Mapping the Universe:
With Lensing & Redshift Surveys

Jean-Paul KNEIB
Laboratoire d’Astrophysique de Marseille, France
Outline

- Motivation
- Basics of (Weak) Lensing & Redshift Surveys
- Dark Matter in the COSMOS (Clusters & Galaxies/DM connections)
- Spectroscopic Redshift Surveys (BOSS & e-BOSS)
- Conclusion
‘Geo-meter’

- First « good » world map in the XVIIIth century, as the “Longitude problem” got solved

- « Perfect » maps nowadays with space Earth observatories

- Deep understanding of our planet: navigation, climatology, seismology ...
What is the fabric of our Universe?

“Normal” matter [5%]: in stars, galaxies, IGM … traced by photons

Dark matter (~1930) [23%] in clusters, galaxies, LSS traced by gravitational effects

Dark energy (~2000) [72%] everywhere! revealed by Universe accelerated expansion, sensitive to geometry & growth of structures
What are the structures in our Universe?

Galaxies \([\sim 10^{11} \text{ Msun}, \sim 10 \text{ kpc}]\):  
made of stars, ISM, DM; “bricks” of the LSS, traced by: visible/NIR light

Groups/Clusters \([10^{13-15} \text{ Msun}, \sim 1 \text{ Mpc}]\):  
made of galaxies, Hot Gas, DM; traced by galaxy over-densities, X-ray, SZ, Lensing

Large Scale Structures \([\sim 1-100s \text{ Mpc}]\):  
made of galaxies, WHIM, DM; traced by galaxy over-density, (lensing)
Motivation for the ‘Cosmos-meter’

Mapping the Universe:
• Geometry & Mass-Energy
• Dark Matter: necessary and essential ingredient - what nature? cold/dark? neutrinos?
• Baryons/Stars: the visible tracers - How biased to DM?
• Dark Energy: seed of the accelerated expansion - What origin/nature?
• ... should deeply impact our understanding of Cosmology and Fundamental Physics
Intro: Gravitational Lensing
Gravitational Lensing the ‘Dark Matter’-meter tool

CFHT 1990

Z_cluster=0.375
Z_arc=0.725 (Soucail et al 1988)

Observer

Lens

Source

Non-Linear

Multiple Images

Arclets

Weak Shear

Linear

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

Optical Path

Wave Front

Multiple Images Area
Lens Mapping

Amplification Matrix:

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

\(\kappa\): convergence

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

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

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

Reduced shear (what we can measure):

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

Oct 13, 2011
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

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

Lensing equation for ellipticity vectors

\[ \varepsilon_S = \frac{\varepsilon_I - \gamma}{1 - g\varepsilon_I} \sim \varepsilon_I - \gamma \]

Ellipticity distribution

Ellipticity vector

Oct 13, 2011
Measuring Weak Shear

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

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

\[ \gamma(x, y) \leftrightarrow \sum(x, y) \]

• 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:

\[ \sigma^2(\varepsilon_I) = \sigma^2(\gamma) \propto \frac{\sigma^2(\varepsilon_S) + \delta^2 \varepsilon_I}{N} \]
Galaxy-galaxy Weak Lensing technique

Measure the tangential shear rescaled by the distance scaling (Critical Sigma) to measure Delta Sigma:

$$\Delta \Sigma(r) \equiv \Sigma(< r) - \Sigma(r) = \Sigma_{\text{crit}} \times \gamma_t(r)$$

Delta Sigma is the relative surface mass density. 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.

S/N increase with the number of pairs - i.e. with survey size
‘Shear-meters’

- **Hubble** delivers best images but on limited field of view: best to trace mass in clusters and around structures => COSMOS survey (2007)
- **CFHT/Megacam** 1st wide-field imager dedicated for lensing measurement
  - CFHT-LS (2004-2009) [Results presented at AAS 2012],
  - CFHT-Stripe 82 (2010)

- **EUCLID**: *selected* european next generation space wide-field imager (2020?) ... but also WFIRST (2025 ??)
Intro: Redshift Surveys
Matter Power Spectrum

Today’s maps of the Universe

SDSS galaxy redshift map

Turn-over depends upon horizon size at matter-radiation equality

Dark energy: sound horizon scale at recombination (BAO)

Primordial non-gaussianity

Gravitational growth

Neutrino mass

Cold/Warm DM

Galaxy halo occupation of dark matter halos (HOD)
‘Redshift-meters’

