Observational tests of the fundamental hypotheses of Cosmology

Carlos Bengaly
Outline

● The concordance model (CM) of Cosmology

● We have a CM, but do we really understand the cosmos?

● Observational tests of the CM foundations
  - Testing the cosmological principle with radio observations
  - Probing the current temperature of the CMB and the absolute magnitude of SNe
  - Miscellaneous stuff

● Concluding remarks and perspectives
A little bit about myself..

- **Carlos A P. Bengaly**, B.Sc. in Physics *(UFRJ, 2011)*, 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)*, currently holding a postdoc position at ON-MCTI *(2020-2023?)* as a PCI fellow

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

Lattes [http://lattes.cnpq.br/6562331419311591](http://lattes.cnpq.br/6562331419311591)
Inspire [https://inspirehep.net/authors/1703361](https://inspirehep.net/authors/1703361)
[https://orcid.org/0000-0001-5731-3348](https://orcid.org/0000-0001-5731-3348)
The concordance model of Cosmology as of today
The concordance model of Cosmology

Credits: Planck Collaboration

What is dark matter?

What is dark energy?
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 $\Lambda$CDM model really about?
\( \Lambda \text{CDM} \) model

- \( \Lambda \text{CDM} = \Lambda \) represents the Cosmological Constant, responsible for the late-time cosmic acceleration, whereas \( \text{CDM} = \text{cold dark matter} \)
**ΛCDM model**

- $\Lambda$CDM = $\Lambda$ represents the Cosmological Constant, responsible for the late-time cosmic acceleration, whereas CDM = *cold dark matter*

- Cold dark matter:
LambdaCDM model

- LambdaCDM = \( \Lambda \) represents the Cosmological Constant, responsible for the late-time cosmic acceleration, whereas CDM = cold dark matter

- 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)
**ΛCDM model**

- $ΛCDM = Λ$ represents the Cosmological Constant, responsible for the late-time cosmic acceleration, whereas $CDM = \text{cold dark matter}$

- Dark energy:
\( \Lambda CDM \) model

- \( \Lambda CDM = \Lambda \) represents the Cosmological Constant, responsible for the late-time cosmic acceleration, whereas CDM = \textit{cold dark matter}

- **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 \( \Lambda \), where \( w = -1 \)
  - \( \Lambda \) associated with \textit{vacuum density energy}. However, if \( \Lambda = \text{vacuum} \), we have \textbf{120 orders of magnitude} between cosmological observations and quantum field theory predictions (!!!)
  - main \( \Lambda \) alternatives: \textit{quintessence fields}, \textit{dynamical dark energy}, \textit{modified gravity models} like \( f(R) \), Gauss-Bonnet etc.
Accelerated Expansion of the Universe

- Dark age
- Relic radiation (CMB)
- Dark energy accelerated expansion
- Big Bang - Inflation

13.7 billion years
$\Lambda CDM$ model

- $\Lambda CDM = \Lambda$ represents the Cosmological Constant, responsible for the late-time cosmic acceleration, whereas $CDM = \text{cold dark matter}$

- **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
Ok, we have a model which explains very well cosmological observations...
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Moreover, there are some possible “cracks” on the CM, like the \(~4.4\sigma\) H0 tension and \(~2.5\sigma\) \(\sigma_8\) 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 CM, like the ~4.4σ $H_0$ tension and ~2.5σ $\sigma_8$ 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
The foundations of the concordance model

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- The Cosmological Principle (CP)
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  - Universe is statistically homogeneous and isotropic (at large scales!)
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  - Universe is statistically homogeneous and isotropic (at large scales!)
  - FLRW metric
The foundations of the concordance 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 from this scale onwards *(r>100Mpc)*
The foundations of the concordance model

- 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?
(How) can we test the CP?

- Testing isotropy is straightforward; we just need one observer, like ourselves, and perform statistics across the entire sky.
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- Testing homogeneity, however, is not; We perform observations down the past lightcone, but not on the time-constant hypersurfaces.
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- Testing isotropy is **straightforward**; we just need one observer, like ourselves, and perform statistics across the entire sky.

- Testing homogeneity, however, **is not**; We perform observations down the past lightcone, but not on the time-constant hypersurfaces.

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)
see also Clarkson & Maartens 2010; arxiv:1005.2165
(How) can we test the CP?

- We can probe cosmological isotropy using the counts of cosmic objects across the sky
(How) can we test the CP?

- We can probe cosmological isotropy using the **counts of cosmic objects** across the sky.

- Radio sources are powerful tracers of the large-scale structure, and can be observed at high redshifts ($z \sim 5$).
Part I: Testing isotropy with source counts

- We can probe cosmological isotropy using the counts of cosmic objects across the sky.

