ΛCDM: Triumphs, Puzzles and Remedies

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Abstract. The consistency level of ΛCDM with geometrical data probes has been increasing with time during the last decade. Despite of these successes, there are some puzzling conflicts between ΛCDM predictions and dynamical data probes (bulk flows, alignment and magnitude of low CMB multipoles, alignment of quasar optical polarization vectors, cluster halo profiles). Most of these puzzles are related to the existence of preferred anisotropy axes which appear to be unlikely close to each other. A few models that predict the existence of preferred cosmological axes are briefly discussed.

A wide range of precise cosmological observations (Hicken et al., 2009; Astier et al., 2006; Kowalski et al., 2008; Komatsu et al., 2009; Reid et al., 2010) that developed during the past two decades are well described by a class of cosmological models that rely on a set of simple assumptions:

- The universe is homogeneous and isotropic on scales larger than a few hundred Mpc.
- General Relativity is the correct theory that describes gravity on all macroscopic scales.
- The universe consists of radiation (photons), matter (dark matter, baryons and leptons) and dark energy (a substance with repulsive gravitational properties which dominates at recent cosmological times and leads to accelerating cosmic expansion (Copeland, Sami & Tsujikawa, 2006)).
- Primordial fluctuations that gave rise to structure formation were created as quantum fluctuations in an approximately scale invariant process that took place during inflation.

The simplest representative of the above class of models is the ΛCDM model (Sahni, 2002; Padmanabhan, 2003). In this model the role of dark energy is played by the cosmological constant, a homogeneous form of energy whose density remains constant even in an expanding background. This is the current standard cosmological model and it is consistent with the vast majority of cosmological observations. Such observations involve geometric probes (Hicken et al., 2009; Astier et al., 2006; Kowalski et al., 2008; Komatsu et al., 2009; Reid et al., 2010) (direct probes of the large scale cosmic metric) and dynamical probes (Bertschinger, 2006; Nesseris & Perivolaropoulos, 2008) of the large scale cosmic structure that probe simultaneously the large scale cosmic metric and the gravitational growth of perturbations, namely the theory of gravity on large scales.

Geometric probes of the cosmic expansion include the following:

- Type Ia supernovae (SnIa) standard candles (Hicken et al., 2009; Astier et al., 2006; Kowalski et al., 2008).
The angular location of the first peak in the CMB perturbations angular power spectrum (Komatsu et al., 2009). This peak probes the integrated cosmic expansion rate using the last scattering horizon as a standard ruler.

Baryon acoustic oscillations of the matter density power spectrum. These oscillations also probe the integrated cosmic expansion rate on more recent redshifts using the last scattering horizon as a standard ruler (Reid et al., 2010).

Other less accurate standard candles (Gamma Ray Bursts (Basilakos & Perivolaropoulos, 2008), HII starburst galaxies (Plionis et al., 2009)) and standard rulers (cluster gas mass fraction (Allen et al., 2004) as well as probes of the age of the universe (Krauss & Chaboyer, 2003).

Dynamical probes of the cosmic expansion and the gravitational law on cosmological scales include:

- X-Ray cluster growth data (Rapetti et al., 2008).
- Power spectrum of Ly-\(\alpha\) forest at various redshift slices (McDonald et al., 2005; Nesseris & Perivolaropoulos, 2008).
- Redshift distortion observed through the anisotropic pattern of galactic redshifts on cluster scales (Hawkins et al., 2003)
- Weak lensing surveys (Benjamin et al., 2007; Amendola, Kunz & Sapone, 2008)

These cosmological observations converge on the fact that the simplest model describing well the cosmic expansion rate is the one corresponding to a cosmological constant (Padmanabhan, 2003) in a flat space namely

\[
H(z)^2 = H_0^2 \left[ \Omega_{0m} (1 + z)^3 + \Omega_\Lambda \right] \tag{1}
\]

where \(H(z)\) is the Hubble expansion rate at redshift \(z\), \(H_0 = H(z = 0)\), \(\Omega_{0m}\) the present matter density normalized to the present critical density for flatness and \(\Omega_\Lambda = 1 - \Omega_{0m}\) is the normalized dark energy density which is time independent in the simplest case of the cosmological constant (\(\Lambda\)CDM).

