Cosmology with weak lensing peaks and voids

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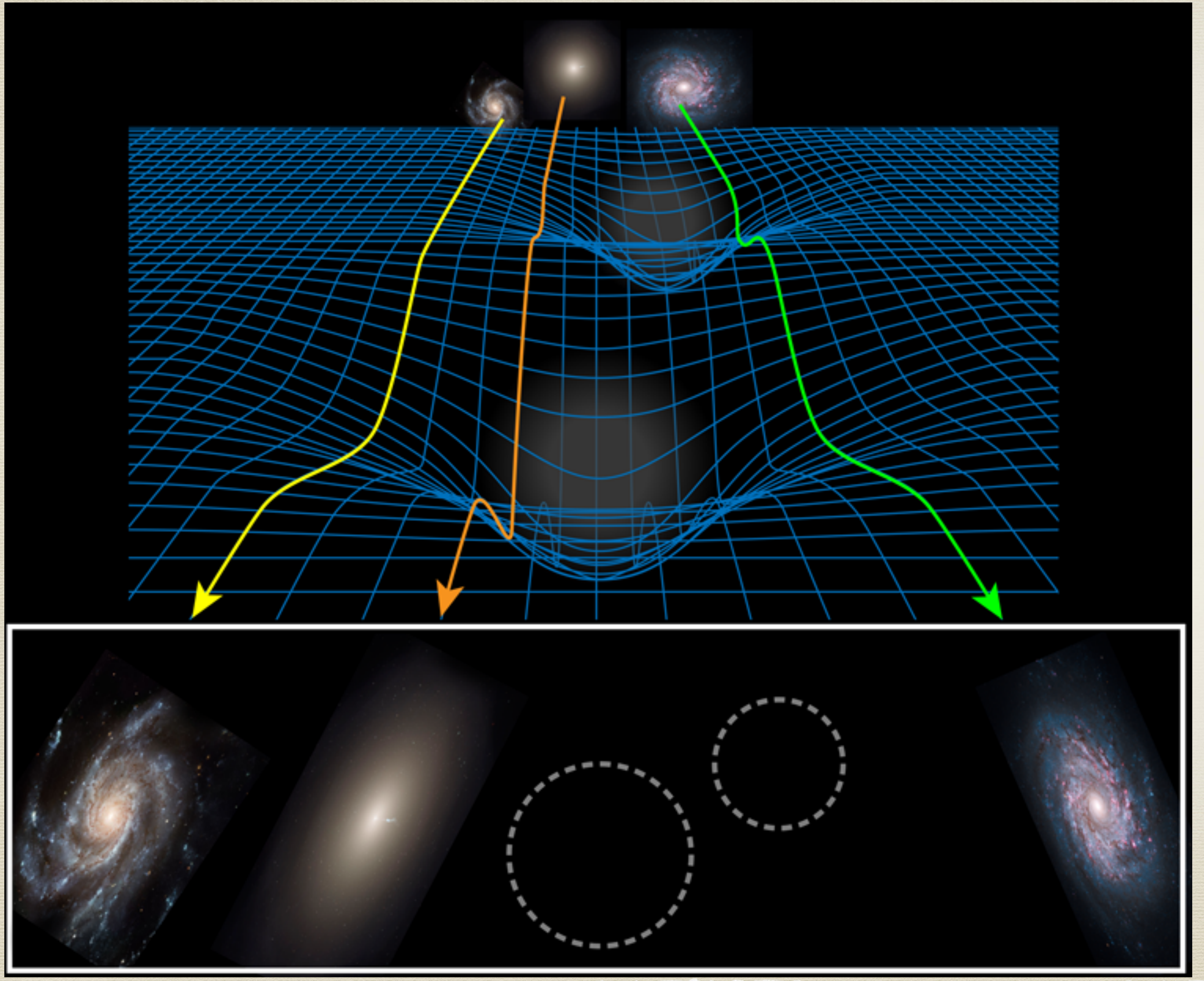
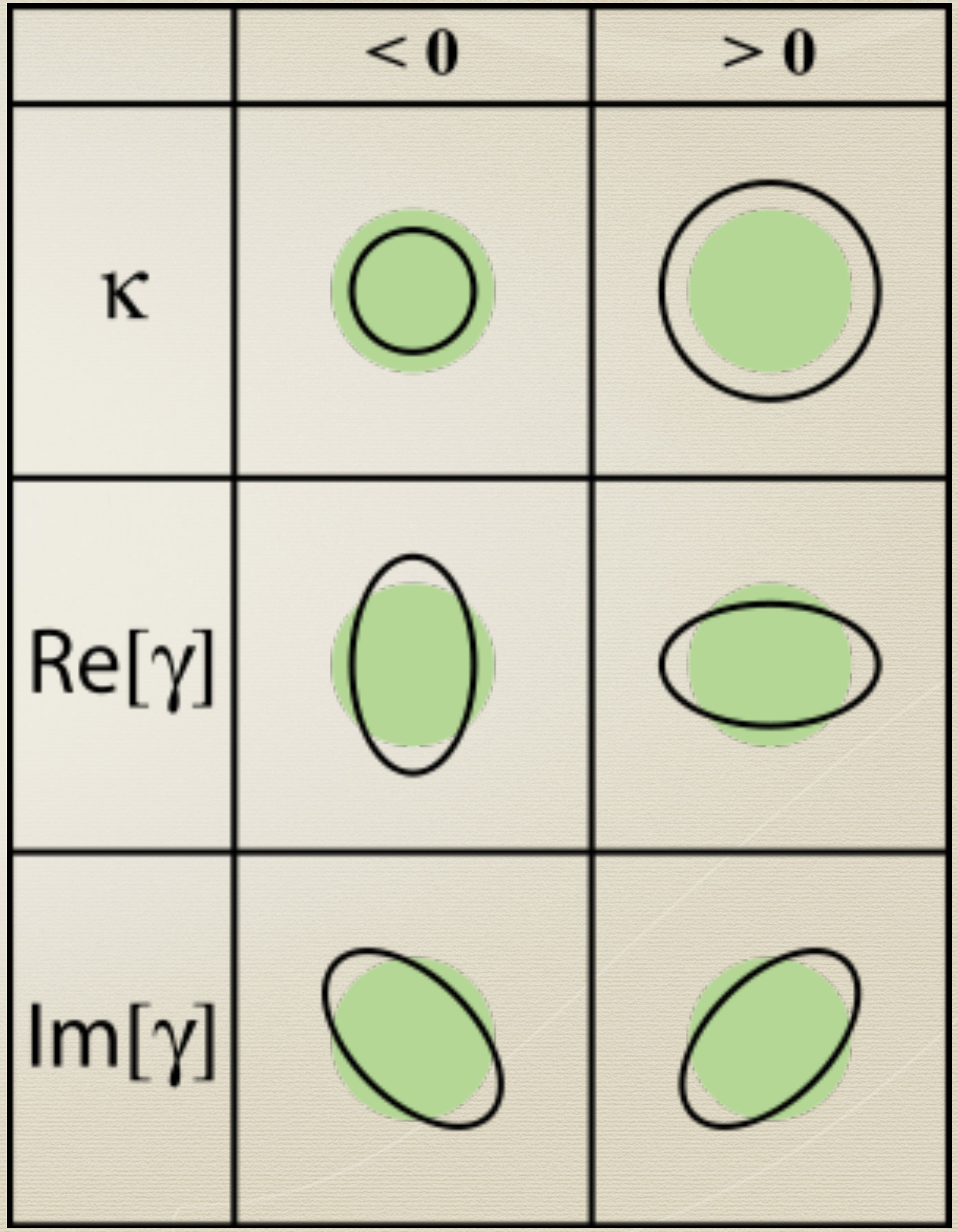
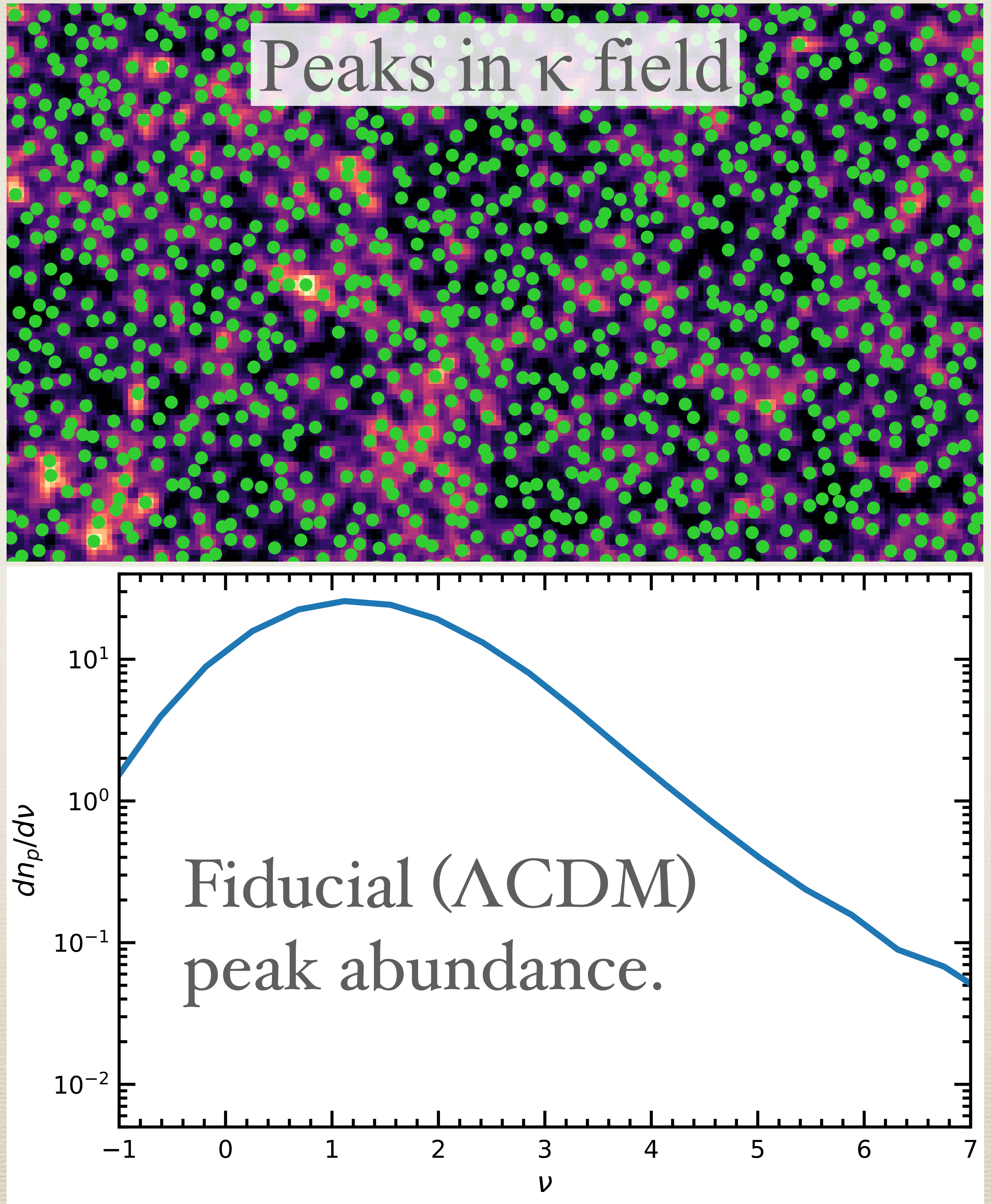
Weak gravitational lensing



