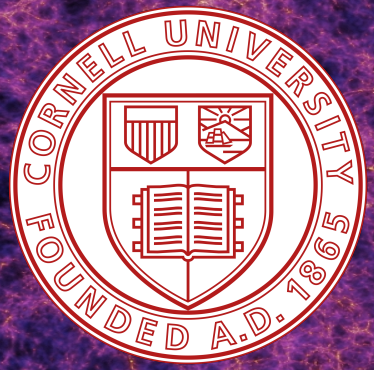
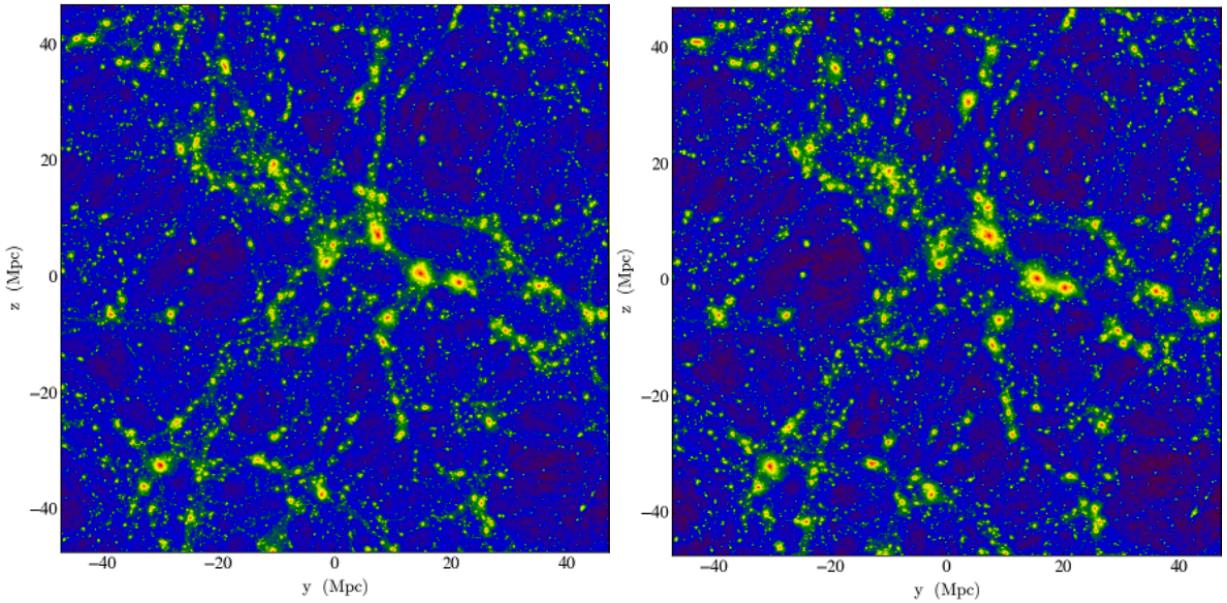
Beyond δ:
Tailoring marked statistics to reveal modified gravity