In view of the wide range of successful predictions of \(\Lambda\)CDM, three possible approaches develop for cosmological research:

- **Mainstream Observers Approach:** Supporters of this approach focus on the majority of cosmological data that are consistent with \(\Lambda\)CDM. Thus, one assumes validity of \(\Lambda\)CDM and uses cosmological observations to impose constraints on the model parameters (such as \(\Omega_{0m}\)) with the best possible accuracy. The advantage of this approach is that given the present status of cosmological observations, it is the most likely to lead to accurate physical results. On the other hand, this approach is unlikely to reveal any new physics beyond \(\Lambda\)CDM if such physics is hidden in the data.

- **Theorist’s Approach:** This approach focuses on theoretical motivation and uses intuition and theoretical appeal to construct models more general than \(\Lambda\)CDM which usually include the standard model as a special point in parameter space. In this approach, the parameter space of the theory is initially enlarged in directions motivated by theoretical arguments. Subsequently, cosmological observations are used to constrain this parameter space in a region which is usually around the point corresponding to \(\Lambda\)CDM. The advantage of this approach is that it can produce beautiful and exciting theoretical results and predictions. On the other hand, it is unlikely to lead to the discovery of new physics because the simplicity of \(\Lambda\)CDM makes it a preferable model -in the context of a Bayesian approach- compared to any more complicated theoretical model.
• **Outlier Data Approach:** This approach focuses on the minority of data (outliers) that are inconsistent with ΛCDM at a level of more than $2 - 3\sigma$. Then one identifies common features of these data and constructs theoretical models consistent with these features. These models are used to make non-trivial predictions for upcoming cosmological observations. The construction of these models is not guided by theoretical motivation but by existing data which however may be affected by systematic or large statistical fluctuations. The disadvantage of this approach is that there is a relatively high probability that these ‘outlier’ data may be infected by large systematic or statistical fluctuations. As a result, the corresponding theoretical models may turn out to be unrealistic by future observations. On the other hand, if the ‘outlier’ data turn out to be representative of the real world, this approach is the most likely to reveal the existence of new physics. Historically, it may be verified that indeed this approach has led to the discovery of new models that constitute better descriptions of Nature than previous ‘standard models’. For example, in the early ’90s preliminary ‘outlier’ data (Efstathiou, Sutherland & Maddox, 1990) had challenged the sCDM model ($\Omega_{0m} = 1$) which was at the time the ‘standard’ cosmological model. Such data had provided early hints that $\Omega_{0m} < 1$ but at the time they were considered systematic or statistical fluctuations. Only after the SnIa data (Perlmutter et al., 1999), it was realized that the sCDM model needs to be abandoned in favor of ΛCDM.

Therefore, the question that needs to be addressed is the following: *Are there currently similar data that challenge the current standard model (ΛCDM) and what are their common features?* The answer to this question is positive. Indeed, these challenging to ΛCDM data may be summarized as follows (Perivolaropoulos, 2008):

(i) **Large Scale Velocity Flows:** ΛCDM predicts significantly smaller amplitude and scale of flows than what observations indicate. It has been found that the dipole moment (bulk flow) of a combined peculiar velocity sample extends on scales up to $100h^{-1} Mpc$ ($z \leq 0.03$) with amplitude larger than 400 km/sec (Watkins, Feldman & Hudson 2009). The direction of the flow has been found consistently to be approximately in the direction $l \simeq 282^\circ$, $b \simeq 6^\circ$. Other independent studies have also found large bulk velocity flows on similar directions on scales of about $100h^{-1} Mpc$ (Lavaux et al., 2010) or larger (Kashlinsky et al., 2009). The expected rms bulk flow in the context of ΛCDM normalized with WMAP5 ($\Omega_{0m}, \sigma_8$) = ($0.258, 0.796$) on scales larger than $50h^{-1} Mpc$ is approximately 110 km/sec. The probability that a flow of magnitude larger than 400 km/sec is realized in the context of the above ΛCDM normalization (on scales larger than $50h^{-1} Mpc$) is less than 1%. A possible connection of such large scale velocity flows and cosmic acceleration is discussed by Tsagas (2010).

(ii) **Alignment of low multipoles in the CMB angular power spectrum:** The normals to the octopole and quadrupole planes are aligned with the direction of the cosmological dipole at a level inconsistent with Gaussian random, statistically isotropic skies at 99.7% (Copi et al., 2010). The corresponding directions are: octopole plane normal $(l, b) = (308^\circ, 63^\circ)$ (Tegmark, de Oliveira-Costa & Hamilton 2003), CMB dipole moment $(l, b) = (240^\circ, 63^\circ)$ (Lineweaver et al., 1996). A related effect has also been recently observed by considering the temperature profile of ‘rings’ in the WMAP temperature fluctuation maps (Kovetz, Ben-David & Itzhaki, 2010). It was found that there is a ring with anomalously low mean temperature fluctuation with axis in the direction $(l, b) = (276^\circ, -1^\circ)$ which is relatively close to the above directions (particularly that corresponding to the bulk velocity flows).

