How Dark are Filaments in the Cosmic Web?

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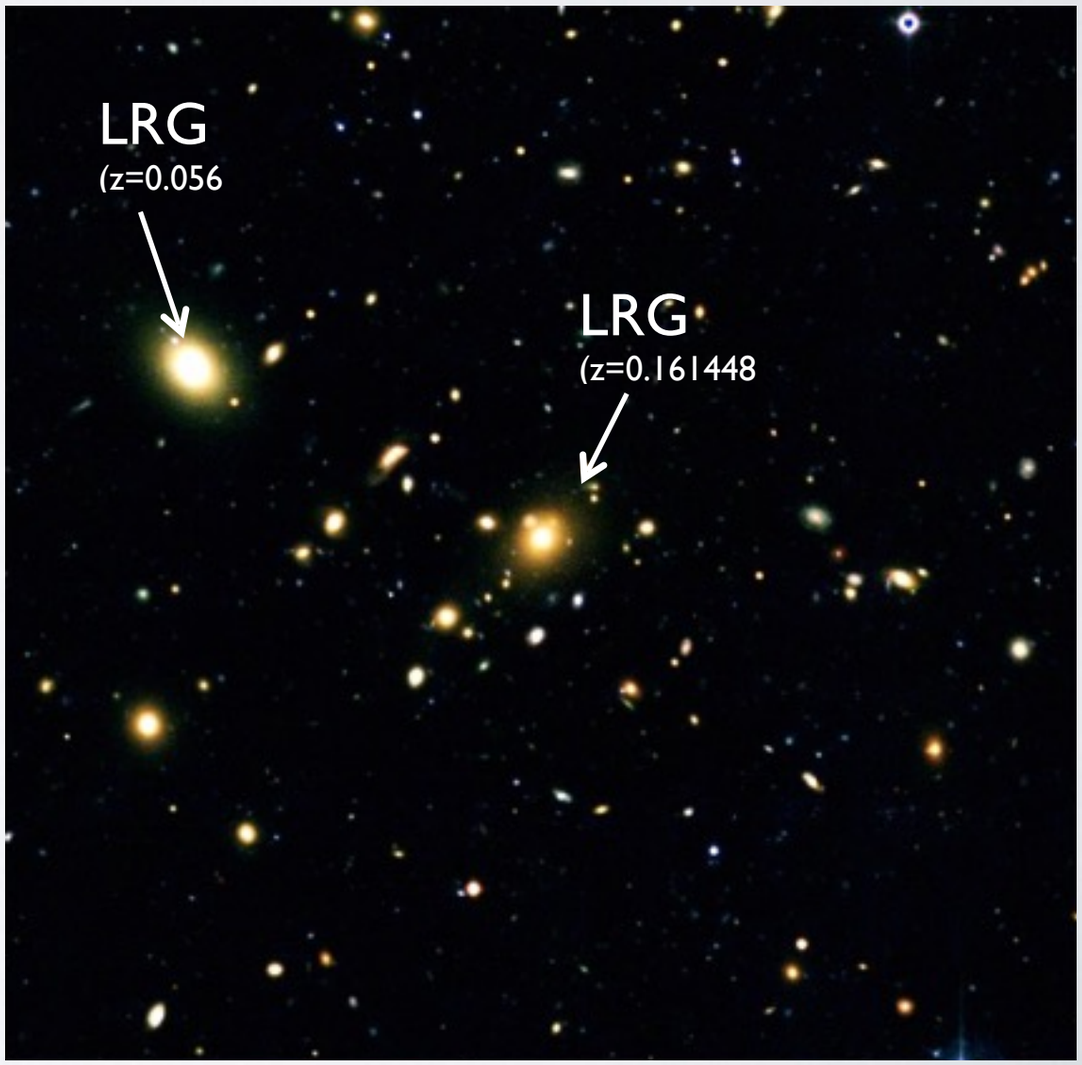
arXiv link: https://arxiv.org/abs/2001.10943
(work done with Michael J. Hudson & Niayesh Afshordi)

MOTIVATION

- Low density contrast structures ($\delta \sim$ few): difficult

- Epps S. D. & Hudson M. J. 2016 detection using LRG (luminous red galaxy) pairs : confirm the filamentary structure observationally (using WL) at 5σ 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

$$6h^{-1}\mathrm{Mpc} \leq R_{\mathrm{sep}} < 10h^{-1}\mathrm{Mpc}$$

$$|\Delta z| < 0.002$$

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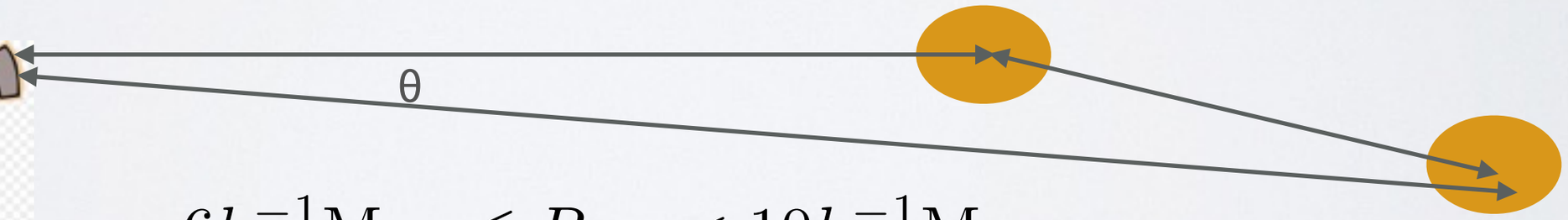

$$6h^{-1}\mathrm{Mpc} \leq R_{\mathrm{sep}} < 10h^{-1}\mathrm{Mpc}$$

$$0.033 \leq \Delta z \leq 0.05$$

MASS MAP

Data:

CFHT: Erben *et al.*, 2013; Hildebrandt *et al.*, 2012; Miller *et al.*, 2013; Heymans *et al.*, 2012,2013

SDSS: Eisenstein *et al.*, 2011; Dawson *et al.*, 2012

- **Lenses**: LRG galaxy pairs from SDSS-BOSS survey from redshift 0.15-0.7 → 15,254 LRG physical pairs in total : $\langle z_{\rm pair} \rangle = 0.47$

- **Sources**: from CFHT photometric catalogue with ~ 6×10^6 object and mean redshift = 0.64 (within an area of ~ 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:

$$6h^{-1}\mathrm{Mpc} \leq R_{\mathrm{sep}} < 10h^{-1}\mathrm{Mpc}$$

$$|\Delta z| < 0.002$$

ROTATE

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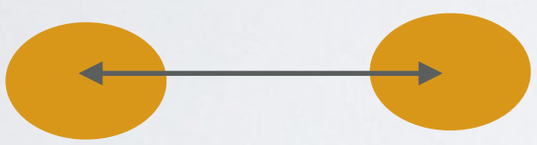

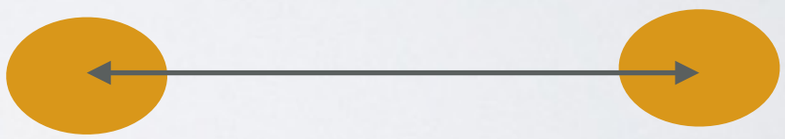

RESCALE

- 15254 pairs of LRGs were selected between projected separation:

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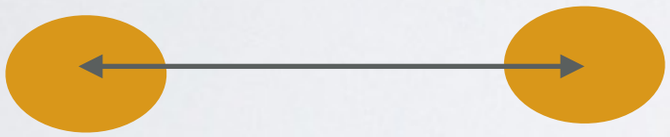
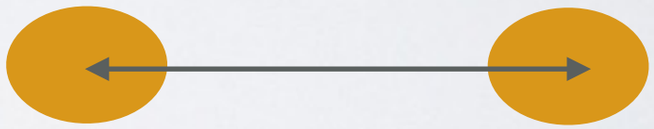
$$|\Delta z| < 0.002$$





