How Dark are Filaments in the Cosmic Web?

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arXiv link: https://arxiv.org/abs/2001.10943
(work done with Michael J. Hudson & Niayesh Afshordi)
MOTIVATION

• Low density contrast structures ($\delta \sim \text{few}$): difficult

• Epps S. D. & Hudson M. J. 2016 detection using LRG (luminous red galaxy) pairs: confirm the filamentary structure observationally (using WL) at $5\sigma$ level. (arXiv link: https://arxiv.org/abs/1702.08485)

• Are filaments are completely dark or there are galaxies in it? → M/L ratio.
PHYSICAL VERSUS NON-PHYSICAL LRG PAIRS

\[ 6h^{-1}\text{Mpc} \leq R_{\text{sep}} < 10h^{-1}\text{Mpc} \]
\[ |\Delta z| < 0.002 \]
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$0.033 \leq \Delta z \leq 0.05$
MASS MAP

Data:

- **Lenses**: LRG galaxy pairs from SDSS-BOSS survey from redshift 0.15-0.7 → 15,254 LRG physical pairs in total: $\langle z_{\text{pair}} \rangle = 0.47$
- **Sources**: from CFHT photometric catalogue with $\sim 6 \times 10^6$ object and mean redshift = 0.64 (within an area of $\sim 154$ square degrees)

+ two independent redshift bins (LOWZ and CMASS in BOSS) to investigate how the properties of filaments evolve with redshift
ROTATE, RESCALE, SHIFT AND STACK

- 15254 pairs of LRGs were selected between projected separation:

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15254 pairs of LRGs were selected between projected separation: $6h^{-1}\text{Mpc} \leq R_{\text{sep}} < 10h^{-1}\text{Mpc}$ and $|\Delta z| < 0.002$

Rotate, rescale shift and stack background galaxies
RESULTING SHEAR MAP

Kaiser & Squires `93 to get convergence (surface mass density) from shears
LENSING MAP (WHOLE SAMPLE)

8 Mpc/h

physical pairs

non-physical pairs
EXCESS MASS MAP

\[ \langle z_{\text{pair}} \rangle = 0.47 \]

\[ \overline{M_{\text{total,fil}}} = (4.25 \pm 1.57) \times 10^{13} M_\odot \]
SCALING OF FILAMENT MASS AS REDSHIFT

- Predicted from the evolution of the three-point correlation function (Clampitt et al. 2014)

\[ \Sigma_m(z) \equiv \Sigma_{\text{crit}} \zeta_{gg\kappa} = \Sigma_{\text{crit}} \langle \delta_g(\vec{x}_1) \delta_g(\vec{x}_2) \kappa(\vec{x}_3) \rangle = \left( \frac{b(z)}{b(z = 0)} \right)^2 \left( \frac{D(z)}{D(z = 0)} \right)^4 \Sigma_m(z = 0) \]

- For the evolution of galaxy bias, we show two possibilities. One uses a constant galaxy bias, the other is an evolving bias model: \( b-1 = (b_0-1)/D(z) \), where \( b_0 \) is the linear bias extrapolated to present day.
Although the measurement uncertainties are large, the data are consistent with the predicted redshift scaling.
LIGHT MAP

- We produce the light map using similar approach.

- After the projection, stacking:
  - Physical LRG pairs = LRG (from entire BOSS coverage: \(\sim 450,000\) pairs) + excess galaxies in the filament + background/foreground galaxies (from SDSS)

  Non-physical LRG pairs = LRG + identical background/foreground galaxies
\[ \overline{L_{\text{fil}}} = 0.68 \pm 0.04 \times 10^{11} L_{\odot,0.1r} \]
\[ M_{\text{stellar,fil}} = 1.91 \pm 0.09 \times 10^{11} M_\odot \]
\[ \Sigma(y) = \frac{\rho_0 \pi r_c^2}{\sqrt{r_c^2 + y^2}} - \text{constant} \]

Abel transformed from the 3D profile

\[ \rho(r) = \frac{\rho_0}{1 + \left( \frac{r}{r_c} \right)^2} \]

suggested by Colberg et al. (2005)

reduced \( \chi^2 \sim 1.45 \)
STILL NOT ENOUGH...

- To compute the total M/L: need to compensate for the missing light!!!

- Flux limit of the SDSS data, as well possible outliers in the photometric redshifts

\[
N(m) = n_\star \int_{L_{\text{min}}}^{L_{\text{max}}} \left( \frac{L}{L_\star} \right)^\alpha e^{-L/L_\star} \frac{dL}{L_\star}.
\]

\[
\chi^2(n_\star, \alpha, M_\star) = [N_{\text{obs}}(m) - N_{\text{mod}}(m)]^T C^{-1} [N_{\text{obs}}(m) - N_{\text{mod}}(m)].
\]
Universe M/L (Loveday et al., 2015)

- Filament: LOWZ
- Filament: CMASS
- Filament: LOWZ+CMASS
MAIN CONCLUSION:

Filaments are not entirely dark!!!
CONCLUSION:

- First measurements of the mass-to-light ratio of filaments in the cosmic web: mass and light are simultaneously measured in a consistent way.

- Analyses are conducted for two independent samples (LOWZ and CMASS):
  - no significant evolution of total mass-to-light mass ratio of filaments.
  - the average colours of galaxies in filaments are consistent with the universal average.

- The uncertainties remain large for this analysis, given current data.
