cross-correlation of spectroscopic & photometric surveys

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bottom line

More efficient way of using galaxy surveys:

X-correlation -> Understanding Galaxy bias -> x100
REWARD IN COSMOLOGICAL PARAMETER MEASUREMENTS
**Figure of Merit** \[ \text{FoM}_w = \frac{1}{\text{det}[F^{-1}]} \]

\[ \text{FoM}_{w, \gamma} \times 10^3 \]

\[ w(z) \rightarrow \text{Expansion History (background metric)} \]

we will use \( w_0 \) and \( w_a \)

\[ \gamma \rightarrow \text{Growth History (metric perturbations)} \]

probably need one more parameter here

\[ \theta = - f(\Omega) \delta \]

\( f = \text{growth rate factor: tell us if gravity is really responsible for structure formation!} \)

Could also tell us about cosmological parameters or Modify Gravity

\[ \sigma(\text{FoM}) = \frac{1}{\sigma(w_0) \sigma(w_a) \sigma(\gamma)} \]

\( \Omega_m - \text{ODE} - h - \text{sig8} - \text{Ob} - w_0 - w_a - \gamma - \text{ns} - \text{bias}(z) \)
Cosmology with Galaxy Clustering: Probes used

1. Angular clustering: Galaxy-Galaxy (GG) autocorrelation in narrow redshift bins

2. Weak Lensing: Shear-Shear (SS), Galaxy-Shear (GS) & Magnification (MAG = GG cross-correlations)

3. Redshift Space Distortions: RSD, ratio transverse to radial modes

Focus here only on large scales, where bias is only weakly non-linear (and r~1) but evolves with redshift and luminosity b=b(z)

Combine (cross-correlate) Photometric & Spectroscopic Surveys
Galaxy Clustering: 2pt
(in real space)

- 3D: all modes to be measured
- traces galaxies (not DM)
- is biased: can not be used for precision cosmology (unless modeled)
- considerable effort to understand bias => galaxy formation models

Millenium Simulation (MS) Springel
Galaxy Biasing:
On large scales, DM halos (that host galaxies) and dark-matter particles trace very similar structures (LSS): we can use halos (and galaxies) to study LSS.
DES-MICE Galaxy Catalog
Data Release v0.3 r1.0

MICE matter overdensity at z=1

DES-MICE galaxy overdensity at z=1
Galaxy bias evolution (~ luminosity evolution): how many parameters?

The characteristic time scales for bias evolution is \( \Delta a > 0.1 \), corresponding to \( t > 1 \text{Gyr} \), which is typical of galaxy evolution: 4-5 values between \( z = 0.2-1.5 \).

Simulations show that 4 values (between \( z=0.2-1.4 \)) of \( b(z) \) are enough for 1% accuracy.
Some conclusions for galaxy bias in simulations:

- does not depend on scale and $r=1$ for $r_{12} > 20$ Mpc (at <1% accuracy)

- $b(z)$ evolves over time-scales of 1 Gyr (as $D(z)$ or galaxy evolution) => 4 parameters

We can therefore use galaxy clustering for precision (1%) cosmology if we restrict to linear scales and use $b(z)$ for evolution.

But note that $b(z)$ is degenerate with $D(z)$:

$$P_G(k,z) = D^2(z) b^2(z) P_m(k,0)$$

so galaxy-galaxy (in real space) alone is not enough to measure growth: $\gamma$
Weak Lensing

- galaxy fluctuations due to lensing  \( \delta_g = (2.5s - 1)\delta_\mu \simeq (5s - 2)\delta_\kappa \)
- galaxy fluctuations  \( \hat{\delta}_{gj}(\tilde{\theta}) \simeq b_j\delta_{mj}(\tilde{\theta}) + \epsilon_j(\tilde{\theta}) + \sum_{i<j} p_{ij}\delta_{mi}(\tilde{\theta}) \)
- galaxy & shear correlations compared to matter
  \[ < \hat{\delta}_{gi}\hat{\delta}_{gi} > \simeq b_i^2 < \delta_{mi}\delta_{mi} > \]
  \[ < \hat{\delta}_{gi}\hat{\delta}_{gj} > \simeq b_ip_{ij} < \delta_{mi}\delta_{mi} > \quad i < j \]
  \[ < \hat{\delta}_{gi}\hat{\delta}_{k-j} > \simeq b_i\bar{p}_{ij} < \delta_{mi}\delta_{mi} > \quad i < j \]
Photometric Sample

Weak Lensing traces 2D unbiased dark matter distribution in front of sources

\[
C_{\kappa j \kappa j} (\ell) = \int_0^{z_j} dz \, p_{\kappa j}^2 (z) \, \mathcal{P}(k, z)
\]

\[
p_{\kappa j} (z) \simeq \frac{3 \Omega_m H_0}{2 H(z) a} \frac{r(z) r(z_j; z)}{r_0 r(z_j)}
\]

\[
\mathcal{P}(k, z) \equiv \frac{P(k, z)}{r_H(z) r^2(z)}
\]

where \( r_H(z) \equiv c/H(z) \), and \( \mathcal{P} \) is the adimensional power spectrum at \( k = (\ell + 1/2)/r \). In linear theory \( P(k, z) = D^2(z) P(k) \).
Shear-shear tomography is still 2D

\[ C_{\kappa_i \kappa_j}(\ell) = \int_0^{z_j} dz \, p_{\kappa_i}(z) \, p_{\kappa_j}(z) \, P(k, z) \]

\[ k = \ell / r(z) \]

\[ \propto \int_0^{z_i} \frac{dz}{r_H} \left( \frac{3 \Omega_m H_0}{2 H a r_0} \right)^2 \frac{r(z_i; z) r(z_j; z)}{r_i r_j} P(k, z) \]