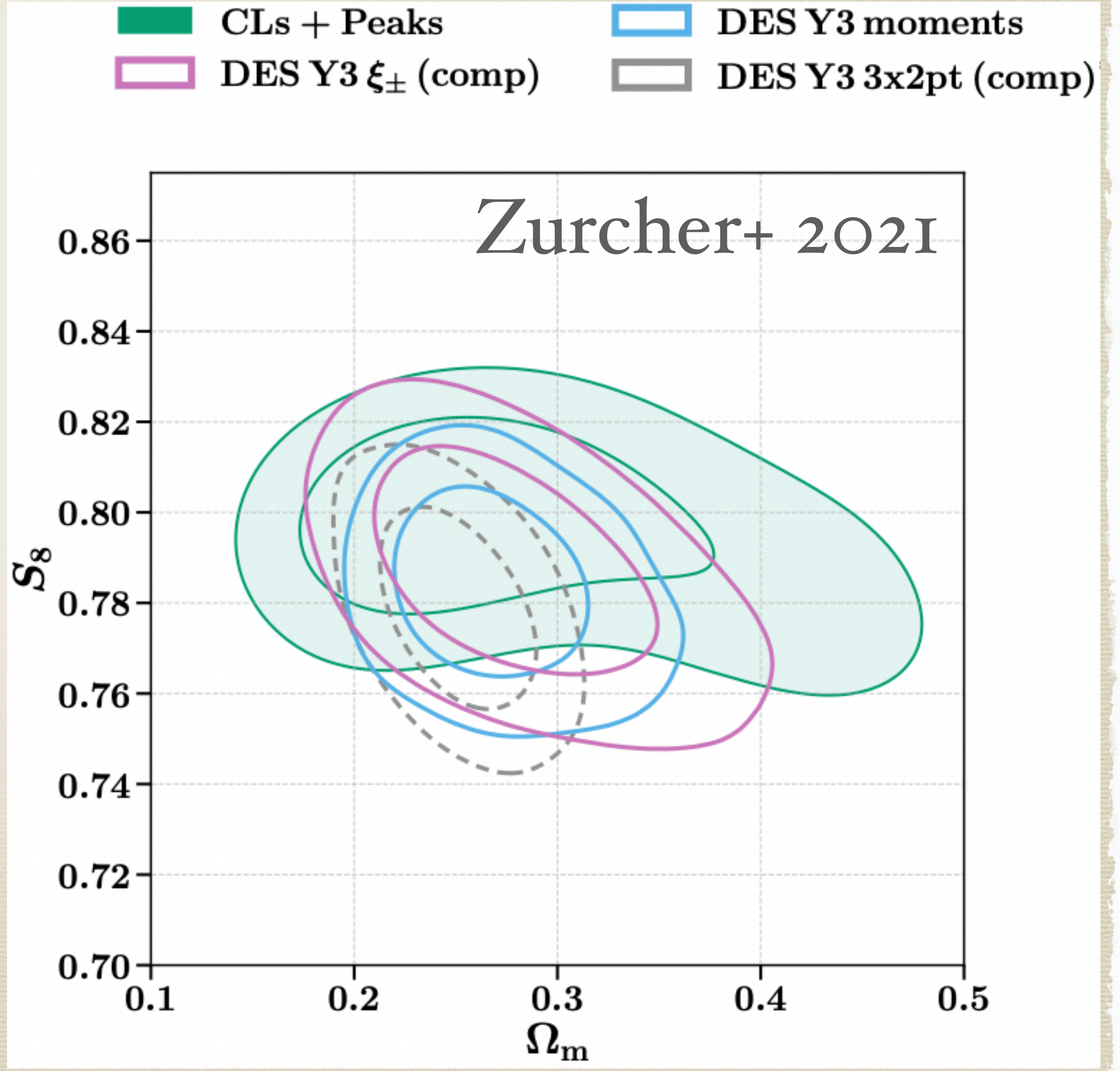


Weak lensing peak abundance

* $\kappa > 0$ = over-density
  $\kappa < 0$ = under-density
* High amplitude peaks correspond to clusters along the line of sight.
* Low amplitude peaks correspond to chance alignments of low mass haloes along the line of sight.
* This makes weak lensing peaks a useful cosmological probe.



DES Y3 Peaks and 3x2pt constraints



What else can we do with WL peaks?

Measure peak statistics:

Peak abundance (Well established)

Peak two-point correlation function (new)

Use peaks to find voids:

Void abundance (new)

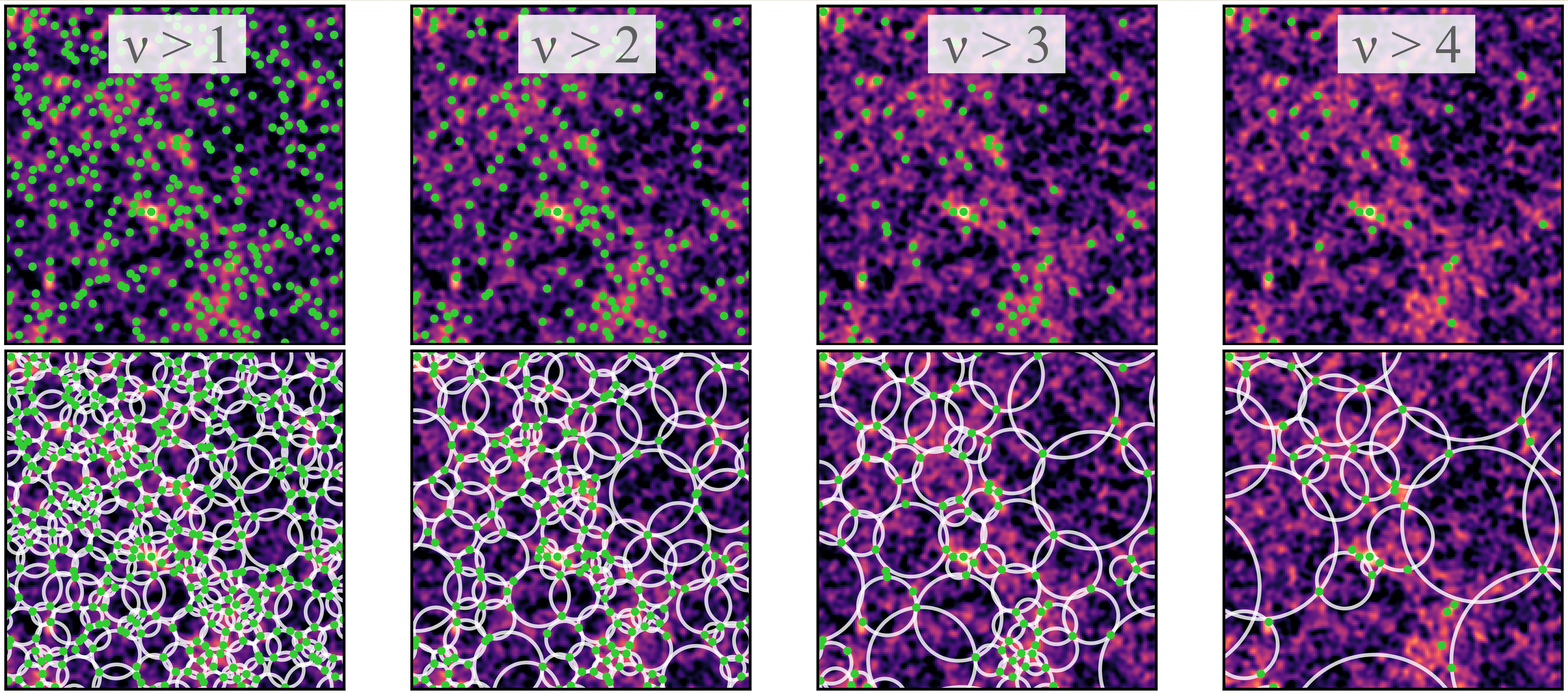
Void lensing profiles (new)

First steps for higher order peak analysis

* Make multiple peak catalogues by removing peaks below a given ν threshold (top row).

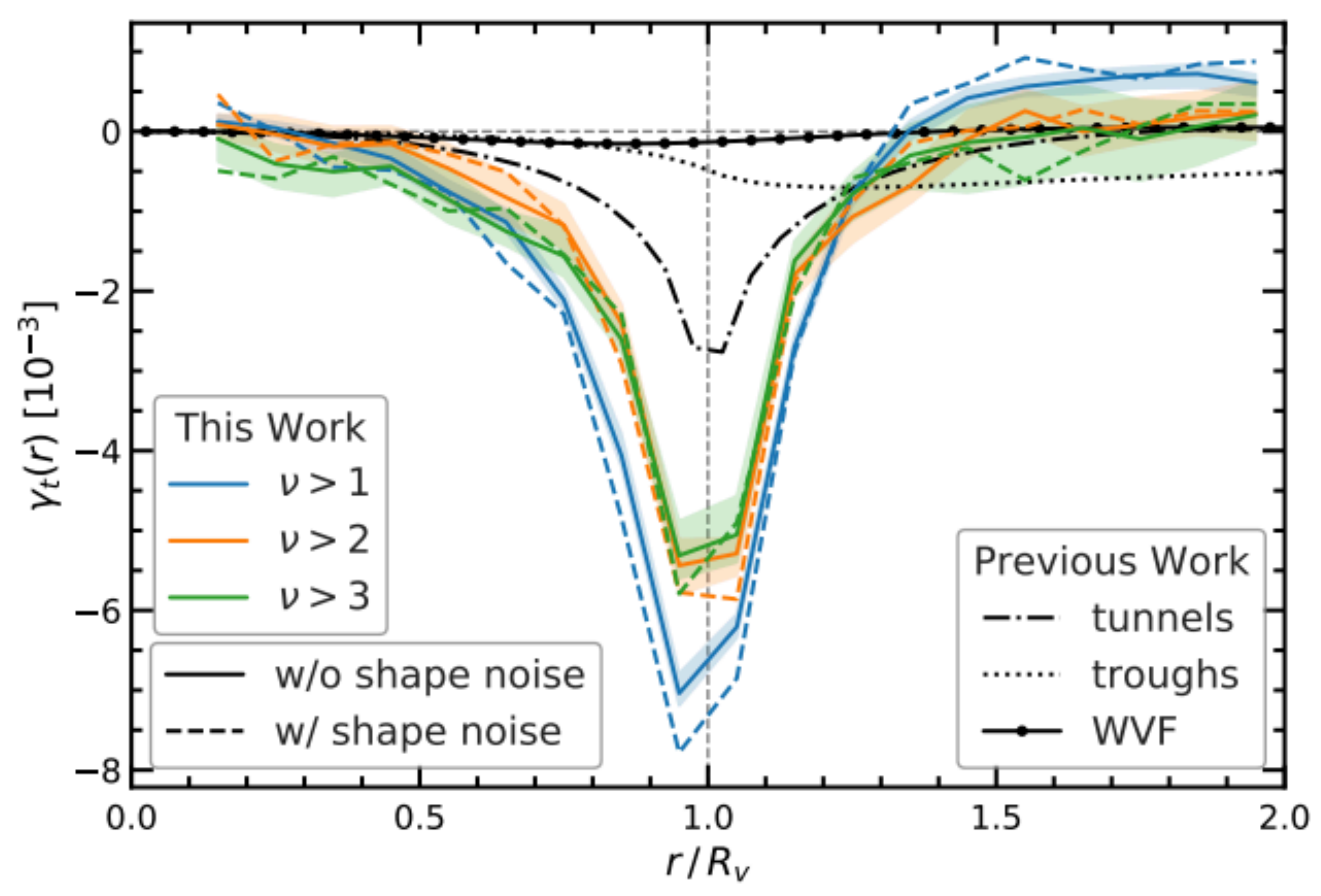
* Use peak catalogues to find voids (bottom row).

