100 Years of the Cosmological Constant: What’s Next?

Ofer Lahav (University College London)
Energy in General Relativity

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When studying gravitational wave, gravitational field energy is transformed into electromagnetic energy and finally in an easy to handle form. Consequently, gravitational waves on earth are not to be forgotten. However, at a two-loop level, the concept of energy is associated with the existence of special correlations in spacetime. The problem of identifying energy may be made difficult when extending gravity theories, such as electromagnetism and statistical mechanics, to finite general relativistic systems that involve finite amounts of energy. Hence we review the significant steps in the search for global and local conservation laws in problems and addressed.

1. Vector Conservation Laws and General Relativity

The first, well known, and most important aspect of conservation laws is their vector character in spacetime. In classical mechanics, fluid dynamics, electrodynamic and relativistic field theories (in flat spacetime), there are various conservation laws. The most notable technique to find these laws is Noether's method of theorems which relates to a finite number of symmetries of flat spacetime. In general relativity there is a problem with conservation that is not properly vector spacetimes are curved and whose symmetry in general.

The archetype of a differential conservation law in special relativity is that of particle number with density $\rho$ and density flux $J$ of components $\rho_j$ in the X,Y,Z directions: denoting $\partial_\mu J^\mu$, T the time, by $\partial_\mu J^\mu$, we have

$$\partial_\mu J^\mu + \partial_\nu J^\nu = 0 \quad (\alpha = 1, 2, 3)$$

This equation holds in an inertial frame and is written in orthogonal (Minkowski) coordinates. All conservation laws have the form: a four dimensional divergence of a two vector in some sense is equal to zero. In particular, if $T^\mu_\nu$ is the density of energy and $T^\mu_\nu$ the flux of energy with components $T^\mu_\nu$, then the local differential equation representing conservation of energy reads

$$\partial_\mu T^\mu + \partial_\nu T^\nu = 0$$

Likewise the 3 components of linear momentum density $T^\mu_\nu$ and their density fluxes $T^\mu_\nu$ with components $T^\mu_\nu$ satisfy a conservation equation of the same form:

$$\partial_\mu T^\mu + \partial_\nu T^\nu = 0$$

In special relativity the components of energy density $T^\mu_\nu$ and energy flux as well as linear momentum density $T^\mu_\nu$ and linear momentum flux combine into a single entity.

Outline

• 100 years of Λ
• Λ on Mpc scales
• The Dark Energy Survey
• More than Dark Energy:
  • Gravitational Wave follow-ups
• The era of Big Data
What accelerates the Universe?

“a simple but strange universe”
100 years of Lambda

Modified Newtonian

\[ \nabla^2 \phi - \lambda \phi = 4\pi \kappa \rho \]

Modified GR

\[ g_{\mu \nu} - \lambda g_{\mu \nu} = -\kappa \left( T_{\mu \nu} - \frac{1}{2} g_{\mu \nu} T \right) \]

In a static universe:

\[ \lambda = \frac{\kappa \rho}{2} = \frac{1}{R^2} \]

Einstein (February 1917)
See review O’Raifeartaigh et al. (1701.07261)
Lambda from the APM galaxy clustering (1990)
\[ \Omega^\Lambda = 1 - 0.2 = 0.8 \]

The cosmological constant and cold dark matter
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Department of Physics, University of Oxford, Oxford OX1 3RH, UK

THE cold dark matter (CDM) model\(^1\)\(^-\)\(^4\) for the formation and distribution of galaxies in a universe with exactly the critical density is theoretically appealing and has proved to be durable, but recent work\(^5\)\(^-\)\(^8\) suggests that there is more cosmological structure on very large scales (\(> 10 h^{-1}\) Mpc, where \(h\) is the Hubble constant \(H_0\) in units of 100 km s\(^{-1}\) Mpc\(^{-1}\)) than simple versions of the CDM theory predict. We argue here that the successes of the CDM theory can be retained and the new observations accommodated in a spatially flat cosmology in which as much as 80\% of the critical density is provided by a positive cosmological constant, which is dynamically equivalent to endowing the vacuum with a non-zero energy density. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant. As well as explaining large-scale structure, a cosmological constant can account for the lack of fluctuations in the microwave background and the large number of certain kinds of object found at high redshift.

