Is there evidence for anomalous dipole anisotropy in the large-scale structure?

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ABSTRACT
We probe the anisotropy of the large-scale structure (LSS) with the WISE-2MASS catalogue. This analysis is performed by a directional comparison of the galaxy number counts through the entire celestial sphere once systematic effects, such as star-galaxy separation and foreground contamination, are properly taken into account. We find a maximal hemispherical asymmetry whose dipolar component is \( A = 0.0507 \pm 0.0014 \) toward the \((l, b) = (323^\circ, -5^\circ)\) direction, whose result is consistent with previous estimations of our proper motion in low and intermediate redshifts, as those carried out with Type Ia Supernovae and similar LSS catalogues. Furthermore, this dipole amplitude is statistically consistent (\( p \)-value = 0.061) with mock catalogues simulated according to the expected \( \Lambda \)CDM matter density fluctuations, in addition to observational biases such as the incomplete celestial coverage and anisotropic sky exposure. Our results suggest, therefore, that there is no strong evidence for anomalous anisotropy in the LSS, given the limitations and systematics of current data, in the concordance model scenario.

Key words: Cosmology: observations; The large-scale structure of the Universe; Cosmological Principle

1 INTRODUCTION
The isotropy of the Universe is one of the most fundamental pillars of the standard model of cosmology. Along with the hypothesis that the Universe must be homogeneous on large scales, it constitutes the so-called Cosmological Principle (CP), which states that there are no intrinsic privileged directions and positions throughout its entire extension (Goodman 1995; Wu et al. 1999; Maartens 2011; Clarkson 2012). Albeit the standard \( \Lambda \)CDM model, which is based on the CP, excellently describes cosmological observations such as the Cosmic Microwave Background (CMB) temperature fluctuations (Hinshaw et al. 2013; Ade et al. 2015a), the growth rate of the large-scale structure (LSS) (Peacock et al. 2001; Blake et al. 2011a; Reid et al. 2012), besides time scales from the galaxy ages, and cosmological distances from Type Ia Supernovae (SNe) as well as baryonic acoustic oscillations (BAO) (Riess et al. 1998; Perlmutter et al. 1999; Alcaniz & Lima 1999; Alcaniz et al. 2003; Eisenstein et al. 2005; Blake et al. 2011b; Beutler et al. 2011; Suzuki et al. 2012; Betoule et al. 2014; Aubourg et al. 2015; Carvalho et al. 2016), the validity of the CP remains yet to be directly assessed. Therefore, it is crucial to perform observational tests of cosmic isotropy and homogeneity, since a violation of at least one of such hypotheses would lead to a complete reformulation of the standard cosmological scenario.

It has been well known that the CMB exhibits a dipolar anisotropy in its temperature due to Doppler boost and aberration effects, i.e., the kinematic dipole, which is attributed to our relative motion through the Universe. Such effect was predicted and detected still in the late 1960s (Stewart & Sciama 1967; Conklin 1969), being confirmed many years later in the full-sky CMB map from COBE (Kogut et al. 2013), WMAP (Hinshaw et al. 2009) and Planck (Aghanim et al. 2014) maps. This measurement shows that our motion is characterised by a velocity of \( v \approx 384 \) km/s toward the \((l, b) = (264^\circ, 48^\circ)\) direction. Attempts to obtain this signal in the LSS appeared as early as the 1960s (De Vaucouleurs & Peters 1968), whose efforts increased given the rapidly growing improvements of infra-red and optical galaxy surveys, such as the IRAS PSCz and 2MASS, during the following decades (Yahil et al. 1986; Lahav et al. 1988; Lynden-Bell et al. 1989; Strauss et al. 1992; Basilakos & Plionis 1998; Rowan-Robinson et al. 2000; Maller et al. 2003; Erdögoń et al. 2006; Basilakos & Plionis 2006; Bilić et al. 2011). The goal, in these cases, was the amplitude and direction of the so-called clustering dipole, which gives a preferred direction in the low-z LSS due to the galaxy clustering responsible for the acceleration of the Local Group, thus allowing one to deter-

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mine the consistency (and convergence) with the CMB kinematic dipole.