- **Hubble (1930):** expanding Universe
- **CfA Redshift Survey (1985):** first large scale structures (wall, filaments)
- **2dF (~2000):** 1500 sqdeg
- **SDSS (~2002):** 5700 sqdeg
- **VVDS/DEEP2 (~2004):** deep Universe ~1 sqdeg
- **WiggleZ (2011):** 800 sqdeg BAO
- **VIPERS (2012):** 25 sqdeg RSD
- **SDSS-III/BOSS (2014):** 10,000 sqdeg BAO/LSS
- **e-BOSS (2014-2018?)**
- **BigBOSS, PFS (2018?)**
- **EUCLID (2020), WFIRST (2025?)**
‘Redshift-meters’

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Mapping the Universe

- **Imaging survey**: shapes of (millions) galaxies (WL)
  \[ \langle \gamma^2 \rangle \propto \sigma_8^2 \ z_s^{1.7} \ \Omega_m^{1.7} \ \theta \left( \frac{n-1}{2} \right) \]

- **Redshift survey**: bring 3rd dimension
  - Photo-z: (WL, BAO?, clusters)
    - less accurate (-) => need calibration
    - larger number of galaxies (+)
    - requires multi-color visible/NIR imaging
  - Spectro-z: (BAO, clusters)
    - More accurate (+) => Reveal the true underlying structures
    - Smaller number of galaxies (-) => provide calibration to photo-z
Wide Field Lensing: structures in “COSMOS”
The COSMOS Hubble Survey

- 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 $I_{F814} < 26.6$ (5σ)
- 0.5 millions galaxies useful for lensing
- ~100 astronomers
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
- Ultra-VISTA: z,Y,J,H,K
- **Spitzer**: IRAC & MIPS
- **Herschel**: PACS & Spire
- **GALEX**
- **VLA**
- XMM, Chandra
- .....

Public data!
http://irsa.ipac.caltech.edu/Missions/cosmos.html
Photometric Redshift

Fitting SED templates with photometry from 30 photometric bands!
IR reduces catastrophic errors
intermediate bands reduce scatter for bright objects (Ilbert et al 2008, 2010)

3.6μm > 1μJy

No NIR

With NIR
Making of the ACS lensing

• 575 tiles
• 1.5 million detections using « hot-cold » Sextractor method
• 0.5 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
Mass map of COSMOS survey

Signal: E mode

Noise: B mode

Massey et al 2007
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
How to improve this 1st measurement?

- Add new information!
- Better redshift measurement (more spectro-z, better photometry), better lensing catalogue (improving PSF+CTE model)
- Priors on where is the mass:
  - 1) X-ray groups,
  - 2) galaxies (and how they correlates)
- Better analysis using halo models and galaxy-galaxy lensing techniques.
Lensing: Group/Cluster scale
Clusters/groups in COSMOS

~200 XMM cluster candidates:
64 clusters: 0.5<z<1.0
50 clusters: z> 1
(Finoguenov et al 2007, 2008)

Photo-z concentration

X-ray clusters
Lensing Mass Map vs. Optical and X-ray identified groups
Aim: calibration of the Mass-Temperature/Luminosity 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
Weak Lensing in COSMOS not only allows tomography but makes possible a direct measurement of mass of structures down to galaxy sizes (Leauthaud et al 2010).

The EUCLID can do a lot in measuring WL cluster/group - but likely not as sensitive as COSMOS survey.

~100 X-ray selected clusters in COSMOS
M(lensing)-L_X relation

- Lensing Mass-L_X relation
- Good agreement with SDSS and massive cluster measurements (although scatter could be improved!).
- Lack of point at intermediate X-ray luminosity (need wider survey such as CFHT-LS or CFHT-Stripe 82)

Leauthaud et al 2010
Lensing: Galaxy Scale
Galaxy scale: The 3 Dark Matter Probes

The galaxy stellar mass function:
- Number of galaxies per unit volume
- “easy” to calculate
- Typically modelled through “abundance matching”

Galaxy auto correlation function:
- Excess probability above random of finding two galaxies with a given separation
- Typically modelled through HOD models

Galaxy-galaxy lensing:
- Measures the galaxy-matter correlation function
- Weak signal that is difficult to measure
- Tells us directly about the galaxy-dark matter connection

Leauthaud et al 2011
Most studies so far have only ever used one type of probe to study the link between galaxies and DM.