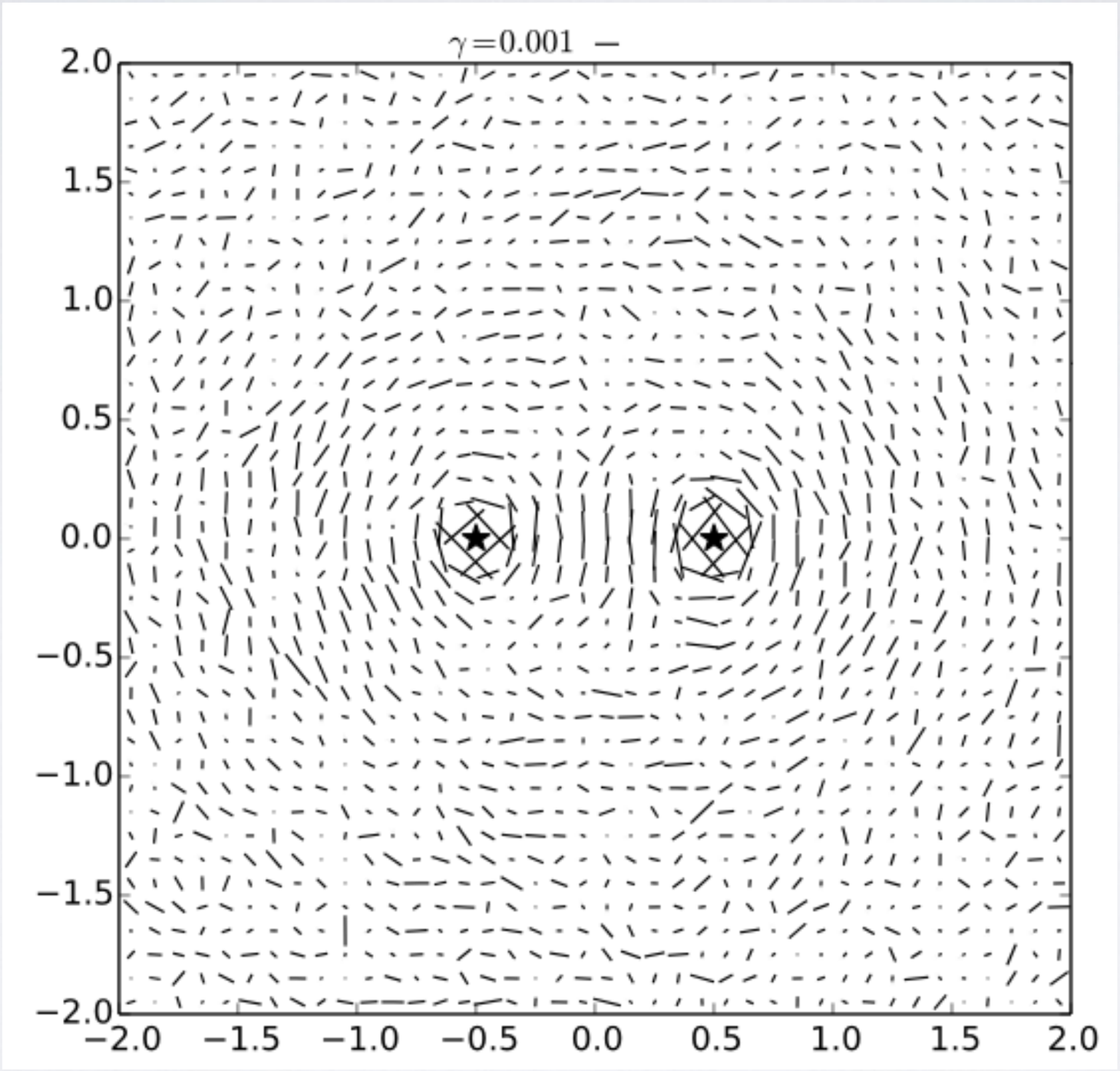
SHIFT AND STACK

- 15254 pairs of LRGs were selected between projected separation:

$$6h^{-1}\mathrm{Mpc} \leq R_{\mathrm{sep}} < 10h^{-1}\mathrm{Mpc}$$
$$|\Delta z| < 0.002$$

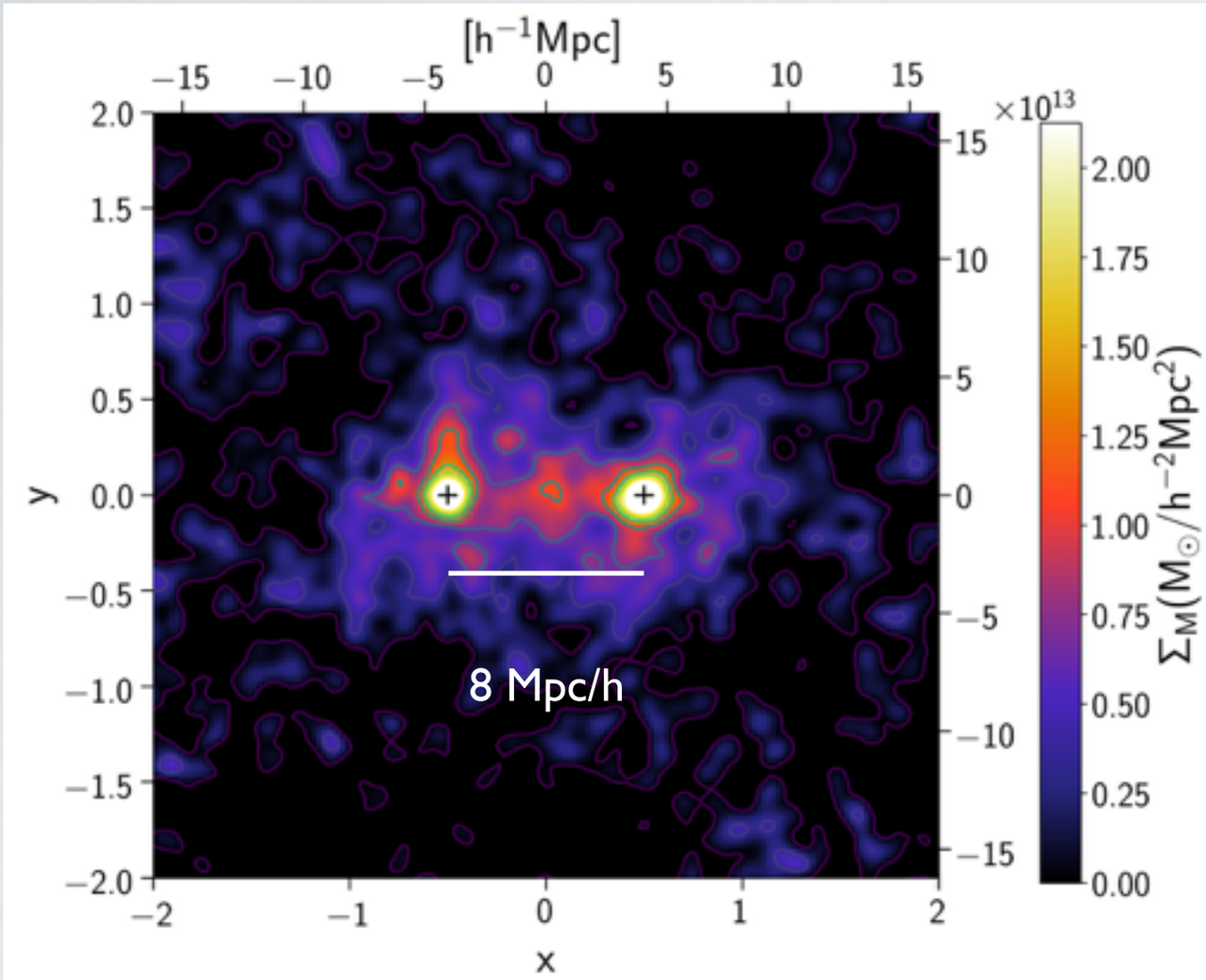
Rotate, rescale shift and stack background galaxies

