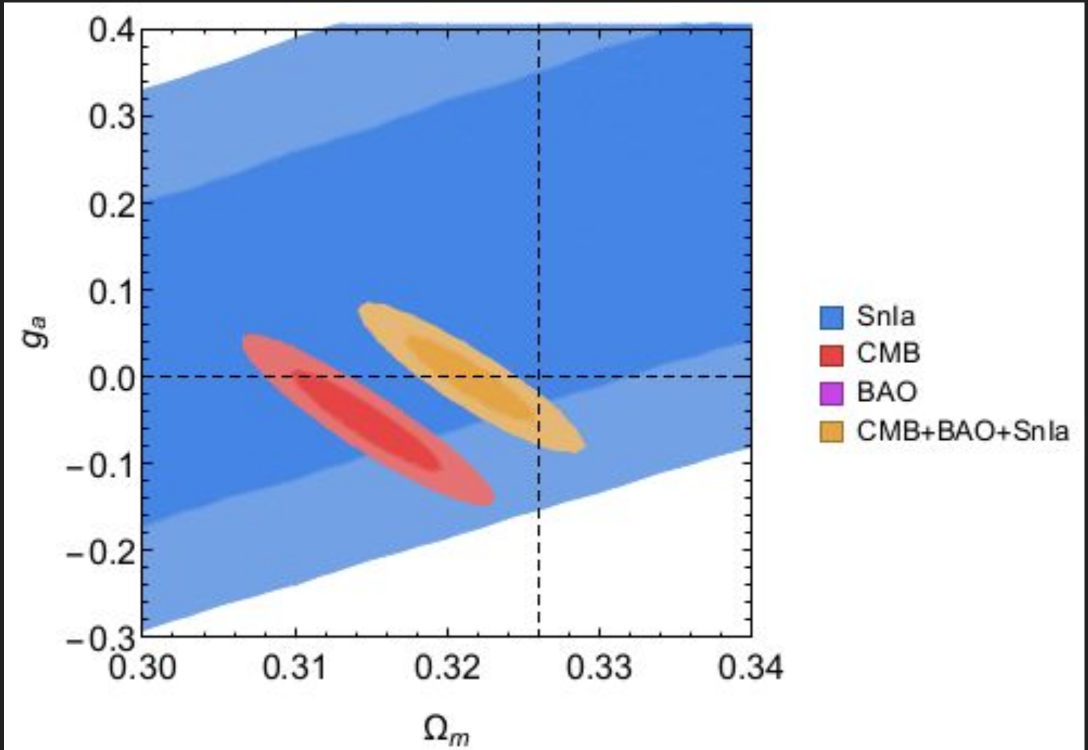
- Such Mabs evolution could mimic dark energy. If this was true, SNe would not be able to underpin the evidence for late-time cosmic acceleration - see Mohayee, Rameez, Sarkar (e-Print: 2106.03119)

- Goal: Measure the Mabs of Pantheon SNe compilation using several approaches:
  - Direct Mabs fit in different redshift bins
  - different parametrisations of M(z) = M0 + M1 * f(z)
  - modified gravity: M(z) = M0 + (15/4)log(Geff/Gn), Geff/Gn = 1+ga[z/(1+z)]^n
  - LTB model



Sapone, Nesseris, CB *Phys.Dark Univ.* 32 (2021) 100814



Sapone, Nesseris, CB

Phys.Dark Univ. 32 (2021) 100814

	$\mathcal{M}_0$	$\mathcal{M}_1$	$\Omega_{m,0}$	α	χ^2_{min}
Λ	-1.191 ± 0.011	0	0.299 ± 0.022	-	1025.6
M1	-1.194 ± 0.020	0.061 ± 0.381	0.299 ± 0.064	-	1025.6
M2	-1.190 ± 0.013	-0.474 ± 0.177	0.032 ± 0.069	-	1024.9
M3	-1.192 ± 0.016	0.031 ± 0.462	0.311 ± 0.188	1	1025.6
$\overline{\textbf{M3}}$	-1.195 ± 0.012	1.204 ± 0.055	1	1	1025.9
M4	-1.193 ± 0.570	0.001 ± 0.579	0.298 ± 0.287	-1	1025.6

TABLE II: The best fit values for model 1 (**M1**), model 2 (**M2**), model 3 (**M3**) and model 4 (**M4**) allowing the absolute magnitudes $\mathcal{M}_0$ and $\mathcal{M}_1$ free. The model 3 ($\overline{\textbf{M3}}$) refers to **M3** where we fix $\Omega_{m,0} = 1$. The results have been obtained assuming flatness and fixing the dark energy equation of state $w = -1$. **Λ** refers to the ΛCDM model.