Measuring the acceleration of the Universe

- Alternative Universes for Constant $w$
  - $w = -1.03$
  - $w = -0.97$

- $\Omega_m = 0.27$
- $\Omega_x = 0.73$
- $\Omega_m = \frac{2}{3}$
- $\Omega_x = \frac{1}{3}$
- $w = -1$

- SNe (binned)
- BOSS
- DESI (predicted)

- past ← today → future
1% distances with Baryonic Acoustic Oscillations

**BOSS - Anderson et al (2013)**
Growth of structure
galaxy surveys vs. Planck
Gravitational Lensing: Weak and Strong

HST CLASH  cluster MACS1206
So what is Dark Energy?

- Systematics mimic DE?
- Lambda-CDM, EoS $w = -1.00$?
- Dynamical scalar field $w(z)$?
- Signatures of modified gravity?
- Inhomogeneous Universe?
- Multi-verse & Anthropic Principle?
- An unknown unknown??
Paradigm shifts: a new entity or a new theory?

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>New Entity</th>
<th>New theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranus’ orbit</td>
<td>Neptune</td>
<td>(Bessel’s specific gravity ruled out)</td>
</tr>
<tr>
<td>Mercury’s orbit</td>
<td>(Hypothetical planet Vulcan ruled out)</td>
<td>General Relativity</td>
</tr>
<tr>
<td>Beta decay</td>
<td>Neutrino</td>
<td>(violation of angular momentum ruled out)</td>
</tr>
<tr>
<td>Galaxy flat rotation curves</td>
<td>Dark Matter?</td>
<td>Modified Newtonian Dynamics?</td>
</tr>
<tr>
<td>Accelerating universe (SN Ia and other data)</td>
<td>Dark Energy?</td>
<td>Modified General Relativity?</td>
</tr>
</tbody>
</table>

OL & Michela Massimi (A&G 2014)
Lucy Calder & OL (Physics World 2010)
Weighing the Local Group in the presence of Dark Energy

\[ a = -\frac{GM}{r^2} + \frac{\Lambda}{3} r \]

- At present the Milky Way and Andromeda galaxies are separated by \( r=770 \text{ kpc} \) and are “falling” towards each other at \( v=109 \text{ km/sec} \).
- Given the age of the universe \( t=13.8 \text{ Gyr} \) and Dark Energy fraction of 70% we find that the mass is \( M = (4.73 \pm 1.03) \times 10^{12} \text{ M}_{\odot} \)
- 13% more than in the absence of Dark Energy

With \( \Lambda \): Binney & Tremaine (2008), Partridge, OL & Hoffman (2012), McLeod et al. (2017)
30k LG-like pairs in MultiDark simulations

McLeod, Libeskind, Hoffman & OL (arXiv:1606.02694)
Tension in LCDM?

- $h = 0.67$ (Planck) or $0.73$ (SN)?
- The amplitude $\Sigma_8$ in Planck vs WL
- Anomalies: the CMB Cold spot
- Tests of GR on large scales $\Rightarrow$ Modified Gravity?
KidS 450 sq degr: tension with Planck 2015?

Hildebrandt et al. (2016)
Testing GR: Gravitational redshifts in Clusters
ISW&RS effects in the CMB

The CMB Cold Spot & supervoid

\[ \Delta v_{gc} = -11^{+7}_{-5} \text{ km/s} \] (for \( 1 < r_{gc}/r_{200} < 2.5 \))

Szapudi et al. (2015)
Nadathur et al. (2014)

Wojtak et al. (2011)
Sadeh, Lerh & OL (2015)
The Dark Energy Survey

- Multi-probe approach
  - Wide field: Galaxy Clustering, Weak Lensing, Cluster Counts
  - Time domain: Supernovae

