Cosmology with the large-scale structure of the universe

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The Large-Scale Structure (LSS)

- 3D structure of the observable universe
- Galaxy redshift surveys probe LSS

From: KICP homepage, 2MASS homepage
Galaxy redshift survey

- Sloan Digital Sky Survey (SDSS): The largest redshift survey ever made
From: Virgo simulations: Jenkins+ (1998)
Table 2. The Cosmological Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Einstein-de Sitter</th>
<th>$\Omega_m = 0.25 \pm 0.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flat</td>
<td>Open</td>
</tr>
<tr>
<td>1a. Dynamical mass measures</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>1b. World time $t(z)$: ages of stars &amp; elements</td>
<td>X??</td>
<td>✓</td>
</tr>
<tr>
<td>1c. Redshift-magnitude relation</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>1d. Lensing of quasars by galaxies</td>
<td>✓?</td>
<td>✓??</td>
</tr>
<tr>
<td>1e. Counts: $dN = f(m, z)dm dz$</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>2a. Large-Scale structure</td>
<td>X?</td>
<td>✓?</td>
</tr>
<tr>
<td>2b. CBR anisotropy</td>
<td>X?</td>
<td>✓?</td>
</tr>
<tr>
<td>2c. Cluster evolution</td>
<td>X?</td>
<td>✓?</td>
</tr>
<tr>
<td>2d. Baryon mass fraction in clusters</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>2e. Galaxy formation</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>3a. Aesthetics</td>
<td>✓</td>
<td>X?</td>
</tr>
<tr>
<td>3b. Inflation</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

$z < 0.1$

Survey should be DEEPER & WIDER

- **Merits of deep survey** (z ~ 1 or larger)
  - expansion history
  - geometry
  - evolution of structures

- **Merits of wide survey** (~10,000 square degrees)
  - statistics
  - large-scale clustering ( > 100 Mpc)
Current & Future galaxy surveys

- deeper and wider surveys are going on

From: WiggleZ survey homepage + Euclid

Euclid [? 2018-2025]
Cosmology with galaxy clustering

- Cosmological redshift-space distortion

\[
D_A(z) = \frac{1}{H_0 \sqrt{\Omega_K}} \sinh \left( H_0 \sqrt{\Omega_K} \int_0^z \frac{dz'}{H(z')} \right) \equiv (1 + z) d_A(z)
\]

\[
H(z) = H_0 \sqrt{(1 + z)^3 \Omega_M + (1 + z)^2 \Omega_K + (1 + z)^3 \exp \left( 3 \int_0^z \frac{w_{DE} \, dz}{1 + z} \right) \Omega_{DE}}
\]
BAO as a standard ruler

- Baryon Acoustic Oscillations (BAO)
- Oscillation scale can be calculated
Correlation function in 2D

- In 2D, “BAO ring” is a double ruler
- (velocity distortions included)

Primordial non-Gaussianity in LSS

- Primordial non-Gaussianity increases the power spectrum of galaxies on VERY LARGE SCALES

\[ \Phi(r) = \Phi_L(r) + f_{NL} \left( \Phi_L^2(r) - \langle \Phi_L^2(r) \rangle \right) \]

\[ \Delta b(M, k) = 3f_{NL}(b-1)\delta_c \frac{\Omega_m}{k^2T(k)D(z)} \left( \frac{H_0}{c} \right)^2 \]

From: Desjacque+ (2009)
Constraining modified gravity

\[ f_g(z) = \frac{d \ln D}{d \ln a} \approx \Omega_M^\gamma \]

Current

Future

From: Guzzo+ (2008); Euclid Yellow Book (2011)
Warning: Some complexities

- **Nonlinear evolutions**
  - analytically hard problem
  - even important on large-scales (for precision cosmology)

- **Redshift-space distortions (RSD)**
  - peculiar velocities of galaxy displace the position in redshift space

- **Biasing**
  - galaxies are not unbiased tracers of matter
Perturbation theory approach

- Nonlinear evolutions can be solved by the perturbation theory (on large scales)

\[ \text{Continuity:} \quad \frac{\partial \delta}{\partial t} + \frac{1}{a} \nabla \cdot [(1 + \delta)v] = 0 \]

\[ \text{Euler:} \quad \frac{\partial v}{\partial t} + \frac{\dot{a}}{a} v + \frac{1}{a}(v \cdot \nabla)v = -\frac{1}{a} \nabla \Phi \]

\[ \text{Poisson:} \quad \Delta \Phi = 4\pi G a^2 \bar{\rho} \delta \]

\[ \delta = \delta^{(1)} + \delta^{(2)} + \delta^{(3)} + \cdots \]
Integrated perturbation theory (iPT)

- Integration of Four “Non-’s”
  - nonlinear perturbation theory
  - nonlocal bias
  - nonlinear redshift-space distortions
  - non-Gaussianity of primordial density fields
Integrated perturbation theory (iPT)

- Lagrangian resummation theory
- nonlinear RSD
- nonlocal biasing scheme
- primordial nG
BAO with iPT

(scale-dependent bias due to nonlinearity)

From: Sato, TM (2011)
Scale-dependent bias from nG with iPT

- Most accurate among known methods
- powerful probe of primordial nG

From: TM, in prep
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Modified Gravity</th>
<th>Dark Matter $m_\phi/eV$</th>
<th>Initial Conditions $f_{NL}$</th>
<th>Dark Energy $w_p$</th>
<th>$w_a$</th>
<th>$FoM$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euclid Primary</td>
<td>0.010</td>
<td>0.027</td>
<td>5.5</td>
<td>0.015</td>
<td>0.150</td>
<td>430</td>
</tr>
<tr>
<td>Euclid All</td>
<td>0.009</td>
<td>0.020</td>
<td>2.0</td>
<td>0.013</td>
<td>0.048</td>
<td>1540</td>
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<tr>
<td>Euclid+Planck</td>
<td>0.007</td>
<td>0.019</td>
<td>2.0</td>
<td>0.007</td>
<td>0.035</td>
<td>4020</td>
</tr>
<tr>
<td>Current</td>
<td>0.200</td>
<td>0.580</td>
<td>100</td>
<td>0.100</td>
<td>1.500</td>
<td>~10</td>
</tr>
<tr>
<td>Improvement Factor</td>
<td>30</td>
<td>30</td>
<td>50</td>
<td>&gt;10</td>
<td>&gt;50</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>

From: Euclid Red Book
In Summary

• LSS is a powerful tool in cosmology
  • dark energy (expansion history)
  • primordial density field (Inflation? or other?)
  • tests of gravity (Einstein? or modified?)

• Needs for precise modeling
  • nonlinear evolutions
  • nonlinear RSD
  • biasing
  • => developing a perturbation theory approach