Darkness Visible with the Next Generation Galaxy Surveys

- More on Neutrino masses
- Brief History of Dark Energy
- Can we distinguish DE from Modified GR?
- Photometric vs. Spectroscopic Surveys
- Examples: DES, Euclid, CLASH
Neutrinos decoupled when they were still relativistic, hence they wiped out structure on small scales

\[ k > k_{nr} = 0.026 \left( \frac{m_\nu}{1 \text{ eV}} \right)^{1/2} \Omega_m^{1/2} \frac{h}{\text{Mpc}} \]

\[ \Omega_\nu h^2 = M_\nu / (94 \text{ eV}) \]

CDM+

1.9 eV neutrinos

CDM

Agarwal & Feldman 2010
Neutrino mass from MegaZ-LRG
700,000 galaxies within 3.3 (Gpc/h)^3

Total mass < 0.28 eV (95% CL)

Thomas, Abdalla & Lahav, PRL (2010) 0911.5291
Total Neutrino Mass

DES+Planck vs. KATRIN

$M_\nu < 0.1 \text{ eV}$  \hspace{1cm} $M_\nu < 0.6 \text{ eV}$

Lahav, Kiakotou, Abdalla and Blake (2010) 0910.4714
The Chequered History of the Cosmological Constant $\Lambda$

* The old CC problem: Theory exceeds observational limits on $\Lambda$ by $10^{120}$!

* The new CC problem: Why are the amounts of Dark Matter and Dark Energy so similar?
Pre-Supernovae paradigm shift

• Peebles (1984) advocated Lambda
• APM result for low matter density (Efstathiou et al. 1990)
• Baryonic fraction in clusters (White et al. 1993)
• The case for adding Lambda (Ostriker & Steinhardt 1995)
• Cf. linear Lambda-like force (Newton 1687 !)

Probes of Darkness

Observational data
• Type Ia Supernovae
• Galaxy Clusters
• Cosmic Microwave Background
• Large Scale Structure
• Gravitational Lensing
• Integrated Sachs-Wolfe

Physical effects:
• Geometry
• Growth of Structure

Both depend on the Hubble expansion rate:

$$H^2(z) = H^2_0 \left[ \Omega_M (1+z)^3 + \Omega_{DE} (1+z)^3 (1+w) \right]$$

(flat)
Can we rule out $w = -1$?

**TABLE 4**

**SUMMARY OF THE 68% LIMITS ON DARK ENERGY PROPERTIES FROM WMAP COMBINED WITH OTHER DATA SETS**

<table>
<thead>
<tr>
<th>Section</th>
<th>Curvature</th>
<th>Parameter</th>
<th>$+\text{BAO}+H_0$</th>
<th>$+\text{BAO}+H_0+D_{\Delta t}$&lt;sup&gt;a&lt;/sup&gt;</th>
<th>$+\text{BAO}+\text{SN}$&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 5.1</td>
<td>$\Omega_k = 0$</td>
<td>Constant $w$</td>
<td>$-1.10 \pm 0.14$</td>
<td>$-1.08 \pm 0.13$</td>
<td>$-0.980 \pm 0.053$</td>
</tr>
<tr>
<td>Section 5.2</td>
<td>$\Omega_k \neq 0$</td>
<td>Constant $w$</td>
<td>$-1.44 \pm 0.27$</td>
<td>$-1.39 \pm 0.25$</td>
<td>$-0.999_{-0.056}^{+0.057}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Omega_k$</td>
<td>$-0.0125_{-0.0067}^{+0.0064}$</td>
<td>$-0.0111_{-0.0063}^{+0.0060}$</td>
<td>$-0.0057_{-0.0068}^{+0.0067}$</td>
</tr>
<tr>
<td>Section 5.3</td>
<td>$\Omega_k = 0$</td>
<td>$w_0$</td>
<td>$-0.83 \pm 0.16$</td>
<td>$-0.93 \pm 0.13$</td>
<td>$-0.93 \pm 0.12$</td>
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<tr>
<td></td>
<td></td>
<td>$w_a$</td>
<td>$-0.80_{-0.83}^{+0.84}$</td>
<td>$-0.41_{-0.71}^{+0.72}$</td>
<td>$-0.38_{-0.65}^{+0.66}$</td>
</tr>
</tbody>
</table>
Spectroscopic Surveys

SDSS

CfA

2MRS

2dFGRS
Standard rulers
Redshift Distortion as a test of Modified Gravity

Guzzo et al. 2008
Growth of structure results

- Flat ΛCDM with $\Omega_m=0.30$, $\sigma_8=0.80$
- Flat DGP with $\Omega_m=0.30$, $\sigma_8=0.64$

Credit: Chris Blake
Probing the Geometry of the Universe with Supernovae Ia

‘Union’ SN Ia sample (Kowalski et al. 2008)
The Integrated Sachs-Wolfe Effect

gravitational potential traced by galaxy density

potential depth changes as cmb photons pass through

\[ \frac{\delta T}{T} = -2 \int \Phi(\tau) d\tau \]

In EdS the potential is constant with time, hence no ISW effect.