RESULTING SHEAR MAP

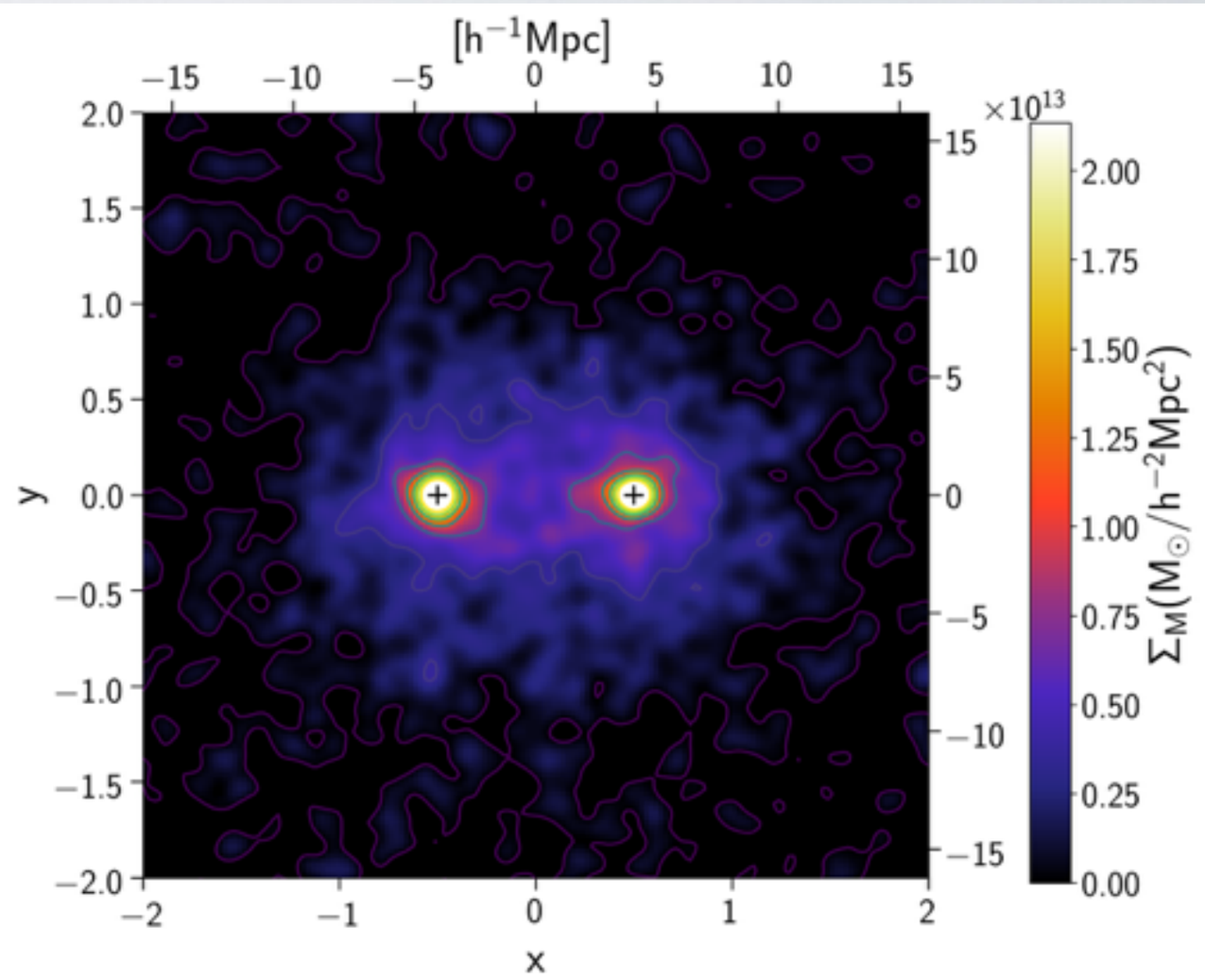


Kaiser & Squires `93 to get convergence (surface mass density) from shears

LENSING MAP (WHOLE SAMPLE)