Sapone, Nesseris, CB
Phys.Dark Univ. 32 (2021) 100814

Conclusions

- We found no evidence for a hotter Universe that could solve H0 tension, and neither for evolution of SNe absolute magnitude

- However, the H0 and Mabs tensions still linger…

- Some possible solutions include:
  - a rapid Geff transition at $z < 0.01$ (Marra and Perivolaropoulos 21)
  - w-Mabs phantom transition at $z<0.1$ (Alestas, Kazantzidis and Perivolaroupoulos PRD 2021)
  - see more at Perivolaropoulos and Skaras review (e-Print: 2105.05208)

Part IV:
Cosmology: A search for two numbers revisited.
What can future redshift surveys tell about them?

01 FEBRUARY 1970 • page 34

Cosmology: A search for two numbers

Precision measurements of the rate of expansion and the deceleration of the universe may soon provide a major test of cosmological models

Allan R. Sandage

Mount Wilson and Palomar Observatories

Physics Today **23**, 2, 34 (1970); https://doi.org/10.1063/1.3021960

Part II: Searching for H0 and q0

- H0 and q0 need to be constrained with ~1% level precision in order to underpin the concordance model - or rule it out

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- H0 and q0 need to be constrained with ~1% level precision in order to underpin the concordance model - or rule it out

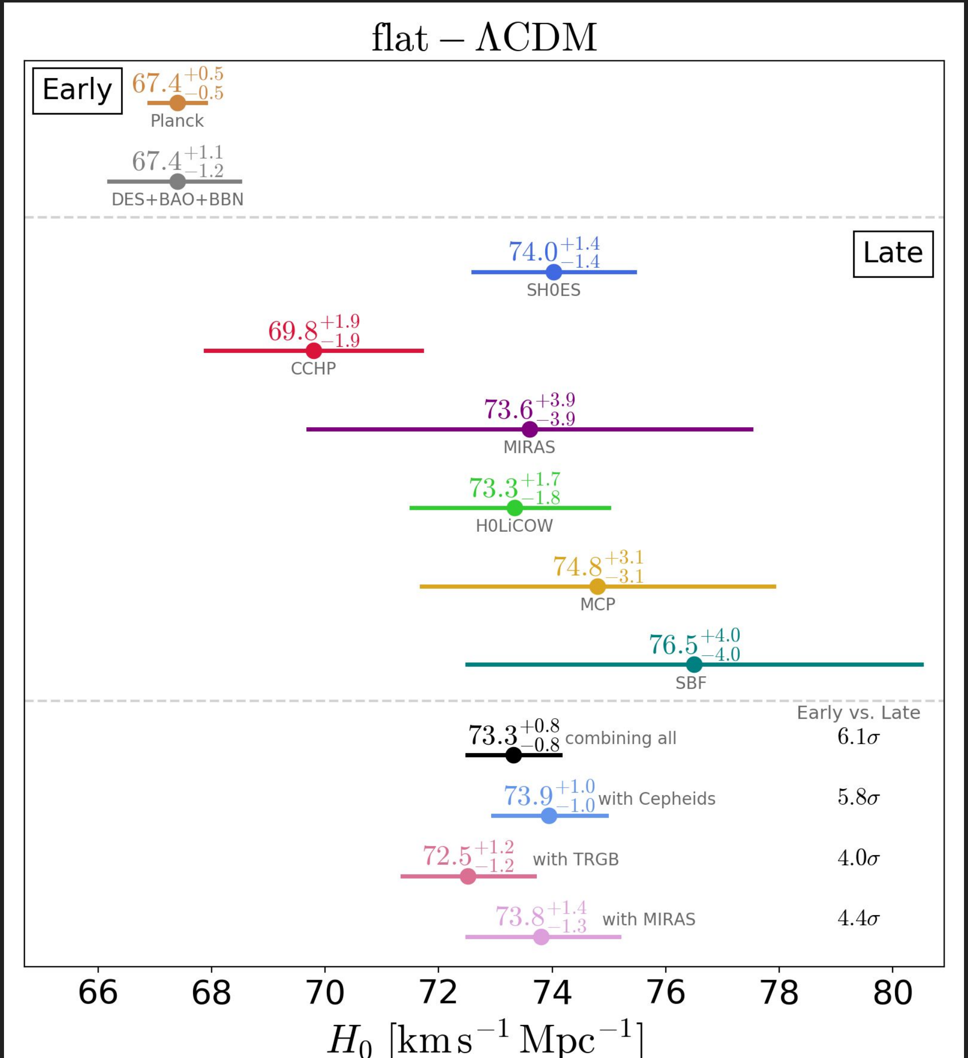
- Future redshift surveys like Euclid, SKA, DESI, J-PAS, will provide precise measurements of H(z) from the radial BAO mode