Georgios Valogiannis
Cornell University
Oxford, April 18th, 2018

Cosmological scales as probes of viable MG models

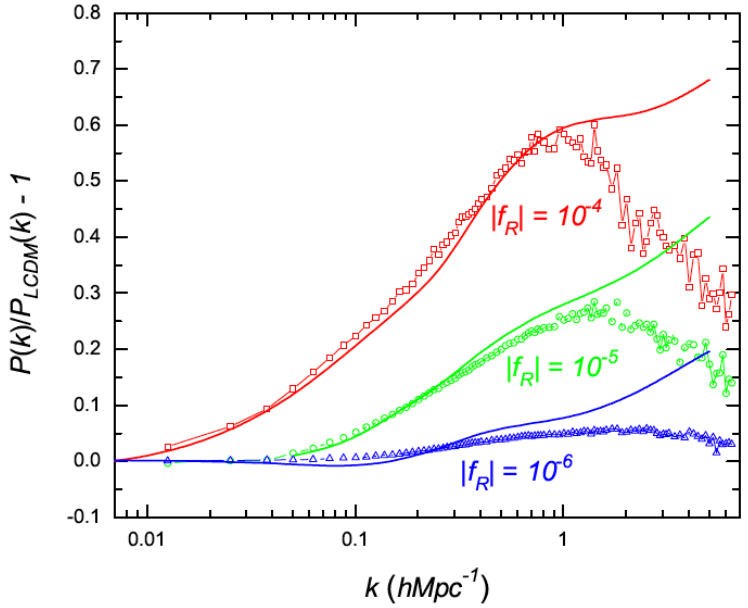
- Alternative proposals to ΛCDM
  - Modified gravity
- Any deviation from GR should satisfy tight solar system constraints
- Invoke screening mechanisms
  - Suppress deviations in high densities
  - Guarantees phenomenological viability
- MG-ΛCDM degeneracy broken at cosmological scales



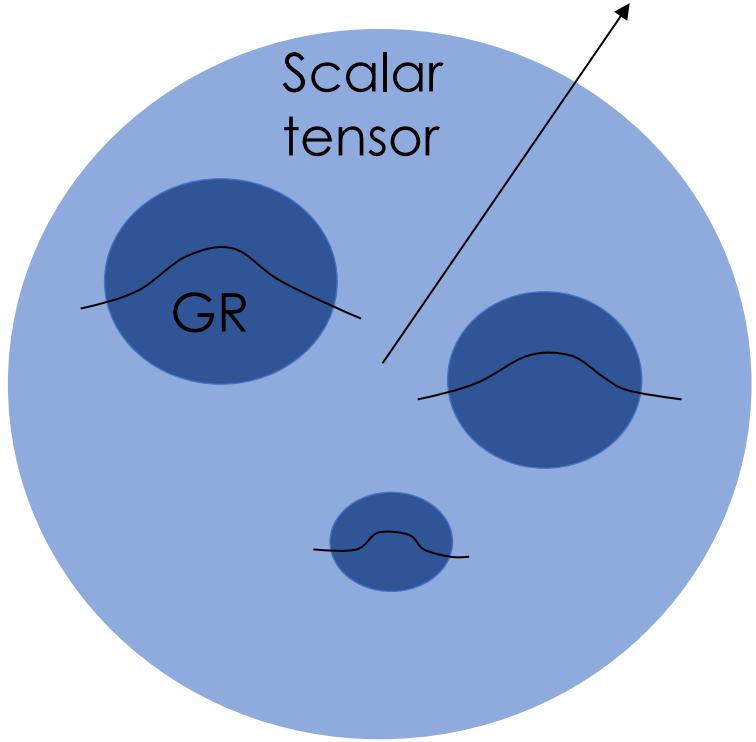
K. Koyama, 2015

Need for a new statistic

- (Mildly non-) linear scales – Scalar tensor regime
  - Modifications to gravity important
- Non-linear scales – GR regime
  - Deviations suppressed, tends to GR
- Collapsed structures dominate 2-point statistics
- Signals strongly suppressed by screening – detection challenging
- Need for a new statistic



B. Li et al. 2011



K. Koyama 2017

Marked density transformation

- **Up-weighting low density, unscreened regions** and down-weight highly screened regime can **highlight** MG signals in density fields
- Fundamental quantity of interest

$$\delta(\mathbf{x}, a) = \frac{\rho_m(\mathbf{x}, a)}{\bar{\rho}_m} - 1$$

- Variety of density transformations in literature
  - Logarithmic re-mapping (M. Neyrinck et al. 2009)

$$\delta' = \ln(\delta + 1)$$

  - Clipping density field (F. Simpson et al. 2011)

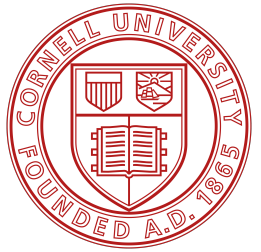
$$\delta' = \delta_c = \begin{cases} \delta & \text{if } \delta < \delta_0 \\ \delta_0 & \text{if } \delta > \delta_0 \end{cases}$$

