Mapping
Baryonic & Dark Matter in the Universe

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A. Leauthaud, R. Massey, J. Rhodes, the COSMOS team, and many others
Outline

- Motivation
- Basics of (Weak) Lensing
- Dark Matter mapping in “COSMOS”
- Future prospects
‘Geo-meter’

• First « good » world map in the XVIIIIs century

• « Perfect » maps nowadays with space Earth observatories

• Deep understanding of our planet
What about our Universe?

“Normal” matter:
in stars, galaxies, IGM … traced by photons

Dark matter (~1930)
in clusters, galaxies … traced by gravitational effects

Dark energy (~2000)
everywhere!
traced by Universe geometry, & Dark Matter growth
Motivation for the ‘Cosmos-meter’

Mapping (Dark) matter:

- DM is a necessary and essential ingredient of the Universe
- Its distribution is shaping up galaxies (the visible bricks of our Universe): DM & baryons interactions
- Growth of DM is a tracer of Dark Energy: new physics?
- … should deeply impact galaxy evolution and our understanding of Physics
Gravitational Lensing the ‘Cosmos-meter’ tool

\[ \alpha = \frac{D_{LS}}{D_{OS}} \nabla \varphi \propto M \]

Non-Linear

Multiple Images

Arclets

Weak Shear

Linear

Observer

Lens

Source

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CFHT 1990

Z_{cluster}=0.375

Z_{arc}=0.725 (Soucail et al 1988)

Ned Wright
Cluster of Galaxies

- Identify multiple images, measure their redshift
Cluster of Galaxies

• Identify multiple images, measure their redshift
• Model the cluster by a sum of: cluster components and dark halos around galaxy clusters
• Galaxies halos contribute for ~10% of the total mass in cluster cores
• **Lenstool software, MCMC optimisation (Jullo et al 2007)**
Where is the Matter in A2218?

Strong Lensing constraints in Abell 2218:

- Mass distribution proportional to the stellar mass produce a BAD FIT to the lensing data
- Require large scale mass distribution (cluster DM)
- Important difference between DM, Galaxy distribution and X-ray gas (different physics)
- But scaling relation should exists

Mass scales with stellar mass

Eliasdottir et al. 2008
Lens Mapping

Amplification Matrix:

\[ A^{-1} = \begin{pmatrix}
1 - \kappa & \gamma_1 & -\gamma_2 \\
-\gamma_2 & 1 - \kappa & + \gamma_1
\end{pmatrix} \]

\( \kappa \): convergence

\[ \kappa = \frac{\Delta \varphi}{2} = \frac{\Sigma}{2\Sigma_{crit}} \]

\( \gamma(\gamma_1, \gamma_2) \): shear vector

\[ \gamma_1 = \frac{(\partial_{yy} \varphi - \partial_{xx} \varphi)}{2} \quad \gamma_2 = \partial_{xy} \varphi \]

Reduced shear (what we can measure):

\[ g = \frac{\gamma}{1 - \kappa} \]

\[ \Sigma_{cr} = \frac{c^2}{4\pi G} \frac{D_s}{D_d D_{ds}} \]

\[ = 0.35 \text{ g cm}^{-2} \left( \frac{D}{1 \text{ Gpc}} \right)^{-1} \]
Weak Lensing

Morphometry and shear measurement

\[ M_{ij} \propto R_\theta \begin{pmatrix} a^2 & 0 \\ 0 & b^2 \end{pmatrix} R_{-\theta} \]

Lensing equation for image moments

\[ M^S = A^{-1} M^I (A^{-1})^t \]

Lensing equation for ellipticity vectors

\[ \boldsymbol{\varepsilon}^S = \frac{\boldsymbol{\varepsilon}^I - g}{1 - g \varepsilon^I} \sim \boldsymbol{\varepsilon}^I - \gamma \]

Ellipticity distribution
Measuring Weak Shear

- In the **weak regime**, the shape of galaxies are linearly modified by the gravitational shear:

  \[ \varepsilon_I = \varepsilon_S + \gamma \]

