Observing the Dark Universe

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Why should I believe in dark matter?

\[ \frac{mv^2}{R} = \frac{GM(<R)m}{R^2} \]

Bershady et al 2010

\[ V_{\text{circ}} \text{ (km/s)} \]

\[ \text{Radius (kpc)} \]

Bershady et al 2010
LUX-ZEPLIN Dark Matter detector
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Why should I believe in dark matter?
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Guzzo et al 2013

VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY

Guzzo et al 2013
Why should I believe in dark energy?

If there was no dark energy

Cluster Search (SCP)
Amanullah et al. (2010) (SCP)
Riess et al. (2007)
Tonry et al. (2003)

Contreras et al. (2010)
Hicken et al. (2009)
Kowalski et al. (2008) (SCP)
Jha et al. (2006)
Riess et al. (1999)
Krisciunas et al. (2005)
Hamuy et al. (1996)

Suzuki et al 2012
Why should I believe in a dark universe?
Before lensing galaxies are randomly oriented*
The intervening dark matter “lenses” the light from distant galaxies.
Weak Gravitational Lensing

Galaxies

Dark Matter

Lensed galaxies align
Dark Matter

Van Waerbeke et al 2013
DM-Stellar Mass scaling relation

Galaxies

Red/Early-type

Blue/Late-type

\(\frac{M_{200}}{\langle M_\star \rangle}\)

\(\langle M_\star \rangle \left[h_7^{-2} M_\odot\right]\)
CFHTLenS

- The state-of-the-art cosmological survey with 155 sq degrees, ugriz to $i<24.7$ ($7\sigma$ extended source)
- Uses 5 yrs of data from the Deep, Wide and Pre-survey components of the CFHT Legacy Survey
High resolution: 17 gals per sq arcmin
Deep imaging: $z_m = 0.75$
Accurate redshifts: $\sigma_z = 0.04(1+z)$ with 4% outliers
Accurate shear: weak calibration corrections
$<m> = -0.06$ $<c> = 0.001$
Robust to systematic errors: 75% of the data used
The CFHT Lensing Survey
Dark Matter changes the shapes of galaxies by \( \sim 1\% \)

Telescopes and the Atmosphere change the shapes of galaxies by \( \sim 15\% \)

We need to understand our instrumentation to a higher precision than ever before

Kitching et al 2010
\[ \xi_{\pm}(\theta) = \int dk \, k J_{\pm}(k\theta) \int dw \, G(w) P_\delta \left( \frac{k}{f_k(w)}, w \right) \]

Survey depth

Non-linear PS 
\[ (\Omega_m \Omega_\Delta \sigma_8 \, w \, H_0 ..) \]
\[ \xi_{\pm}(\theta) = \int dk \ k J_{\pm}(k\theta) \int dw \ G(w) P_\delta \left( \frac{k}{f_k(w)}, w \right) \]

Survey depth

Non-linear PS

\((\Omega_m \Omega_{\Delta} \sigma_8 w H_0..)\)

Heymans et al 2013

Galaxy pair separation
How aligned the galaxy pairs are

Galaxy pair separation

Heymans et al. 2013
Heymans et al (2013) explored how much dark matter there is and how clumpy the dark matter is.

The diagram illustrates the relationship between the matter density parameter $\Omega_m$ and the matter power spectrum normalization $\sigma_8$ in the context of Flat LCDM models, considering data from various experiments like WMAP7, CFHTLenS, BOSS + WMAP7 + R11, and CFHTLenS + BOSS + WMAP7 + R11. The scatter plots and contours show the 68% and 95% confidence levels for these parameters.
Dark matter and dark energy

Dark energy affects the growth of large-scale structures

$\Lambda$CDM  $z = 5.00$

$\Omega$CDM  $z = 5.00$

The way dark matter structures evolve in time reveals the nature of dark energy
Heymans et al. 2013

- How much dark matter there is
- The equation of state of dark energy
- The curvature of the universe

Flat wCDM

Curved wCDM
What is causing the accelerated expansion of the Universe?

- Cosmological constant: Vacuum Energy?
- A new scalar field: Is the Universe experiencing a new period of inflation?
- Colliding Brane Worlds or Multiverses?
- Beyond Einstein Gravity: Do we need to modify Einstein's theory of gravity?
- None of the above!
Going beyond Einstein

<table>
<thead>
<tr>
<th>Newton</th>
<th>Einstein</th>
<th>?</th>
</tr>
</thead>
<tbody>
<tr>
<td>gravity = stuff attracts stuff</td>
<td>gravity bends space and time</td>
<td>Does gravity bends space and time differently?</td>
</tr>
<tr>
<td>G is a fundamental constant</td>
<td>G is a fundamental constant</td>
<td>Is G really a constant everywhere?</td>
</tr>
</tbody>
</table>
Beyond-Einstein gravity theories

\[ ds^2 = (1 + 2\Psi)dt^2 + a^2(t)(1 + 2\Phi)dx^2 \]

\[ \nabla^2 \Phi = 4\pi G a^2 \bar{\rho} \delta \]

GR fully tested on solar system scales, so any modification must be length or time dependent.
Beyond-Einstein gravity theories

\[ ds^2 = (1 + 2\Psi)dt^2 + a^2(t)(1 + 2\Phi)dx^2 \]

\[ \nabla^2 \Psi = 4\pi G a^2 \bar{\rho}\delta [1 + \mu(a)] \]

\[ \nabla^2 [\Phi + \Psi] = 8\pi G a^2 \bar{\rho}\delta [1 + \Sigma(a)] \]
CFHTLenS Data release:

Download now from [www.cfhtlens.org](http://www.cfhtlens.org):

- 155 sq degrees $ugriz$ lensing quality reduced deep pixel data
- Combined Lensing Shear and Photometric redshift catalogues to $i<24.7$
The next generation

Naess et al 2014
KiDS-VIKING

- 1500 sq degrees ugri+zyJHK
- Exceptional data quality both in shapes and photometry
- Depth zm~ 0.6
- Photo-z scatter < 0.06(1+z)
- ~10 gals per sq arcmin

VST 2.6m, 1 sq degree FOV

VISTA 4m, 0.6 sq degree FOV
Lensng–spectroscopy overlap in NGP

W: CFHTLenS (155), R: RCSLenS (700), KiDS (1500)

Lensng–spectroscopy overlap in SGP

2dFLenS
BOSS
WiggleZ
GAMA

PI: Chris Blake
Ground-based imaging

Slide courtesy of Meghan Gray
Euclid and LSST

- LSST: US Project
  - (8.4m ground-based)
- UK proposal to join
- Ultra-deep optical imaging

- Euclid: ESA/NASA
  - (1.2m space-based)
- Hubble Space Telescope
  - quality images across the whole sky (optical and NIR)
Audience Poll

What do you think Euclid and LSST will discover?

A. It is the vacuum energy that is causing the Universes expansion to accelerate
B. We need to upgrade our theory of gravity
C. Astronomers got it wrong all along and misunderstood their observations
D. None of the above!!
Our final understanding of the dark Universe is likely to involve new physics that will forever change our view on the Universe.

Lensing is a powerful tool to chart the Dark Universe.