- Goal: forecast the constraints on H0 and q0 using H(z) data mimicking these surveys using a model-independent approach
  CB, Clarkson, Maartens, JCAP2020, CB MNRAS2020

The first number: H0

CB, Clarkson, Maartens

JCAP 05 (2020) 053
e-Print:1908.04619 [astro-ph.CO]



There is a persisting tension between early and late-Universe measurements of H0; Alternative dark energy models, or local underdensities, cannot easily solve this tension

Credits: Vivien Poulin [http://arxiv.org/abs/1907.10625]

Part IIa: The H0 tension with next-gen surveys

- How well can we measure H0 with future redshift surveys like SKA and Euclid?
- Model-independent approaches, as those based on non-parametric reconstructions, can tell H0 regardless of the cosmological model assumed
- If we can measure H0 down to a few per cent, we can tell early- and late-Universe H0 values apart at ~5sigma and solve this tension

Work Outline

- Simulate H(z) data following Euclid- and SKA-like (B1 and B2) surveys, with uncertainties taken from SKA1 red book (arxiv:1811.02743)

- Fiducial model based on Planck 2018 flat LCDM best-fit

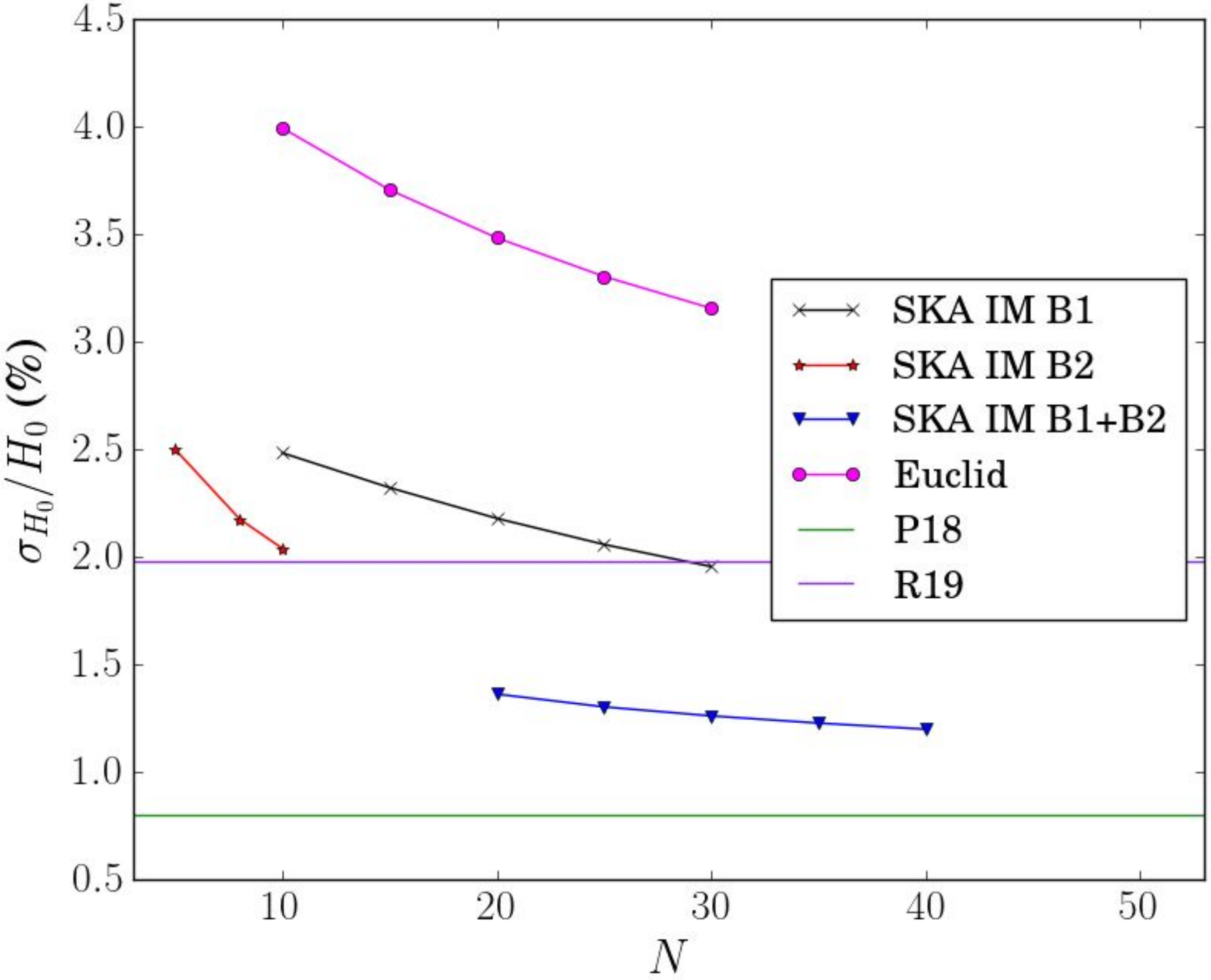
- Rather than forecasting H0 uncertainty using eg Fisher Matrix, we perform a non-parametric regression over the H(z) data points all the way to H(z=0) using Gaussian Processes GaPP code https://github.com/carlosandrepaes/GaPP
  Seikel, Clarkson & Smith JCAP 1206 (2012) 036