- The average of galaxy shape is an unbiased estimator of the gravitational shear:

  \[ \langle \varepsilon_I \rangle = \langle \varepsilon_S \rangle + \langle \gamma \rangle \]

  \[ \neq 0 \]

- Error on shear is a function of intrinsic shape, measurement error and number of galaxies:

  \[ \sigma^2(\varepsilon_I) = \sigma^2(\gamma) \propto \frac{\sigma^2(\varepsilon_S) + \delta^2\varepsilon_I}{N} \]

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Galaxy Properties

- PSF correction
- Survey size & depth
- & method
Weak Lensing: recipe and results

- start with detecting objects in the CCD frame
- select galaxies removing stars, defects, stellar spikes
- correct for PSF circularization and anisotropy
- estimate a redshift for each galaxy (using photometric redshift if color information is available)
- select galaxies to be used as the ‘background sample’

- Compute weak lensing statistics to constrain cosmology
- reconstruct the dark matter map
- probe the mass distribution of groups and galaxies
- confirm the results by comparing to other dataset
Coupling Strong and Weak Lensing

Absolute central mass

relative total mass and slope

$1 h_\text{100} \text{ Mpc} \text{ at } z=0.39$

Perturbation
Cl0024+1654
HST wide field
sparse mosaic

- 76 orbits, 38 pointings
- Probe regions up to ~5Mpc

Aim: learn cluster physics of clusters by comparing with other mass estimates: X-ray, dynamics, learn on galaxy halo mass stripping

0024: Shear/Mass Profile

- Extrapolate strong lensing models at large scale by exploring various cluster mass profile.
- Rule out SIS model
- NFW (with large c~20) or Power-law profile give a good fit.
- Large ‘c’ is unexpected from CDM simulations!
  - Line of sight alignment/merger?
  - Very old structure?
  - Systematics (N(z), and others)?

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The most massive cluster: Abell 1689

• Mass models form different groups w. or w/o weak lensing
• Massive spectroscopic surveys (2003-2006)
• 41 multiple image systems, 24 with spectro-z with $1.1 < z < 4.9$

Broadhurst et al 2005
Halkola et al 2007
Limousin, et al. 2007
Richard et al. 2007
Frye et al 2007
Leonard et al 2007

 KECK/LRIS
 VLT/FORS
 CFHT/MOS
 MAGELLAN
 /LDSS2
 Littérature
Mass Profile of Clusters (SL+WL)

- Background source selection is critical to accurately measure WL.
- Improved lensing constraints, revised concentration from c~15 to c~8.
- Better agreement with current understanding of structure formation.

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The « Bullet Cluster »: Direct Proof of DM

- Encounter of 2 massive clusters
- Significant offset between X-ray gas and lensing mass peaks
  ⇒ probably best evidence for « collisionless dark matter »
  ⇒ lensing better mass estimator for counting cluster?

Clowe et al 2006, Bradac et al 2006
Combining Lensing & Photo-z in wide field surveys

- Weak lensing distortion depends on the cumulative mass distribution along the line of sight.
- Knowledge of the galaxy redshift (photo-z) allows *tomography of the mass distribution* in the Universe at various scales and allow comparison to the galaxy distribution
- **Ultimate aim**: measure the growth of structures, which will impact our understanding of cosmology (dark energy)
The COSMOS *Hubble* Survey

- Largest ever HST program
  - 10% of Hubble during 2 years
  - 575 contiguous ACS fields in F814W (~I band); ~50min int.time per pixel
  - 1.64 square degrees
  - 20 Giga pixel image (0.03′/pixel)
  - 0.12′ image resolution
  - 1.2 millions of galaxies with $I_{F814}<26.6$ (at 5σ)
  - 0.4 millions galaxies useful for lensing
  - ~100 astronomers
Comparison to other *Hubble* Surveys
COSMOS: Multi-wavelength follow-up

Optical/IR follow-up:

- **SUBARU**: (~5% time/year)
  - BgVriz+NB
  - **seeing 0.9-1.5’’**
- **CFHT**: (~5% time/year):
  - U band
  - H-K-band
- **UKIRT** Y-J band
- **Spitzer**:
  - IRAC ~200h (3.6 to 8 \( \mu m \))
  - MIPS ~400h (24 \( \mu m \))
- **GALEX**
- **VLA**
- **XMM, Chandra**