One of the most popular approaches to perform the estimation of the clustering dipole makes use of galaxy luminosity function and magnitudes measured in different distances (thus the flux-weighted dipole). Then, this information is compared with the expected peculiar velocity in these corresponding scales via linear perturbation theory (Peebles 1980). Some of the latest results reported dipoles roughly aligned with the CMB one. For example, Rowan-Robinson et al. (2000) obtained \((l, b) = (267^\circ, 50^\circ)\) adopting IRAS PSCz data set, while Maller et al. (2003) and Erdogdu et al. (2006) analyses provided \((l, b) = (264.5^\circ, 43.5^\circ)\) and \((l, b) = (245^\circ, 39^\circ)\), respectively, both using different versions of the 2MASS data. The convergence of this flux-weighted dipole amplitude in large scales, nevertheless, is still a matter of debate (Bilicki et al. 2011). Similar analyses have been carried out in the X-ray spectrum with this flux-weighted method in the galaxy clusters luminosity function (Plionis & Kolokotronis 1998; Kocevski et al. 2004), besides the dipole anisotropy in the diffuse X-ray background due to Compton-Getting effect with both ROSAT (Plionis & Georgantopoulos 1999) and HEAO1 (Scharf et al. 2000; Bouhm et al. 2002) surveys. The results are similar to the optical and infra-red analyses, although many authors claimed greater difficulties in the X-ray band than in the former cases because of less controlled systematics.

Given the increasing amount and precision of the observational LSS data, it has become possible to probe its dipole anisotropy using only projected two-dimensional counts from these all-sky galaxy catalogues: Gibelyou & Huterer (2012) performed such analysis with a large variety of observational samples, Appleby & Shafieloo (2014) and Alonso et al. (2015) adopted the 2MASS data with photometric redshifts (2MPZ, Bilicki et al. 2014) with this purpose, whereas Yoon et al. (2014) performed a dipole estimation with the Wide Infrared Satellite Explorer (WISE, Wright et al. 2010) data. All these works presented good agreement with the clustering dipole results obtained with the flux-weighted method, with the advantage that this 2D projected estimators do not require further information (or assumptions) about the magnitudes and luminosity function of the sources other than their celestial distribution.

On the other hand, the isotropy of the large-scale LSS had been tested with radio surveys as well, which are much deeper than the current optical and infra-red catalogues, thus, being ideal data sets to directly probe the consistency with the CMB kinematic dipole. One of the early attempts were carried out by Baleisis et al. (1998), who joined both Green Bank and Parkes-MIT-NRAO radio catalogues, yet could not detect such signal due to the large shot-noise number counts in this sample. The first statistical significant report of this dipole were made by Blake & Wall (2002), who adopted the much larger radio catalogue from NVSS and obtained a velocity dipole whose amplitude and direction shows reasonably good agreement with the CMB’s. However Singal (2011) revised these data and found a nearly five times larger velocity than the expected value from the CMB dipole, although the direction is still roughly consistent with it, as well as Blake & Wall (2002) results. This surprising result was later confirmed by Rubart & Schwarz (2013); Tiwari et al. (2014); Fernández-Cobos et al. (2014); Tiwari & Jain (2015), albeit with moderately smaller velocities, while later on Tiwari & Nusser (2016) showed that a bias choice of \(b \geq 2.0\) for these radio sources decreases this discrepancy between the CMB and the radio dipole to 2.3σ – 2.8σ. In addition, some previous works obtained large scale flows using peculiar velocity probes, such as nearby galaxies and SNe (Watkins et al. 2009) as well as the kinematic Sunyaev-Zeldovich (kSZ) effect from galaxy clusters (Kashlinsky et al. 2009, 2010, 2011; Attrio-Barandela et al. 2015), than the ΛCDM predictions in the scales they probed, besides claims of statistical isotropy violation in the CMB temperature fluctuations, e.g. the hemispherical power asymmetry firstly showed in the first WMAP release Eriksen et al. (2004); Hansen et al. (2004), then confirmed in its later versions, as well as in the Planck data (Bernui 2008; Bernal et al. 2014; Hofu et al. 2009; Akrami et al. 2014; Polastri et al. 2015; Zhao & Santos 2015; Ghosh et al. 2016; Cheng et al. 2016). The physical motivation of these possible violations of isotropy hypothesis remains an open issue by the present moment.