* For each catalogue we measure: Peak abundance + Peak 2PCF, and Void statistics

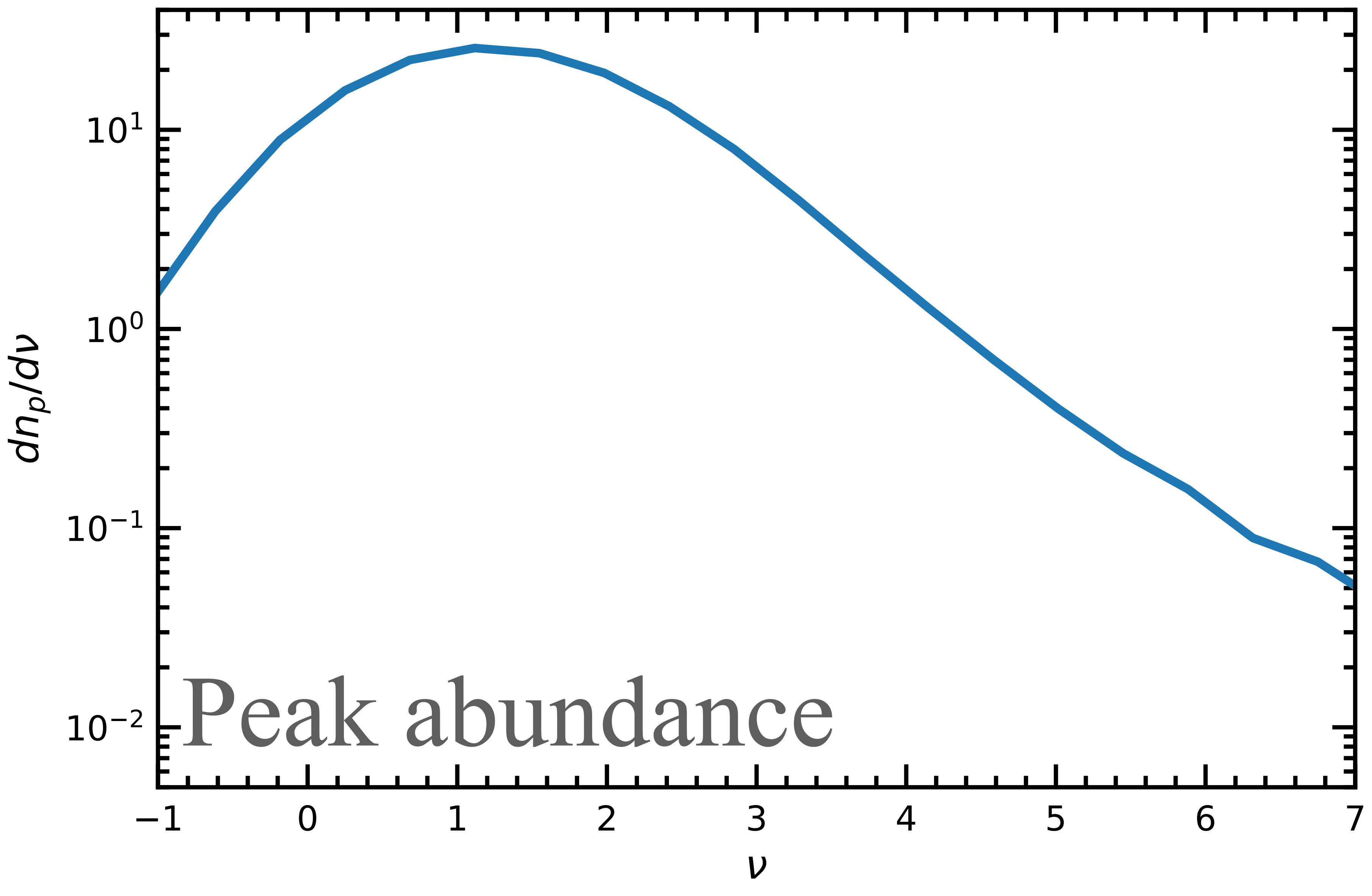


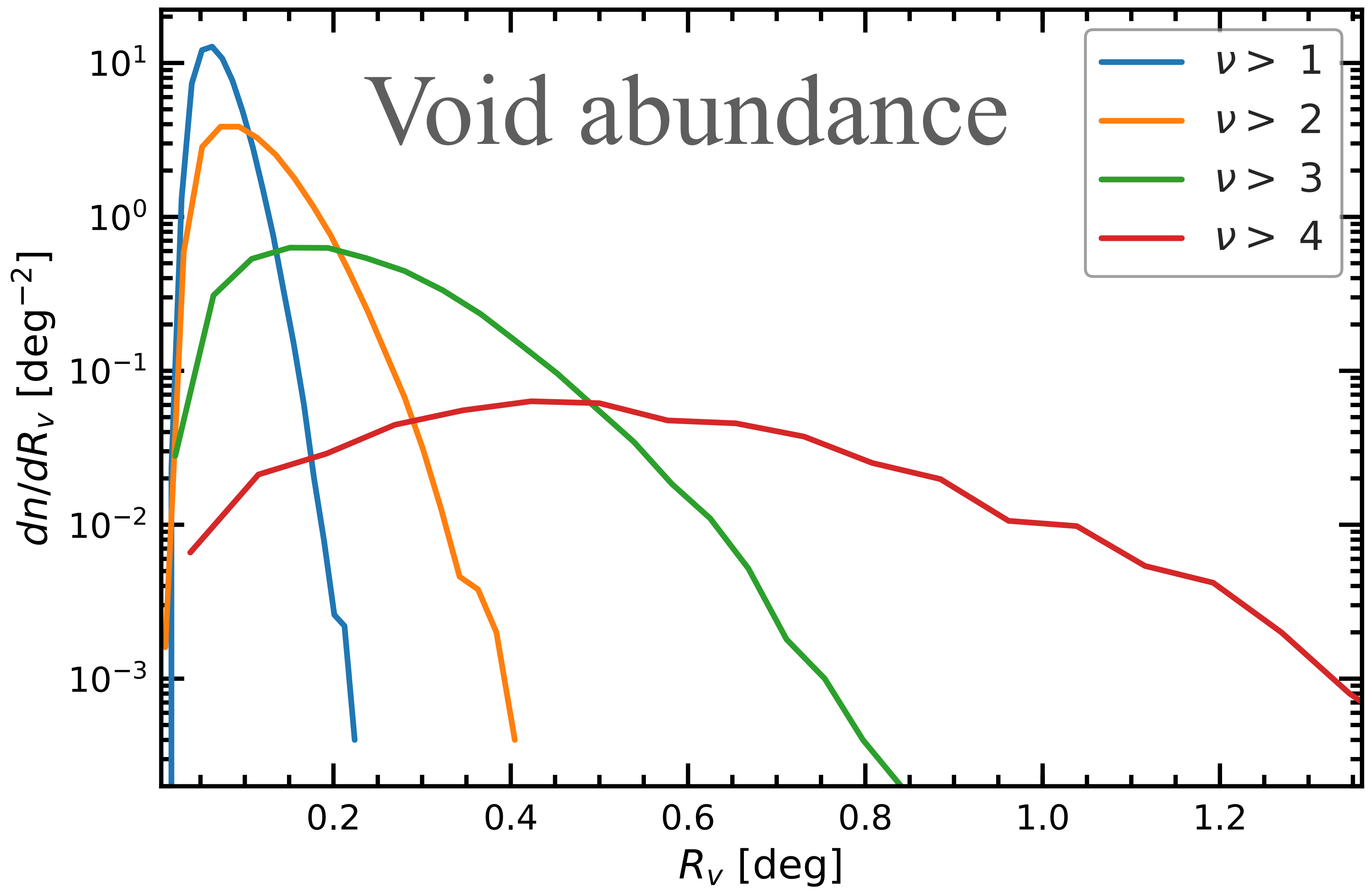
Advantages of weak lensing voids compared to galaxy voids

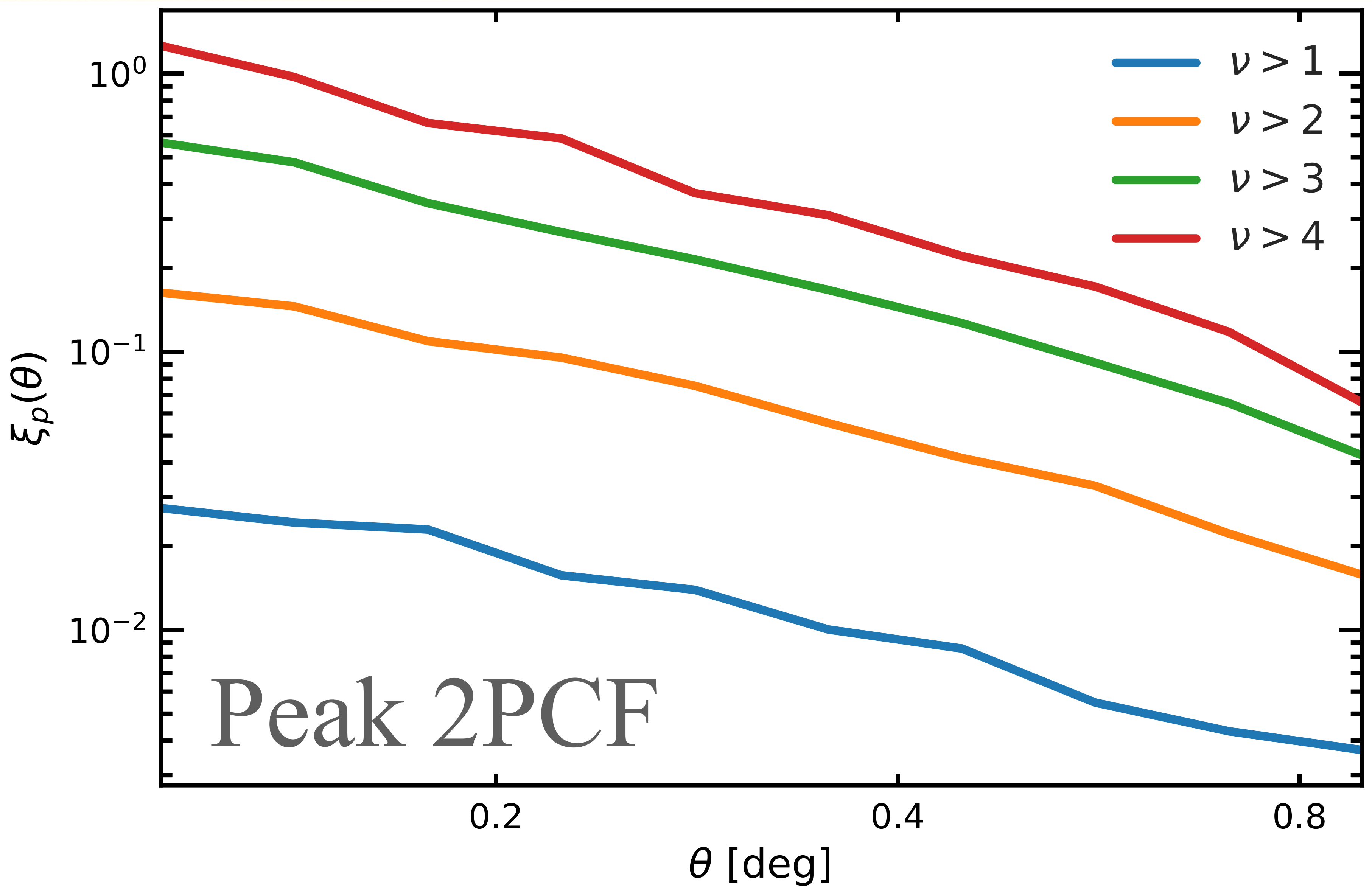
* WL voids have deeper lensing profiles compared to galaxy voids.
  * WL voids correspond to deeper under densities along the line of sight.
* Convergence field is closely linked to the total matter field.
  * Do not need to worry about galaxy halo connection.

