

Λ CDM: Triumphs, Puzzles and Remedies

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Abstract. The consistency level of Λ CDM with geometrical data probes has been increasing with time during the last decade. Despite of these successes, there are some puzzling conflicts between Λ CDM 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.

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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 Λ CDM 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), III 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- α 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

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

where $H(z)$ is the Hubble expansion rate at redshift z , $H_0 = H(z=0)$, Ω_{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 (Λ CDM).

In view of the wide range of successful predictions of Λ 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 Λ CDM. Thus, one assumes validity of Λ CDM and uses cosmological observations to impose constraints on the model parameters (such as Ω_{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 Λ 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 Λ 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 Λ 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 Λ 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 Λ CDM 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 (flat $\Omega_{0m} = 1$) 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 Λ CDM.

Therefore, the question that needs to be addressed is the following: *Are there currently similar data that challenge the current standard model (Λ CDM) and what are their common features?*

The answer to this question is positive. Indeed, these challenging to Λ CDM data may be summarized as follows (Perivolaropoulos, 2008):

- (i) **Large Scale Velocity Flows:** Λ CDM 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 $400km/sec$ (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 Λ CDM normalized with WMAP5 (Ω_{0m}, σ_8) = (0.258, 0.796) on scales larger than $50h^{-1}Mpc$ is approximately $110km/sec$. The probability that a flow of magnitude larger than $400km/sec$ is realized in the context of the above Λ CDM 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 $(l, b) = (308^\circ, 63^\circ)$, quadrupole plane normal $(l, b) = (240^\circ, 63^\circ)$ (Tegmark, de Oliveira-Costa & Hamilton 2003), CMB dipole moment $(l, b) = (264^\circ, 48^\circ)$ (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 $(l, b) = (267^\circ, 69^\circ)$ (Hutsemekers *et. al.*, 2005).
- (iv) **Profiles of Cluster Haloes:** Λ CDM predicts shallow low concentration and density profiles in contrast to observations which indicate denser high concentration cluster haloes (Broadhurst *et. al.*, 2005; Umetsu & Broadhurst, 2008).
- (v) **Missing power on the low l multipoles of the CMB angular power spectrum** which leads to a vanishing correlation function $C(\theta)$ on angular scales larger than 60° (Copi *et. al.* 2007; Copi *et. al.*, 2010)

In addition to the above large scale effects there are issues on galactic scales (missing satellites problem (Klypin *et. al.*, 1999) and the cusp/core nature of the central density profiles of dwarf galaxies (Gentile *et. al.*, 2004)).

Three of the above five large scale puzzles are large scale effects related to preferred cosmological directions (CMB multipole alignments, QSO polarization alignment and large scale bulk flows) which appear to be not far from each other (Antoniu & Perivolaropoulos, 2010). Their direction is approximately normal to the axis of the ecliptic poles $(l, b) = (96^\circ, 30^\circ)$ and lies close to the ecliptic plane and the equinoxes. This coincidence has triggered investigations for possible systematic effects related to the CMB preferred axis but no significant such effects have been found (Copi *et. al.*, 2010).

In addition, it has been shown recently (Antoniu & Perivolaropoulos, 2010) that the Union2 SNIa data hint towards a direction of maximum accelerating expansion that is abnormally close to the directions of the above preferred axes. In Table 1, I show the directions of the

Table 1. Directions of Preferred axes from different cosmological observations.

Cosmological Obs. & l	b	Reference	
SnIa Union2	309°	18°	(Antoniou & Perivolaropoulos, 2010)
CMB Dipole	264°	48°	(Lineweaver <i>et. al.</i> , 1996)
Velocity Flows	282°	6°	(Watkins, Feldman & Hudson 2009)
Quasar Alignment	267°	69°	(Hutsemekers <i>et. al.</i> , 2005)
CMB Octopole	308°	63°	(Bielewicz, Gorski & Banday, 2004)
CMB Quadrupole	240°	63°	(Bielewicz, Gorski & Banday, 2004)
Mean	$278^\circ \pm 26^\circ$	$45^\circ \pm 27^\circ$	-

preferred axes from different cosmological observations along with the corresponding references.

These directions are also shown in Figure 1 in galactic coordinates. It is straightforward to show (Antoniou & Perivolaropoulos, 2010) that the probability of such proximity among axes directions that should be independent of each other is less than 1%. Thus, unless there is a hidden common systematic (Peiris & Smith, 2010), the existence of a cosmological preferred axis may be attributed to physical effects. An incomplete list of these effects is the following:

- An anisotropic dark energy equation of state (Zumalacarregui *et. al.*, 2010; Koivisto & Mota, 2006; Battye & Moss, 2009) due perhaps to the existence of vector fields (Armendariz-Picon, 2004; Esposito-Farese, Pitrou & Uzan, 2010).
- Dark Energy and/or Dark matter perturbations on scales comparable to the horizon scale

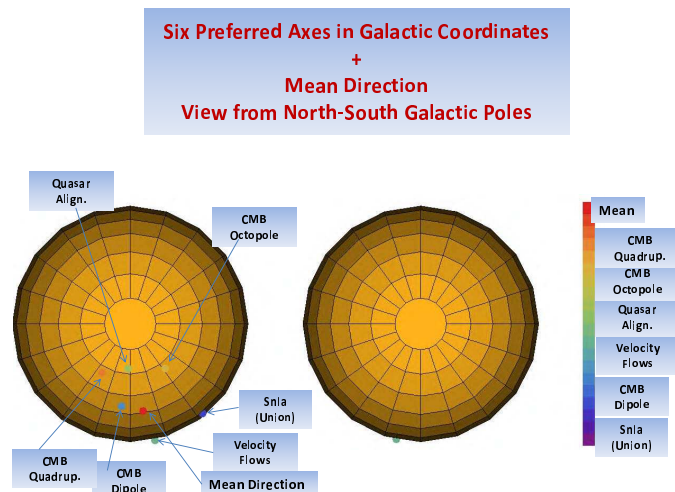


Figure 1. The coordinates of the preferred axes of Table 1 are all located in a region less than a quarter of the North Galactic Hemisphere (left). The south galactic hemisphere (right) is also shown for completeness. The bulk flow direction is also visible in the south galactic hemisphere because it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

(Rodrigues, 2008; Jimenez & Maroto, 2009). For example an off center observer in a 1Gpc 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 (Akofer *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 (Kahniashvili, 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. 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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