An effect is expected in a universe with DE, and it can be detected by cross-correlating the CMB with galaxy maps (Crittenden et al).
In 3 Dimensions

Massey et al. 2007
Deviations from standard GR?

\[ ds^2 = -a^2(\tau) \{d\tau^2[1 + 2\psi(x, \tau)] + dx^2[1 - 2\phi(x, t)]\} \]

Lensing is sensitive to the sum of potentials, while velocities respond to the temporal potential.

\[ \gamma(k, a) \equiv \frac{\ln(\delta_c/\mathcal{H}\delta_c)}{\ln \Omega_m(a)}, \quad \eta(k, a) \equiv \frac{\phi(k, a)}{\psi(k, a)}, \]

Dark energy vs Modified Gravity

DES-like (WL, clusters, SN, BAO)

Assumed DE

Assumed Mod Grav

Shapiro et al. (2010)
Combining imaging & spectroscopy to constrain modified gravity

Guzik, Jain & Takada 2009
Photo-z – Dark Energy cross talk

• Approximately, for a photo-z slice:

\[
\frac{\delta w}{w} = 5 \frac{\delta z}{z} = 5 \frac{\sigma_z}{z} N_s^{-1/2}
\]

=> the target accuracy in \( w \) and photo-z scatter \( \sigma_z \) dictate the number of required spectroscopic redshifts

\[N_s = 10^5 - 10^6\]
1.5M LRGs ("MegaZ")
photo-z code comparison

ANNz

HpZ+BC

Le PHARE

HpZ+WWC

Abdalla, Banerji, Lahav & Rashkov

Cf. PHAT (Hildebrandt et al. 2010)
# Photometric and Spectroscopic surveys 2010-2020

<table>
<thead>
<tr>
<th>Survey</th>
<th>Depth (mag or redshift)</th>
<th>Area (sq deg)</th>
<th>Imaging Filters/ Spectra Resolution</th>
<th>Schedule</th>
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<tbody>
<tr>
<td>KIDS (+Viking)</td>
<td>$r' &lt; 24.4$</td>
<td>1500</td>
<td>ugriz, ZYH</td>
<td>2010-</td>
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<tr>
<td>DES (+VHS)</td>
<td>$r &lt; 24$</td>
<td>5000</td>
<td>grizYJHK</td>
<td>2011-2016</td>
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<td>Pan-STARRS1</td>
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<td>grizY</td>
<td>2010-</td>
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<tr>
<td>Pan-STARRS4</td>
<td>$r &lt; 25.6$</td>
<td>30000</td>
<td>grizY</td>
<td>?</td>
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<td>Hyper-Suprime</td>
<td>$r &lt; 25$</td>
<td>2000</td>
<td>BVRiz</td>
<td>2011-2016</td>
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<tr>
<td>Skymapper</td>
<td>$g &lt; 22.9$</td>
<td>15000</td>
<td>Uvgriz</td>
<td>2008-2011</td>
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<tr>
<td>PAU</td>
<td>$i &lt; 23$</td>
<td>8000</td>
<td>50 narrow bands</td>
<td>2011-2015</td>
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<tr>
<td>LSST</td>
<td>$g &lt; 26$</td>
<td>30000</td>
<td>Ugriz</td>
<td>2014-</td>
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<tr>
<td>SNAP</td>
<td>$R &lt; 28.3$</td>
<td>4000</td>
<td>9 visible and IR</td>
<td>?</td>
</tr>
<tr>
<td>Euclid-imaging</td>
<td>$RIZ&lt;24.5$</td>
<td>20000</td>
<td>RIZ+YJH</td>
<td>2017-</td>
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<tr>
<td>WiggleZ</td>
<td>$r &lt; 22.5$ (+ UV)</td>
<td>1000</td>
<td>~400</td>
<td>2006-2010</td>
</tr>
<tr>
<td>BOSS (SDSS3)</td>
<td>$r &lt; 20$ (LRG)</td>
<td>10000</td>
<td>2000</td>
<td>2009-2014</td>
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<tr>
<td>Hectex</td>
<td>$1.8 &lt; z &lt; 3.8$</td>
<td>200</td>
<td>850</td>
<td>2009-</td>
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<tr>
<td>WFMOS $z=1$ (3)</td>
<td>$R_{ab} &lt; 22.7$ (24.5)</td>
<td>2000 (300)</td>
<td>5000</td>
<td>? (Sumire)</td>
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<tr>
<td>BigBOSS</td>
<td>$z &lt; 3.5$</td>
<td>14000</td>
<td>5000</td>
<td>?</td>
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<tr>
<td>SNAP</td>
<td>$0.3 &lt; z &lt; 1.7$</td>
<td>4000</td>
<td>~200</td>
<td>?</td>
</tr>
<tr>
<td>ADEPT</td>
<td>$z &gt; 0.8$</td>
<td>20000</td>
<td></td>
<td>?</td>
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<tr>
<td>SKA</td>
<td>$z &lt; 1.5$</td>
<td>20000</td>
<td></td>
<td>2020</td>
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<tr>
<td>Euclid-spectroscopic</td>
<td>$0.5 &lt; z &lt; 2.0$</td>
<td>20000</td>
<td>400</td>
<td>2017-</td>
</tr>
</tbody>
</table>
The Dark Energy
http://www.darkenergysurvey.org
Dark Energy Science Program