- Survey strategy
  - 300 million photometric redshifts (grizY) over 5000 deg²
  - 3500 SN Ia (over 27 sq deg fields)
  - overlap with VHS + SPT+ OzDES + …

- Science Verification (SV): 250 sq deg to full depth
- Y1: approx 2000 sq deg 40% of depth.
  - Median seeing FWHM approx 0.9”
  - (as required for WL in riz)
- Y2: approx remaining 3000 sq deg same depth
- Y3: done
- Y4: done

- The DES journey started in 2003
- Nearly about 4/5 of the programme done
- Over 90 DES papers on the arXiv
Dark Energy Survey Collaboration

~400 scientists from 7 nations

Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOA0, University of Michigan, University of Pennsylvania, Argonne National Lab, Ohio State University, Santa-Cruz/SLAC/Stanford, Texas A&M

UK Consortium:
UCL, Cambridge, Edinburgh, Nottingham, Portsmouth, Sussex

ETH Zurich
Ludwig-Maximilians Universität

Spain Consortium:
CIEMAT, IEEC, IFAE

Brazil Consortium

OzDES Consortium

CTIO
Mass-Light Correlations

DES galaxies per type (main/red)

Mass from DES Weak Lensing

Mass from CMB (Planck/SPT) Weak Lensing
WL mass map from DES SV
WL mass map from DES SV

Chang et al. (2016)  Jeffrey et al. (in prep)
DES galaxy and kappa pdf: Log Normal? Or a better model?

- Lognormal better than Gaussian, all scales
- Lognormal better than Gaussian at scales < 20 arcmin (< 5 Mpc/h)

Clerkin et al. (arXiv:1605.02036)
Testing LCDM with DES Weak Lensing and clustering

Kwan et al. 1604.07871
(dashed line: DES Collaboration 1507.05552)

Kacprzak et al. 1603.05040
Year 1 papers soon – stay tuned!

- WL: About $35\text{M}$ galaxies with shape measurements over (in riz) $1300\text{ sq deg}$
- 10 times SV in both galaxies and in area
- cf. KiDS, HSC
- 3 times 2pt functions: gal-gal, gal-shear, shear-shear
Subaru HSC mass maps
(167 sq deg; 25 galaxies per sq arc min)

Mass from WL  Light from LRG stellar mass

arXiv:1705.06792
DES: more than Dark Energy

- Solar system objects
- MW, dwarf satellites, LMC
- Galaxy evolution (including biasing and intrinsic alignments)
- Strong lensing
- QSOs (+ lensed QSOs)
- Super-luminous SN
- Gravitational wave follow ups

Low and high hanging fruit

<table>
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<tr>
<th>Objects</th>
<th>As of Dec 2015</th>
<th>Expected from full 5yr DES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galaxies with photo-z (&gt; 10 sigma)</td>
<td>7M (SV), 100M (Y1+Y2),</td>
<td>300M</td>
</tr>
<tr>
<td>Galaxies with shapes</td>
<td>3M (SV), 80M (Y1+Y2)</td>
<td>200M</td>
</tr>
<tr>
<td>Galaxy clusters (lambda&gt;5)</td>
<td>150K (Y1+Y2)</td>
<td>380K</td>
</tr>
<tr>
<td>SN Ia SLSN</td>
<td>1000 2 + confirmed + candidates</td>
<td>Thousands 15-20</td>
</tr>
<tr>
<td>New Milky Way companions</td>
<td>17</td>
<td>25</td>
</tr>
<tr>
<td>QSO’s at z&gt; 6 Lensed QSO’s</td>
<td>1 + confirmed + candidates</td>
<td>375 100 (i&lt;21)</td>
</tr>
<tr>
<td>Stars (&gt; 10 sigma)</td>
<td>2M (SV), 30M (Y1+Y2)</td>
<td>100M</td>
</tr>
<tr>
<td>Solar System: Trans Neptunian Objects</td>
<td>32 in SN fields + 2 in the WF</td>
<td>50 + many more in the wide field</td>
</tr>
<tr>
<td>Jupiter Trojans</td>
<td>19</td>
<td>500-1000</td>
</tr>
<tr>
<td>Main Belt asteroids</td>
<td>300K (Y1+Y2)</td>
<td></td>
</tr>
<tr>
<td>Kuiper Belt Objects</td>
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</tbody>
</table>
The new window of Gravitational Waves
DES LIGO GW follow ups