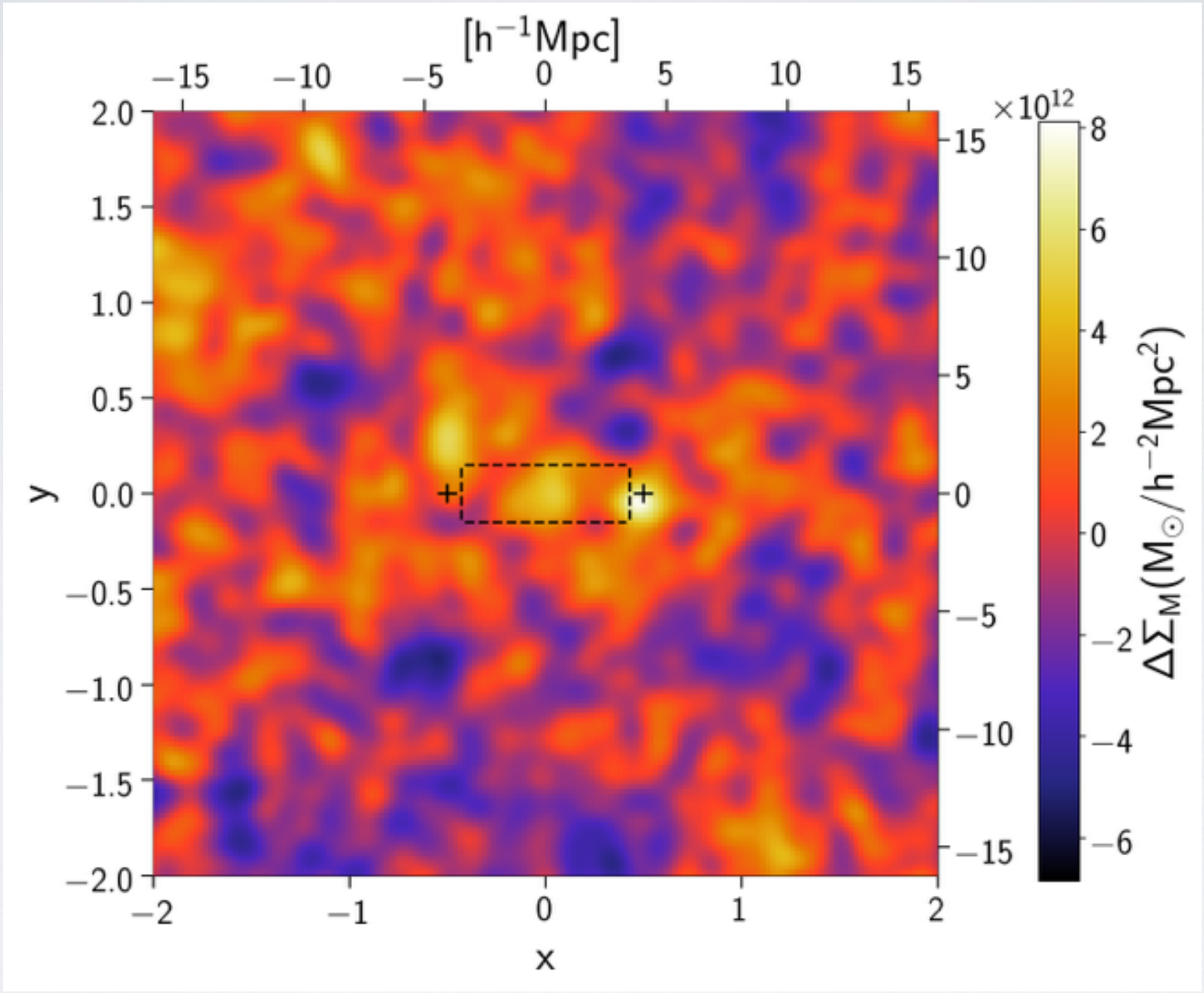


physical pairs



non-physical pairs

EXCESS MASS MAP



$\langle z_{\rm pair} \rangle = 0.47$

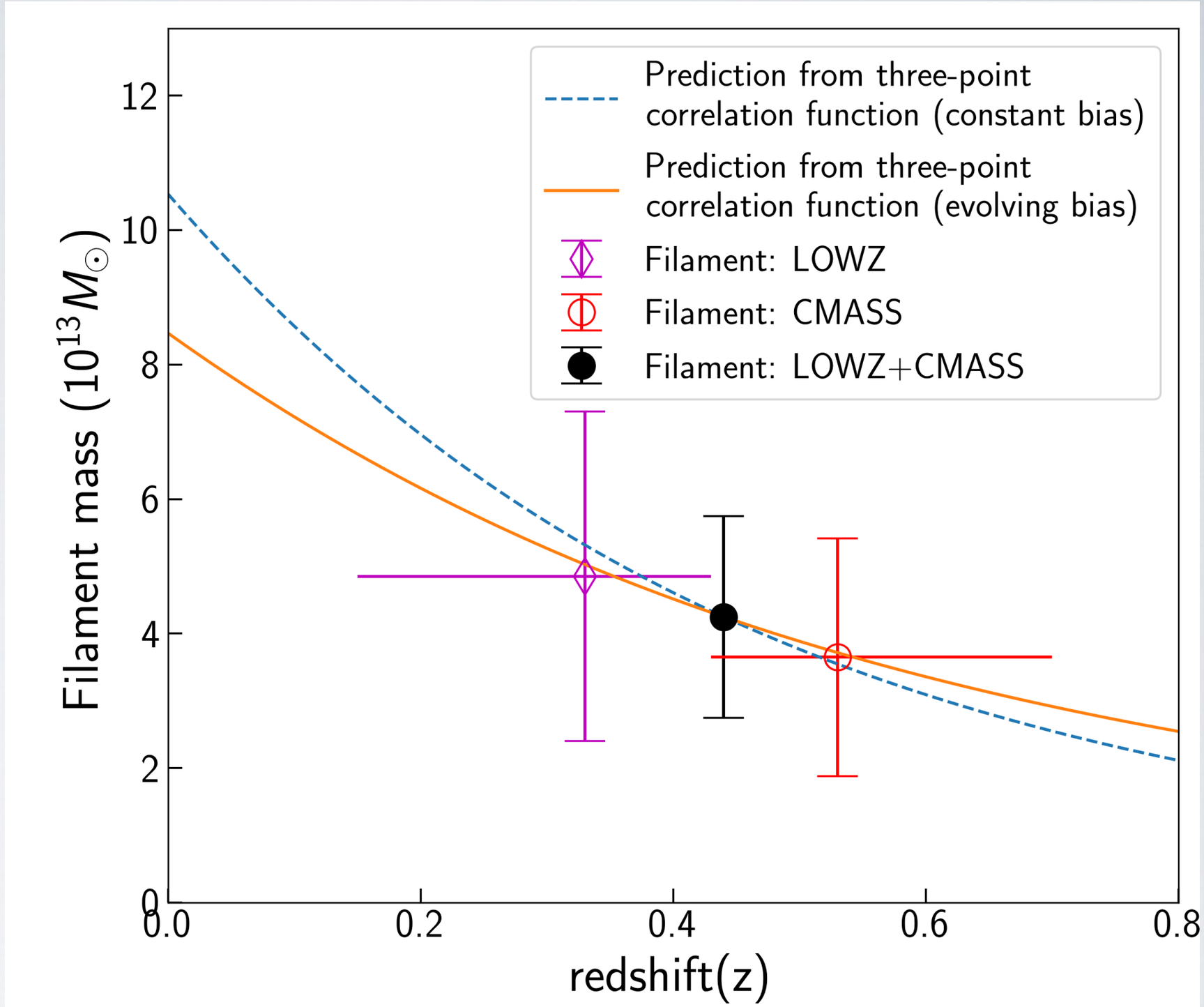
$\overline{M_{\rm total,fil}} = (4.25 \pm 1.57) \times 10^{13} M_\odot$

SCALING OF FILAMENT MASS AS REDSHIFT

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

$$\Sigma_m(z) \equiv \Sigma_{\rm crit}\zeta_{gg\kappa} = \Sigma_{\rm crit}\langle\delta_g(\vec{x_1})\delta_g(\vec{x_2})\kappa(\vec{x_3})\rangle = \left(\frac{b(z)}{b(z=0)}\right)^2\left(\frac{D(z)}{D(z=0)}\right)^4\Sigma_m(z=0)$$

- 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.



(Normalization is fixed to agree with the mean filament mass at the mean filament redshift)

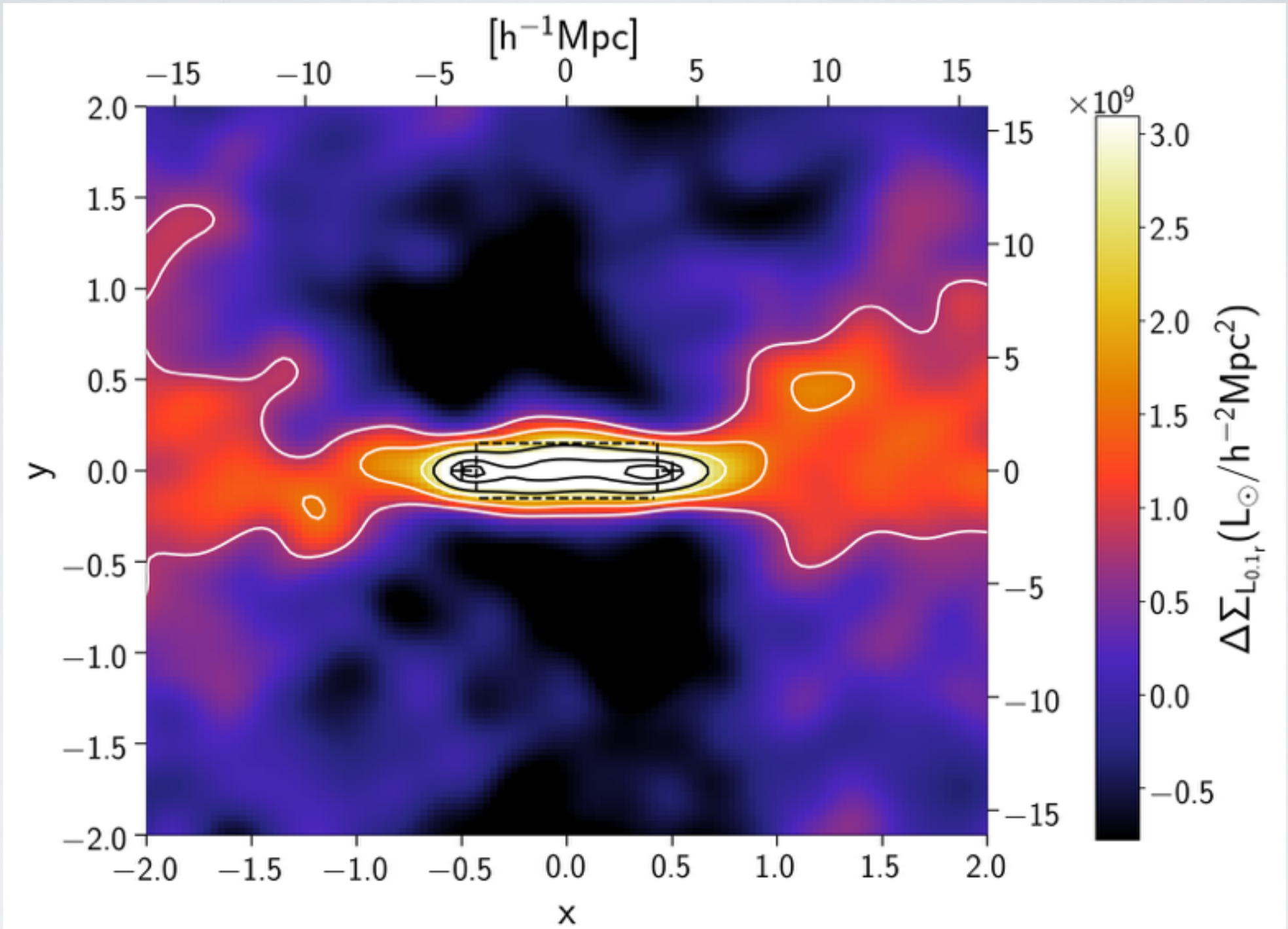
Although the measurement uncertainties are large, the data are consistent with the predicted redshift scaling.