- Radio sources are powerful tracers of the large-scale structure, and can be observed at high redshifts ($z \sim 5$).

- **Goal:** test consistency between the CMB temperature (ascribed to our relative motion) with the radio source count dipole; strong inconsistencies may lead to departure of the CP.
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CB, Santos, Maartens JCAP2018; CB, Maartens, Randriamiarinarivo, Baloyi JCAP2019; CB, Siewert, Schwarz, Maartens MNRAS2019;
(How) can we test the CP?

- We can probe cosmological isotropy using the **counts of cosmic objects** across the sky
- Radio sources are powerful tracers of the large-scale structure, and can be observed at high redshifts \((z \sim 5)\)
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The dipole anisotropy of radio counts

CB, Santos, Maartens

JCAP 04 (2018) 031

e-Print: 1710.08804 [astro-ph.CO]
Is the Universe isotropic?
Is the Universe isotropic?

The dipole anisotropy in the CMB
Is the Universe isotropic?

\[ \nu \approx 369 \text{ km/s} \quad (l, b) = (264^\circ, 48^\circ) \]
Is the Universe isotropic?

Can we detect this dipole in number counts?
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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IF DIPOLE OF RADIO COUNTS $\neq$ CMB DIPOLE: CP IS NOT VALID!
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COUNTS OF RADIO CATALOGUES

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CP IS NOT VALID!

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)

\[
N_{\text{obs}} = N_{\text{rest}} \left[ 2 + x(1 + \alpha) \right] \beta \cos \theta
\]
The dipole anisotropy in radio number counts

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\[ N_{\text{obs}} \propto A \cos \theta \]
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)

\[
A = 0.00462 \\
\alpha = 0.76, \ x = 1.0, \ \beta = 0.00123
\]
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

  \[ 100 < S_{\text{TGSS}} < 5500 \text{ mJy} \quad f_{\text{sky}} \approx 0.687; \quad N_{\text{tot}} = 233,395 \]
  \[ 20 < S_{\text{NVSS}} < 1000 \text{ mJy} \quad f_{\text{sky}} = 0.657; \quad N_{\text{tot}} = 253,313 \]
We further cleaned both catalogues as follows:

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

- Elimination of galactic plane \(|b|<10\text{deg}\)

- Elimination of pixels within \(1\text{deg}\) of local radio sources and local clusters

- Regions whose radio galactic foreground emission exceeds \(T=50\text{mK}\) 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
Results

NVSS (left) versus TGSS (right) dipole
Direction is consistent with CMB, amplitude is much higher!
### Results

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

Direction is quite right, **but the amplitude is much higher!**
Results: mock data performance
Results: mock data performance

dipole amplitude, data vs. flux calibration-corrected mocks

- TGSS data
- NVSS data
- TGSS mocks
- NVSS mocks

frequency

A
What happens in smaller angular scales?

CB, Maartens, Randriamiharinarivo, 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)
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)

- What SKA can tell about the radio dipole?
What about the future in radio?

CB, Siewert, Schwarz, Maartens

*MNRAS 486 (2019), 1, 1350*

e-Print: 1810.04966 [astro-ph.CO]

See also:

SKA1 red book, PSAP 37 (2020) e007
e-Print: 1811.02743 [astro-ph.CO]
SKA radio continuum forecasts: prescription

- **SKA1 specs:** ~20000 sq. degrees, $S>10\mu$Jy and $S>20\mu$Jy;
- **SKA2 specs:** ~25000 sq. degrees, $S>1\mu$Jy and $S>5\mu$Jy

- $n(z)$, $s(z)$ and $b(z)$ taken from Alonso et al. 2015 *(LF code)*

- Planck 2015 best fit as fiducial power spectrum *(CAMB)*

- Number count mocks: lognormal realisations using *flask code* *(Xavier et al 2016)*

- Full and $z>0.5$ sample - the latter suppresses local structures
We estimate the kinematic dipole signal from the mocks following

\[
\min \sum_p \frac{\left[ N_p(n, S) - \bar{N}(S) (1 + A \cos \theta_p) \right]^2}{\bar{N}(S) (1 + A \cos \theta_p)}
\]