GW150914

Soares-Santos et al. (2016)
Annis et al. (2016)
Abbott et al. (2016)

GW151226

Cowperthwaite et al. (2016)
DES observing run in Sep 2015: on the night of 16 Sep a LIGO trigger, but a mag 8.3 earthquake!
DES LIGO GW follow ups

- So far DES followed up 2 out of the 3 GW events, both BH-BH mergers: no detections
- Current theoretical paradigm is that BH-BH mergers have no EM counterparts, but other models are being considered.
- DES search is sensitive to NS-NS and NS-BH out to 200 Mpc.
- The current main limitation is the poor angular localization (until Virgo and other GW experiments come online).
The DES followup strategy

• DES: wide-field, large aperture, red-sensitive CCD
• Aim at observations within 24hr of trigger
• For GW150914: 102 sq deg observed, in 28 fields (90 sec) + 20 fields in the (5 sec) in the LMC [search for core-collapse events, eg redupergiants progenitors]
• For GW151226: 36 sq deg
• Employ templates and difference imaging pipeline
• Spinoffs: detection of other objects with time variability; preparations for the LSST era.
The era of DESI, Euclid, LSST,…
Dark Energy Spectroscopic Instrument (DESI) – 10 times BOSS

Mayall telescope available up to 100% of dark time,
5000 fibres, 20min base integration time
> 20 million targets
14,000 to 18,000 deg² survey

1 million Ly-A QSOs
+2.5 million QSOs
18 million ELGs
4 million LRGs
Cosmic Vision forecast

![Graph showing improvement over current constraints for Stage IV and Stage V.](image)

arXiv:1604.07626
Possible outcomes of ongoing and future surveys

- $W = \frac{P}{\rho} = -1.00 \pm 0.01$
- $W = 0.12 \pm 0.01$
  
  Or $W = -1.23 \pm 0.01$
  
  or $W(z)$

- The Unknown
  
  Unknown

  ???

Back to Lambda

‘Accuracy’ vs ‘Precision’

A new paradigm shift?

Back to fundamental Physics

Back to systematics/Astrophysics

Anthropic Principle?

Then fundamental Physics
Big Data in Astrophysics and HEP

- Google: 3.5 Billion Google searches per day
- LHC: 600 Million collisions per second
  (only 100 per second are ‘interesting’)
- SDSS: 200 Giga\((10^9)\) Bytes per night
- DES: 1 Tera \((10^{12})\) Bytes per night
- LSST: 15 Tera Bytes per night
- SKA: 1 Peta \((10^{15})\) Bytes per day
Big numbers

• Exo-planets: 9-1 (+1?) +2000+…
• Gaia: 1B stars
• DES: 300M galaxies
• Euclid/LSST: 1B galaxies
• Simulations: N-body, Hydro
  (many times the data)
Data Intensive Science @ UCL

New STFC-funded UCL’s Centre for Doctoral Training in Data Intensive Science
http://www.hep.ucl.ac.uk/cdt-dis/

33 PhD students; first PhD intake Sep 2017
20 industry partners

Decision Trees
Artificial Neural Networks
Summary

• 25 years of LCDM: supported by most observations.
• Important to test LCDM further (local dynamics, CMB Cold Spot, gravitational redshift)
• DES does “see” DM, and good correlations between DM and galaxies.
• DES on the path to DE from LSS, WL, Clusters & SN Ia (+ cross correlations).
• DES: successor of APM, 2dF & SDSS; precursor of LSST, DESI, Euclid and WFIRST; Big Data
• What are the prospects for a new paradigm shift, beyond LCDM, eg w(z) or ModGrav?