Constraining chameleon $f(R)$ gravity using cosmic voids

Forecast for Euclid and LSST

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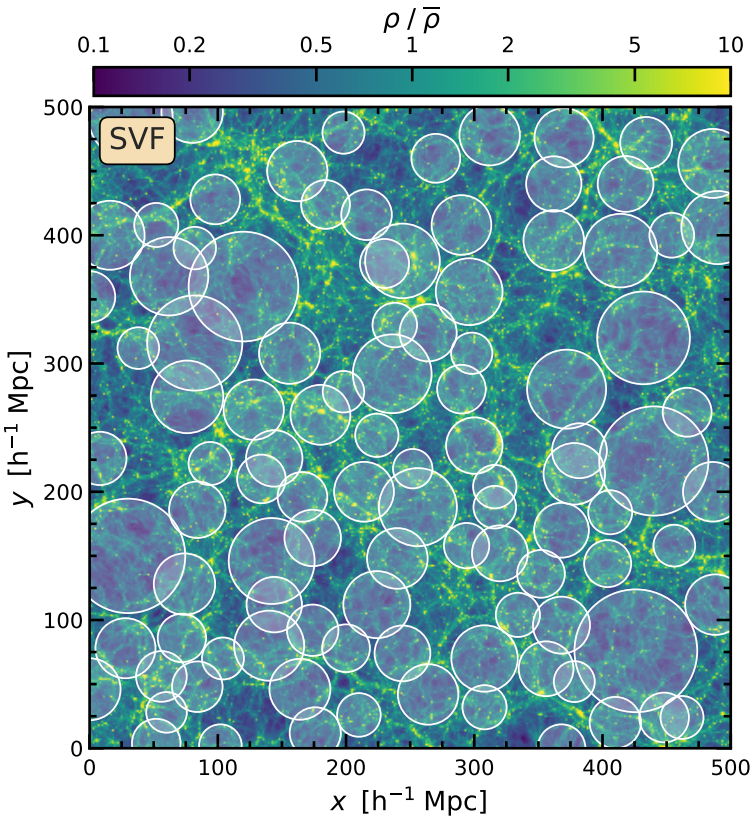
4 Summary

Voids: quantifying the emptiness of the Universe

- Regions in the Universe with low density of matter or low number density of tracers
- Occupy the majority of the space volume
- Testbeds for modified gravity, where screening doesn't work in low-density regions



Objectives

- Voids have irregular shapes and can be defined in **different** ways
- Voids have many **different** observational properties
- Voids properties are sensitive to **different** gravity models in **different** ways

Objectives: A systematic and comprehensive study of the potential of using **various** observational properties of voids defined in **various** ways to constrain **various** modified gravity models, using data from **various** cosmological surveys

$f(R)$ gravity – a useful testbed

$$S = \int \mathrm{d}^4x\sqrt{-g}\frac{1}{16\pi G}\left[R + f(R)\right]$$

$$f(R) = -M^2\frac{c_1\left(-R/M^2\right)^n}{c_2\left(-R/M^2\right)^n + 1}$$

- Popularity – One of the most widely-studied modified gravity models
- Rich phenomenology – representative of many models in the scalar-tensor family
- Computational advantage – simulations with greatly improved speed

- ~~*What can observations tell us about the functional form of $f(R)$?*~~
- *To which extent can observations constrain chameleon-type deviations from GR?*

N-body simulations

- ELEPHANT (Extended LEnsing PHysics with ANalytic ray Tracing) simulations
- performed with the ECOSMOG code, which is an extension to RAMSES
- 5 realisations for each model; same initial condition within each realisation

parameter	physical meaning	value
Ω_m	present fractional matter density	0.281
Ω_Λ	$1 - \Omega_m$	0.719
h	$H_0/(100\ \mathrm{km\ s^{-1}Mpc^{-1}})$	0.697
n_s	primordial power spectral index	0.971
σ_8	r.m.s. linear density fluctuation	0.820
n	HS $f(R)$ parameter	1.0
$\lvert f_{R0}\rvert$	HS $f(R)$ parameter	0 (GR), 10^{-6} (F6), $10^{-5}(F5)$
L_{box}	simulation box size	$1024\ h^{-1}$Mpc
N_{p}	simulation particle number	1024^3
m_{p}	simulation particle mass	$7.78 \times 10^{10} h^{-1} M_\odot$
N_{dc}	domain grid cell number	1024^3