Nonetheless, each probe contains different information. Combining probes makes sense in order to understand the “elephant”: 

**The Elephant Problem**

- It’s a Fan!
- It’s a Spear!
- It’s a Snake!
- It’s a Wall!
- It’s a Tree!
- It’s a Rope!
Parametric form for the stellar-to-halo mass relation \((M_1, M^*_{0}, \beta, \delta, \gamma)\)

\[
\log_{10}(f^{-1}_{\text{SHMR}}(M_*)) = \log_{10}(M_h) = \\
\log_{10}(M_1) + \beta \log_{10}\left(\frac{M_*}{M^*_{0}}\right) + \frac{\left(\frac{M_*}{M^*_{0}}\right)^\delta}{1 + \left(\frac{M_*}{M^*_{0}}\right)^{-\gamma}} - \frac{1}{2}
\]

Central occupation function \((\sigma_{\log(M^*)})\)

\[
\langle N_{\text{cen}}(M_h|M_t^1) \rangle = \\
\frac{1}{2} \left[ 1 - \text{erf}\left(\frac{\log_{10}(M_t^1) - \log_{10}(f_{\text{SHMR}}(M_h))}{\sqrt{2}\sigma_{\log(M^*)}}\right) \right]
\]

Satellite occupation function \((B_{\text{cut}}, B_{\text{sat}}, \beta_{\text{cut}}, \beta_{\text{sat}})\)

\[
\langle N_{\text{sat}}(M_h|M_t^1) \rangle = \langle N_{\text{cen}}(M_h|M_t^1) \rangle \left(\frac{M_h}{M_{\text{sat}}}\right)^{\alpha_{\text{sat}}} \exp\left(\frac{-M_{\text{cut}}}{M_h}\right)
\]

\[
\frac{M_{\text{sat}}}{10^{12}M_\odot} = B_{\text{sat}} \left(\frac{f^{-1}_{\text{SHMR}}(M_t^1)}{10^{12}M_\odot}\right)^{\beta_{\text{sat}}}
\]

\[
\frac{M_{\text{cut}}}{10^{12}M_\odot} = B_{\text{cut}} \left(\frac{f^{-1}_{\text{SHMR}}(M_t^1)}{10^{12}M_\odot}\right)^{\beta_{\text{cut}}}
\]

+ Tinker et al. 2008 halo mass function
+ Tinker et al. 2010 bias function
+ Halo exclusion
The Stellar-to-Halo mass relation (SHMR)

Adopted from Behroozi et al. 2010

\[ M_1 : y\text{-axis (halo mass) normalization} \]
\[ M_{*0} : x\text{-axis (stellar mass) normalization} \]
\[ \beta : \text{low mass slope} \]
\[ \delta : \text{controls high mass sub-exponential behaviour} \]
\[ \gamma : \text{controls transition regime} \]
#### Clustering

- **w bin1**
- **w bin2**
- **w bin3**
- **w bin4**
- **w bin5**
- **w bin6**

#### Stellar mass function

- High Mass
- Low Mass

**Log_{10}(M_{\odot})**
- $10^{-6}$
- $10^{-5}$
- $10^{-4}$
- $10^{-3}$
- $10^{-2}$

**Log_{10}(dN/d\log M_{\odot})**
- $10^{-1}$
- $10^{0}$
- $10^{1}$

**z** = [0.22, 0.48]

#### Galaxy-galaxy lensing

- **W(θ)**
- **ΔΣ [h^{72} M_\odot pc^{-2}]**

- **g-g bin1**
- **g-g bin2**
- **g-g bin3**
- **g-g bin4**
- **g-g bin5**
- **g-g bin6**
- **g-g bin7**

**Physical transverse distance R [Mpc h^{72\text{-1}}]**
- $10^{2}$
- $10^{1}$
- $10^{0}$
- $10^{-1}$
- $10^{-2}$

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- **COSMOS, this work**
- **SDSS, Li et al. 2009**
- **SDSS, Baldry et al. 2008**
- **SDSS, Panter et al. 2004**

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- **Galaxy-galaxy lensing**
- **Clustering**
Clustering

Galaxy-galaxy lensing

Stellar mass function

$z = [0.74, 1.0]$
Stellar mass vs Halo mass

Stellar mass $M_*$ vs Halo mass $M_{200b}$

Typical systematic error in stellar masses (between different surveys)