Four Probes of Dark Energy

- **Galaxy Clusters**
  - clusters to $z>1$
  - SZ measurements from SPT
  - Sensitive to growth of structure and geometry

- **Weak Lensing**
  - Shape measurements of 300 million galaxies
  - Sensitive to growth of structure and geometry

- **Large-scale Structure**
  - 300 million galaxies to $z = 1$ and beyond
  - Sensitive to geometry

- **Supernovae**
  - 15 sq deg time-domain survey
  - ~3000 well-sampled SNe Ia to $z \sim 1$
  - Sensitive to geometry

Plus QSOs, Strong Lensing, Milky Way, Galaxy Evolution
The Dark Energy Survey (DES)

• Proposal:
  – Perform a 5000 sq. deg. survey of the southern galactic cap
  – Measure dark energy with 4 complementary techniques

• New Instrument:
  – Replace the PF cage with a new 2.2 FOV, 520 Mega pixel optical CCD camera + corrector

• Time scale:
  – Instrument Construction 2008-2011

• Survey:
  – Area overlap with SPT SZ survey and VISTA VHS
The 5 lenses are now being polished

Polishing & coating coordinated by UCL (with 1.7M STFC funding)
Image Level Simulations

DECam Focal Plane

62 2kx4k Science CCDs
(520 Mpix)

A single simulated DECam pointing
(= tile = hex)

1 GB per single 3 deg² pointing
Euclid

Wide Survey: Extragalactic sky (20,000 deg$^2$ = 2$\pi$ sr)

- Visible: Galaxy shape measurements to $RIZ_{AB} \leq 24.5$ (AB, 10$\sigma$) at 0.16” FWHM, yielding 30-40 resolved galaxies/amin$^2$, with a median redshift $z \sim 0.9$

- NIR photometry: Y, J, H $\leq 24$ (AB, 5$\sigma$ PS), yielding photo-z’s errors of 0.03-0.05(1+$z$) with ground based complement (PanStarrs-2, DES. etc)

- Concurrent with spectroscopic survey for 50 million galaxies (0.5$< z < 2.0$)

Deep Survey: 40 deg$^2$ at ecliptic poles
Simulation of dark matter around a forming cluster (Springel et al. 2005)

Deep HST image of massive cluster

25 clusters

PI: Postman from UCL: Lahav, Host, Jouvel

Simulation of dark matter around a forming cluster (Springel et al. 2005)
What will be the next paradigm shift?