(iii) **Large scale alignment in the QSO optical polarization data:** Quasar polarization vectors are not randomly oriented over the sky with a probability often in excess of 99.9%. The alignment effect seems to be prominent along a particular axis in the direction...
Table 1. Directions of Preferred axes from different cosmological observations.

| Cosmological Obs. & l  | b     | Reference                        |
|------------------------|-------|----------------------------------|
| SnIa Union2            | 309°  | 18°                             |
| CMB Dipole             | 264°  | 48°                             |
| Velocity Flows         | 282°  | 6°                             |
| Quasar Alignment       | 267°  | 69°                             |
| CMB Octopole           | 308°  | 63°                             |
| CMB Quadrupole         | 240°  | 63°                             |
| Mean                   | 278° ± 26° | 45° ± 27°                       |
void would experience the existence of a preferred cosmological axis through the Lemaitre-Tolman-Bondi metric (Alexander et. al., 2009; Garcia-Bellido & Haugboelle, 2008; Dunsby et. al., 2010; Garfinkle, 2010).

- Turbulent structure formation could also lead to large scale non-Gaussian features which would lead to the existence of a preferred axis (Schild & Gibson, 2008).
- Deviations from the isotropic cosmic expansion rate induced by a fundamental violation of the cosmological principle eg through a multiply connected non-trivial cosmic topology (Luminet, 2008), rotating universe coupled to an anisotropic scalar field (Carneiro & Mena Marugan, 2001), non-commutative geometry (Akofor et. al., 2008) or simply a fundamental anisotropic curvature (Koivisto et. al., 2011).
- Statistically anisotropic primordial perturbations (Armendariz-Picon, 2007; Pullen & Kamionkowski, 2007; Ackerman, Carroll & Wise 2007). For example, inflationary perturbations induced by vector fields (Dimopoulos et. al., 2009; Bartolo et. al., 2009). Note however that inflationary models with vector fields usually suffer from instabilities due to the existence of ghosts (Himmetoglu, Contaldi & Peloso, 2009).
- The existence of a large scale primordial magnetic field (Kahnishvili, Lavrelashvili & Ratra, 2008; Barrow, Ferreira & Silk, 1997; Campanelli, 2009). Evidence for such a magnetic field has recently been found in CMB maps (Kim & Naselsky, 2009).

The confirmation of the existence of a cosmological preferred axis would constitute a breakthrough in cosmological research. Given the present status of cosmological observations such a confirmation is one of the most probable directions from which new physics may emerge.

Given the preliminary evidence for anisotropy discussed above, it is important to extend and intensify efforts for the possible confirmation of this evidence. Such confirmation may be achieved by extending the SnIa compilations towards larger datasets and deeper redshifts that span as uniformly as possible all directions in the sky. This is important in view of the fact that the Union2 compilation is less uniform and detailed in the south galactic hemisphere.

The coordinates of the preferred axes of Table 1 are all located in a region less than a quarter of the North Galactic Hemisphere (left). The south galactic hemisphere (right) is also shown for completeness. The bulk flow direction is also visible in the south galactic hemisphere because it is close to the equator. The mean direction obtained in Table 1 with coordinates \((l, b) = (278^\circ, 45^\circ)\) is also shown.

**Figure 1.** The coordinates of the preferred axes of Table 1 are all located in a region less than a quarter of the North Galactic Hemisphere (left). The south galactic hemisphere (right) is also shown for completeness. The bulk flow direction is also visible in the south galactic hemisphere because it is close to the equator. The mean direction obtained in Table 1 with coordinates \((l, b) = (278^\circ, 45^\circ)\) is also shown.
In addition it is important to extend other cosmological data related to CMB low multipole moments, bulk velocity flows and quasar polarization to confirm the present existing evidence for preferred axes in these datasets. Finally, alternative probes of cosmological anisotropies may be considered like higher CMB multipole moments, non-gaussian features and polarization in the CMB maps, alignments of geometric features of various structures on large scales (there is already some preliminary evidence for alignment of handedness of spiral galaxies (Longo, 2009) along an axis not far from the directions of the other preferred axes of Table 1), alignment of optical polarization from various cosmological sources or studies based on cosmic parallax (Quartin & Amendola, 2010). It is also important to derive observational signatures that can clearly distinguish between the various different origins of the preferred axes.