LIGHT MAP

- We produce the light map using similar approach.
- After the projection, stacking:
  - Physical LRG pairs = LRG (from entire BOSS coverage:~450,000 pairs) + excess galaxies in the filament + background/foreground galaxies (from SDSS)

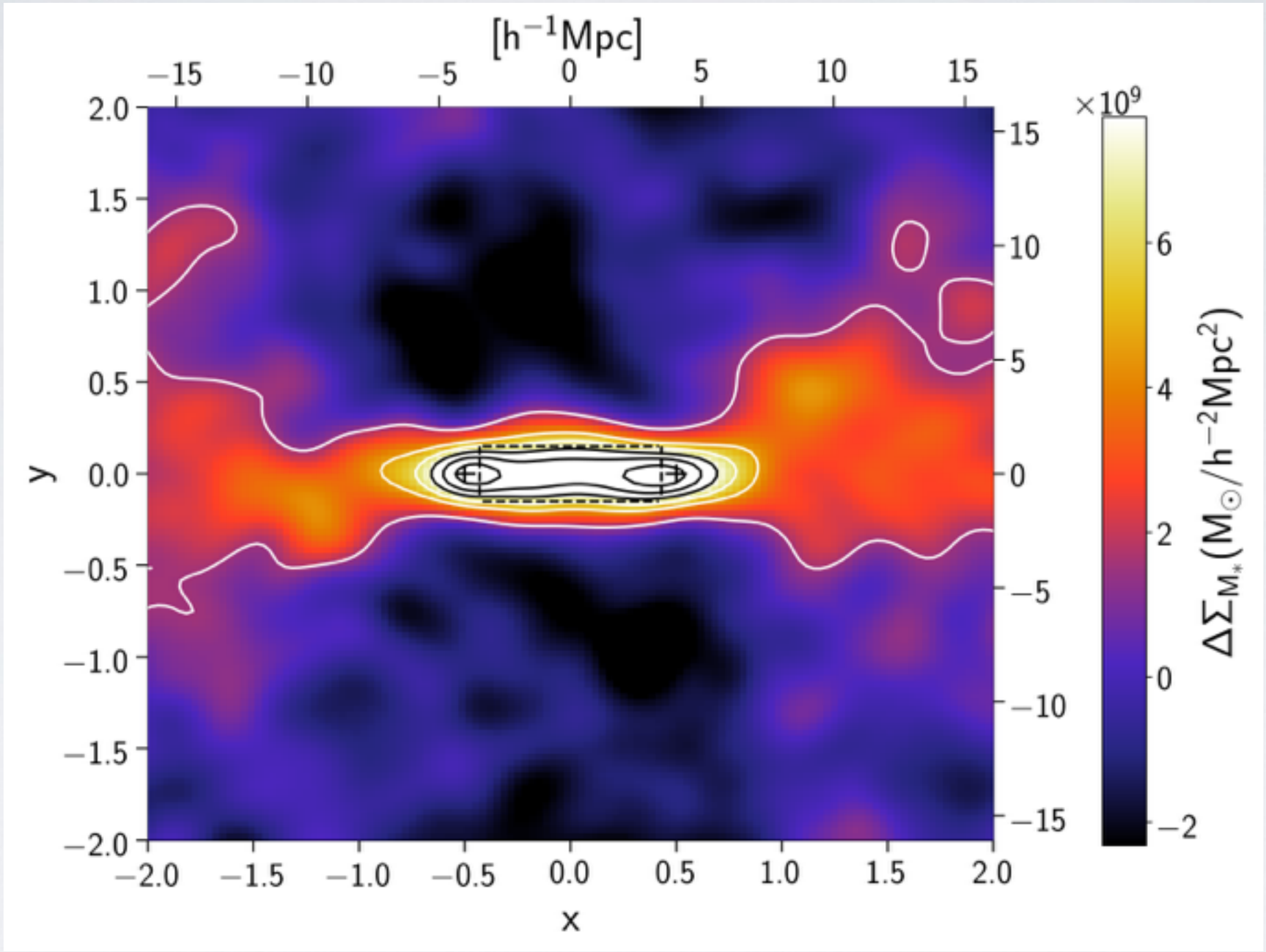
  Non-physical LRG pairs = LRG + identical background/foreground galaxies

EXCESS LIGHT MAP (WHOLE SAMPLE)