The method

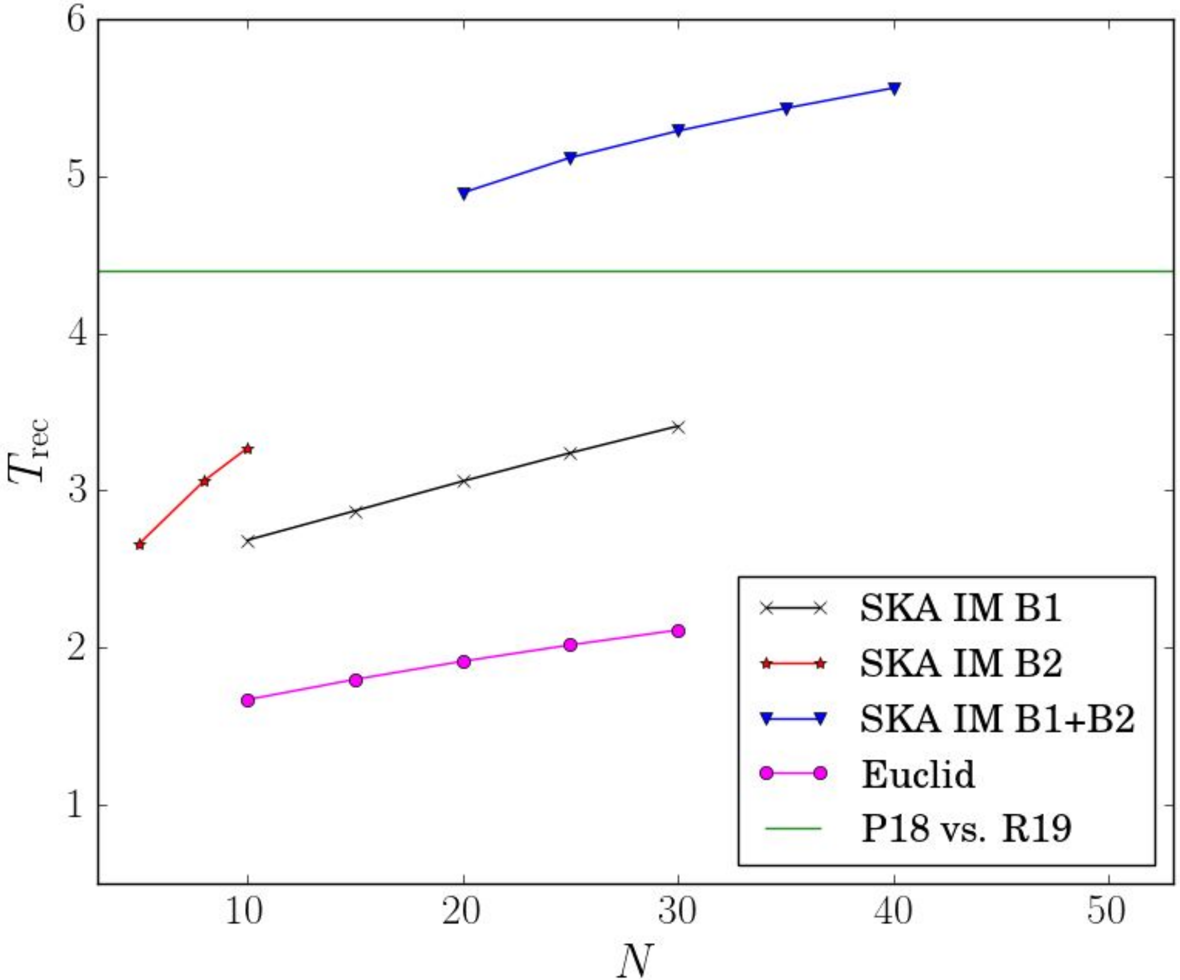
- Gaussian Processes (GP): "A Gaussian Process is a collection of random variables, any finite number of which have (consistent) joint gaussian distributions"