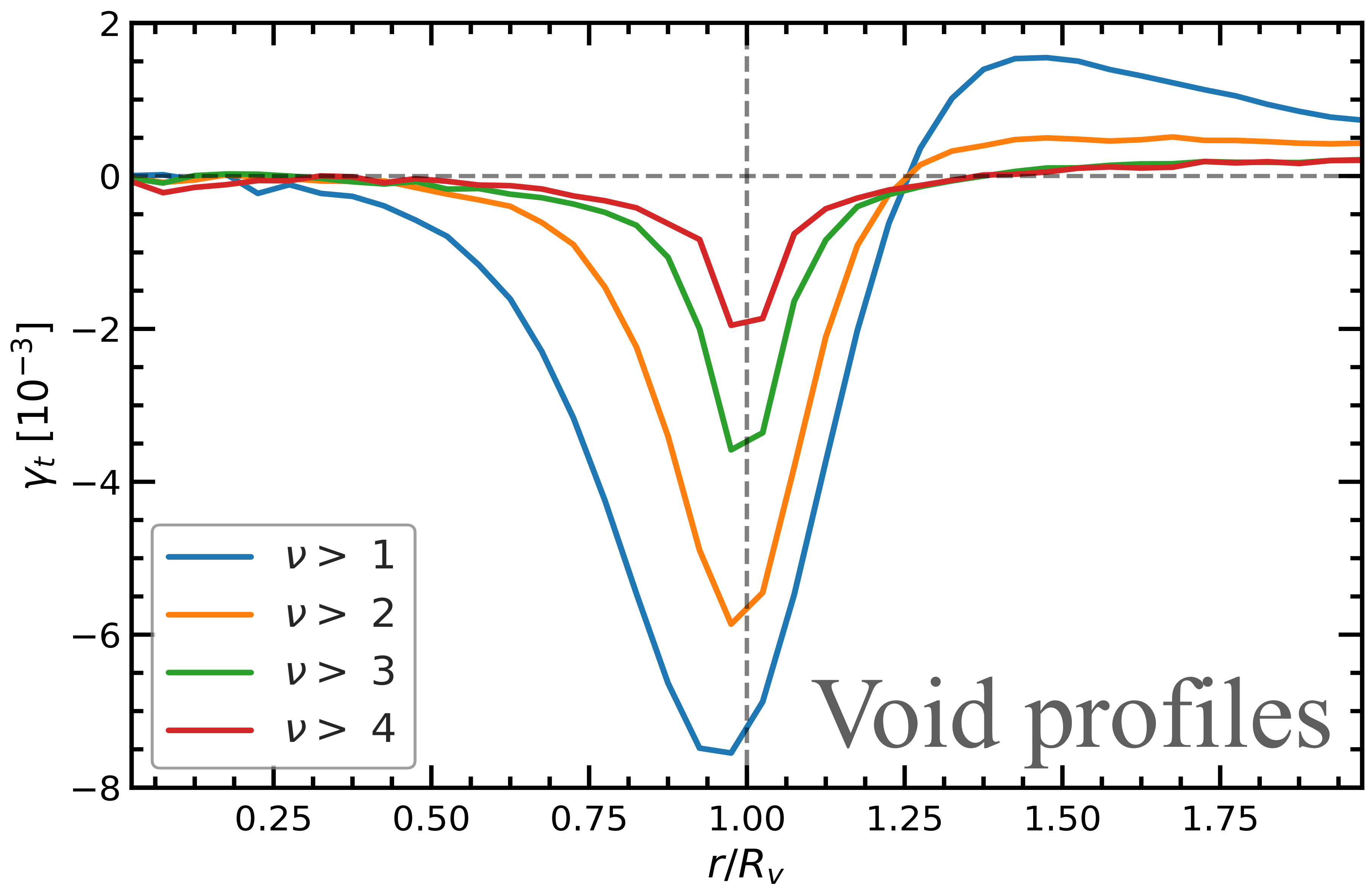


Varying the ν threshold



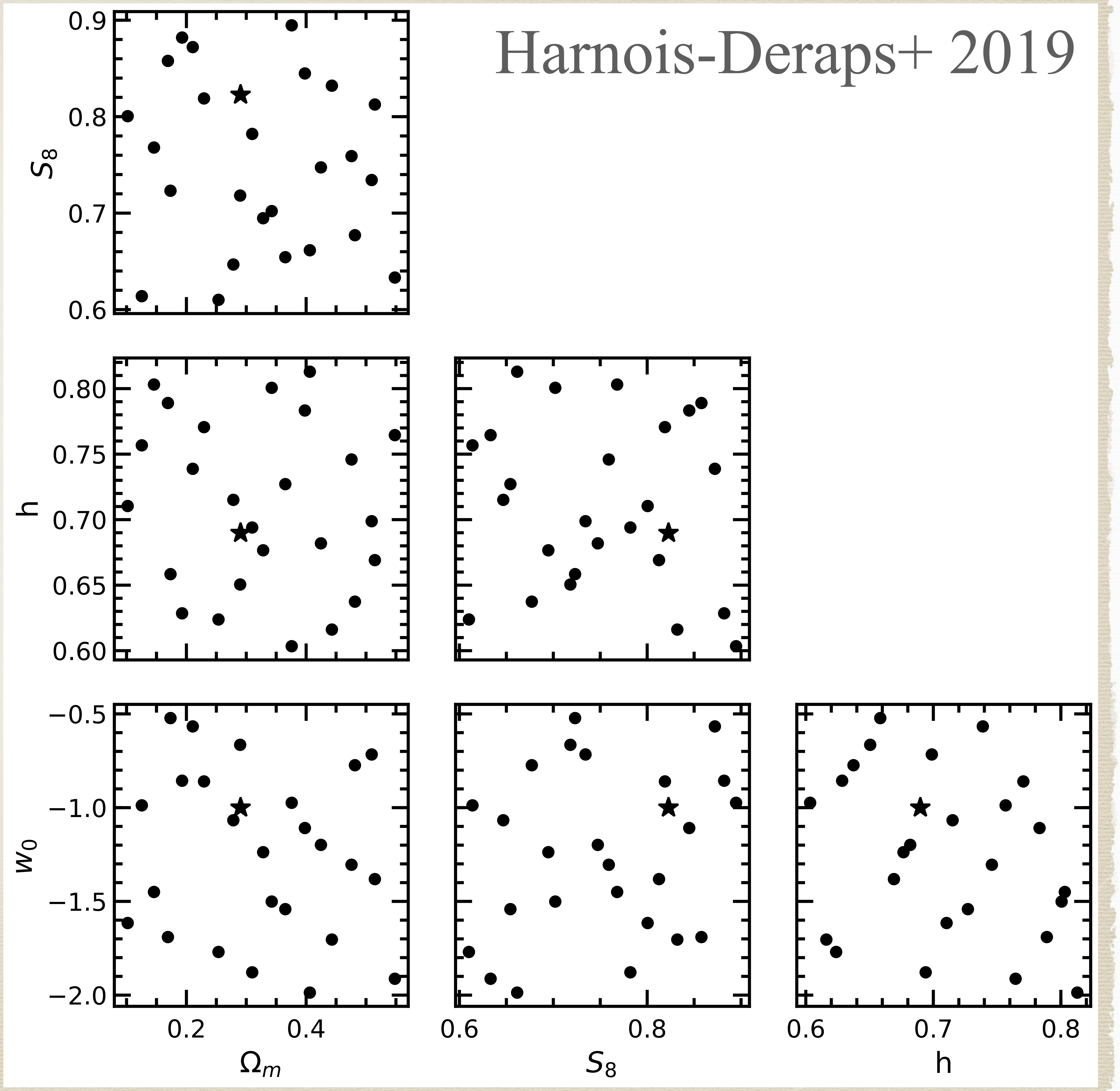






Forecast for stage IV surveys

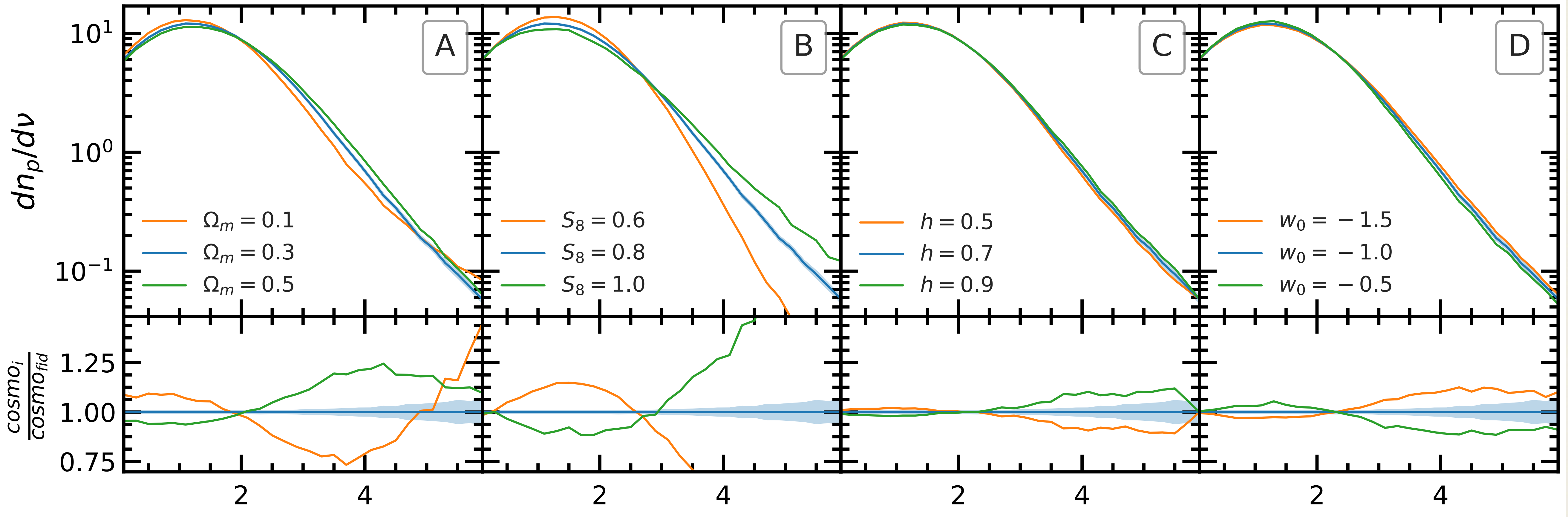
* Measure statistics as a function of wCDM parameters with the cosmoSLICS suite.
  * 26 nodes in a 4D wCDM parameter space (Ω_m, S_8, h, w_0).
* 50 WL kappa maps for each node
  * Ray-traced from N-body simulations.
  * Matches Rubin n(z).
  * Each map is 10x10 deg^2.
  * Suppressed cosmic variance
* 615 realisations at fiducial ΛCDM cosmology (black star) for covariance estimation.
* Use statistics from these maps to train Gaussian process emulator.
* Use emulator to generate posterior forecasts for Rubin.