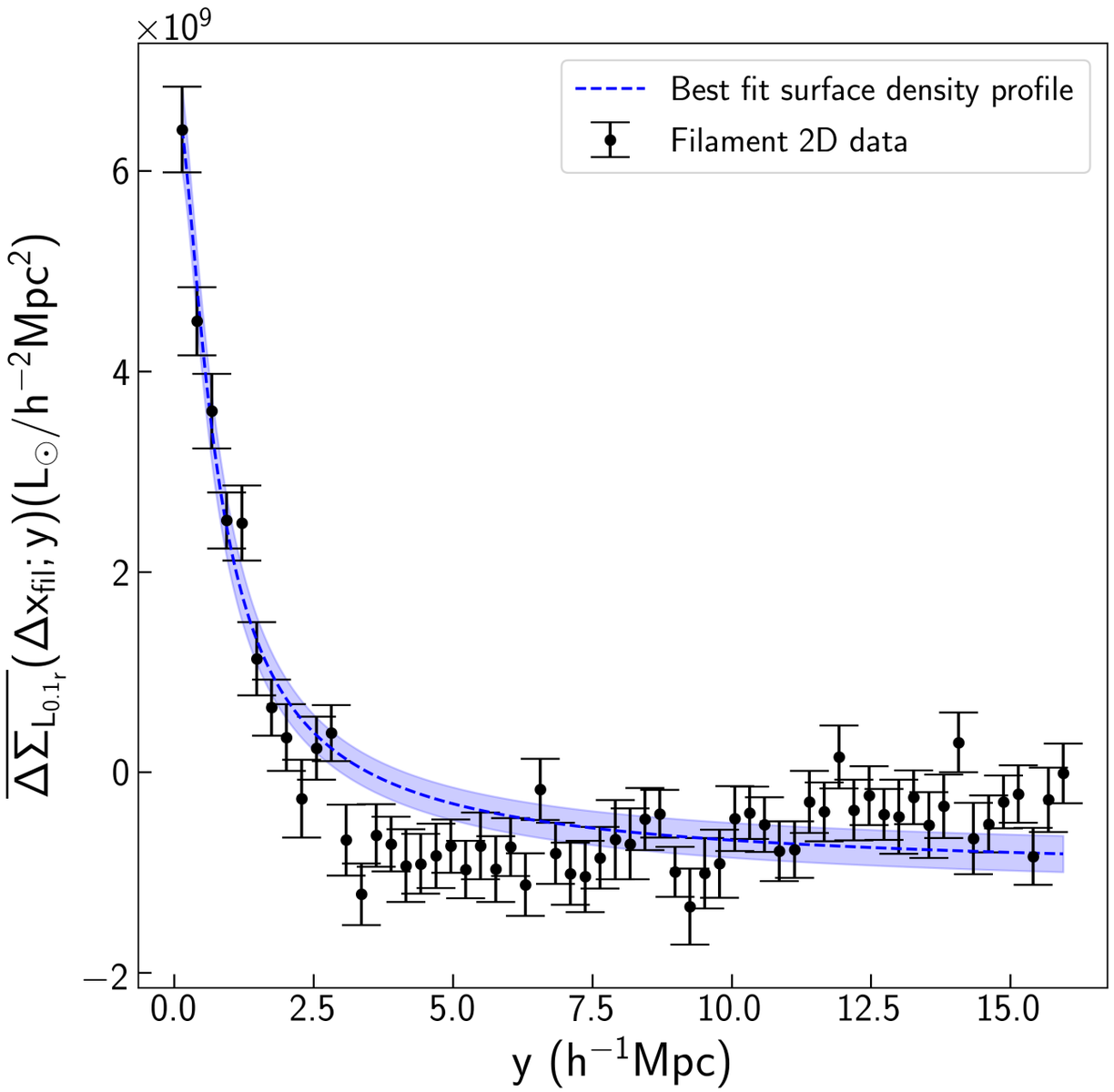


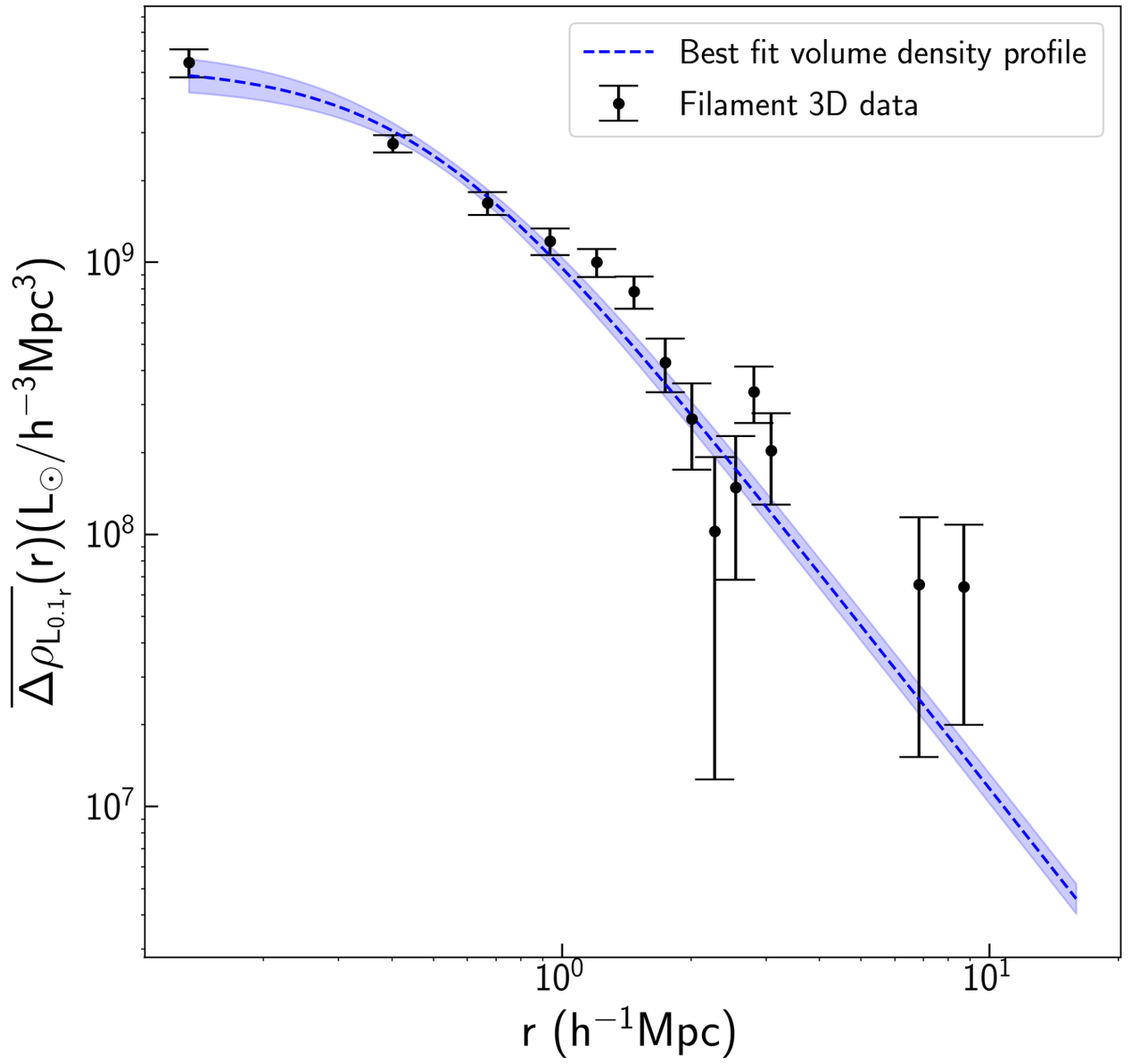
$$\overline{L_{\rm fil}} = 0.68 \pm 0.04 \times 10^{11} L_{\odot,^{0.1}r}$$

EXCESS STELLAR MASS MAP (WHOLE SAMPLE)



$$\overline{M_{\mathrm{stellar,fil}}} = 1.91 \pm 0.09 \times 10^{11} M_{\odot}$$





$$\Sigma(y) = \frac{\rho_0 \pi {r_c}^2}{\sqrt{{r_c}^2 + y^2}} - \text{constant}$$

Abel transformed from the 3D profile

reduced χ^2 ~1.45

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

suggested by Colberg et al. (2005)