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References

Ackerman, L., Carroll, S. M. and Wise, M. B. (2007). Imprints of a Primordial Preferred Direction on the Microwave Background. Phys. Rev. D 75, 083502 [Erratum-ibid. D 80, 069901 (2009)].

Akofor, E., Balachandran, A. P., Jo, S. G., Joseph, A. and Qureshi, B. A. (2008). Direction-Dependent CMB Power Spectrum and Statistical Anisotropy from Noncommutative Geometry. JHEP 0805, 092.

Alexander, S., Biswas, T., Notari A. and Vaid, D. (2009). Local Void vs Dark Energy: Confrontation with WMAP and Type Ia Supernovae. JCAP 0909, 025.

Allen, S. W., Schmidt, R. W., Ebeling, H., Fabian A. C. and van Speybroeck, L. (2004). Constraints on dark energy from Chandra observations of the largest relaxed galaxy clusters. Mon. Not. Roy. Astron. Soc. 353, 457.

Amendola, L., Kunz M. and Sapone D. (2008). Measuring the dark side (with weak lensing). JCAP 0804, 013.

Antoniou, I. and Perivolaropoulos, L. (2010). Searching for a Cosmological Preferred Axis: Union2 Data Analysis and Comparison with Other Probes. JCAP 1012, 012.

Armendariz-Picon, C. (2004). Could dark energy be vector-like? JCAP 0407, 007.

Armendariz-Picon, C. (2007). Creating Statistically Anisotropic and Inhomogeneous Perturbations. JCAP 0709, 014.

Astier, P. et al. [The SNLS Collaboration] (2006). The Supernova Legacy Survey: Measurement of $\Omega_M$, $\Omega_{\Lambda}$ and from the First Year Data Set. Astron. Astrophys. 447, 31.

Barrow, J. D., Ferreira P. G. and Silk, J. (1997). Constraints on a Primordial Magnetic Field. Phys. Rev. Lett. 78, 3610.

Bartolo, N., Dimastrogiovanni, E., Matarrese S. and Riotto, A. (2009). Anisotropic bispectrum of curvature perturbations from primordial non-Abelian vector fields. JCAP 0910, 015.

Basilakos S. and Perivolaropoulos L. (2008). Testing GRBs as Standard Candles. Mon. Not. Roy. Astron. Soc. 391, 411.

Battye, R. and Moss, A. (2009). Anisotropic dark energy and CMB anomalies. Phys. Rev. D 80, 023531.
Benjamin, J. *et al.* (2007). Cosmological Constraints From the 100 Square Degree Weak Lensing Survey. Mon. Not. Roy. Astron. Soc. **381**, 702.

Bertschinger, E. (2006). On the Growth of Perturbations as a Test of Dark Energy. Astrophys. J. **648**, 797.

Bielewicz, P., Gorski K. M. and Banday, A. J. (2004). Low order multipole maps of CMB anisotropy derived from WMAP. Mon. Not. Roy. Astron. Soc. **355**, 1283.

Broadhurst, T. J., Takada, M., Umetsu, K., Kong, X., Arimoto, N., Chiba, M. and Futamase, T. (2005). The Surprisingly Steep Mass Profile of Abell 1689, from a Lensing Analysis of Subaru Images. Astrophys. J. **619**, L143.

Campanelli, L. (2009). A Model of Universe Anisotropization. Phys. Rev. D **80**, 063006.

Carneiro S. and Mena Marugan, G. A. (2001). Anisotropic cosmologies containing isotropic background radiation. Phys. Rev. D **64**, 083502.

Copeland E. J., Sami M. and Tsujikawa S. (2006). Dynamics of dark energy. *Int. J. Mod. Phys. D* **15**, 1753.

Copi, C. J., Huterer, D., Schwarz, D. J. and Starkman G. D. (2006). On the large-angle anomalies of the microwave sky. Mon. Not. Roy. Astron. Soc. **367**, 79.

Copi, C., Huterer, D., Schwarz D. and Starkman, G. (2007). The Uncorrelated Universe: Statistical Anisotropy and the Vanishing Angular Correlation Function in WMAP Years 1-3. Phys. Rev. D **75**, 023507.