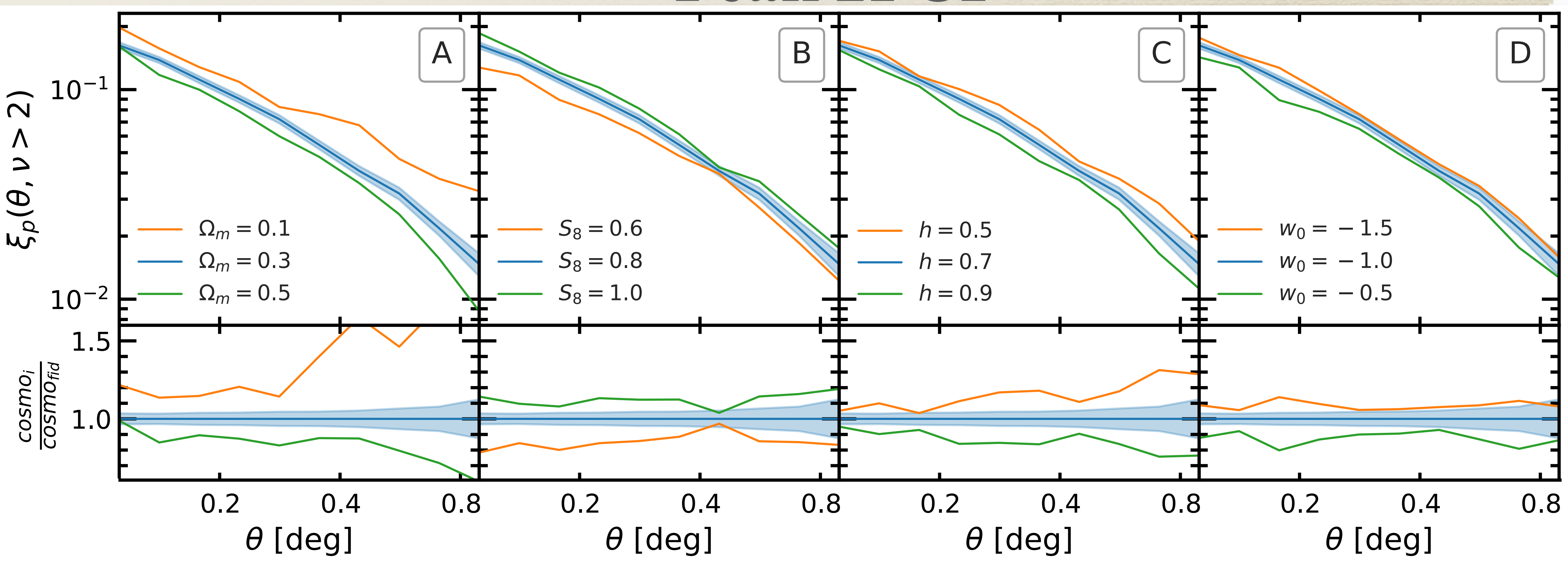
Emulate statistics with GPR

Learn about the physics behind the statistics,
by using the emulator to vary one cosmological parameter at a time.