Mock galaxy catalogues

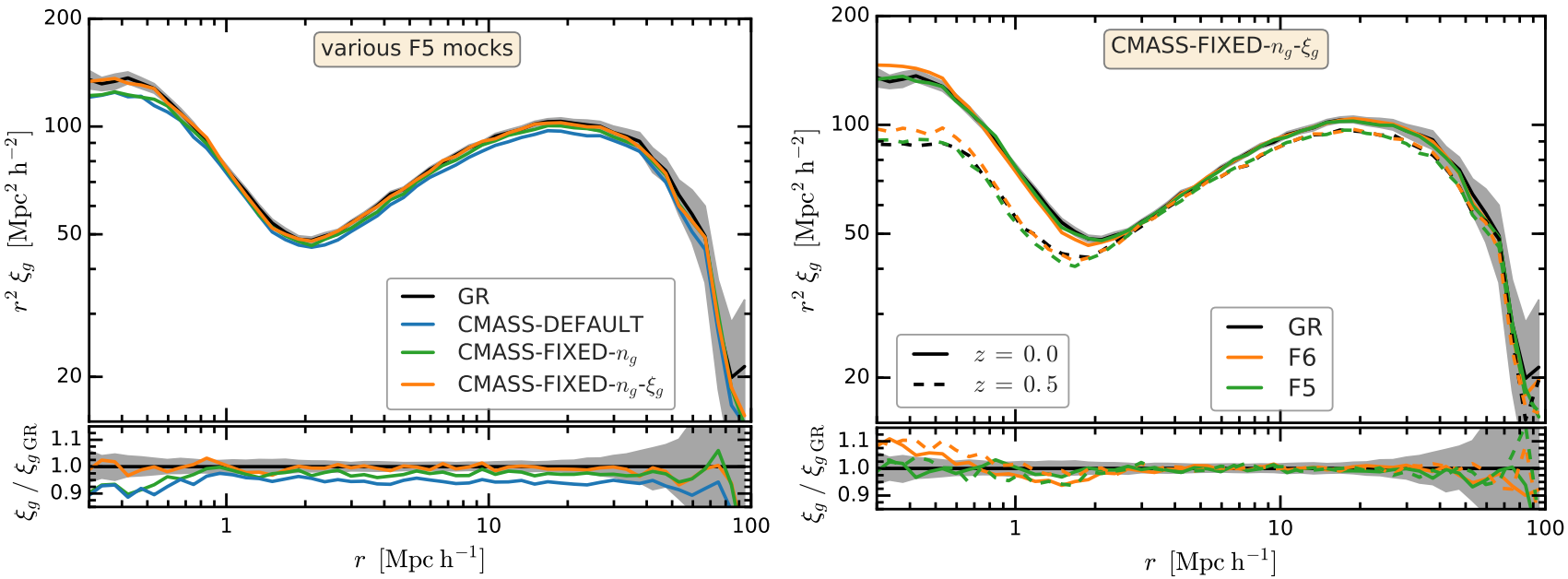
- dark matter haloes identified using ROCKSTAR halo finder; mass definition M_{200c}
- haloes populated with galaxies using halo occupancy distribution (HOD)

$$\langle N_{\rm cen}(M)\rangle = \frac{1}{2}\left[1+{\rm erf}\left(\frac{\log M-\log M_{\rm min}}{\sigma_{\log M}}\right)\right],$$
$$\langle N_{\rm sat}(M)\rangle = \langle N_{\rm cen}\rangle\left(\frac{M-M_0}{M_1}\right)^{\alpha}$$

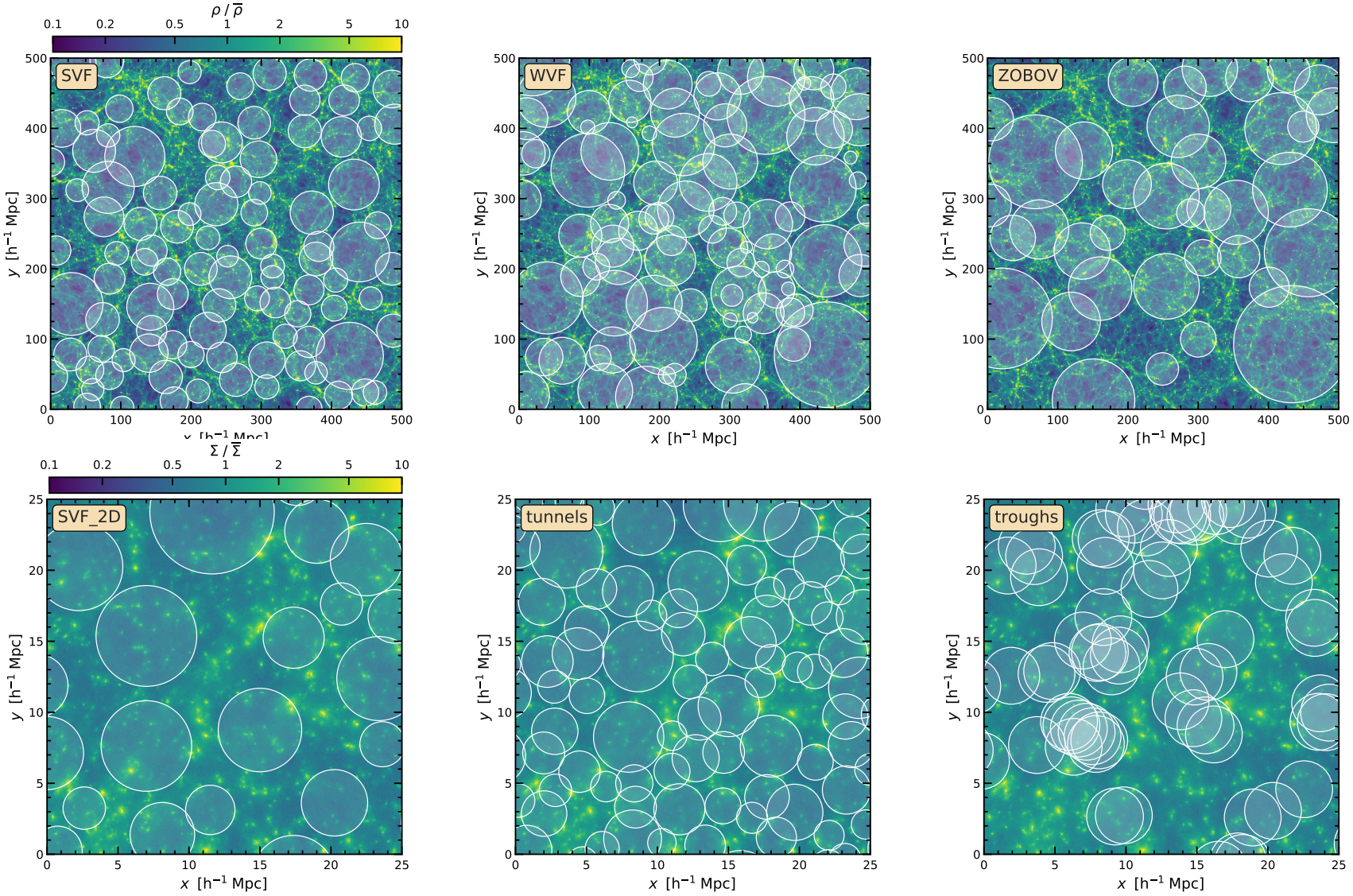
- HOD parameters for GR chosen to match BOSS CMASS galaxy clustering data
- *HOD parameters for $f(R)$ models tuned to match the galaxy number density n_g and two-point clustering ξ_g of GR*