reduced χ^2 ~1.93

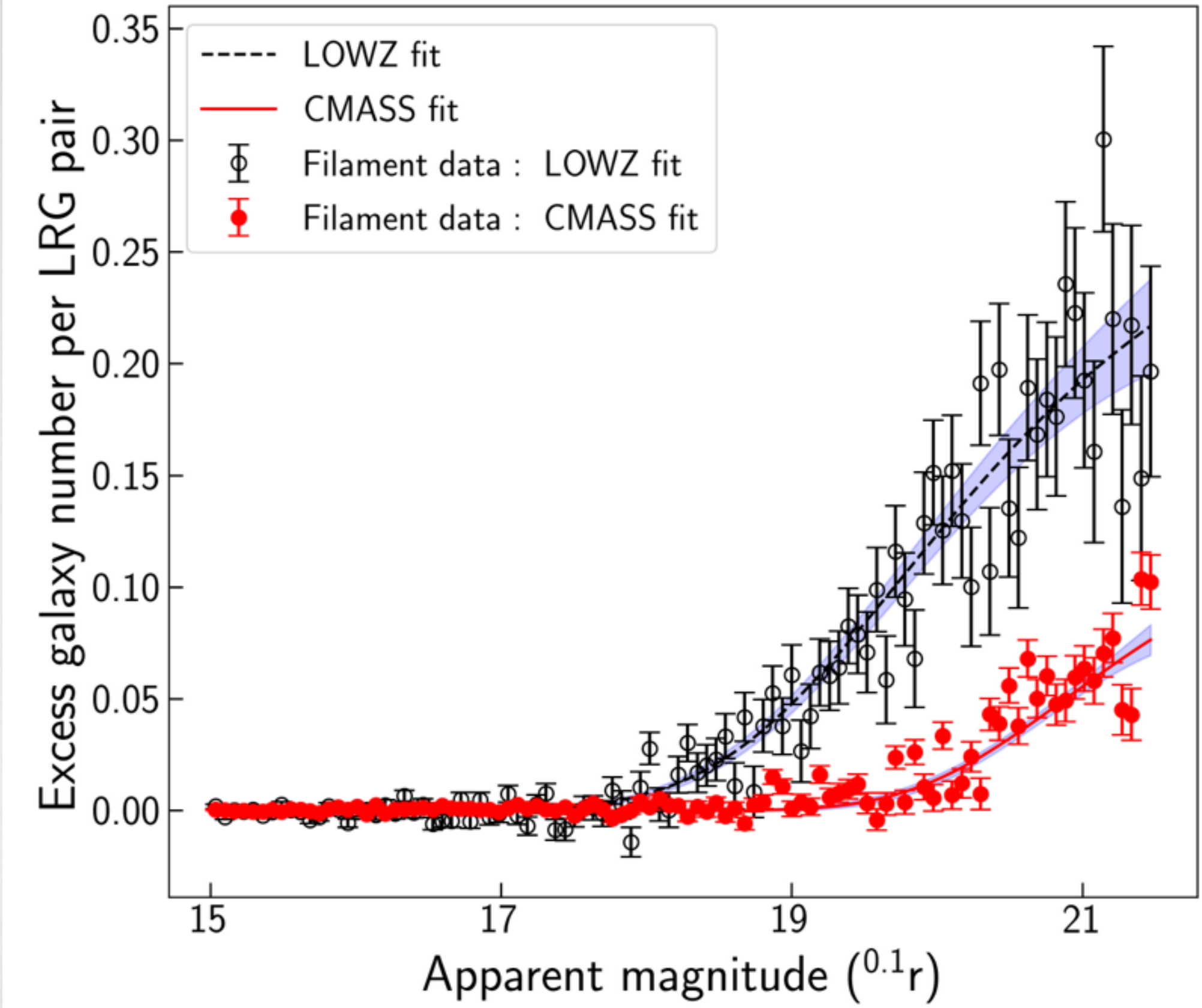
STILL NOT ENOUGH…

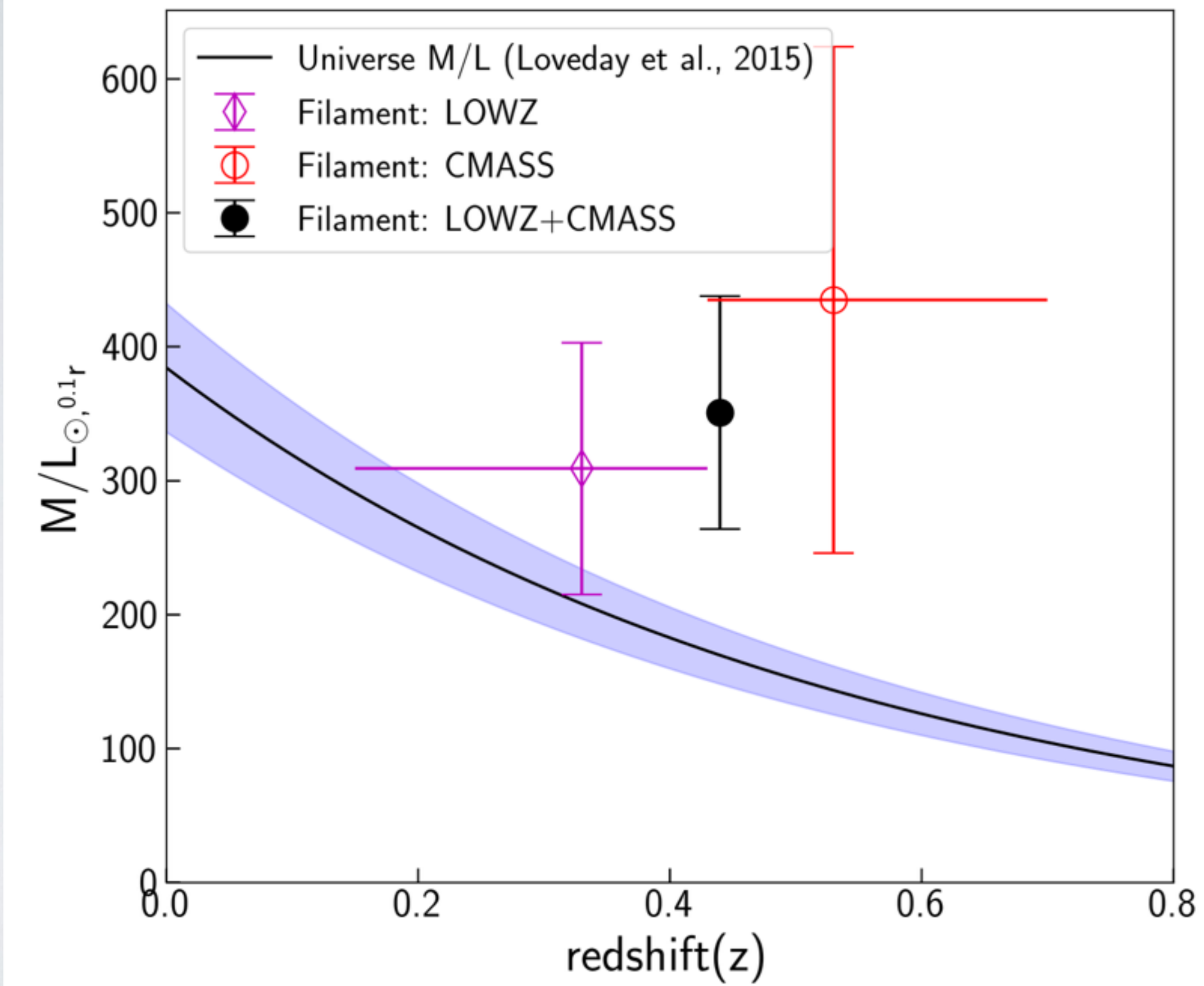
- To compute the total M/L : need to compensate for the missing light!!!