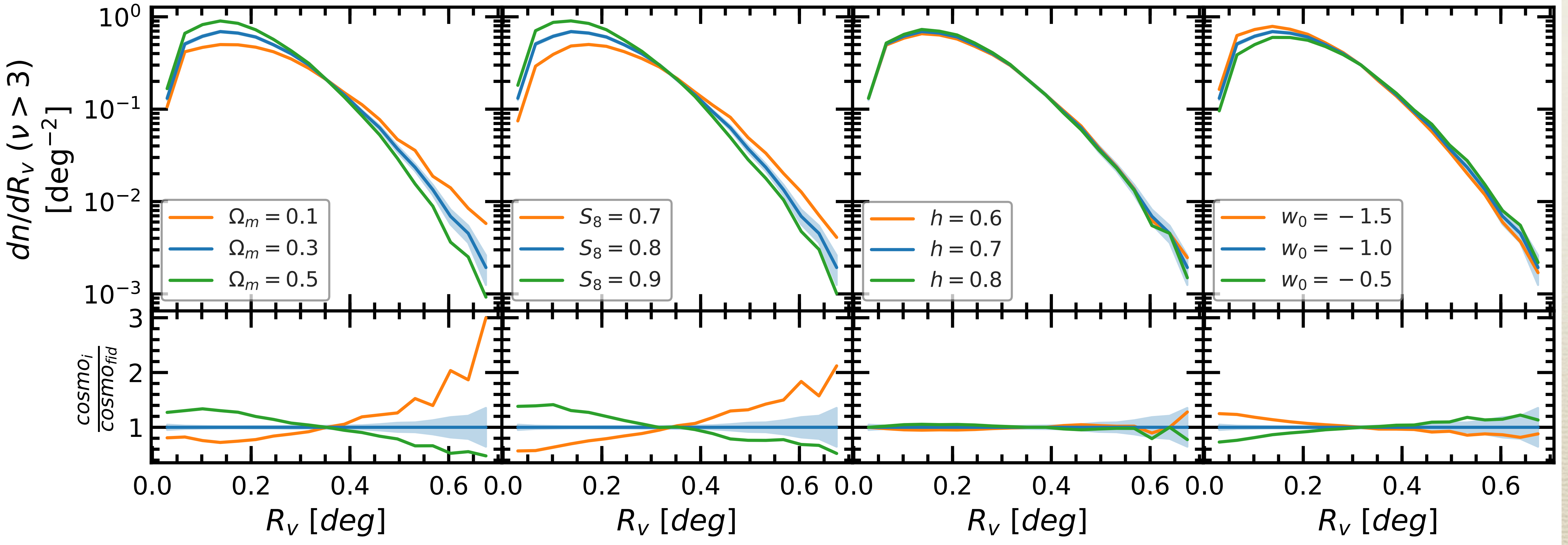
Peak abundance



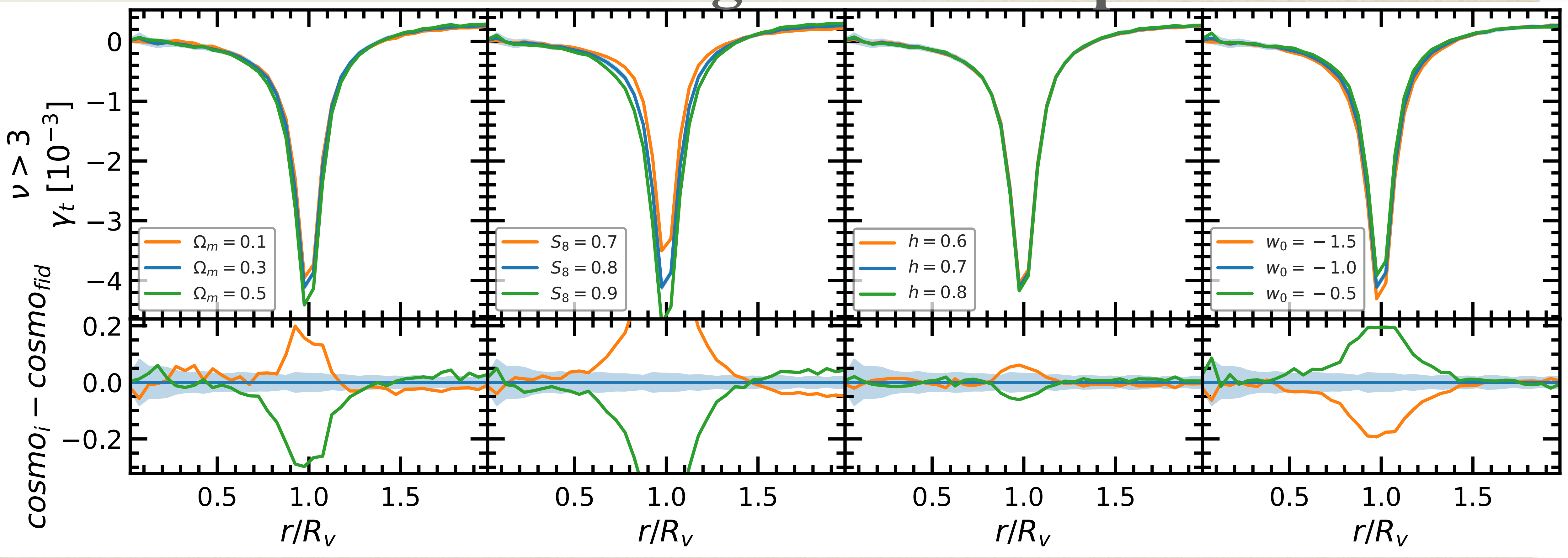
Peak 2PCF



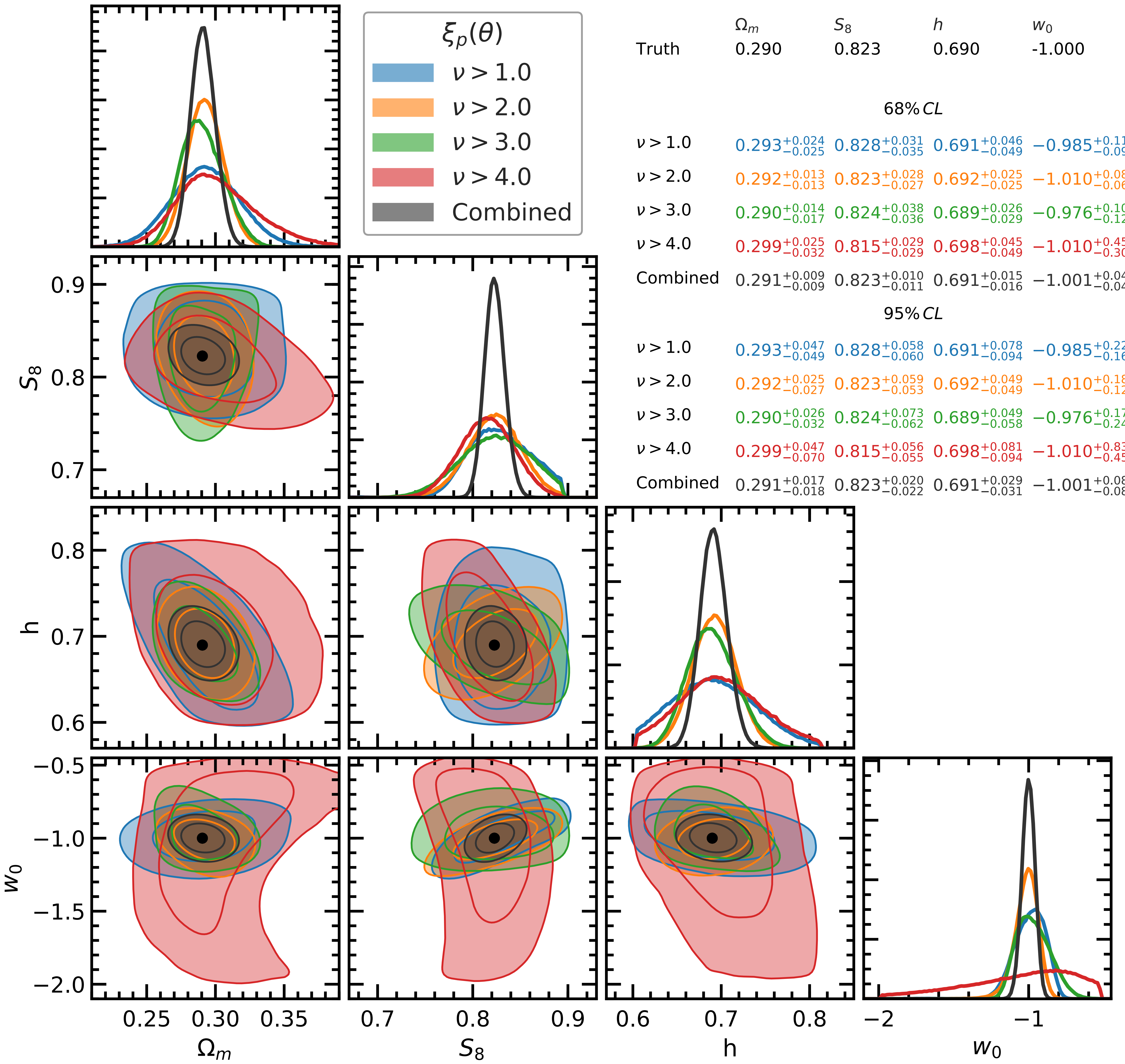
Void abundance



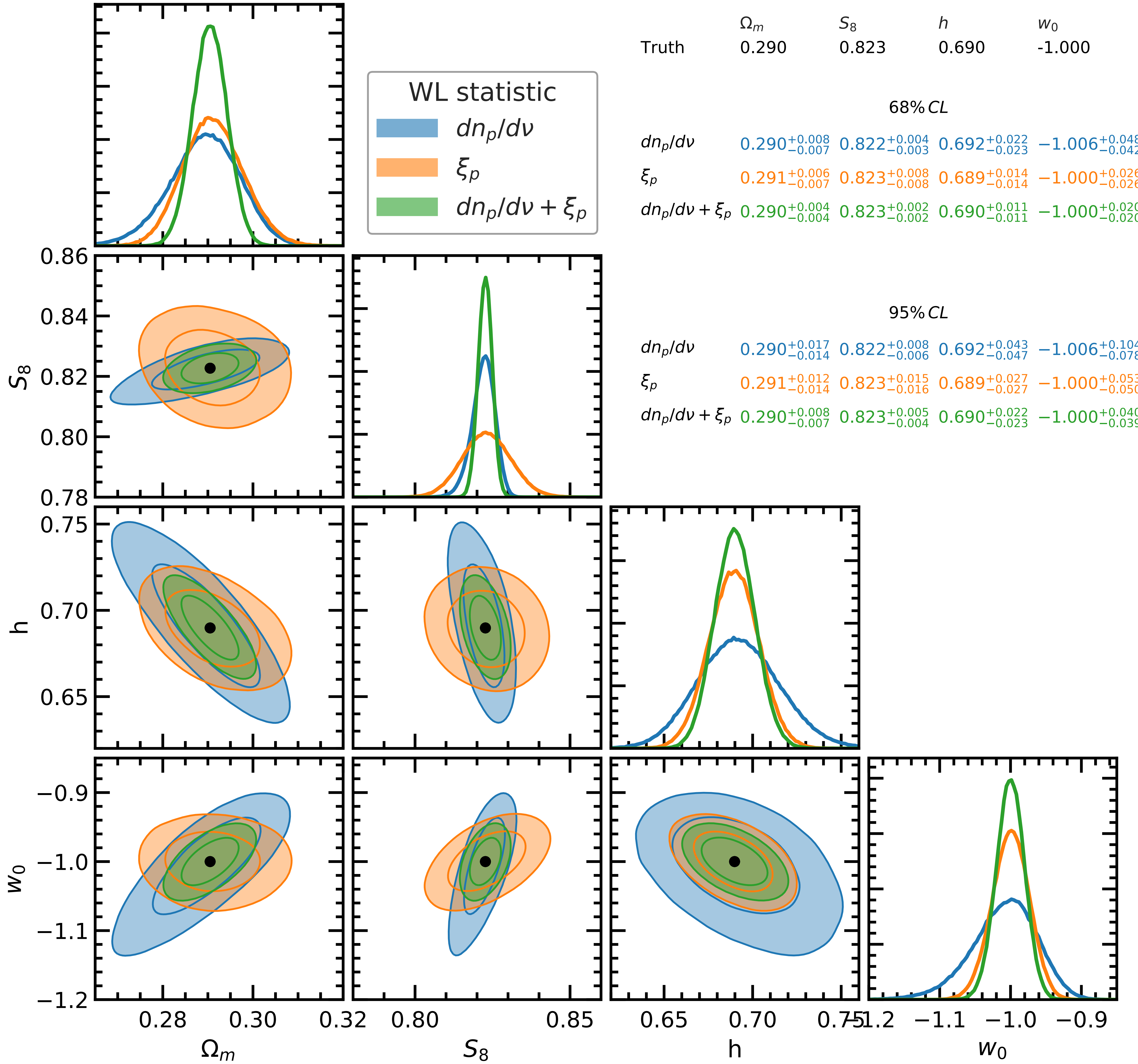
Void tangential shear profile



Peak forecasts

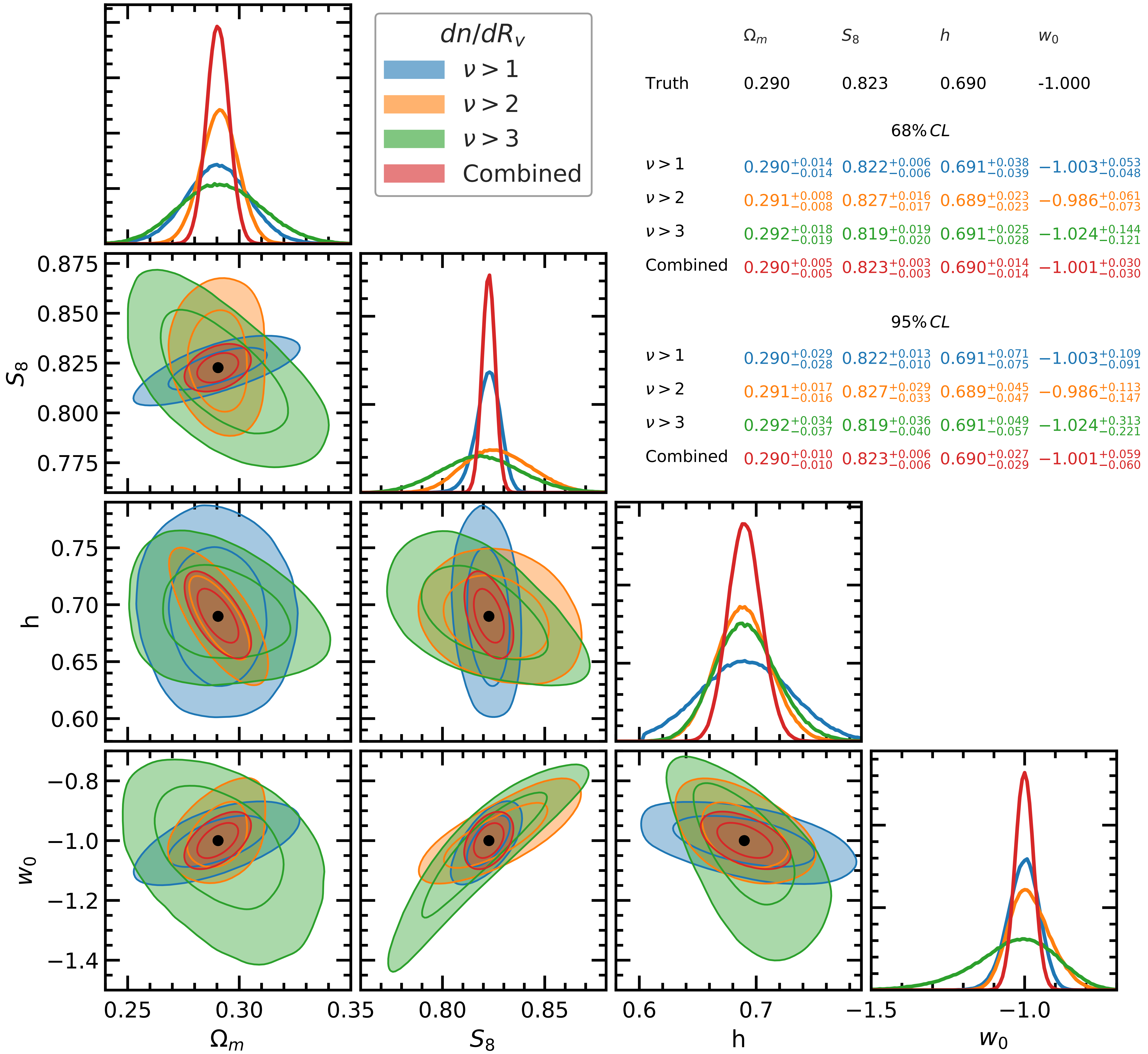


	Ω_m	S_8	h	w_0
Truth	0.290	0.823	0.690	-1.000
68% CL				
$\nu > 1.0$	$0.293^{+0.024}_{-0.025}$	$0.828^{+0.031}_{-0.035}$	$0.691^{+0.046}_{-0.049}$	$-0.985^{+0.112}_{-0.096}$
$\nu > 2.0$	$0.292^{+0.013}_{-0.013}$	$0.823^{+0.028}_{-0.027}$	$0.692^{+0.025}_{-0.025}$	$-1.010^{+0.081}_{-0.069}$
$\nu > 3.0$	$0.290^{+0.014}_{-0.017}$	$0.824^{+0.038}_{-0.036}$	$0.689^{+0.026}_{-0.029}$	$-0.976^{+0.103}_{-0.125}$
$\nu > 4.0$	$0.299^{+0.025}_{-0.032}$	$0.815^{+0.029}_{-0.029}$	$0.698^{+0.045}_{-0.049}$	$-1.010^{+0.450}_{-0.301}$
Combined	$0.291^{+0.009}_{-0.009}$	$0.823^{+0.010}_{-0.011}$	$0.691^{+0.015}_{-0.016}$	$-1.001^{+0.043}_{-0.042}$
95% CL				
$\nu > 1.0$	$0.293^{+0.047}_{-0.049}$	$0.828^{+0.058}_{-0.060}$	$0.691^{+0.078}_{-0.094}$	$-0.985^{+0.222}_{-0.166}$
$\nu > 2.0$	$0.292^{+0.025}_{-0.027}$	$0.823^{+0.059}_{-0.053}$	$0.692^{+0.049}_{-0.049}$	$-1.010^{+0.188}_{-0.129}$
$\nu > 3.0$	$0.290^{+0.026}_{-0.032}$	$0.824^{+0.073}_{-0.062}$	$0.689^{+0.049}_{-0.058}$	$-0.976^{+0.177}_{-0.244}$
$\nu > 4.0$	$0.299^{+0.047}_{-0.070}$	$0.815^{+0.056}_{-0.055}$	$0.698^{+0.081}_{-0.094}$	$-1.010^{+0.839}_{-0.451}$
Combined	$0.291^{+0.017}_{-0.018}$	$0.823^{+0.020}_{-0.022}$	$0.691^{+0.029}_{-0.031}$	$-1.001^{+0.085}_{-0.080}$