Star formation efficiency

Leauthaud et al 2011

- WL, COSMOS this paper, $z=0.37$
- WL, Mandelbaum et al. 2006, $z=0.1$
- WL, Leauthaud et al. 2010, $z=0.3$
- WL, Hoekstra et al. 2007, $z\sim0.2$
- AM, Moster et al. 2010, $z=0.1$
- AM, Behroozi et al. 2010, $z=0.1$
- SK, Conroy et al. 2007, $z\sim0.06$
- SK, More et al. 2010, $z\sim0.05$
- TF, Geha et al. 2006, $z=0$
- TF, Pizagno et al. 2006, $z=0$
- TF, Springob et al. 2005, $z=0$
**Pivot masses**: location of the minimum of $M_{200b}/M^*$

marks the halo mass in which accumulated stellar growth of the central galaxy has been the most efficient.
Centrals dominate the total stellar content at $M_h < 3.10^{13} \ M_{\odot}$

Satellites dominate the total stellar content at $M_h > 3.10^{13} \ M_{\odot}$

At $M_h < 10^{12} \ M_{\odot}$: stellar growth outpaces halo growth

At $M_h > 10^{12} \ M_{\odot}$: halo growth outpaces stellar growth (smooth accretion)

Leauthaud et al 2011, Also see Conroy & Wechsler 2009
Total baryons as a function of halo mass

Above $M_h > 10^{13} \, M_{\odot}$: Hot gas component start to dominate the stellar contribution.

There are some uncertainties on the stellar mass estimate depending on the IMF assumed.

*Leauthaud et al. 2011b*
Spectroscopic Surveys
Sloan Telescope & BOSS spectrograph

- SDSS has a 2.5m f/5 modified Ritchey-Chrétien wide-field altitude-azimuth telescope
- The telescope achieves a very wide (3°) distortion-free field by the use of a large secondary mirror and two corrector lenses
- 5-filter camera (decommissioned)
- 1000 Fiber spectrograph (2 Blue & Red channels)
BOSS Commissioning Spectra

Survey started Jan 2010

Luminous red galaxy at $z=0.78$ (galaxy in white, sky background in red)

H-alpha emission at 1216A, redshifted to 4462A

3600-10000 Angstrom - R~2000

Quasar at $z = 2.67$

Lyman-alpha forest – absorption by H$_2$ clouds tracing the distribution of large scale structure in the universe

Thanks to Shirley Ho
BOSS goals

- Measure power spectrum of 1.4 million LRGs and 160,000 Ly-alpha quasars. Measure the BAO peak, the redshift space distortion, to constrain cosmological model.

- Many ancillary science: galaxy evolution, clusters, lensing, quasar science.
First galaxy correlation results from the first 45 000 luminous red galaxies at z~0.55 (first 6 months of data, 1600 sq.deg.). - White et al 2011

450 000 already observed !!!
More results at the AAS in January 2012

at z=0.6
e-BOSS: Extending BOSS
The novel Sloan legacy cosmological survey

Proposal submitted Sept 1st, 2011 to AS3


(66 co-Is, from 29 institutes)

If interested Let me know!
e-BOSS ideas

- a ~4-year cosmology project that pushes the reach of the Sloan Telescope to *map the LSS beyond z=0.6 (BAO, RSD)*:
  - probe 0.6<z<~1.6 with Emission-Line-Galaxies (ELG)
  - probe 0.6<z<0.8 with Luminous Red Galaxies (LRG)
  - probe 1<z<~2.2 with QSOs
  - increase the sample of z>2.2 QSOs for Ly-forest survey

- provide **new competitive BAO+RSD+WL Dark Energy constraints** in the footprint of new DES+(KIDS) WL/cluster DE survey:
  - double the signal in the Ly-alpha forest compared to BOSS
  - a factor of ~2+ improvement in DETF-FOM compared to BOSS.
  - develop synergy with the new WL and cluster DE probes.

- provide a **wealth of ancillary sciences**:
  - Galaxy Evolution and Quasar/IGM sciences
  - Lensing (photo-z calibration and tracing clusters/groups, strong lensing)
  - Multi-wavelength science using synergy with other very wide field survey
e-BOSS LSS mapping

from Anze Slozar
e-BOSS numbers

- **Survey Strategy:**
  - ~3,100 sq.deg. on the equatorial region of SGC and NGC
  - *survey area visited every year for 4 years* (finish before BigBOSS starts), ~1h exposures (similar to BOSS)
    - ~1 million ELGs
    - 300,000 new LRGs (~half at z>0.6)
    - 390,000 QSOs (140,000 at z>2.2)
  - repeat observations on some targets (Ly-alpha QSOs, hi-z LRGs, time-variability spectroscopy), and observation of close objects closer than the fiber collision limit (galaxy pairs, galaxy members in a cluster, galaxy-quasar close pairs ...) offer new science topics!
e-BOSS Survey Area

2*~1500 sq.deg. regions on each the SGC and NGC

Aim to use better photometric data than Sloan
e-BOSS imaging data

- DR8: 10k sqdeg (Backup Solution - but aim for better imaging data)

- DES (yearly repeat observation strategy for 4 years starting fall 2012): current survey design only ~500 sqdeg overlap. *Aim to increase to 1500 sq.deg on South Galactic cap. Apply for DECam imaging on NGC.*

- VST/KIDS: 750 sq.deg on the Equator NGC (should be publicly accessible on some form by mid-2014) - no repeat strategy

- HSC: 2000 sq.deg on the equator ~1500 sq.deg on NGC, ~500 sq.deg on SGC? (access?)