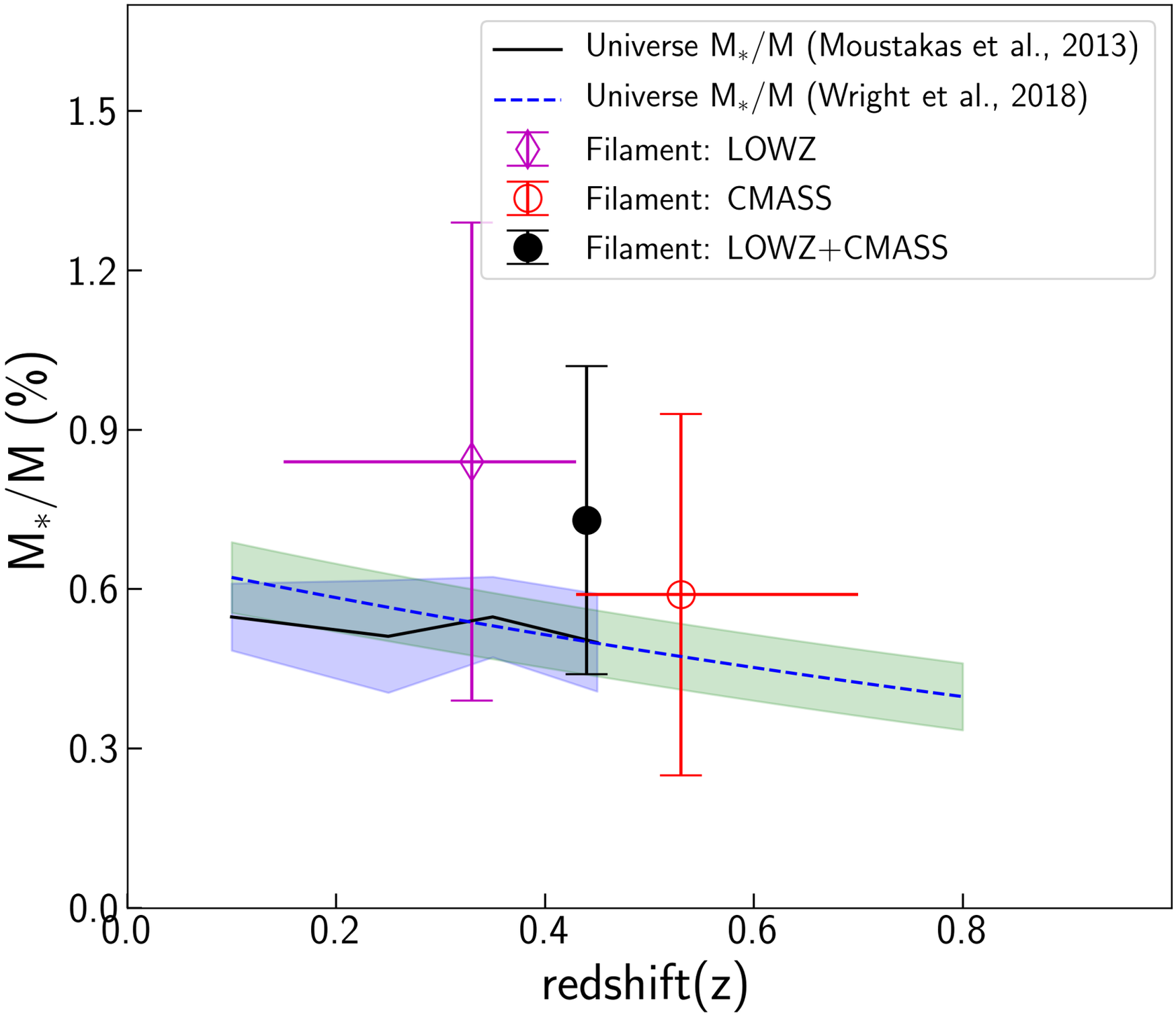
- Flux limit of the SDSS data, as well possible outliers in the photometric redshifts

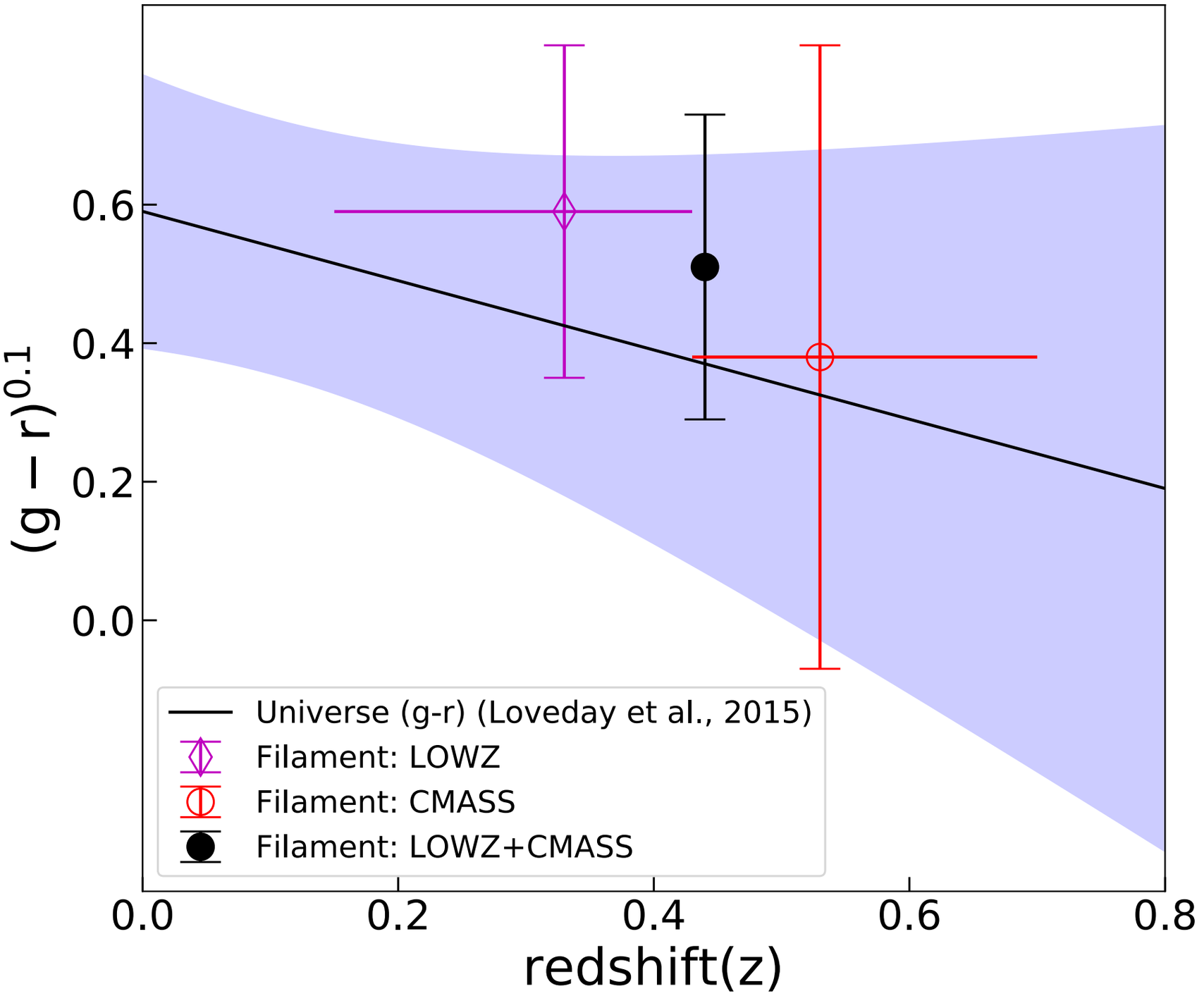
$$N(m) = n_* \int_{L_{\min}}^{L_{\max}} \left(\frac{L}{L_\star}\right)^\alpha e^{-L/L_\star} \frac{dL}{L_\star}.$$

$$\chi^2(n_\star, \alpha, M_\star) = [N_{\rm obs}(m) - N_{\rm mod}(m)]^T C^{-1} [N_{\rm obs}(m) - N_{\rm mod}(m)]$$


LOWZ fit
CMASS fit
Filament data : LOWZ fit
Filament data : CMASS fit
Excess galaxy number per LRG pair
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
15
17
19
21
Apparent magnitude ($^{0.1}$r)


Universe M/L (Loveday et al., 2015)
Filament: LOWZ
Filament: CMASS
Filament: LOWZ+CMASS
600
500
400
300
200
100
0
M/L⊙,0.1r
0.0
0.2
0.4
0.6
0.8
redshift(z)


Universe M$_*$/M (Moustakas et al., 2013)
Universe M$_*$/M (Wright et al., 2018)
Filament: LOWZ
Filament: CMASS
Filament: LOWZ+CMASS
M$_*$/M (%)
redshift(z)
0.0
0.3
0.6
0.9
1.2
1.5
0.0
0.2
0.4
0.6
0.8


0.6
0.4
0.2
0.0
(g − r)^0.1
0.0
0.2
0.4
0.6
0.8
redshift(z)
Universe (g-r) (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.