In the light of these intriguing results, it is of great importance to test the isotropy assumption with other probes and methods, investigating whether a similar feature can be detected in these data. Therefore, we adopt the WISE-2MASS catalogue in this work. Our goal is to look for large-angle anisotropies in the galaxy number counts (GNC) caused by galaxy clustering, and to determine the statistical significance of the result according to the expectations of the concordance model. This assessment is performed via log-normal mock realisations, which incorporate the matter density fluctuations expected from the ΛCDM model given the WISE-2MASS source counts variance, besides potential observational bias such as incomplete sky coverage, because of dust obscurity, as well as anisotropic sky exposure of WISE’s observational strategy. Also, it may provide a consistency check with previous CMB and LSS anisotropy studies, besides complimentary analyses performed with cosmological distance indicators such as SNe or nearby galaxies (Watkins et al. 2009; Antoniou & Perivolaropoulos 2010; Colin et al. 2011; Dai et al. 2011; Mariano & Perivolaropoulos 2012; Turnbull et al. 2012; Wiltshire et al. 2013; Cai et al. 2013; Rathaus et al. 2013; Kalus et al. 2013; Feindt et al. 2013; Ma & Pan 2013; Jiménez et al. 2015; Appleby et al. 2015; Bengaly et al. 2015a; Javanmardi et al. 2015; Carvalho & Marques 2015; Springob 2016; Lin et al. 2016a; McKay & Wiltshire 2016; Migkas & Plionis 2016; Carvalho & Basilakos 2016; Lin et al. 2016b; Bolejko et al. 2016).

Hence, the structure of the paper is the following: In Section 2 we describe the WISE data, the construction of its catalogue, and the appropriate masking procedure in order to avoid foreground contamination. Section 3 is dedicated to the methodology developed for testing the GNC anisotropy, as well as the construction of the mock data. The obtained results are presented in Section 4, followed by a discussion and our main conclusions in Section 5.

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1 Some attempts on performing such analyses in partial sky maps can be found in Pullen & Hrata (2010); Hazra & Shafieloo (2015) for estimates on Sloan Digital Sky Survey (SDSS) galaxy and Lyman-α, respectively, besides the LSS dipole test applied in SDSS galaxy sample from Data Release 6 (Itoh et al. 2010).

2 We remark that we had only considered the two-dimensional projected approach in our analyses, not the flux-weighted one. A detailed discussion on these approaches, in addition to the expected consistency between each other, and the behaviour of the dipole amplitude when reaching deeper and deeper scales is made in Gibelyou & Huterer (2012).

3 For the interested reader on other CMB features, such as large-scale alignments and power deficit, we refer to Schwarz et al. (2015).
2 DATA SET PREPARATION

The data set adopted in this analysis corresponds to the WISE release named "AllWISE", which is publicly available since late 2013 in the IRSA website. It originally consists of nearly 750 million objects in four bands centred at 3.4, 4.6, 12, and 22 μm wavelengths, corresponding to the W1, W2, W3, and W4. We follow the points discussed by Kovács & Szapudi (2015), who matched WISE and 2MASS magnitude in the J band (henceforth $J_{\text{2MASS}}$) in order to enhance the WISE biases and purity, such as removing objects according lying in the 12.0 < $W_1$ < 15.2 range, besides the $J_{\text{2MASS}} > 16.5$ cut, as these authors showed that such objects are spatially biased due to the instrumental capability limitations in the latter case. In addition, a colour cut of $W_1 - J_{\text{2MASS}} < -1.7$ has been carried out in order to optimise the galaxy-star separation (hence the name WISE-2MASS of the catalogue). From the original value of 750 million objects, nearly 2.4 million points remained after applying these criteria.

Another crucial issue in data sets like WISE-2MASS is Galactic contamination. Therefore, a mask template has been constructed following Kovács & Szapudi (2015) as well, where, in practice, we have removed pixels in the sky for which the colour excess satisfies $E(B-V) \geq 0.1$ according to the reddening map provided by Schlegel et al. (1998). Pixels localised in regions with high extinction contamination according to the WMAP dust template, obtained in the same web site, have also been removed, albeit most of them coincide with the reddening constraint. The resulting map of extra-galactic sources is shown in the left panel of Figure 1 with HEALpix (Górski et al. 2005) $N_{\text{side}} = 128$ resolution. It comprises ~1.7 million sources with observed sky fraction of $f_{\text{sky}} \simeq 0.60$, whose characteristic depth is $ar{\ell} \simeq 0.16$ according to Yoon et al. (2014).