**Public data!**
http://irsa.ipac.caltech.edu/Missions/cosmos.html
Subaru
SuprimeCAM
g,r,z
6.5 x zoom
Photometric Redshift

Fitting SED templates with photometry from:
7 broad optical bands, 6 intermediate bands + K-band + IRAC 3.6&4.5 μm

IR reduces catastrophic errors
intermediate bands reduce scatter for bright objects
Making of the ACS lensing catalogue

• 575 tiles
• 1.5 million detections using « hot-cold » sextractor method
• 0.4 million galaxies surviving various cuts (masking, PSF correction, photo-z, weak lensing S/N …)
• With the better photo-z, more galaxies will be used for lensing

Leauthaud et al 2007
Size vs Magnitude & Completeness

Hubble/ACS data
mainly surface brightness limited

Ground based Seeing limit
Lensing in COSMOS: PSF variation

- ACS PSF is varying with time (focus is changing with T variation)
- TinyTim PSF model adjusted by measuring the shape of stars (~20 per pointing)
- provide PSF correction for any position on ACS chips.
- CTE corrections

Rhodes et al 2007
Analytic correction of the CTE
Charge Transfer Efficiency Correction Needed
Number density of galaxies in the ACS catalogue

\[ \sigma^2(\varepsilon_I) = \sigma^2(\varepsilon_S) + \delta^2 \varepsilon_I N \]

Galaxy Properties

PSF correction & method

Survey size & depth

d Size = FWHM/2

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[Graphs showing number density of galaxies versus magnitude and redshift]
Shape Noise as a function of Mag, Size, Redshift

\[ \sigma^2(\varepsilon_I) = \sigma^2(\gamma) \propto \frac{\sigma^2(\varepsilon_S) + \delta^2 \varepsilon_I}{N} \]

RMS ellipticity \( \sigma (\varepsilon_s) = 0.26 \) is constant with magnitude, size, redshift.
Mass map of COSMOS survey

Massey et al 2007

Signal: E mode

Noise: B mode
Mass vs light

Massey et al 2007
Panchromatic view of COSMOS

- Contours: DM
- Blue: Stellar mass
- Yellow: gal. number density
- Red: hot gas (x-ray)

Massey et al 2007

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Tomography Mapping

By isolating the faint background galaxies at different redshift, we are sensitive to the mass distribution in different redshift slices, and then can reconstruct the 3D map of the dark matter along the line of sight.

Massey et al 2007

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How to improve this first measurement?

• Add new information!
• Redshift measurement
• Analysis of the mass of individual structures: groups/clusters and galaxies
Lensing Mass Map vs. Optical and X-ray identified groups

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3D density field of galaxies

Combination of 
~10k spectro-z and 200k photo-z

Kovac et al 2007
142 XMM cluster candidates:
64 clusters: $0.5 < z < 1.0$
23 clusters: $z > 1$
Redshift distribution of structures

- **Grey**: photo-z concentration
- **Black**: extended X-ray sources
Aim: calibration of the Mass-Temperature relation.

- How to center the stacked signal? Currently using the BCG.
- Need to understand the offset between X-ray/BCG/optical distribution?
  (Chandra data will help)
- Extend the groups sample to lower masses by stacking WL data.
Comparing X-ray selected clusters with weak lensing detection

Detected in the Mass map
Effective lensing sensitivity for a direct analysis
Stacking lensing analysis
X-Ray selected group mass in COSMOS

- Measuring mass of X-ray selected groups in COSMOS
- Identify groups with similar properties in redshift and X-ray luminosity
- Stack weak lensing signal
X-Ray selected group mass in COSMOS

Leauthaud et al 2007 in prep
M(lensing)-L relation

- Wrong behavior at lowest X-ray luminosity?
- Need to explore intermediate X-ray luminosity

Leauthaud et al 2008
• 16+(50) lens candidates identified (by eye) based on photometric selection of ~9000 Elliptical galaxies with: $0.3 < Z_{\text{phot}} < 1$

• 16 SL candidates in COSMOS => expect more than 200,000 strong lensing systems over the whole visible sky
Galaxy morphology

Principal component analysis
(A, C, G, M20, e)

→ Three main PC’s : PC1, PC2, PC3

We show four separate unit cubes of PC1-PC2-PC3 space, centered around the values reported in the labels. In every unit cube, a few representative galaxies of the population are shown.