  - **«Marked»** transformation (M. White, 2016)

$$\delta' = m(\delta) = \left(\frac{\rho_* + 1}{\rho_* + \rho_m}\right)^p = \left(\frac{\rho_* + 1}{\rho_* + \bar{\rho}_m(\delta + 1)}\right)^p$$

  - Restricted logarithmic transform (C. Llinares & N. McCullagh 2017)

Quantifying enhancement



- Dark matter N-body simulations using Particle-Mesh (PM) code (Valogiannis & Bean 2017)
- Simulation box side L=200 Mpc/h, 256^3 particles, resolved on 512^3 grid
- 40 density snapshots at z=0 for ΛCDM, f(R) and symmetron cosmologies
- 2D projection → 3x40=120 power spectra
- Covariance matrix

$$C_{ij} = \frac{1}{N_{seed}-1}\sum_{r}^{N_{seed}}\Big(P_r(k_i)-\bar{P}(k_i)\Big)\Big(P_r(k_j)-\bar{P}(k_j)\Big)$$

- Fisher information in the parameter

$$I_\alpha = \sum_{i,j}^{N_{bins}} \frac{\partial P(k_i)}{\partial \alpha} C_{ij}^{-1} \frac{\partial P(k_j)}{\partial \alpha}$$

- Signal-to-Noise Ratio (SNR)

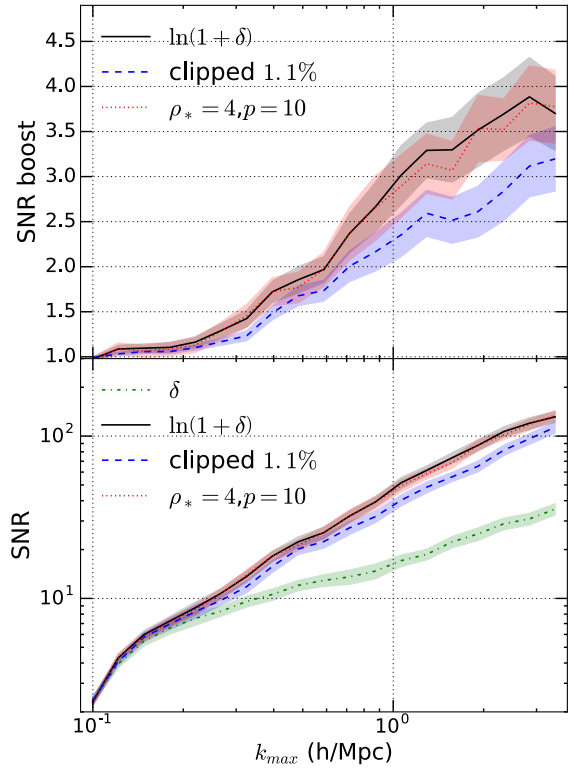
$$SNR = \sqrt{\sum_{i,j}^{N_{bins}} \bar{P}(k_i) C_{ij}^{-1} \bar{P}(k_j)}$$