Copi, C. J., Huterer, D., Schwarz D. J. and Starkman, G. D. (2010). Large-angle anomalies in the CMB. Adv. Astron. **2010**, 847541.

Dimopoulos, K., Karciauskas, M., Lyth D. H. and Rodriguez, Y. (2009). Statistical anisotropy of the curvature perturbation from vector field perturbations. JCAP **0905**, 013.

Dunsby, P., Goheer, N., Osano, B. and Uzan, J. P. (2010). How close can an Inhomogeneous Universe mimic the Concordance Model? JCAP **1006**, 017.

Efstathiou, G., Sutherland, W. J. and Maddox, S. J. (1990). The cosmological constant and cold dark matter. Nature **348**, 705.

Esposito-Farese, G., Pitrou C. and Uzan, J. P. (2010). Vector theories in cosmology. Phys. Rev. D **81**, 063519.

Garcia-Bellido J. and Haugboelle, T. (2008). Confronting Lemaître-Tolman-Bondi models with Observational Cosmology. JCAP **0804**, 003.

Garfinkle, D. (2010). The motion of galaxy clusters in inhomogeneous cosmologies. Class. Quant. Grav. **27** 065002.

Gentile, G., Salucci, P., Klein, U., Vergani, D. and Kalberla, P. (2004). The cored distribution of dark matter in spiral galaxies. Mon. Not. Roy. Astron. Soc. **351**, 903.

Gorski K. M., Hansen F. K. and Lilje, P. B. (2007). Hemispherical power asymmetry in the three-year Wilkinson Microwave Anisotropy Probe sky maps. Astrophys. J. **660**, L81.

Hawkins, E. *et al.* (2003). The 2dF Galaxy Redshift Survey: correlation functions, peculiar velocities and the matter density of the Universe. Mon. Not. Roy. Astron. Soc. **346**, 78.

Hicken, M. *et al.* (2009). Improved Dark Energy Constraints from 100 New CfA Supernova Type Ia Light Curves. Astrophys. J. **700**, 1097.
Himmetoglu, B., Contaldi C. R., and Peloso, M. (2009). Instability of anisotropic cosmological solutions supported by vector fields. Phys. Rev. Lett. **102**, 111301.

Hutsemekers, D., Cabanac, R., Lamy, H. and Sluse, D. (2005). Mapping extreme-scale alignments of quasar polarization vectors. Astron. Astrophys. **441**, 915.

Jimenez J. B., and Maroto, A. L. (2009). Large-scale cosmic flows and moving dark energy. JCAP **0903**, 015.

Kahniashvili, T., Lavrelashvili G. and Ratra, B. (2008). CMB Temperature Anisotropy from Broken Spatial Isotropy due to an Homogeneous Cosmological Magnetic Field. Phys. Rev. D **78**, 063012.

Kashlinsky A., Atrio-Barandela, F., Kocevski, D., and Ebeling H. (2009). A measurement of large-scale peculiar velocities of clusters of galaxies: results and cosmological implications. Astrophys. J. **686**, L49.

Kim J. and Naselsky, P. (2009). Alfvén turbulence in the WMAP 5 year data and a forecast for the PLANCK. JCAP **0907**, 041.

Koivisto T. and Mota, D. F. (2006). Dark Energy Anisotropic Stress and Large Scale Structure Formation. Phys. Rev. D **73**, 083502.

Koivisto, T. S., Mota, D. F., Quartin M. and Zlosnik, T. G. (2011). On the Possibility of Anisotropic Curvature in Cosmology. Phys. Rev. D **83**, 023509.

Komatsu E. et al. [WMAP Collaboration] (2009). Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation. Ap.J. Suppl. **180**, 330.

Kovetz, E. D., Ben-David, A. and Itzhaki, N. (2010). Giant Rings in the CMB Sky. Astrophys. J. **724**, 374.

Kowalski, M. et al. (2008). Improved Cosmological Constraints from New, Old and Combined Supernova Datasets. Astrophys. J. **686**, 749.

Krauss, L. M. and Chaboyer, B. (2003). Age Estimates of Globular Clusters in the Milky Way: Constraints on Cosmology. Science **299**, 65.

Land, K. and Magueijo, J. (2005). The axis of evil. Phys. Rev. Lett. **95**, 071301 (2005).