- In other words: GP consists on a distribution of functions rather than a distribution of values

- We will look for a function that best describes the data, and then extrapolate it to different ranges. A model-independent approach



4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
σ_{H_0}/H_0 (%)
10
20
30
40
50
N
SKA IM B1
SKA IM B2
SKA IM B1+B2
Euclid
P18
R19



6
5
4
3
2
1
$T_{\rm rec}$
10
20
30
40
50
N
SKA IM B1
SKA IM B2
SKA IM B1+B2
Euclid
P18 vs. R19

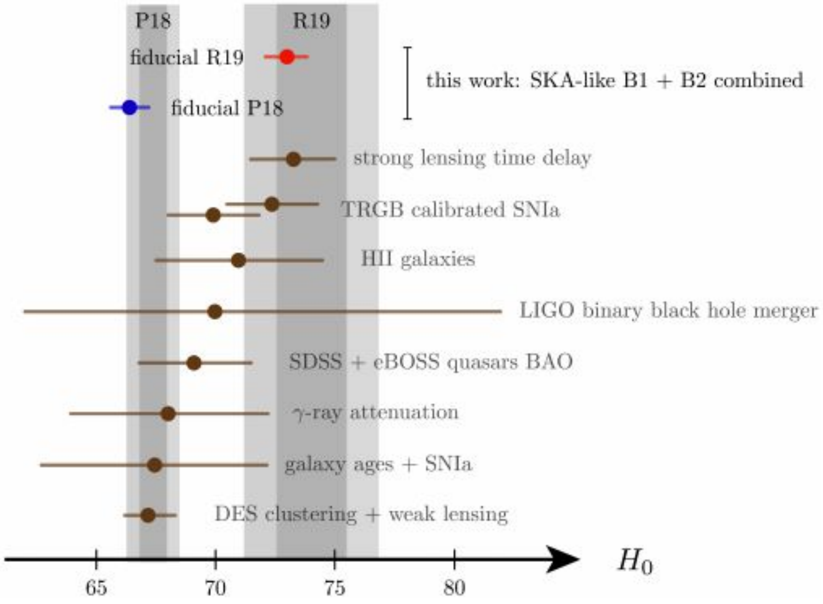


FIG. 3. Compilation of H_0 measurements, with 1σ error bars, shown against 1σ (darker) and 2σ (lighter) error bands for P18 (left) and R19 (right). From bottom to top: DES clustering + weak lensing [37]; galaxy ages + SNIa [19]; γ-ray attenuation [35]; SDSS + eBOSS quasars BAO (direct estimate of H_0) [18]; LIGO binary black hole merger GW170817 [39]; HII galaxies [36]; TRGB calibrated SNIa [7, 8]; strong lensing time delay [6]. Our GP-reconstructed estimates for SKA-like B1+B2 combined are: (fiducial P18, in blue) and (fiducial R19, in red), where the dots indicate the reconstructed $H_0^{\rm P18}$ and $H_0^{\rm R19}$.