Geometry vs Growth

**Fig. 2.** Weak lensing efficiency for shear-shear \( p(\zeta, \zeta_i) p(\zeta, \zeta_j) \) for \( \zeta_j = 1.0 \) and \( \zeta_i = 0.2, 0.4, 0.6, 0.8 \) and 1.0. Top line corresponds to \( p(\zeta, \zeta_j = 1.0) \), for galaxy-shear lensing.
Redshift Space Distortions

- Depends on bias
- But also has a term that only depends on velocity divergence
- $f$ can be separated by comparison of transverse to radial modes

BAO (Baryon Acoustic Oscillations)

- Independent on bias
- 1-2D
\( \gamma = 0.54 \pm 0.17 \)

**BAO:**

- **radial** \( H(z) \)
  \[ H(z=0.34) = 83.8 \pm 3.0 \pm 1.6 \]
  Gaztañaga, Cabre & Hui (2009)

- **Transverse** \( \int \frac{cdz}{H(z)} \)
  \[ \theta(z=0.34) = 3.90 \pm 0.38 \]
  Carnero et al. 2011

**Redshift Space Distortions (RSD)**

\[ \delta_g(k, \mu) = (b + f \mu^2) \delta(k) \]
Cosmology with Galaxy Clustering

Combine (cross-correlate) Photometric & Spectroscopic Surveys and all different probes

1. GG auto-correlations
2. Weak Lensing: SS, GS, MAG=GG cross-correlations
3. Redshift Space Distortion

Model Photo-z influence: transitions and errors

\[ r_{ij} \equiv T_{ij} \frac{N_j}{N_i} = \frac{T_{ij}N_j}{\sum_j T_{ij}N_j} = \frac{T_{ij} < N_j >}{\sum_j T_{ij} < N_j >} \]
Photometric Sample
i $\sim 24$

Spectroscopic Sample
i $\sim 22.5$, narrow radial bins
Cross-correlation Ratios:
Measure bias, ie from $C_{ii}/C_{ij}$
Measure $p_{ij}$, ie from $C_{ij}/C_{ik}$
Measure $P(k)$ ie from $C_{ij}^2/C_{ii}$

$k_i = 1 / \chi_i$

We ignore RSD here
### Forecast

<table>
<thead>
<tr>
<th></th>
<th>RSD(BAO)</th>
<th>WLxG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectroscopic (B=Bright)</td>
<td>✔</td>
<td>✘</td>
</tr>
<tr>
<td>Photometric (F=Faint)</td>
<td>✘</td>
<td>✔</td>
</tr>
<tr>
<td>Combined as independent: B+F</td>
<td>B</td>
<td>F</td>
</tr>
<tr>
<td>Cross-correlate same Area: BxF</td>
<td>B (+F)</td>
<td>BxF</td>
</tr>
</tbody>
</table>

#### Observables:

**WLxG:** Angular clustering of Shear-Shear; Galaxy-Shear; Galaxy-Galaxy

**RSD:** \( f(z)D(z); b(z)D(z) \) from \( P(k,z) \) in 3D with Fisher Matrix of RSD and WLxG are added: transverse modes+radial ratios

**Nuisance parameters:** bias (4 for each B & F), photo-z transitions (rij), noise \((\sigma/n)\)

**Cosmological:** \( \Omega_m - \Omega_{DE} - h - \sigma_8 - \Omega_b - w_0 - w_a - \gamma - n_s - \text{bias}(z) \)

\[
F_{oM_{\gamma}} \sim 2700 \ A^{0.89} \ \eta^{0.22} \ 1.4^{m_l-22.5} \ e^{-\sigma_z^2-\Delta_r A^{0.05}}
\]

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## Forecast: Planck+SNII priors

<table>
<thead>
<tr>
<th>$\text{FoM}_{w\gamma} \times 10^3$</th>
<th>RSD</th>
<th>RSD +BAO</th>
<th>WL Shear</th>
<th>Galaxy-Galaxy</th>
<th>Galaxy-Galaxy + BIAS IS KNOWN</th>
<th>WLxG +RSD</th>
<th>WLxG +RSD + BIAS IS KNOWN (eg 3pt)</th>
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<tbody>
<tr>
<td><strong>Photometric (i&lt;24)</strong></td>
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<td></td>
<td>3.2</td>
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<td><strong>Spectroscopic (i&lt;22.5)</strong></td>
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<td><strong>Cross Correlated over same Area</strong></td>
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</tbody>
</table>

5000 sq.deg.

σ(γ) ~0.04
σ(w0) ~0.03
σ(wa) ~0.07
bias ~ 1%

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**Spectroscopic follow-up strategy**

Given a photometric survey $i<24$ (F5000), a complementary galaxy survey (B5000) will add

<table>
<thead>
<tr>
<th>Probe</th>
<th>sample</th>
<th>FoM$_w$</th>
<th>FoM$_\gamma$</th>
<th>FoM$_{w\gamma}$</th>
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<tbody>
<tr>
<td>RSD</td>
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</tr>
</tbody>
</table>

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Combining Spectroscopic and Photometric samples and different probes can bring a boost of x100 in FoM (roughly 2-5 times smaller errors)

- Req: Photo-z error transitions need to be known to 1% accuracy
- Req: Bias evolves on timescales $>1$ Gyr
- Thanks to measurement of galaxy bias

Spectroscopic follow-up: is better to measure spectra of lenses than doing BAO

Magnification can be as useful as shear

If more is known of bias another x5