Mock galaxy catalogues

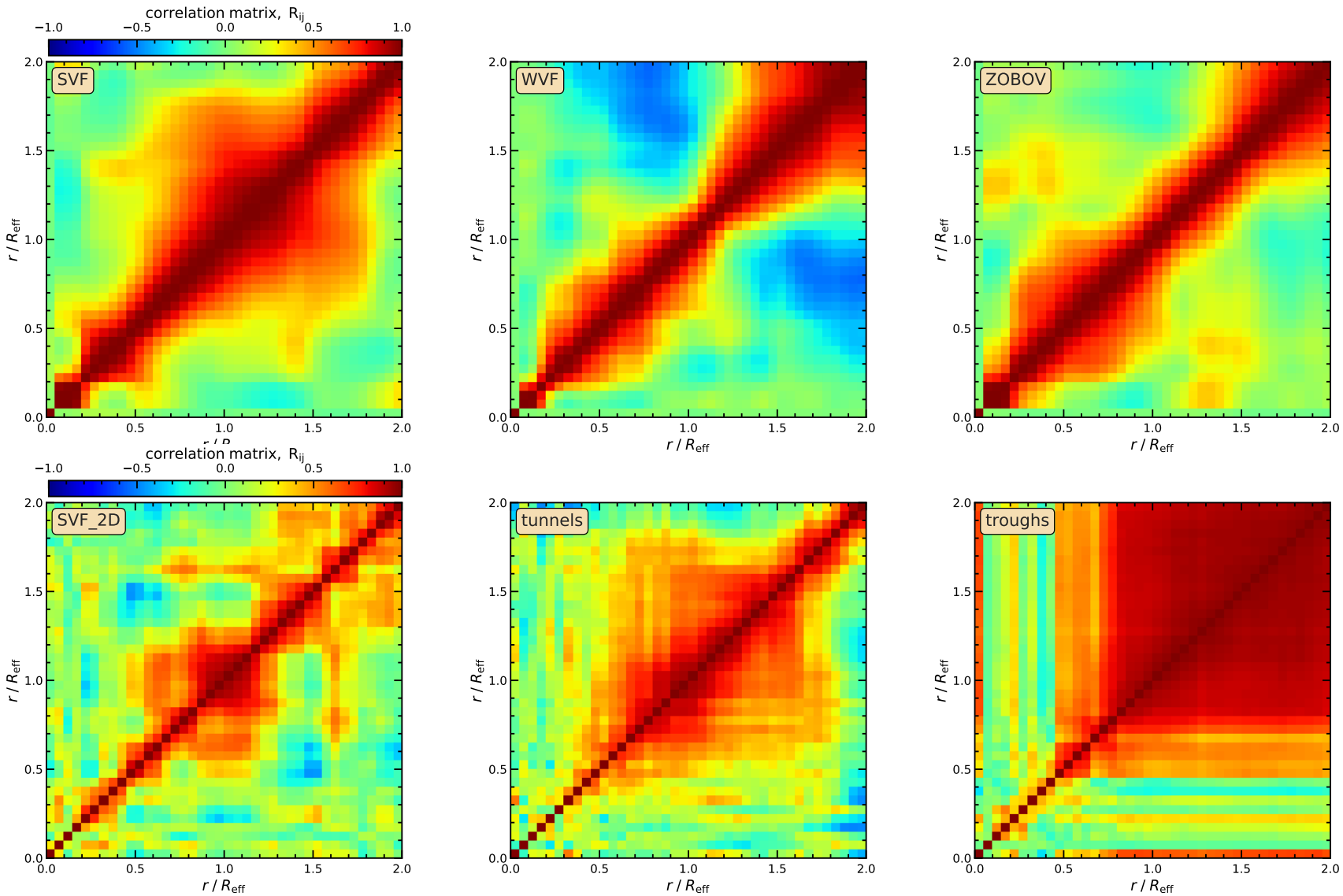
- *left*: F5 (with different HOD tunings) vs GR
- *right*: F6/F5 (HOD tuned to match both n_g and two-point correlation ξ_g) vs GR