Lavaux, G. Tully, R. B., Mohayaee, R. and Colombi, S. (2010). Cosmic flow from 2MASS redshift survey: The origin of CMB dipole and implications for LCDM cosmology. Astrophys. J. **709**, 483.

Lineweaver, C. H., Tenorio, L., Smoot, G. F., Keegstra, P., Banday, A. J. and Lubin, P. (1996). The Dipole Observed in the COBE DMR Four-Year Data. Astrophys. J. **470**, 38.

Longo, M. J. (2009). Evidence for a Preferred Handedness of Spiral Galaxies. [arXiv:0904.2529](http://arxiv.org/abs/0904.2529)

Luminet, J. P. (2008). The Shape and Topology of the Universe. [arXiv:0802.2236](http://arxiv.org/abs/0802.2236) [astro-ph].

McDonald, P. et al. [SDSS Collaboration] (2005). The Linear Theory Power Spectrum from the Lyman-alpha Forest in the Sloan Digital Sky Survey. Astrophys. J. **635**, 761.

Nesseris, S. and Perivolaropoulos, L. (2008). Testing LCDM with the Growth Function δ(a): Current Constraints. Phys. Rev. D **77**, 023504.

Padmanabhan, T (2003). Cosmological constant: The weight of the vacuum. Phys. Rept. **380**, 57.
Peiris H. V. and Smith, T. L. (2010). CMB Isotropy Anomalies and the Local Kinetic Sunyaev-Zel’dovich Effect. Phys. Rev. D 81, 123517.

Perivolaropoulos, L. (2008). Six Puzzles for LCDM Cosmology. Invited article to the TSPU anniversary volume ”The Problems of Modern Cosmology” on the occasion of the 50th birthday of Prof. S. D. Odintsov. arXiv:0811.4684.

Perlmutter S. et al. [Supernova Cosmology Project Collaboration] (1999). Measurements of Omega and Lambda from 42 High-Redshift Supernovae. Astrophys. J. 517, 565.

Plionis, M., Terlevich, R., Basilakos, S., Bresolin, F., Terlevich, E., Melnick, J. and Georgantopoulos, I. (2009). Alternative High-z Cosmic Tracers and the Dark Energy Equation of State. J. Phys. Conf. Ser. 189, 012032.

Pullen A. R. and Kamionkowski, M. (2007). Cosmic Microwave Background Statistics for a Direction-Dependent Primordial Power Spectrum. Phys. Rev. D 76, 103529.

Quartin M. and Amendola, L. (2010). Distinguishing Between Void Models and Dark Energy with Cosmic Parallax and Redshift Drift. Phys. Rev. D 81, 043522.

Rapetti, D., Allen, S. W., Mantz A. and Ebeling, H. (2008). Constraints on modified gravity from the observed X-ray luminosity function of galaxy clusters. arXiv:0812.2259 [astro-ph].

Reid B. A. et al. [SDSS Collaboration] (2010). Baryon Acoustic Oscillations in the Sloan Digital Sky Survey Data Release 7 Galaxy Sample. Mon. Not. Roy. Astron. Soc. 401, 2148.

Rodrigues, D. C. (2008). Anisotropic Cosmological Constant and the CMB Quadrupole Anomaly. Phys. Rev. D 77, 023534.

Sahni, V. (2002). The cosmological constant problem and quintessence. Class. Quant. Grav. 19, 3435.

Schild R. E. and Gibson C. H. (2008). Goodness in the Axis of Evil. arXiv:0802.3229 [astro-ph].

Tegmark, M., de Oliveira-Costa, A. and Hamilton A. (2003). A high resolution foreground cleaned CMB map from WMAP. Phys. Rev. D 68, 123523.

Tsagas, C. G. (2010). Large-scale peculiar motions and cosmic acceleration. Mon. Not. Roy. Astron. Soc. 405, 503.

Umetsu, K. and Broadhurst, T. (2008). Combining Lens Distortion and Depletion to Map the Mass Distribution of A1689. Astrophys. J. 684, 177.

Watkins, R., Feldman, H. A. and Hudson, M. J. (2009). Consistently Large Cosmic Flows on Scales of 100 Mpc/h: a Challenge for the Standard LCDM Cosmology. Mon. Not. Roy. Astron. Soc. 392, 743.

Zumalacarregui, M., Koivisto, T. S., Mota, D. F. and Ruiz-Lapuente, P. (2010). Disformal Scalar Fields and the Dark Sector of the Universe. JCAP 1005, 038.