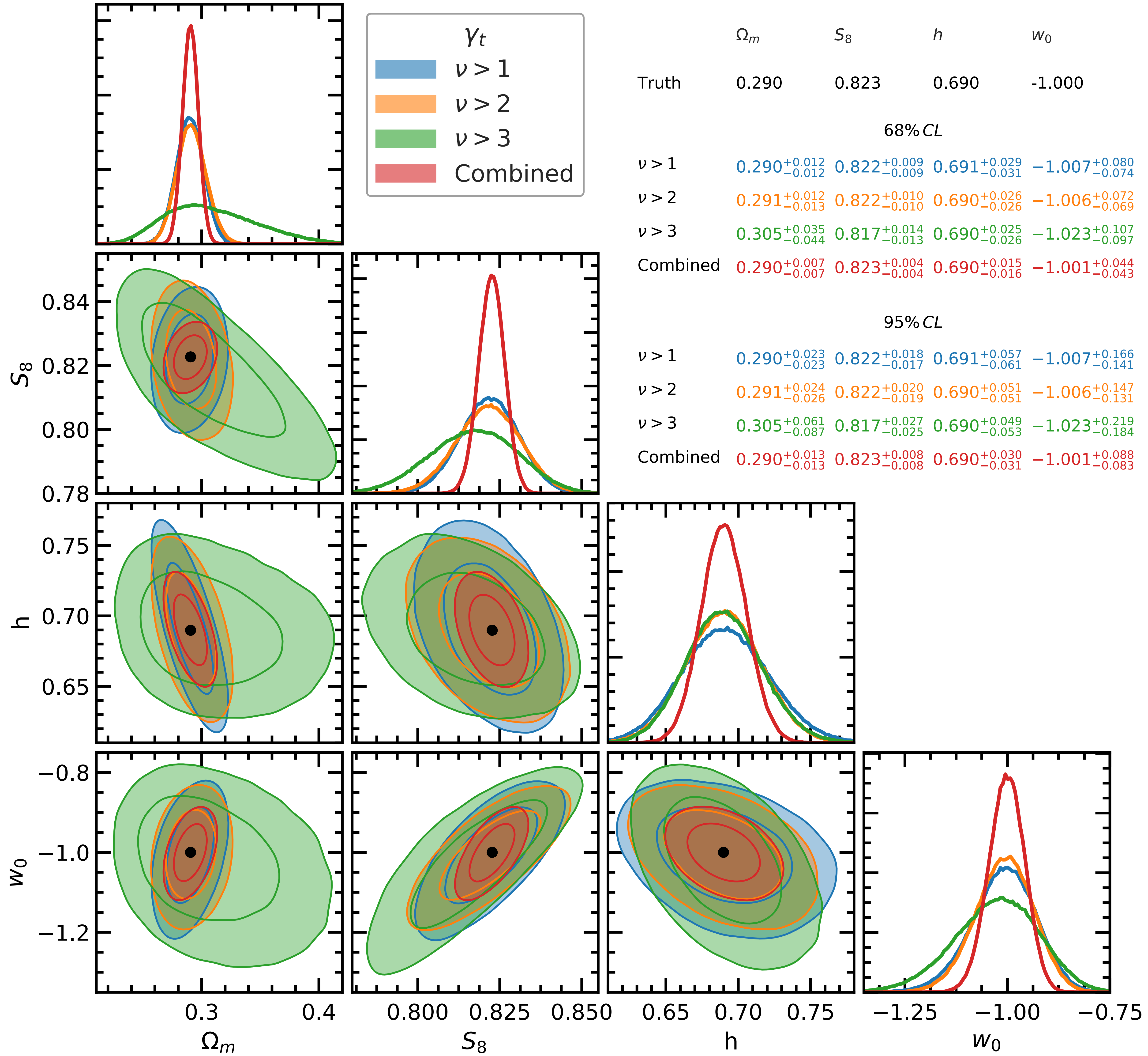


	Ω_m	S_8	h	w_0
Truth	0.290	0.823	0.690	-1.000
68% CL				
$dn_p/d\nu$	$0.290^{+0.008}_{-0.007}$	$0.822^{+0.004}_{-0.003}$	$0.692^{+0.022}_{-0.023}$	$-1.006^{+0.048}_{-0.042}$
ξ_p	$0.291^{+0.006}_{-0.007}$	$0.823^{+0.008}_{-0.008}$	$0.689^{+0.014}_{-0.014}$	$-1.000^{+0.026}_{-0.026}$
$dn_p/d\nu + \xi_p$	$0.290^{+0.004}_{-0.004}$	$0.823^{+0.002}_{-0.002}$	$0.690^{+0.011}_{-0.011}$	$-1.000^{+0.020}_{-0.020}$
95% CL				
$dn_p/d\nu$	$0.290^{+0.017}_{-0.014}$	$0.822^{+0.008}_{-0.006}$	$0.692^{+0.043}_{-0.047}$	$-1.006^{+0.104}_{-0.078}$
ξ_p	$0.291^{+0.012}_{-0.014}$	$0.823^{+0.015}_{-0.016}$	$0.689^{+0.027}_{-0.027}$	$-1.000^{+0.053}_{-0.050}$
$dn_p/d\nu + \xi_p$	$0.290^{+0.008}_{-0.007}$	$0.823^{+0.005}_{-0.004}$	$0.690^{+0.022}_{-0.023}$	$-1.000^{+0.040}_{-0.039}$

Void forecasts



	Ω_m	S_8	h	w_0
Truth	0.290	0.823	0.690	-1.000
68% CL				
$\nu > 1$	$0.290^{+0.014}_{-0.014}$	$0.822^{+0.006}_{-0.006}$	$0.691^{+0.038}_{-0.039}$	$-1.003^{+0.053}_{-0.048}$
$\nu > 2$	$0.291^{+0.008}_{-0.008}$	$0.827^{+0.016}_{-0.017}$	$0.689^{+0.023}_{-0.023}$	$-0.986^{+0.061}_{-0.073}$
$\nu > 3$	$0.292^{+0.018}_{-0.019}$	$0.819^{+0.019}_{-0.020}$	$0.691^{+0.025}_{-0.028}$	$-1.024^{+0.144}_{-0.121}$
Combined	$0.290^{+0.005}_{-0.005}$	$0.823^{+0.003}_{-0.003}$	$0.690^{+0.014}_{-0.014}$	$-1.001^{+0.030}_{-0.030}$
95% CL				
$\nu > 1$	$0.290^{+0.029}_{-0.028}$	$0.822^{+0.013}_{-0.010}$	$0.691^{+0.071}_{-0.075}$	$-1.003^{+0.109}_{-0.091}$
$\nu > 2$	$0.291^{+0.017}_{-0.016}$	$0.827^{+0.029}_{-0.033}$	$0.689^{+0.045}_{-0.047}$	$-0.986^{+0.113}_{-0.147}$
$\nu > 3$	$0.292^{+0.034}_{-0.037}$	$0.819^{+0.036}_{-0.040}$	$0.691^{+0.049}_{-0.057}$	$-1.024^{+0.313}_{-0.221}$
Combined	$0.290^{+0.010}_{-0.010}$	$0.823^{+0.006}_{-0.006}$	$0.690^{+0.027}_{-0.029}$	$-1.001^{+0.059}_{-0.060}$



	Ω_m	S_8	h	w_0
Truth	0.290	0.823	0.690	-1.000
68% CL				
$\nu > 1$	$0.290^{+0.012}_{-0.012}$	$0.822^{+0.009}_{-0.009}$	$0.691^{+0.029}_{-0.031}$	$-1.007^{+0.080}_{-0.074}$
$\nu > 2$	$0.291^{+0.012}_{-0.013}$	$0.822^{+0.010}_{-0.010}$	$0.690^{+0.026}_{-0.026}$	$-1.006^{+0.072}_{-0.069}$
$\nu > 3$	$0.305^{+0.035}_{-0.044}$	$0.817^{+0.014}_{-0.013}$	$0.690^{+0.025}_{-0.026}$	$-1.023^{+0.107}_{-0.097}$
Combined	$0.290^{+0.007}_{-0.007}$	$0.823^{+0.004}_{-0.004}$	$0.690^{+0.015}_{-0.016}$	$-1.001^{+0.044}_{-0.043}$
95% CL				
$\nu > 1$	$0.290^{+0.023}_{-0.023}$	$0.822^{+0.018}_{-0.017}$	$0.691^{+0.057}_{-0.061}$	$-1.007^{+0.166}_{-0.141}$
$\nu > 2$	$0.291^{+0.024}_{-0.026}$	$0.822^{+0.020}_{-0.019}$	$0.690^{+0.051}_{-0.051}$	$-1.006^{+0.147}_{-0.131}$
$\nu > 3$	$0.305^{+0.061}_{-0.087}$	$0.817^{+0.027}_{-0.025}$	$0.690^{+0.049}_{-0.053}$	$-1.023^{+0.219}_{-0.184}$
Combined	$0.290^{+0.013}_{-0.013}$	$0.823^{+0.008}_{-0.008}$	$0.690^{+0.030}_{-0.031}$	$-1.001^{+0.088}_{-0.083}$

Comparison to standard approach

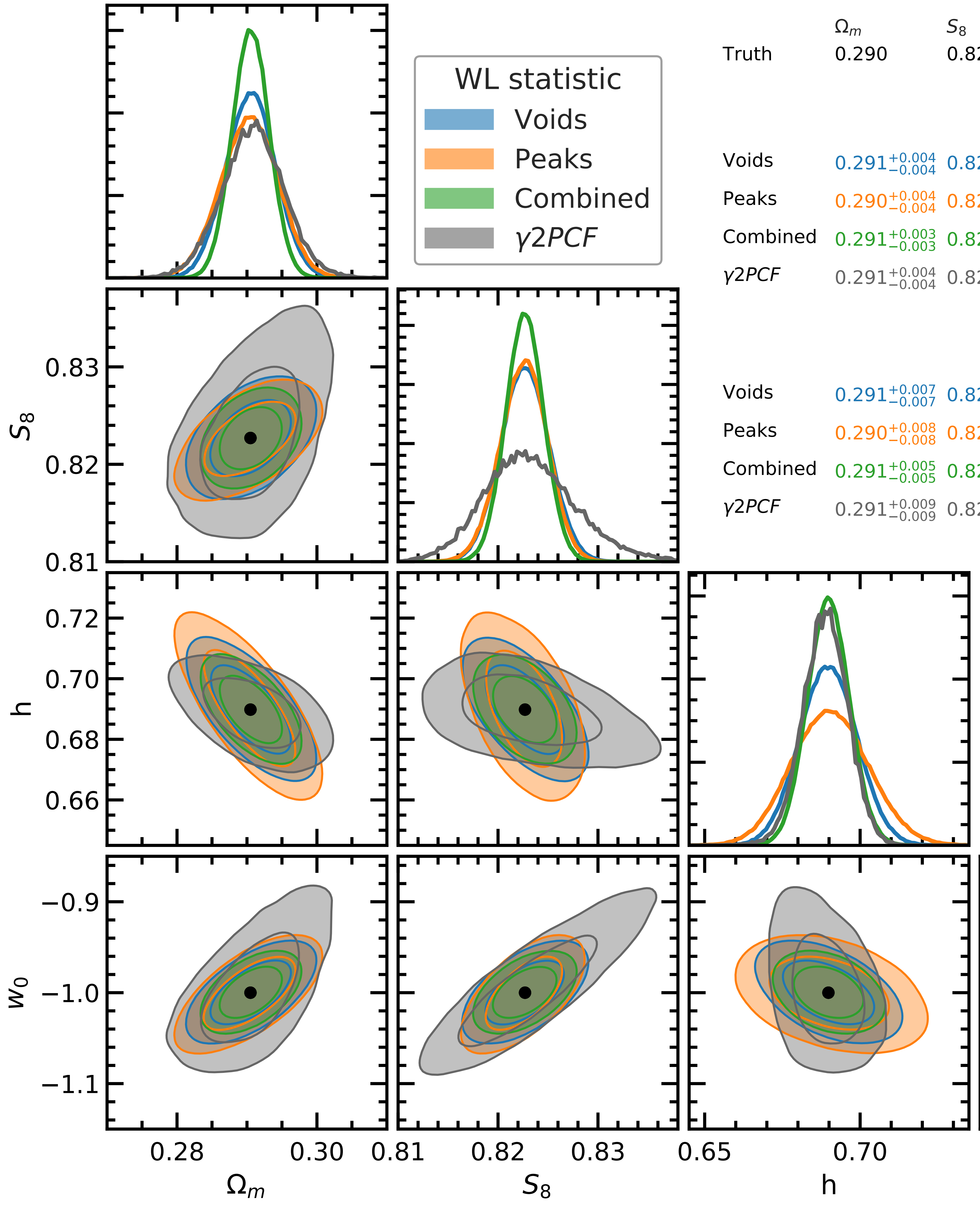
* Both peaks and voids are tighter for S_8 and w_0 compared to Shear 2PCF.