Void finders: a visualisation of six



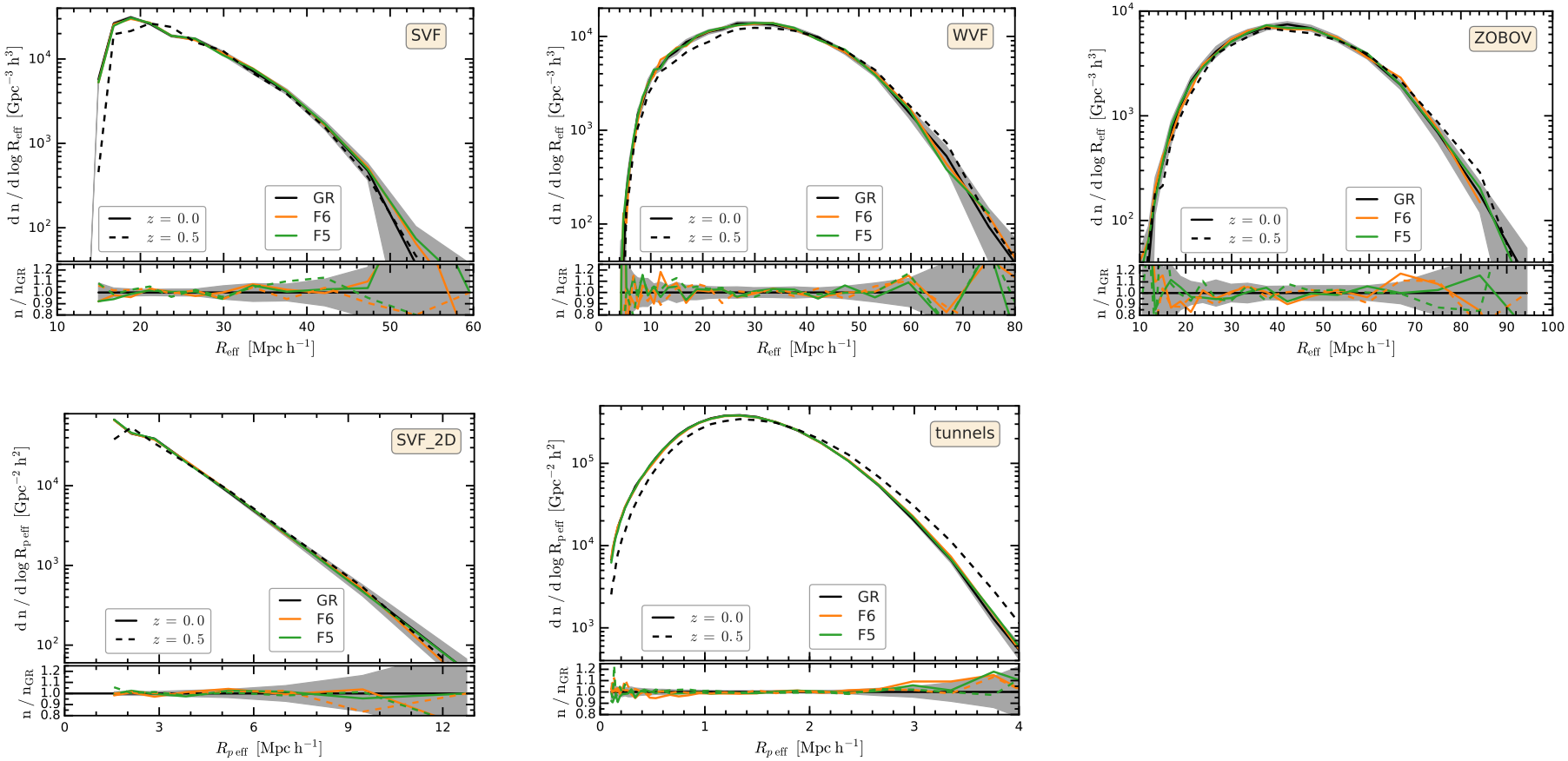
Void finders: correlations of errors



Void abundances

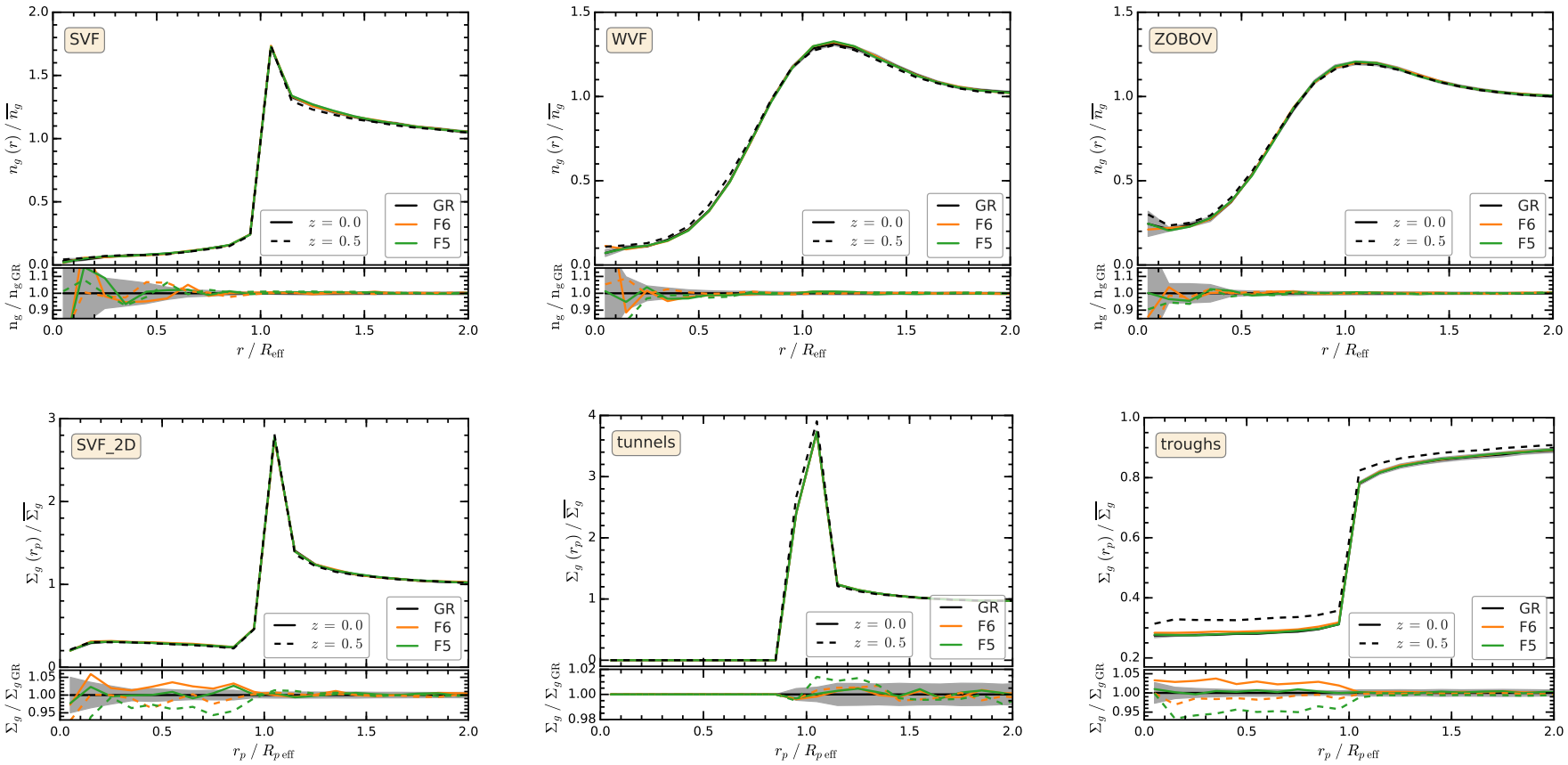
- Many modified gravity models predict larger and emptier voids
- Void abundance (like cluster abundance) was thought to be a good test of models
- Many of previous studies studied the abundance of voids identified from the dark matter field, rather than a galaxy field, which is directly observable
- Concerns that void abundance is too sensitive to the specific void finder