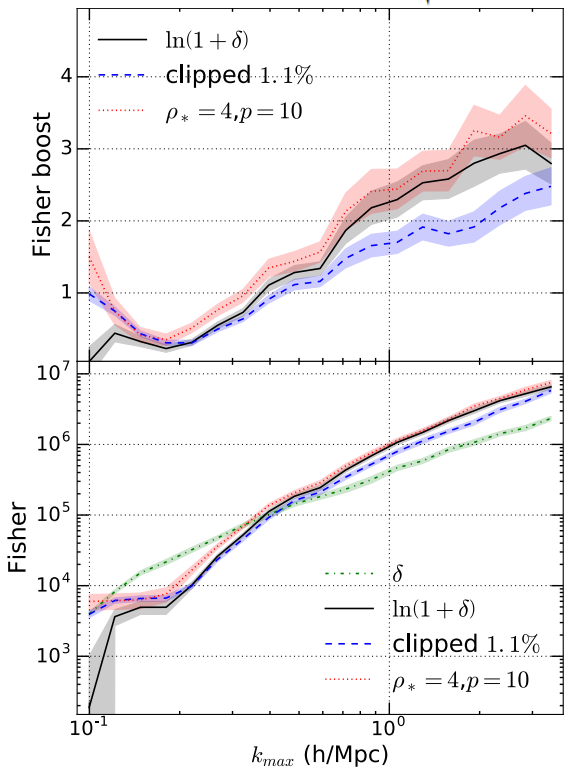
Information boost

- Assess level of additional information encoded, in terms of "boost"
- Marked transformation **increases** information relative to standard δ

$$\text{SNR boost} = \frac{\text{SNR}(\delta')}{\text{SNR}(\delta)}$$

$$\text{Fisher boost} = \sqrt{\frac{I_\alpha(\delta')}{I_\alpha(\delta)}}$$



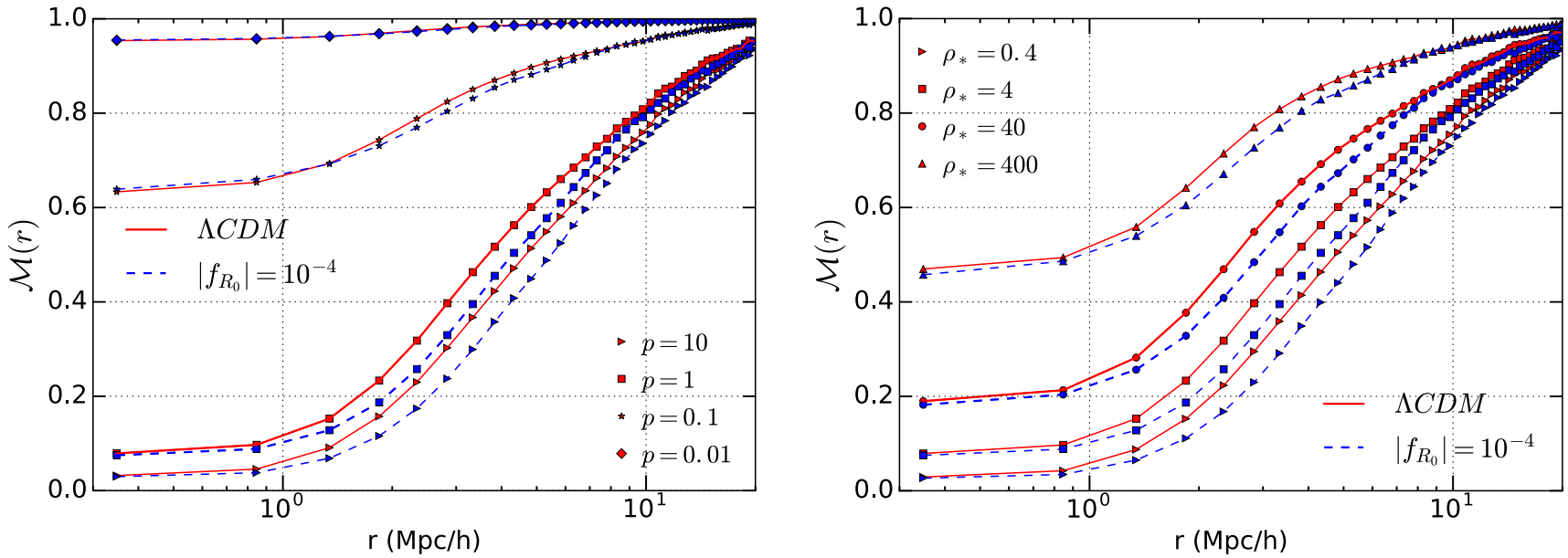


Valogiannis & Bean, 2018

Marked correlation function

- Screening mechanism produces unique density dependent signature
- What other density-dependent statistics?
- Marked correlation function (Sheth, R.K., Connolly, A.J., & Skibba, R. 2005)
- Real space statistic