3 METHODOLOGY

3.1 The Delta-Map

Our GNC hemispherical analysis is performed using a number counts estimator based on Alonso et al. (2015), which is defined as

$$\Delta_i \equiv 2 \times \left( \frac{n_i^U - n_i^D}{n_i^U + n_i^D} \right),$$  \hspace{1cm} (1)

where $n_i^j \equiv N_i^j / (4\pi f_{\text{sky}}^j)$, $i$ denotes the hemisphere centre defined by the HEALpix pixelisation grid with $N_{\text{side}} = 8$ resolution, and $j$ represents the "up" ($U$) and "down" ($D$) hemispheres according to this scheme. $N_i^j$ and $f_{\text{sky}}^j$ are the number of objects and the observed fraction of the sky encompassed in each of these hemispheres, respectively. We call the collection of measurements $\Delta_i$ a "delta-map". The GNC anisotropy is calculated by extracting the dipole of the delta-map described in Eq. (1), i.e., by setting all $(a_{\ell m})$ of the delta-map to zero except for those with $\ell = 1$. Hence, the resulting map only contains the dipole term, whose value and position of its "hottest" point denotes, respectively, the amplitude and direction that we will consider throughout this work. Note, also, that there might be some non-zero couplings in the dipole term, as from the multipole, quadrupole and octopole, due to the cut-sky LSS map, but nonetheless we found it negligible in our delta-map analysis.

3.2 Mock data

The mock data used in this study are full-sky lognormal realisations of galaxy distribution created by the flasK code (Xavier et al. 2016). flasK generates lognormal realizations on spherical redshift shells around the observer (i.e., tomographically) of fields described by a set of angular cross- and auto-power spectra $C_{\ell}^{ij}$ which must be given as input, where the indices $i$ and $j$ refer to the various shells. When generating galaxy distributions, the galaxies are Poisson sampled from the lognormal fields whose statistics are described by the $C_{\ell}^{ij}$s.

In this work we simulated the angular distribution of galaxies in 8 redshift shells (with top-hat profiles) equally spaced in the range $0 < z < 0.4$ following the WISE redshift distribution estimated by Yoon et al. (2014) and the number density $C_{\ell}^{ij}$s (band-limited to $\ell_{\text{max}} = 512$) computed by camb sources (Challinor & Lewis 2011) for galaxies with linear and constant bias $b$ under an isotropic ΛCDM model with cosmological parameters described by Eq. (30) of Challinor & Lewis (2011) (e.g. redshift space distortions and gravitational lensing distortions of the volume elements). The boost due to our proper motion, nevertheless, has not been accounted during this procedure, yet it is incorporated afterwards as explained in more details in the next section. The galaxy distributions simulated in the shells were then projected to form a single galaxy surface density map with the same resolution as the one used for the real WISE data (given by $N_{\text{side}} = 128$). The average galaxy number density in the simulations was set so as to match the observed density of $1.85 \times 10^{-2}$ arcmin$^{-2}$ (~14 galaxies per pixel), and the bias $b$ was set to 1.37 to match the variances $\sigma_g^2$ of the galaxy counts inside the pixels ($\sigma_g^2 \approx 45$). Finally, we applied to the simulated maps the same masking template used on the real data. An example of a simulated map is shown in the right panel of Figure 1. All this simulation procedure was repeated in order to generate 1000 independent mocks.