p stands for the p-th pixel (p=1, ..., 49152) - sky divided in 49152 directions (Healpix Nside=64 grid)
<table>
<thead>
<tr>
<th>Sample</th>
<th>$N_{\text{tot}}$ ($10^9$)</th>
<th>$S &gt;$ (μJy)</th>
<th>$l$ (deg)</th>
<th>$b$ (deg)</th>
<th>$A$ ($10^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>full</td>
<td>2.37</td>
<td>1.0</td>
<td>264.87 ± 6.47</td>
<td>47.42 ± 4.33</td>
<td>4.64 ± 0.33</td>
</tr>
<tr>
<td>$z \geq 0.5$</td>
<td>2.07</td>
<td>1.0</td>
<td>264.64 ± 5.57</td>
<td>47.37 ± 3.67</td>
<td>4.64 ± 0.30</td>
</tr>
<tr>
<td>full</td>
<td>0.72</td>
<td>5.0</td>
<td>265.15 ± 8.43</td>
<td>47.29 ± 5.58</td>
<td>4.67 ± 0.44</td>
</tr>
<tr>
<td>$z \geq 0.5$</td>
<td>0.62</td>
<td>5.0</td>
<td>264.84 ± 5.77</td>
<td>47.43 ± 3.85</td>
<td>4.64 ± 0.30</td>
</tr>
<tr>
<td>full</td>
<td>0.33</td>
<td>10.0</td>
<td>264.50 ± 12.71</td>
<td>47.08 ± 6.18</td>
<td>4.66 ± 0.55</td>
</tr>
<tr>
<td>$z \geq 0.5$</td>
<td>0.29</td>
<td>10.0</td>
<td>264.56 ± 7.34</td>
<td>47.20 ± 3.97</td>
<td>4.62 ± 0.38</td>
</tr>
<tr>
<td>full</td>
<td>0.18</td>
<td>20.0</td>
<td>263.86 ± 25.08</td>
<td>45.50 ± 12.89</td>
<td>4.93 ± 1.03</td>
</tr>
<tr>
<td>$z \geq 0.5$</td>
<td>0.15</td>
<td>20.0</td>
<td>265.49 ± 8.65</td>
<td>46.83 ± 4.64</td>
<td>4.65 ± 0.45</td>
</tr>
<tr>
<td>fiducial</td>
<td>−</td>
<td>−</td>
<td>264.02</td>
<td>48.25</td>
<td>4.62</td>
</tr>
</tbody>
</table>
Figure 5. Constraints on the kinematic dipole amplitude as a function of lower cut in redshift for the realistic SKA1 and SKA2 simulations. The results become more stable from $z_{\text{cut}} > 0.1$ onward since the most strongly clustered structures are eliminated at this redshift range.
Conclusions

- SKA can constrain the dipole direction to a $\sim 8-10$ degrees, and dipole amplitude down to $\text{sigmav}/v < 10\%$. Huge improvement from current surveys like NVSS and TGSS.

- Direction constraints MUCH IMPROVED when local structure is suppressed.

- SKA will also be able to detect the relativistic aberration (Pant, Rotti, CB, Maartens JCAP2019).

- SKA will deliver a precision test of the fundamental hypothesis of Cosmology using radio continuum observations.
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 $T_0 = 2.73$K. FIRAS measured this value with extremely high precision 3 decades ago: $T_0 = 2.72548 \pm 0.00057$ (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 $\sigma_8$ 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!
$M_B$ prior

- Pantheon SNe: best-fit hsCDM with prior on $H_0$
Is there evidence for a hotter Universe?

- We use measurements of $T(z)$ to obtain $T_0$ using parametric and non-parametric approaches
Is there evidence for a hotter Universe?

- We use measurements of $T(z)$ to obtain $T_0$ 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: 13 $T(z)$ measurements in the range $0.02 < z < 0.55$ combined with the 18 $T(z)$ measurements mentioned above.
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- **comb2**: 13 $T(z)$ 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
  \[
  T_0 = 2.72548 \pm 0.00057 \text{ (F09)}
  \]
  \[
  T_0 = 2.564 \pm 0.050 \text{ (IAL20)}
  \]
  \[
  T_0 = 2.839 \pm 0.046 \text{ (BL20)}
  \]

\[
\mathcal{T} = \frac{|T_{0,\text{exp1}} - T_{0,\text{exp2}}|}{\sqrt{\sigma^2_{\text{exp1}} + \sigma^2_{\text{exp2}}}}
\]
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)
Is there any measurable redshift dependence on the SN Ia absolute magnitude?