Void abundances



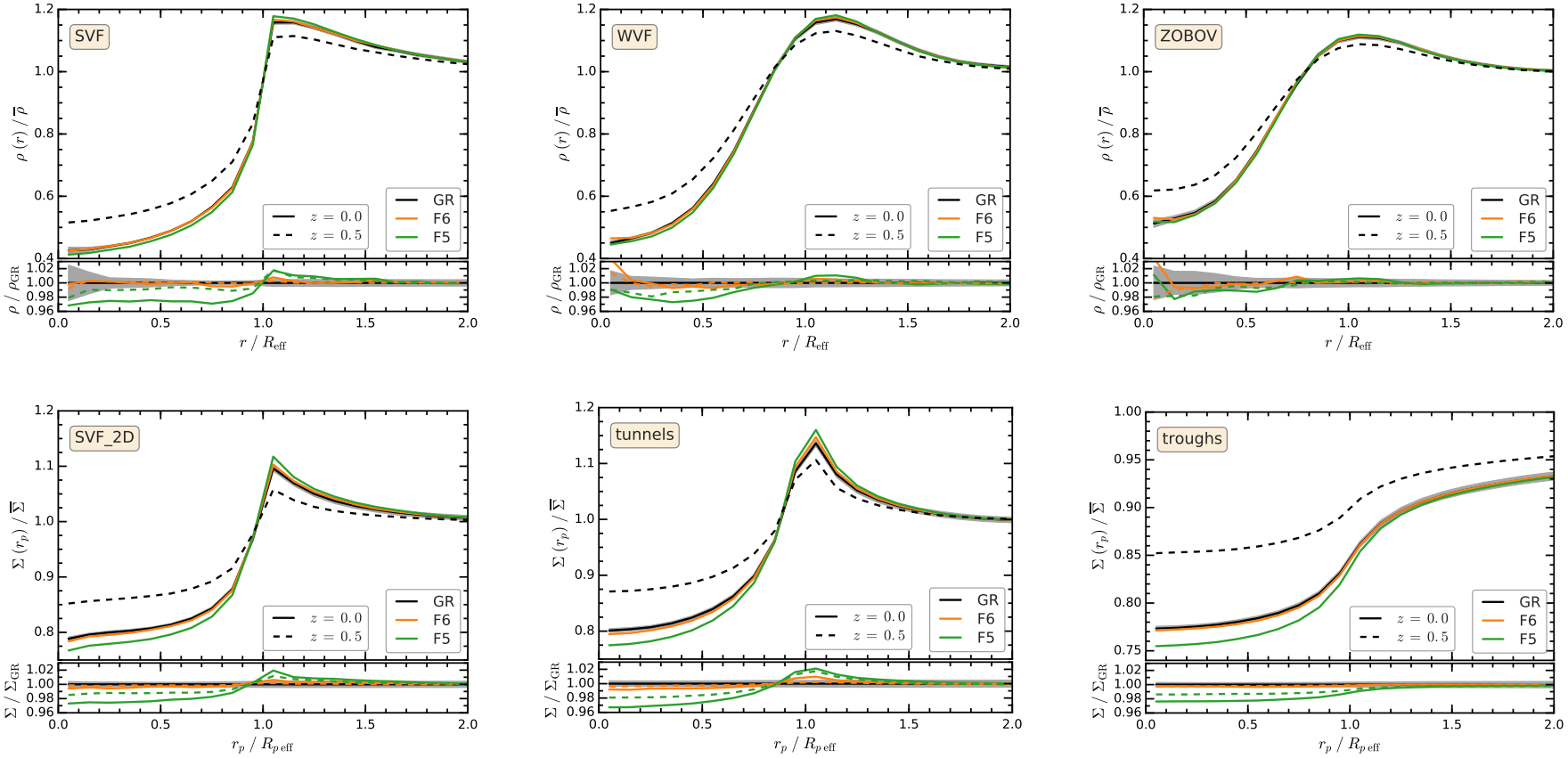
Void abundance not a good discriminator of models

Void galaxy number density profiles



Void galaxy number density profile not a good discriminator of models

Void dark matter density profiles



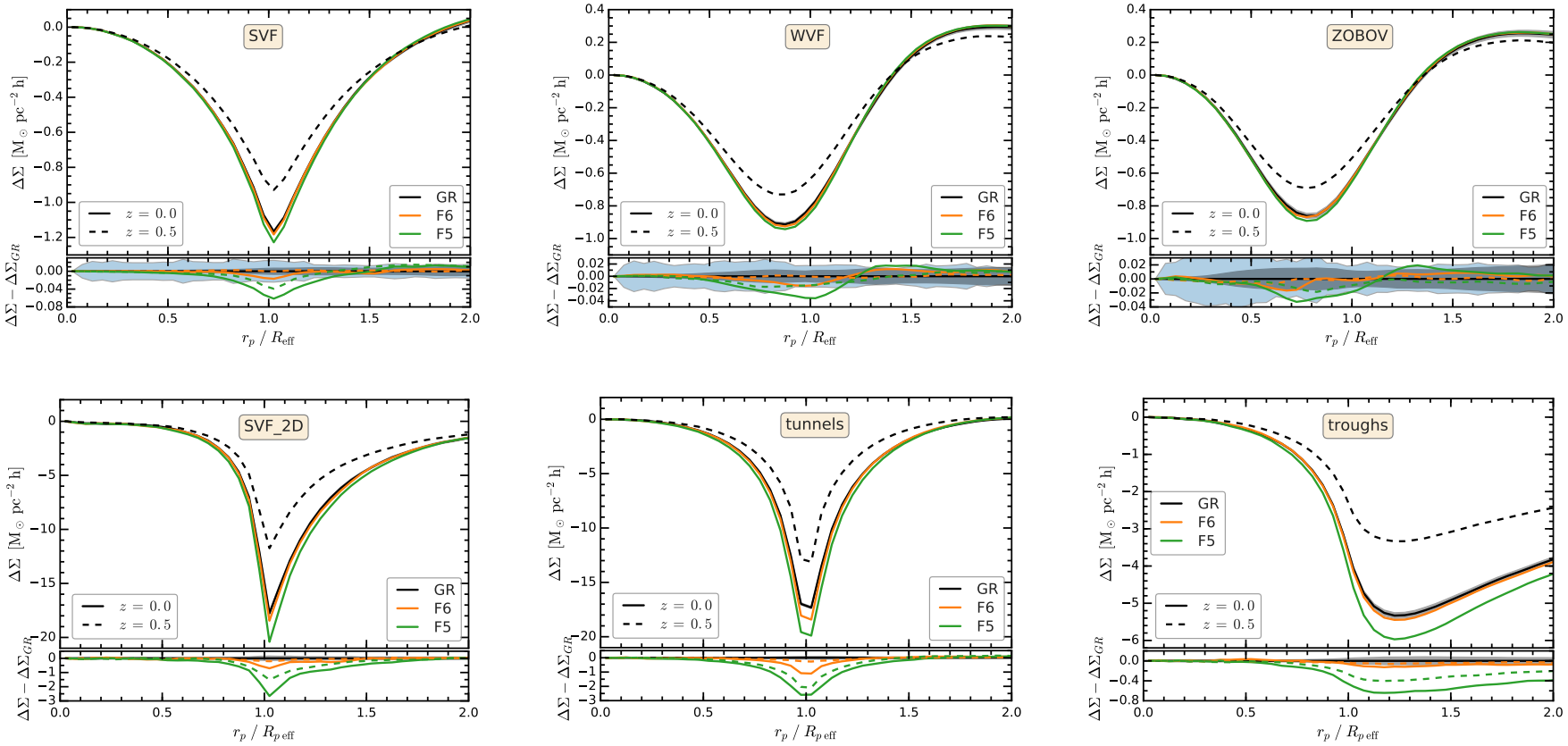
Void dark matter profile a good discriminator of models, but not directly observable