4 http://irsa.ipac.caltech.edu
5 Downloaded from the LAMBDA website http://lambda.gsfc.nasa.gov
6 Other estimators in the literature include the quadratic $\chi^2$, similar to those adopted by Blake & Wall (2002), in addition to a Shannon Entropy estimator proposed by Pandey (2015). We tested the former, and found no significant discrepancy with the results provided by our delta-map method, yet much more costly in terms of computational time. The latter, however, is left for future work.
7 http://www.astro.iag.usp.br/~flask
8 http://camb.info/sources
4 RESULTS

4.1 WISE-2MASS data

The result of the delta-map analysis is exhibited in the left panel of Figure 2, where we obtained an amplitude of $A = 0.0507$ towards the $(l, b) = (323.44^\circ, -4.78^\circ)$ direction. The uncertainty of this dipole amplitude can be estimated from the shot noise due to the discrete distribution of galaxies, as performed by Yoon et al. (2014). This is assessed following $\sigma_A = 1.5 (\sqrt{\pi})^{-1} \sqrt{\Omega / (4\pi\bar{n})}$ (Itoh et al. 2010), being $\Omega$ the total area spanned by the survey, and $\bar{n}$ the average number of sources per steradian. We obtained $\sigma_A = 0.0014$, which is significantly smaller than the total dipole amplitude, besides the cosmic variance, which comprises $40\%$ of it due to the large foreground mask adopted. This result presents good agreement with previous analyses in the literature. For instance, Yoon et al. (2014) obtained a maximal asymmetry with amplitude $A \simeq 0.05 \pm 0.01$ pointing roughly at the $(l, b) = (310^\circ, -15^\circ)$ direction using the same WISE-2MASS data, albeit a different estimator and masking procedure ($f_{\text{sky}} \simeq 0.65$), while Alonso et al. (2015) analysis provided $A = 0.028$ toward $(l, b) = (320^\circ, 6^\circ)$ with the 2MPZ data provided by a local variance estimator similar to that presented in Akrami et al. (2014). Moreover, Appleby & Shafieloo (2014) found a maximal anisotropy at $(l, b) = (315^\circ, 30^\circ)$ in the 2MPZ catalogue as well, whose estimator based on the hemispherical variance of the luminosity function instead. This may explain the larger discrepancy between their preferred direction and the aforementioned works. We remark that our results are also in relative good concordance with the anisotropy analyses carried out with SNe data, as shown in Table 1, thus indicating that our directional analysis could be plausibly explained in terms of the clustering dipole arisen by the bulk flow velocity present in the low-$z$ cosmic web, whose value is commonly ascribed to our relative motion through the Universe.

The right panel of Fig. 2, on the other hand, features the hemi-
spherical anisotropy of the available sky area, i.e., the $f_{d_{bs}}$ variance in antipodal portions of the celestial sphere due to the asymmetric foreground mask. The numbers presented on the colour bar correspond to the fluctuation around 0.30, which is the average $f_{d_{bs}}$ comprised in the hemispheres. We note that the “preferred direction” obtained in this analysis does not coincide with the GNC dipole, since we divided the total number of objects inside each of these hemispheres by this $f_{d_{bs}}$, directional variance, therefore, the incompleteness of the sky coverage does not affect the dipole estimation via delta-map in a significant manner. Moreover, we stress that this dipole signal is robust with respect to different masking procedures that presents smaller or larger $f_{d_{bs}}$, and the same happens when adopting different resolutions for the density number contrast map (as $N_{side} = 64$, for instance), or different number of hemispheres (say 192 or 3072, corresponding to $N_{side} = 4$ or $N_{side} = 16$, respectively) for the delta-map analysis. When carrying out distinct magnitude cuts, the dipole amplitude slightly increases (about 10% of the original $A$ value) when selecting the brightest sources (as $W_1 < 14.2$ or $W_1 < 14.5$) of the catalogue, and decreases in a similar fashion when applying an upper magnitude cut which leaves the deepest sources of the sample. This is an expected result, since the brighter objects, in general, lie closer to us, and thus are more strongly affected by the overdensities of local large-scale structure, while the opposite happens for the deeper sub-samples.

### 4.2 Statistical significance test

We repeat the delta-map analysis of the GNC with a set of 1000 mock WISE-2MASS catalogues produced via lognormal realisations, where the underlying number density contrast field (as explained in Section 3.2) is simulated given the expected redshift and sky coverage of the sample. In addition, we develop a model for the WISE sky exposure, as shown in Fig. 3. Since the satellite visits some patches in the sky more often than others, such as the ecliptic poles, we might expect a higher probability of objects being detected in these regions, thus leading to a potentially larger anisotropy, as found in Bengaly et al. (2015b) with galaxy cluster observations. Such effect is included in the lognormal mocks by weighting the number of sources in each pixel according to this map, therefore the darkest blue regions of this map should present smaller number of objects per pixel than the hotter ones. Furthermore, the expected dipole generated by Doppler boosting...
and aberration of sources due to our relative motion, i.e., the actual kinematic dipole, is also incorporated in these lognormal realisations. Although the WISE-2MASS data set does not satisfy the statistical dipole, is also incorporated in these lognormal realisations, or to the non-uniformities introduced by the anisotropic sky are randomly oriented through the sky. This result demonstrates that the real WISE-2MASS sample, finding that they coincide with the real WISE-2MASS sample, finding that they