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

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- **Goal:** Measure the Mabs of Pantheon SNe compilation using several approaches:
  - Direct Mabs fit in different redshift bins
  - different parametrisations of $M(z) = M_0 + M_1 \cdot f(z)$
  - modified gravity: $M(z) = M_0 + \frac{15}{4} \log\left(\frac{G_{eff}}{G_n}\right)$, $G_{eff}/G_n = 1+g_\alpha[z/(1+z)]^n$
  - LTB model
Number of bins = 5

$\mu_{\text{bin}}(z)/\mu_{\text{CDM}}(z)$ vs. $z$

Sapone, Nesseris, CB *Phys. Dark Univ.* 32 (2021) 100814
<table>
<thead>
<tr>
<th>$\mathcal{M}_0$</th>
<th>$\mathcal{M}_1$</th>
<th>$\Omega_{m,0}$</th>
<th>$\alpha$</th>
<th>$\chi^2_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$</td>
<td>$-1.191 \pm 0.011$</td>
<td>0</td>
<td>$0.299 \pm 0.022$</td>
<td>-1025.6</td>
</tr>
<tr>
<td>M1</td>
<td>$-1.194 \pm 0.020$</td>
<td>$0.061 \pm 0.381$</td>
<td>$0.299 \pm 0.064$</td>
<td>-1025.6</td>
</tr>
<tr>
<td>M2</td>
<td>$-1.190 \pm 0.013$</td>
<td>$-0.474 \pm 0.177$</td>
<td>$0.032 \pm 0.069$</td>
<td>-1024.9</td>
</tr>
<tr>
<td>M3</td>
<td>$-1.192 \pm 0.016$</td>
<td>$0.031 \pm 0.462$</td>
<td>$0.311 \pm 0.188$</td>
<td>1</td>
</tr>
<tr>
<td>$\overline{M3}$</td>
<td>$-1.195 \pm 0.012$</td>
<td>$1.204 \pm 0.055$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>M4</td>
<td>$-1.193 \pm 0.570$</td>
<td>$0.001 \pm 0.579$</td>
<td>$0.298 \pm 0.287$</td>
<td>-1</td>
</tr>
</tbody>
</table>

**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 ($\overline{M3}$) 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 $w = -1$. $\Lambda$ refers to the $\Lambda$CDM model.
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)
Miscellaneous stuff
We verified that cosmic variance due to incomplete sky coverage can ease the H0 tension - from 4.4 down to $(2.7-3.0)\sigma$ at the most extreme cases (CB JCAP 2016; CB, Andrade, Alcaniz EPJC 2019)

We found that the 2D distribution of SDSS-III LRG (Gonçalves+ MNRAS 2018a) and 3D distribution of SDSS-IV QSOs (Gonçalves+ MNRAS 2018b; Gonçalves+ JCAP 2021) does exhibit a characteristic scale of homogeneity, as predicted by the Cosmological Principle

We found that Euclid and SKA will be able to measure H0 at almost percent-level precision, probe cosmic acceleration with $(5-7)\sigma$ cl, and null tests of the CM at a $(3-5)\sigma$ cl - ALL model-independent tests! (CB, Clarkson, Maartens JCAP 2020; CB MNRAS 2020; CB, Clarkson, Kunz and Maartens PDU accepted yesterday (!) 2021)
Gonçalves, Carvalho, Andrade, CB+
JCAP 03 (2021) 029
e-print 2010.06635
Forecasts for a null test of the CM using Euclid simulations
CB, Clarkson, Kunz, Maartens
PDU accepted 2021
Forecasts for a null test of the CM using SKA simulations

CB, Clarkson, Kunz, Maartens

PDU accepted 2021
Concluding remarks and perspectives
Concluding remarks and perspectives

- Current SN and radio count observations can probe the Cosmological Principle, but with limited precision. Future surveys like SKA will enormously improve the quality of these tests.

- No evidence for new physics probing two important quantities in Cosmology, i.e. the CMB current temperature and SNe absolute magnitude.

- Future redshift surveys such as Euclid and SKA can measure H0 and q0 with unprecedented precision without any prior assumption about the underlying Cosmology.

- Future plans:
  - can we detect the homogeneity scale in galaxy clusters?
  - model-independent tests of cosmic curvature
  - model-independent tests of cosmic acceleration with transversal BAO-only
  - deploying machine learning to test the foundations of Cosmology (CB, Dantas, Casarini and Alcaniz in prep.)
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!
Thanks!
Obrigado!
Complimentary slides
Part III:
Cosmology: A search for two numbers revisited. What can future redshift surveys tell about them?
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
Part II: Searching for $H_0$ and $q_0$

- $H_0$ and $q_0$ need to be constrained with $\sim 1\%$ 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
Part II: Searching for $H_0$ and $q_0$

- $H_0$ and $q_0$ 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 $H_0$ and $q_0$ 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 \( H_0 \); alternative dark energy models, or local underdensities, cannot easily solve this tension.

Credits: Vivien Poulin

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*
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 $H_0^{P18}$ and $H_0^{R19}$. 
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 $3\sigma$ ($5\sigma$) 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 3σ) for SKA-like B1 and B2 surveys combined assuming the k$\Lambda$CDM (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.