Modeling Galaxy Surveys with the MICE simulations

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+ DES collaborators (T.Giannantonio,...)
“Cosmic Triangle”

Observations

Theory

Numerical Simulations

BSC

LSS-Garching
July-2015

P. Fosalba
Towards 1% accuracy in Dark-Matter statistics: Power Spectrum

Clustering on large-scales: using Perturbation Theory

- **CDM Perturbation Theory:**
  - Audren & Lesgourgues (2011): 1% precision for $k<0.2 \text{ h/Mpc}$ and $z>2$; 1% precision $k<0.14 \text{ h/Mpc}$ $z=1$. Released as part of CLASS.
  - Crocce et al (2012): MPTBreeze: Fast code for evaluation of multi-point propagators: 2% precision for BAO scales; $z<2.5$ $k<0.5 \text{ h/Mpc (LCDM)}$.
  - Taruya et al (2012): REGPT-Fast: precision 1% for $k<0.2 \text{ h/Mpc (WCDM)}$.

Analytic theory accurate enough (~1%) for BAO scales in real/redshift space

Beyond BAO scales (i.e. $r < 100 \text{ Mpc}$ scales or $k > 0.2-0.3 \text{ Mpc}^{-1}$), harder to model with analytic theory…

Need for simulations to accurately model signal and covariance of observables
State of the art in Nbody simulations

- **MXXL**: Angulo et al.
- **MICE**: Fosalba et al.
- **Horizon Sim**: Teyssier et al.
- **HR1,2,3**: Kim et al.
- **DEUSS**: Alimi et al.
- **Jubilee**: Watson et al.
State of the art in Nbody simulations

Current simulations can model MilkyWay like galaxies ($10^{10} \, L_\odot$) over large volumes

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Stage III (DES/BOSS/PAU) simulation
State of the art in Nbody simulations

MICE
Grand-Challenge simulation

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What is MICE?

➢ Project hosted at ICE to develop very large N-body simulations using the Marenostrum supercomputer (PRACE Tier-0) in Barcelona/Spain

🍎 14+ million CPU hours allocated via open competition (since 2006)

🍎 Used up to 4,000+ processors, 8 TB RAM

🍎 GADGET2 code simulations with $10^9$-$10^{11}$ dark-matter particles in volumes $\sim$ 1-500 Gpc$^3$

🍎 $\sim$50 Terabytes of simulated data stored at PIC (data storage center @ Barcelona)  
**PIC Team:** Carretero, Neissner, Tallada, Tonello

**MICE Team:** P.Fosalba, F.Castander, M.Crocce, E.Gaztañaga, M.Manera

**Collaborators:** A.Bauer, C.Bonnett, J.Carretero, K.Hoffman, A.Izard, A.Pujol, D.Reed, S.Serrano
MICE-Grand Challenge simulation

Developed at Marenostrum @ BSC, used Gadget2, 4100 cores, 3 M-hours
70 billion particles in a 3 Gpc/h box (50 kpc/h soft length)

*Samples 5 decades in dynamic range*

MICE-GC data volume:
Lightcone (z<1.4), 10 TB
Snapshot, 2 TB (x 7)
MICECAT: galaxy mock from MICE-GC

✓ Built on MICE Grand Challenge *simulation*
  70 billion particles, 3 Gpc/h box, \( m_p = 3 \times 10^{10} \, M_\odot \)

✓ 3D Lightcone (up to \( z=1.4 \)), 2D LC up to \( z=100 \) (all sky CMB Lensing map)

✓ FoF halos with \( b=0.2 \): 150 million halos per octant, for \( N_p > 10 \)

✓ 1 octant (5000 sq.deg.), up to \( z<1.4 \), with 200 Million HOD galaxies.
  we can model galaxies down to \( M_r < -18 \)

  Adjust HOD parameters:
  ★ Match LF and color-magnitude diagram to SDSS (low-z)
  ★ Observed SDSS clustering vs. Luminosity and Color

✓ Data publicly available @ Cosmohub.pic.es:
  * magnitudes (multiple bands), halo mass, photo-z, SEDs, colors, shapes,..
  * Lensing properties for galaxies: Convergence, Shear, Lensed positions
MICE-GC simulation papers


HOD galaxy mock method [Carretero et al. 2015, *MNRAS*, 447, 646]
Higher-order clustering [Hoffmann et al. 2015, *MNRAS*, 447, 1724]
Dark-Matter clustering: large-scales

Fosalba et al 2015 [MNRAS, 448, 2987]

P(k) at BAO scales

- RPT
- Emulator
- Revised Halofit

 Resolution Effects in MICE
2.3×10^{11} vs. 3×10^{10} M_{\odot}/h

- 5-10% resolution effects at k>1 h/Mpc
- Increase with redshift

Agreement with hi-res numerical fits
(Heitmann et al 2013; Takahashi et al 2012) within 2% accuracy