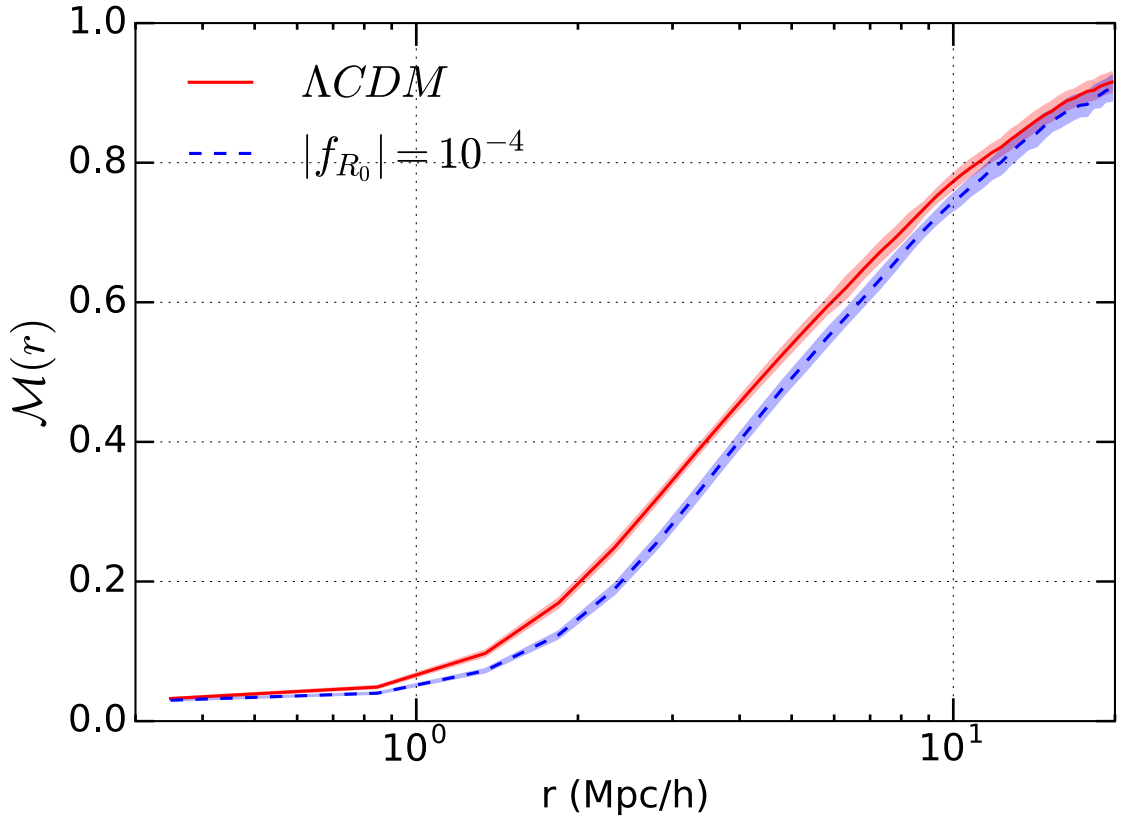
$$\mathcal{M}(r) \equiv \frac{1}{n(r)\bar{m}^2} \sum_{ii} m_i m_j = \frac{1+W}{1+\xi}$$



Valogiannis & Bean, 2018

Marked correlation function

- Degeneracy between MG and ΛCDM broken in unique way
- M(r)<1 at small scales



Valogiannis & Bean, 2018

Summary and future work

- Simple, "marked" density transformations serve as powerful tools for testing gravity
- Up-weight unscreened regions and down-weight high densities
  - Phys. Rev. D 97, 023535 (2018)
- Hybrid COLA scheme for efficient MG chameleon simulations
  - Phys. Rev. D 95, 103515 (2017)
- "Testing the theory of gravity with DESI: estimators, predictions and simulation requirements" white paper in preparation
- C. H. Aguayo et al. (2018) & J. Armijo et al. (2018) on marks
- Further explore use of mark in the context of realistic observations
- Perturbation theory predictions for marked statistics


Thank you!