Void tangential shear profiles

- Different models do predict different void dark matter density profiles
- This can be detected through the weak lensing effect by voids

$$
\begin{aligned}
\gamma_t(r) &= \frac{\Delta\Sigma(r)}{\Sigma_c} = \frac{\bar{\Sigma}(<r) - \Sigma(r)}{\Sigma_c} \\
\bar{\Sigma}(<r) &= \frac{1}{\pi r^2}\int_0^r \Sigma(r')2\pi r' \mathrm{d}r' \\
\Sigma_c &= \frac{c^2}{4\pi G}\frac{D_s}{D_l D_{ls}} = \frac{c^2}{4\pi G}\frac{\chi_s}{a_l \chi_l \chi_{ls}}
\end{aligned}
$$

Void tangential shear profiles



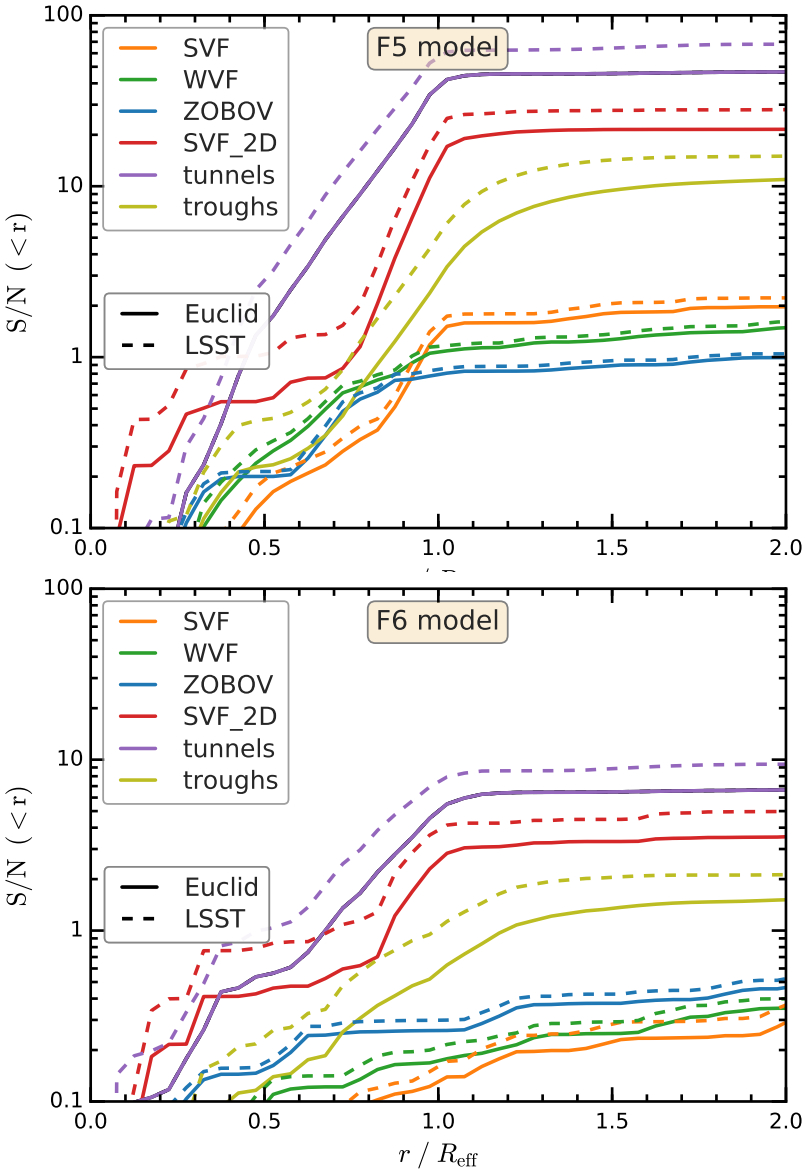
Void lensing a good discriminator of models, but not performance varies across the different void finders