Similar effects seen in the 2PCF and 3PCF
Dark-Matter clustering: redshift space distortions

Fosalba et al. 2015 [MNRAS, 448, 2987]

- RSD effects more important as redshift accuracy of galaxy survey increases
- **Non-linear RSD** effects visible at 1 deg. Scales, even at z=1 (~20 Mpc/h)
Halo and Galaxy bias: small and large scales


**Halos**

Large scales (> 20 Mpc/h):
Decrement (2%) for low mass,
excess (5%) for large mass halos

Small scales (< 20 Mpc/h):
bias becomes steadily scale dependent.
b$_2$ changes sign as mass increases

**Galaxies**

(centrals + satellites)

3D (spectro-z survey)

Scale dependence:
✓ similar to halos on large-scales
✓ NL bias always positive
Weak Lensing observables

“The onion universe: all sky light-cone simulations in spherical shells”

For the convergence field:

\[
\kappa(\theta) = \frac{3H_0^2\Omega_m}{2c^2} \int dr \, \delta(r, \theta) \frac{(r_s - r)r}{r_s a}
\]

..discrete sum over Lightcone shells…

\[
\kappa(i) = \frac{3H_0^2\Omega_m}{2c^2} \sum_j \delta(i,j) \frac{(r_s - r_j)r_j}{r_s a_j} \, dr_j
\]

• Valid in the Born approximation (ie, linear/uncorrelated deflections)
  1% accurate at arcmin scale (as compared to full ray-tracing sims)

• Simple relations (in harmonic space) to model other lensing observables
  (shear, flexion, etc.)
Weak Lensing: Convergence power

Fosalba et al. 2015 [MNRAS, 447,1319]

\[ C(\kappa) = \frac{9H_0^4\Omega_m^2}{4c^4} \int \, dr \, P(k, z) \frac{(r_s - r)^2}{r_s^2 a^2} \]

Mass Resolution: Convergence

\( z_s = 1 \)

\( m_p = 2.3 \times 10^{11} \, M_\odot/h \)

\( m_p = 2.9 \times 10^{10} \, M_\odot/h \)

Symbols - MICE
MICE-IR
MICE-GC

Lines - Fits
Solid: Smith et al 2003
Dashed: Takahashi 2012

Lensing Halos < \( 3 \times 10^{11} \, M_\odot \) give 10-20% contribution to lensing power at < 10 arcmin scales (multipoles > 1000)

Fosalba et al. 2015
MICE simulations for DES-SV

2point galaxy clustering [Crocce et al. 2015a, arXiv:1507.05360]

DESxCMB lensing [Giannantonio et al. 2015, arXiv:1507.05551]
DES-SV clustering: data vs simulations

Crocce et al. 2015, arXiv:1507.05360

DATA: $b(z)$ in 5 $z$-bins, width $\Delta z = 0.2$

- Steep raise at $z > 1$ expected from HOD mocks (~ flux-limited surveys)
- Larger bias expected at low-$z$ (systematics? sample variance?)
**DESxCMB Lensing: data vs simulations**

Giannantonio, Fosalba et al. 2015, arXiv:1507.05551

- Galaxy ACF is consistent with measurement from mocks
- Consistently lower galaxy bias from Gal-CMB reproduced by sims

100 mocks (SV patches out of all-sky simulations) Sampling “galaxies” from the DM distribution in the LC with the DES n(z)
Cross-consistency between linear galaxy bias from ACF and CCF follows mocks
Mismatch between ACF/CCF depends on assumed underlying cosmology…suggests 
*DESxSPT prefers lower values of $\sigma_8\Omega_m$ than best-fit Planck2015 cosmology*

Full-sample

$0.2 < z < 1.2$

< 1-sigma tension

[sigma is DESxCMB stat. errorbar]
MICE galaxy mocks
Recent developments

- Increased completeness: \( i < 24 \) to \( z = 1.4 \)
- Improved lensing resolution (< 1 arcmin)
  - Deeper: 3D lightcone to \( z = 3 \) (ongoing, MICECAT 3.0)
  - Intrinsic alignments (ongoing, MICECAT3.0)
Back-up Slides
HOD galaxy assignment

**Luminosity**  We populate halos with one central and maybe some satellite galaxies (HOD) \( <N_{\text{sat}} > = (M/M_1)^\alpha \)
Luminosities set to match the r - band luminosity of SDSS

**Color**  We assign (g-r) color using the color bi-modality at fixed \( M_r \)

**Clustering**  We place centrals at the halo centers and satellites following an NFW profile with bulk + virial velocity decomposition.
Tune HOD by computing projected correlation function as a function of color and magnitude and comparing with observations.