- Vacuum energy (cosmological constant)?
- Dynamical scalar field?
  - \( w = p/\rho \)
  - for cosmological constant: \( w = -1 \)
- Manifestation of modified gravity?
- Inhomogeneous Universe?
- What if cosmological constant after all?
- Multiverse - Landscape?
- The Anthropic Principle?
THE END
Sources of uncertainties in measuring Dark Energy

- **Theoretical** (e.g. the cosmological model)
- **Astrophysical** (e.g. galaxy and cluster properties)
- **Instrumental** (e.g. image quality)
Photometric redshifts

- Probe strong spectral features (e.g. 4000 break)
- Template vs. Training methods
Neutrino mass from DES:LSS & Planck

Input:
$M_\nu = 0.24 \text{ eV}$

Output:
$M_\nu = 0.24 \pm 0.12 \text{ eV (95\% CL)}$

Lahav, Kiakotou, Abdalla & Blake 2010
(0910.4714)
Baryon Acoustic Oscillations (BAO)

SDSS

Percival et al. (2007)
MegaZ-LRG

- Input: 10,000 galaxies with spectra
- Train a neural network
  - ANNz, Collister & Lahav 2004
- Output: 1,000,000 photo-z
  - Collister, Lahav et al. 2007
- Update using 6 photo-z methods
  - Abdalla et al. 2009

3 (Gpc/h)^3: the largest ever galaxy redshift survey![Photoz scatter of 0.04]
Sensitivity of Cosmology to photo-z methods

- Baryon Fraction

Thomas, Abdalla & OL 2010
Probing darkness vs. scale

Credit: Jain & Khoury 2010
Euclid - impact on Cosmology

<table>
<thead>
<tr>
<th></th>
<th>$\Delta w_p$</th>
<th>$\Delta w_a$</th>
<th>$\Delta \Omega_m$</th>
<th>$\Delta \Omega_\Lambda$</th>
<th>$\Delta \Omega_b$</th>
<th>$\Delta \sigma_8$</th>
<th>$\Delta \eta_s$</th>
<th>$\Delta h$</th>
<th>DE FoM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current+WMAP</td>
<td>0.13</td>
<td>-</td>
<td>0.01</td>
<td>0.015</td>
<td>0.0015</td>
<td>0.026</td>
<td>0.013</td>
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<td>~10</td>
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<tr>
<td>Planck</td>
<td>-</td>
<td>-</td>
<td>0.008</td>
<td>-</td>
<td>0.0007</td>
<td>0.05</td>
<td>0.005</td>
<td>0.007</td>
<td>-</td>
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<tr>
<td>Weak Lensing</td>
<td>0.03</td>
<td>0.17</td>
<td>0.006</td>
<td>0.04</td>
<td>0.012</td>
<td>0.013</td>
<td>0.02</td>
<td>0.1</td>
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<tr>
<td>Imaging Probes</td>
<td>0.018</td>
<td>0.15</td>
<td>0.004</td>
<td>0.02</td>
<td>0.007</td>
<td>0.0009</td>
<td>0.014</td>
<td>0.07</td>
<td>400</td>
</tr>
<tr>
<td>Euclid</td>
<td>0.016</td>
<td>0.13</td>
<td>0.003</td>
<td>0.012</td>
<td>0.005</td>
<td>0.003</td>
<td>0.006</td>
<td>0.020</td>
<td>500</td>
</tr>
<tr>
<td>Euclid +Planck</td>
<td>0.01</td>
<td>0.066</td>
<td>0.0008</td>
<td>0.003</td>
<td>0.0004</td>
<td>0.0015</td>
<td>0.003</td>
<td>0.002</td>
<td>1500</td>
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<tr>
<td>Factor Gain</td>
<td>13</td>
<td>&gt;15</td>
<td>13</td>
<td>5</td>
<td>4</td>
<td>17</td>
<td>4</td>
<td>7</td>
<td>150</td>
</tr>
</tbody>
</table>

Euclid Imaging will challenge all sectors of the cosmological model:

- Dark Energy: $w_p$ and $w_a$ with an error of 2% and 13% respectively (no prior)
- Dark Matter: test of CDM paradigm, precision of 0.04eV on sum of neutrino masses (with Planck)
- Initial Conditions: constrain shape of primordial power spectrum, primordial non-gaussianity
- Gravity: test GR by reaching a precision of 2% on the growth exponent $\gamma$ ($d\ln \delta_m / d\ln a \propto \Omega_m^{\gamma}$)

→ Uncover new physics and Map LSS at 0<$z$<2: Low redshift counterpart to CMB surveys
• Goal: Dark Energy parameters to a few %
• Can w=-1 be ruled out?
• Can we distinguish Dark Energy from Modified Gravity?

* Non-DE science with DE surveys
  (e.g. Neutrino mass, galaxy evolution, MW structure, QSOs)
LCDM - ‘problems on the small scales’

- The MW satellites – too many in simulations?
- Cluster mass profiles – concentration too low in simulations?
- Hierarchical clustering – the wrong order?
- Galaxies in voids - too many in simulations?
- Superclusters – too few in simulations?
- Are we near a centre of a void?