- PTF/PS (+DES) for Ly-alpha quasar variability selection

- WIRO (Adam Myers) u~23 on a few thousand sq.degs

- SCUSS: 3000 sqdeg on SGC to U<23

- CFHT u-band: 10 sqdeg/hour with u<~24 - still a project idea -
e-BOSS BAO Forecast

From Pat McDonald

quick comparison with BigBOSS and EUCLID (Ly-alpha constraints not shown)
A great improvement expected in the measurement of the growth factor by combining e-BOSS RSD and DES WL measurement.

From Bernstein & Cai 2011

Oct 13, 2011
Target Selection
Target Selection: ELGs color boxes

CFHT-LS
Photo-z

COSMOS
Photo-z & [OII] flux distribution for g<22.5 and g<23.5

z<2.2
QSOs
Locus

Oct 13, 2011
BOSS ELGs: few spectra (ugr)

RA=38.66, DEC=-8.85, z=1.17

RA=37.59, DEC=-3.82, z=1.24

RA=38.26, DEC=-4.61, z=1.49

RA=37.32, DEC=-4.69, z=1.54

RA=37.17, DEC=-4.14, z=1.62

RA=38.48, DEC=-4.09, z=0.52

RA=37.46, DEC=-5.82, z=0.65

RA=38.14, DEC=-8.09, z=0.75

RA=37.61, DEC=-7.86, z=1.08

RA=38.03, DEC=-7.99, z=0.92

RA=37.39, DEC=-3.82, z=1.24

RA=38.26, DEC=-4.61, z=1.49

RA=37.17, DEC=-4.14, z=1.62

RA=37.61, DEC=-7.86, z=1.08

RA=38.03, DEC=-7.99, z=1.17
## Observed redshift distribution

### ugr

- 184 luminous ELG
- $g<22.7$
- CFHT

### gri

- 634 ELG, E+A
- $i<21.3$
- SDSS

~1 hour spectra on SDSS-III/BOSS spectrograph

![Graph showing observed redshift distribution for ugr and gri filters.](image-url)
Use a combination of $ugr$ and $gri$ color selection for ELG (as experimented with BOSS data). Considering adding WISE-LRG to the BOSS-LRG. However improvement is possible and likely!
Target Selection: spectra of QSOs

Observed Frame Wavelength (Å)

- **z = 1.79477**
  - SiIV, CIV, CII, MgII

- **z = 1.49553**
  - CIV, CII, MgII

- **z = 1.66239**
  - SiIV, CIV, CII, MgII

- **z = 1.79477**
  - SiIV, CIV, CII, MgII

- **z = 2.00803**
  - Lyα, SiIV, CIV, CII, MgII

**Observed Frame Wavelength (Å)**
Ly-α QSOs (2.2<z<5):
- HI absorption in Ly-α forest
- Difficult to select
  ⇒ it requires variability and photometry
- Experience from BOSS
- Increase S/N from BOSS
- Go deeper (more QSOs)

1<z<2.2 QSOs:
- Tracers of cosmic structures
- Peak at z ~1.5-2
- Main background of Ly-α QSO
- Easy to distinguish from stars
  ⇒ Already a QSO catalogue of 1 Million QSOs from DR7 (~100 qsos/sq.deg)

⇒ Target strategy developed in e-BOSS to select both categories
Conclusion & Prospects: Lensing

- Lensing is a unique tool to study the total mass distribution.
- Important progress regarding: stellar/DM relation in halos when combining lensing+stellar mass +galaxy correlation.
- New lensing surveys on their way (CFHT-Stripe 82, KIDS, DES, HSC)
Conclusion & Prospects: Redshifts

- Major spectroscopic surveys in progress (BOSS) or being planned (e-BOSS). Even better survey will come latter-on.

- Next surveys will combine *Lensing and Redshift information* to put stronger constraints on mass assembly, LSS, and cosmology.