Forecast for Euclid and LSST

- A Euclid-like survey covering 20,000 sq. deg., with source galaxy number density $n_s = 30\mathrm{arcmin}^{-1}$; a LSST-like survey with 18,000 sq. deg, and $n_s = 40\mathrm{arcmin}^{-1}$
- Sky coverage assumed to overlap with spectroscopic surveys with galaxy number density at least comparable to CMASS between $z = 0.3$ and $z = 0.7$
- Source galaxies assumed to be all at a single redshift ($z_s = 0.8$ for Euclid and $z_s = 1.2$ for LSST)
- Lensing voids assumed to have uniform number density between $z = 0.3$ and $z = 0.7$
- Void lensing signal assumed to be roughly constant between $z = 0.3$ and $z = 0.7$, so that the signal can be calculated from simulation voids at $z_l = 0.5$
- Sample variance (incl. projection effect) and shape noise taken into account with full covariance matrices

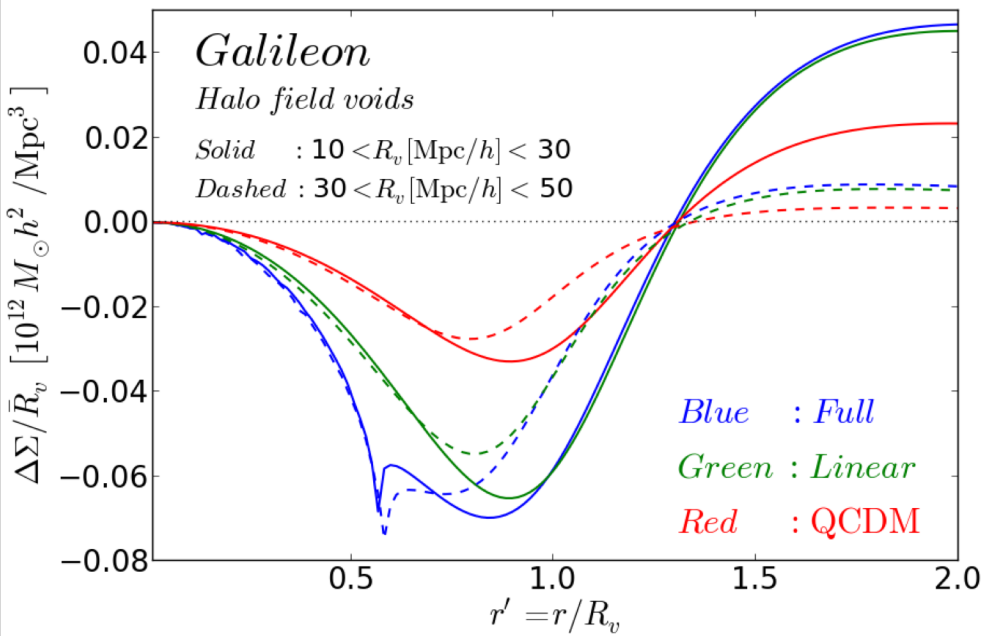
$$(\mathrm{S/N})^2\,(< k) \quad = \quad \sum_{i \leq k;\ j \leq k} \delta\gamma_t(i)\ \ \mathrm{Cov}^{-1}(i,j)\ \ \delta\gamma_t(j)$$

Forecast for Euclid and LSST



What about other models?

- HS $f(R)$ gravity model is representative for subfamilies of scalar tensor models
- Conclusion may not be applicable to models with Vainshtein screening, e.g., DGP
- Models that modify photon geodesics, e.g., Galileons, already in tension with observations



Summary

- Future galaxy surveys offer great opportunities to test gravity, one of which is statistics of regions with few galaxies (voids)
- Voids are mostly found from galaxy catalogues observationally, casting doubts on studies which find voids from dark matter simulations – mock galaxy catalogues are needed
- Void abundance and galaxy number density profiles are not good discriminators of models, as they are fixed (for a given void finder) given an observed tracer field
- Void lensing offers a promising test of gravity as it directly detects the dark matter distribution inside and around voids
- Traditional 3D voids give low signal-to-noise when applied to test $f(R)$ gravity, mainly due to the large uncertainties caused by los projection effect
- Voids identified in 2D projected galaxy field look much more promising
- Euclid and LSST are capable of constraining HS $f(R)$ model to $|f_{R0}| < 10^{-6\sim-5}$