The second number: q0

CB,

MNRAS 499 (2020), 1, L6

e-Print:1912.05528 [astro-ph.CO]

Part IIa: The H0 tension with next-gen surveys

- How well can we measure q0 with future redshift surveys like SKA and Euclid?

- Again, we rely on a non-parametric analysis using GP to reconstruct q(z) all the way to z=0 using $q(z) = (1+z)(H'/H)-1$ using the simulated H(z) measurements for Euclid and SKA-like surveys

- We can check how strong is the evidence for current cosmic acceleration, and so underpin the concordance model

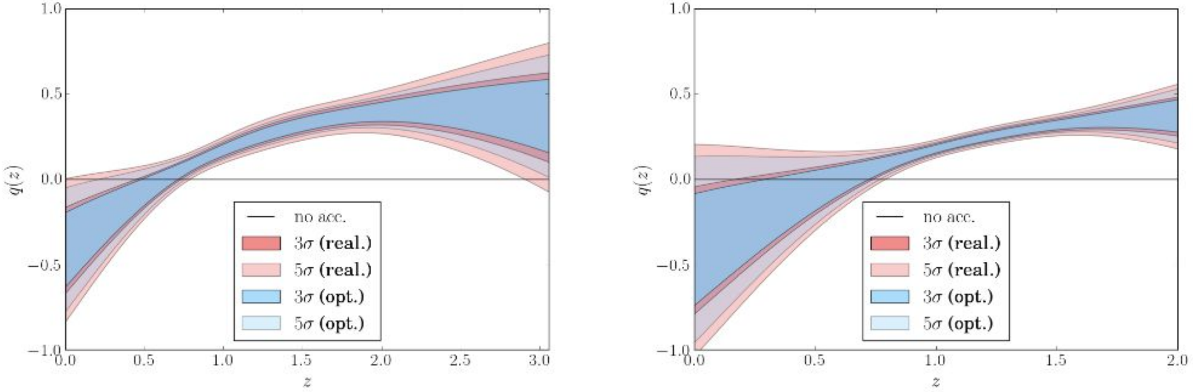


Figure 1. Left panel: Gaussian-processes reconstructed $q(z)$ following Eqs. (6) and (7) for a SKA-like B1 survey assuming the realistic ($N_1 = 10$ and $N_2 = 5$, in blue) and optimistic ($N_1 = 20$ and $N_2 = 10$), in red) specifications. The darker (lighter) shaded curves provide the 3σ (5σ) confidence levels. The black line denotes shows the non-accelerated threshold at $q_0 = 0$. Right panel: Same as the left panel, but valid for an Euclid-like survey.

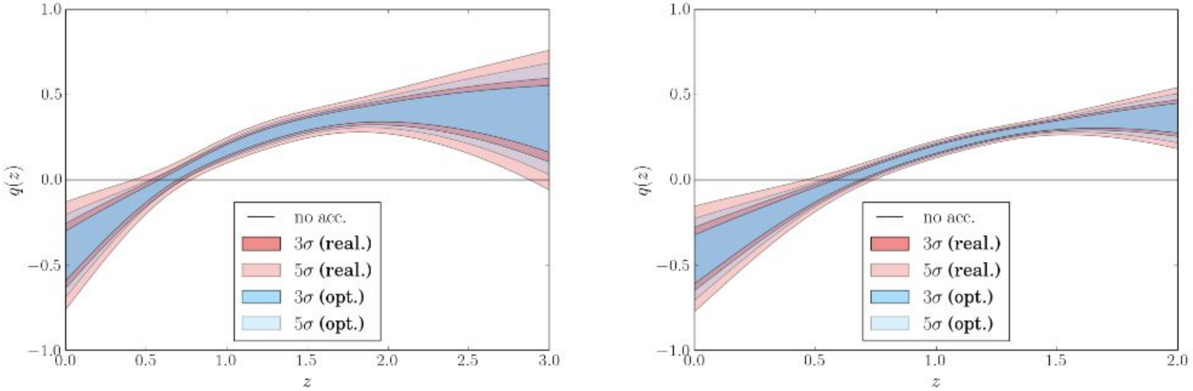


Figure 2. Same as Fig. 1, but including the SKA-like B2 data points.