\[ A = 0.0507, \text{pointing at the (l, b) = (323.44°, −4.78°)} \text{ direction, thus consistent with previous studies in the same redshift range using data of different probes and experiments. We have assessed the statistical significance of this result using WISE-2MASS mocks based on lognormal simulations, which have been produced with the FLASK code (Xavier et al. 2016) under the ΛCDM assumption, and we have posteriorly included observational effects such as the non-uniformities sky exposure, and a fiducial dipole modulation produced by Doppler boosting and aberration. We have found that the GNC dipole obtained in the WISE-2MASS data is not significantly unusual with respect to these realisations (p-value = 0.061).

Thus, we conclude that there is no significant evidence for anomalous dipole anisotropy in the LSS, contrarily to suggested in previous analyses such as the moderately large GNC dipole reported in the same data set, and very large velocity dipoles detected in radio sources and galaxy clusters via kSZ as well. We note, nevertheless, that the WISE-2MASS catalogue cannot actually probe the kinematic dipole that is manifested in the CMB. As discussed in Gibelyou & Huterer (2012) and in Yoon et al. (2014), it is expected that the clustering dipole should dominate in low redshift ranges, as in the case of the WISE-2MASS sources. It is required an observational sample comprising \( N_{\text{val}} \sim 10^4 \) with \( f_{\text{sky}} = 0.75 \), and median redshift \( z \sim 0.70 \), in order to probe such signal with 5σ confidence level, as shown in Yoon & Huterer (2015). Such data set with is not currently available in any redshift range or frequency observed, hence we cannot underpin that the dipole we have detected is, in fact, because of our relative motion through the Universe, the main source of anisotropy expected in the standard cosmological scenario, albeit our results is in good agreement with previous estimations of the clustering dipole (Table 1).

Finally, the amplitude of our reported dipole is also consistent with the ΛCDM GNC fluctuations obtained from its matter density power spectrum once the sample variance and WISE’s celestial exposure are properly taken into account. Nevertheless, a mild discrepancy between this dipole direction between the local probes and the CMB kinematic dipole still persists. This could be ascribed to the fact that the WISE-2MASS sample is not deep enough to obtain the expected convergence between them, as discussed in Gibelyou & Huterer (2012), or perhaps there are some unaccounted anisotropy introduced by the presence of very large structures, such as the Sloan Great Wall (Gott III et al. 2005) or the Eridanus Supervoid (Nadathur et al. 2014; Szapudi et al. 2015; Kovács & García-Bellido 2015; Finelli et al. 2016). A more detailed assessment of such structures in the GNC anisotropy study has yet to be performed, although Rubart et al. (2014); Bolejko et al. (2016) showed that large underdensities are unable to

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induce such large LSS dolples (albeit Kraljic & Sarkar (2016) dis-
puted this result). Our final conclusion is that one of the foundations of
the concordance cosmology, i.e., the cosmic isotropy, is an ass-
sumption that is actually consistent with modern astrophysical data,
given their current limitations. However, the prospect of probing the
large-scale isotropy should be tremendously improved with the advent
of the next-generation LSS surveys such as Large Synoptic
Sky Survey (LSST) (Abell et al. 2009), which has been shown to be
able to probe the cosmic dipole with much better precision than
current surveys (Itoh et al. 2010), and especially with Square
Kilometer Array (SKA) (Jarvis et al. 2015; Maartens et al. 2015;
Schwarz et al. 2015a), since this experiment should provide even
larger data sets covering a wide area of the sky ($f_{\text{sky}} \approx 0.75$). All
these efforts will enable to put under scrutiny the crucial assump-
tions of the standard cosmological scenario with unprecedented

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