PC = -4,0,0
Early Type

PC = 0,-1,-1
Disk Galaxies (face on)

PC = 1,2,2
Disk Galaxies (edge on)

PC = 1,-2,0
Irregular
The Galaxy-Mass Cross Correlation Function (GMCF)

Shapes of galaxies

$\Sigma_{\text{crit}} \times \gamma = \Delta \Sigma(r)$

Redshifts are essential!

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The idea is to measure the tangential shear rescaled by the distance scaling (Critical Sigma) to measure \( \Delta \Sigma \) :

\[
\Delta \Sigma(r) = \Sigma(<r) - \bar{\Sigma}(r) = \Sigma_{\text{crit}} \times \gamma_t(r)
\]

\( \Delta \Sigma \) is the relative surface mass density. To compute \( \Delta \Sigma \), Critical Sigma should be computed for each lens and sources.

\[
\Sigma_{\text{crit}} = \frac{c^2}{4\pi G} \frac{D_{OS}}{D_{OL} D_{LS}}
\]

Need the redshift of both the lens and the source. Spectro-z are more important for the lens than the source.
\[ \Delta \Sigma = \Delta \Sigma_b + \Delta \Sigma_{NFW} + \alpha \Sigma_{NC} \]

1) The Baryonic contribution is determined by the stellar mass
2) A NFW profile is assumed for dark matter halos.
3) \(\alpha\) is the fraction of galaxies in sub-halos.
4) \(\Delta \Sigma_{NC}\) is the off centered ‘group’ contribution.
The Dark Matter Profiles of Elliptical Galaxies

- **Stellar Component**
- **DM halo**
- The ‘bump’ or the ‘two-one halo’ term (cluster/group)
Stellar mass vs. virial mass

Virial and stellar mass are well correlated!

- The relation is linear in between \( M_\star = 10^{10} M_{\odot} \) and \( M_\star = 10^{12} M_{\odot} \)

- No strong variation with redshift between \( Z = 0.2 \) and \( Z = 1.2 \)

- Fitted relation:
  \[
  \log(M_{\text{vir}}) = A \log(M_\star) + B + C(1 + z)
  \]
  
  With
  \[
  A = 1.02 \pm 0.19 \\
  B = 12.41 \pm 0.78 \\
  C = 0.04 \pm 0.47
  \]

Strong lensing, too dependent on \( z_s \) and nearby substructure, more data needed
The Rise of The Red Galaxies

COSMOS Stellar Mass Functions

Dark Matter Mass Function of Elliptical galaxy halo

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WORK in progress

- preliminary analysis of Galaxies selected by the BzK technique (passive red galaxies at z~1.5)
- …can probably extend this to LBG galaxies selected with GALEX

Likely the highest redshift gg-lensing measurement
More work in progress

• Measure galaxy mass for all galaxy types, and check evolution
• Investigate mass of optically selected group
• Refine COSMOS mass map including the mass distribution found at different scales
  => direct probe of filamentary structure
Conclusions & Perspective

Lensing is a unique tool to probe the mass distribution in the Universe

• (Weak) Lensing provide constraints on DM profiles from <100 Mpc scales down to few kpc (baryon/DM physics)

• Combined with photometric redshift information Weak Lensing can map dark matter in 3D for the LSS, and trace galaxy mass evolution

• Future cosmology surveys (particularly those in space) will allow to fully map the 3D structure of the Universe and understand the growth of structures which is a way to probe dark energy.

• Like the ‘geo-meter’, the ‘cosmos-meter’ will not only learn the cosmology (a few numbers) but gain an in-depth knowledge of the physics of DM in the Universe.