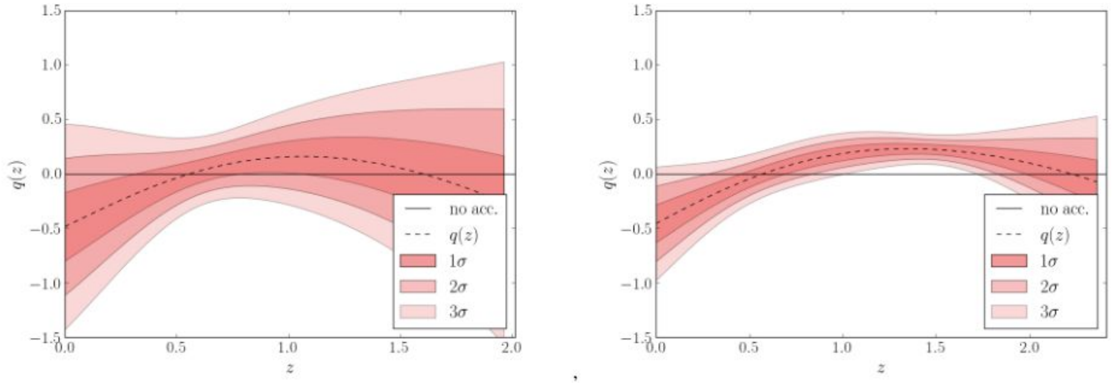


Figure 3. The reconstructed $q(z)$ curves, and their 1, 2 and 3σ uncertainties using real $H(z)$ data from CC (left) and CC combined with BAO measurements from galaxy surveys like SDSS and WiggleZ (right).

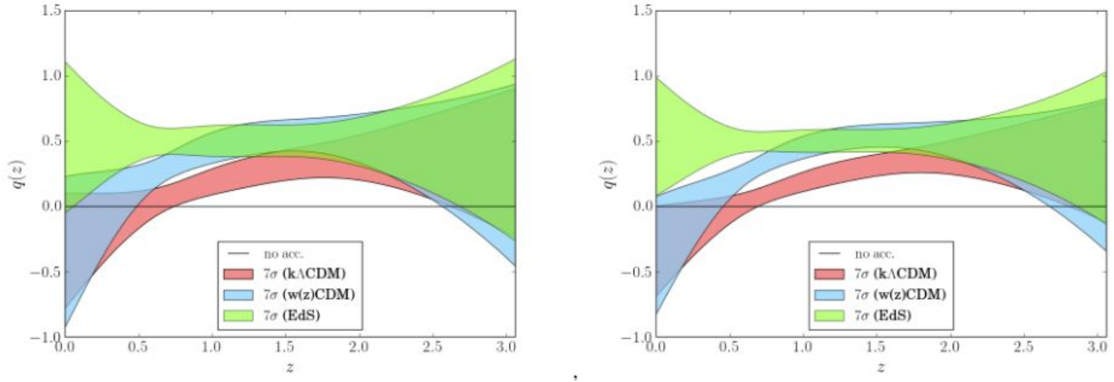


Figure 4. The reconstructed $q(z)$ curves (in 7σ) for SKA-like B1 and B2 surveys combined assuming the kΛCDM (red), w(z)CDM (blue) and EdS (green) models. The left plot displays the results for a realistic survey specification ($N_1 = 10$ and $N_2 = 5$), and the right plot for an optimistic one ($N_1 = 20$ and $N_2 = 10$).

Conclusions

Conclusions

- Euclid can measure H0 with ~3% precision; SKA B1 and B2 alone can measure it with ~2%, but B1+B2 combined can reach almost ~1% precision

- 30 H(z) measurements of SKA B1+B2 can tell early and late-Universe H0 values apart at ~5sigma - thus pinpoint one of the H0 values and help solving this tension

- Euclid and SKA B1 can quantify the evidence for cosmic acceleration at 3 and 5sigma alone - 7sigma if combined with SKA B2

- All these analyses tell us how well can we search for these two numbers with future observations without assuming dark energy a priori