* Voids are slightly tighter than peaks for Ω_m.

* Peaks are slightly tighter than voids for S_8

* Shear 2PCF is better than both peaks and voids for h.

* When peaks and voids are combined, the constraints are tighter than the shear 2PCF for all parameters.

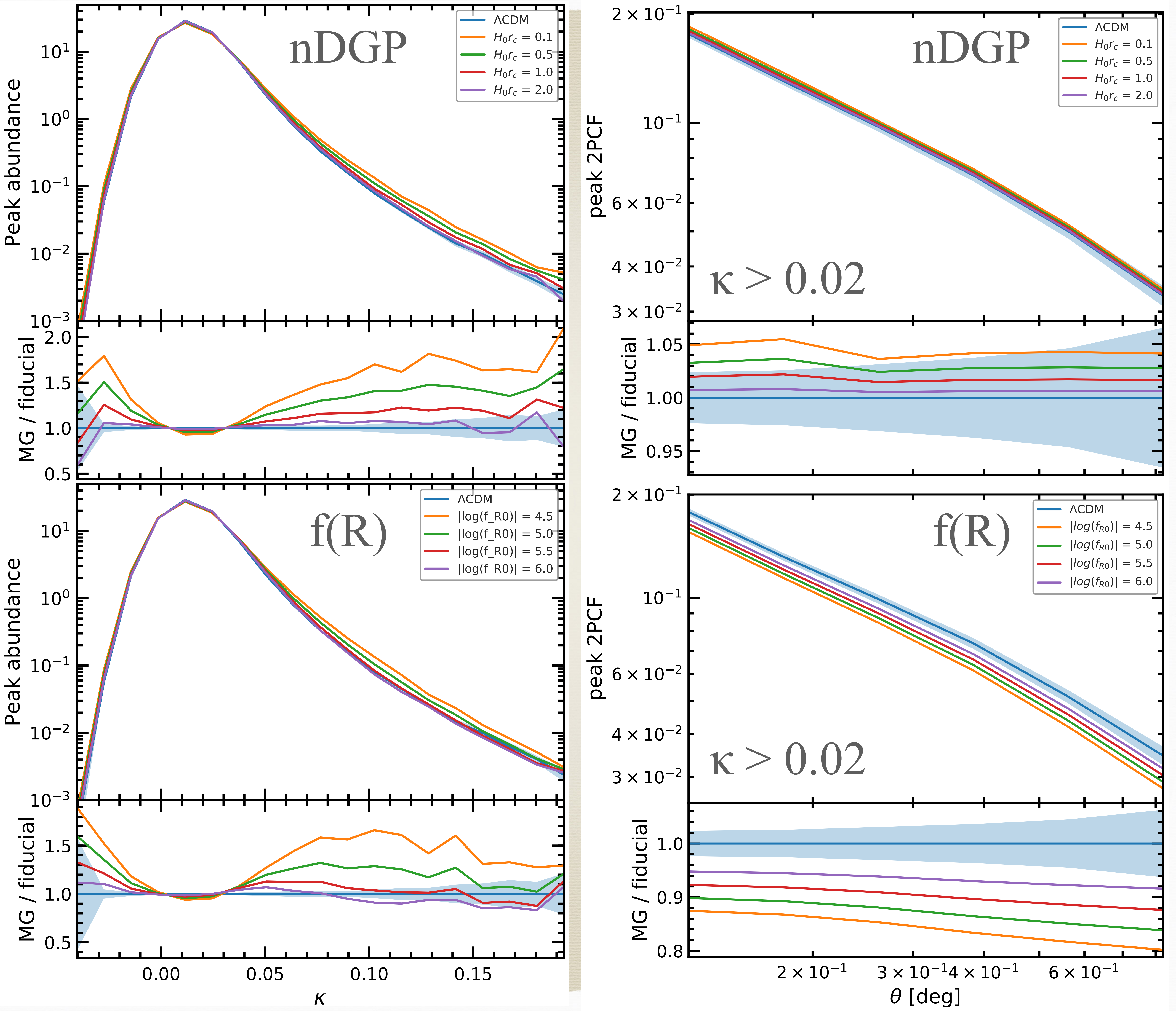


	Ω_m	S_8	h	w_0
Truth	0.290	0.823	0.690	-1.000
		68% *CL*		
Voids	$0.291^{+0.004}_{-0.004}$	$0.823^{+0.002}_{-0.002}$	$0.690^{+0.009}_{-0.009}$	$-1.000^{+0.021}_{-0.021}$
Peaks	$0.290^{+0.004}_{-0.004}$	$0.823^{+0.002}_{-0.002}$	$0.690^{+0.012}_{-0.012}$	$-1.001^{+0.025}_{-0.024}$
Combined	$0.291^{+0.003}_{-0.003}$	$0.823^{+0.002}_{-0.002}$	$0.690^{+0.007}_{-0.007}$	$-1.000^{+0.016}_{-0.016}$
γ2PCF	$0.291^{+0.004}_{-0.004}$	$0.823^{+0.004}_{-0.005}$	$0.689^{+0.007}_{-0.007}$	$-0.998^{+0.036}_{-0.042}$
		95% *CL*		
Voids	$0.291^{+0.007}_{-0.007}$	$0.823^{+0.005}_{-0.005}$	$0.690^{+0.018}_{-0.018}$	$-1.000^{+0.041}_{-0.042}$
Peaks	$0.290^{+0.008}_{-0.008}$	$0.823^{+0.005}_{-0.004}$	$0.690^{+0.023}_{-0.025}$	$-1.001^{+0.050}_{-0.047}$
Combined	$0.291^{+0.005}_{-0.005}$	$0.823^{+0.004}_{-0.004}$	$0.690^{+0.013}_{-0.013}$	$-1.000^{+0.031}_{-0.032}$
γ2PCF	$0.291^{+0.009}_{-0.009}$	$0.823^{+0.008}_{-0.010}$	$0.689^{+0.015}_{-0.014}$	$-0.998^{+0.069}_{-0.091}$

Peaks in modified gravity

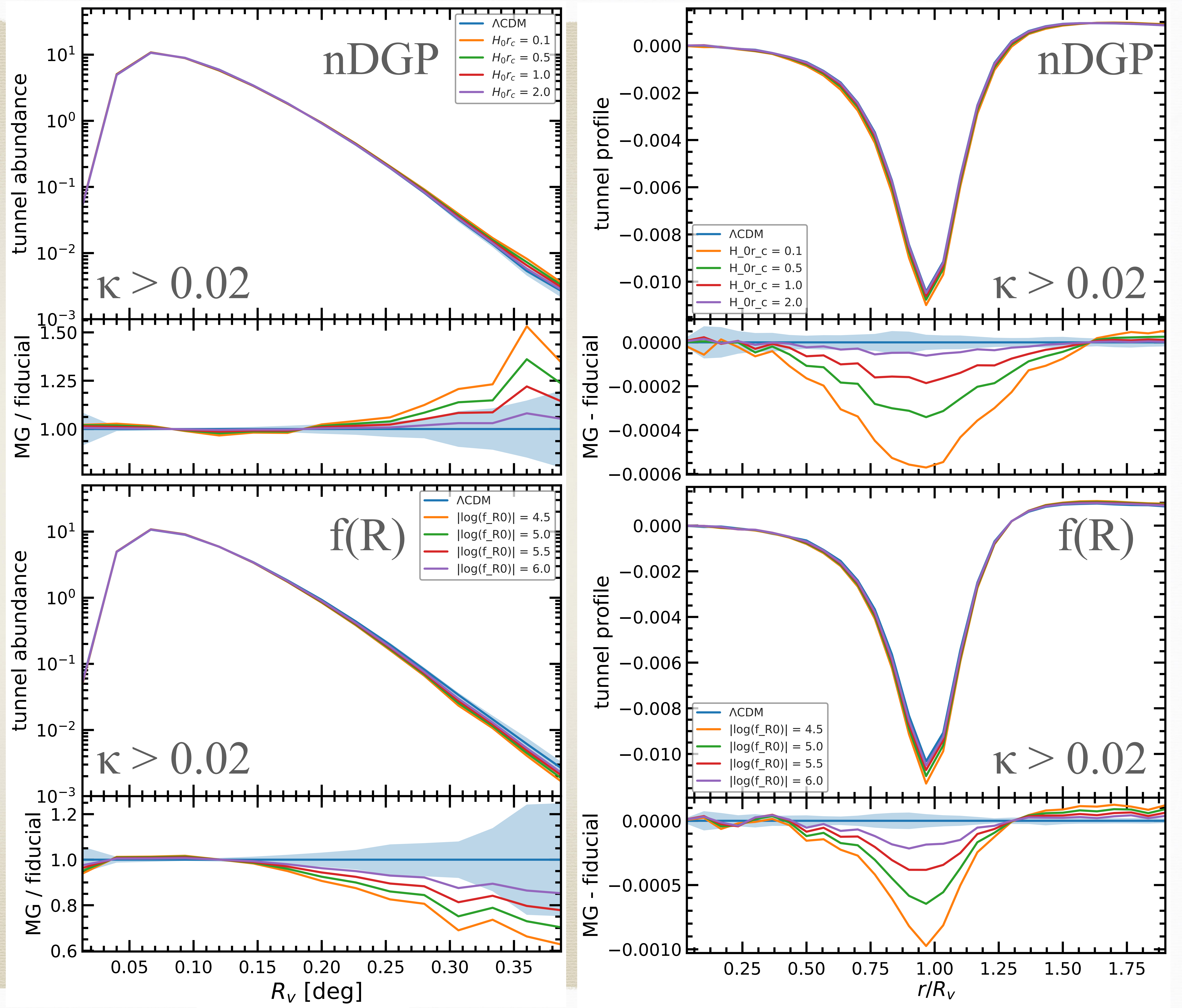
* Both the abundance (left) and the clustering (right) are sensitive to modified gravity

* The clustering is sensitive to the particular modified gravity model



Voids in modified gravity

* Both the abundance (left) and the profiles (right) are sensitive to modified gravity
* The abundance is sensitive to the particular modified gravity model



Conclusions & future work

* Weak lensing peak 2PCF is complementary to the peak abundance.
* Weak lensing voids are as useful as weak lensing peaks.
* Both peaks and voids can outperform the shear 2PCF.
* These higher order WL statistics can be used to constrain modified gravity

Additional slides

Conclusions & future work

* Tomography (On going)
* Modified gravity stage IV forecasts (On going)
* Observational systematics
    * Baryonic physics
    * Intrinsic alignments
    * Masking
* Apply to observational data

Weak lensing & Large scale structure

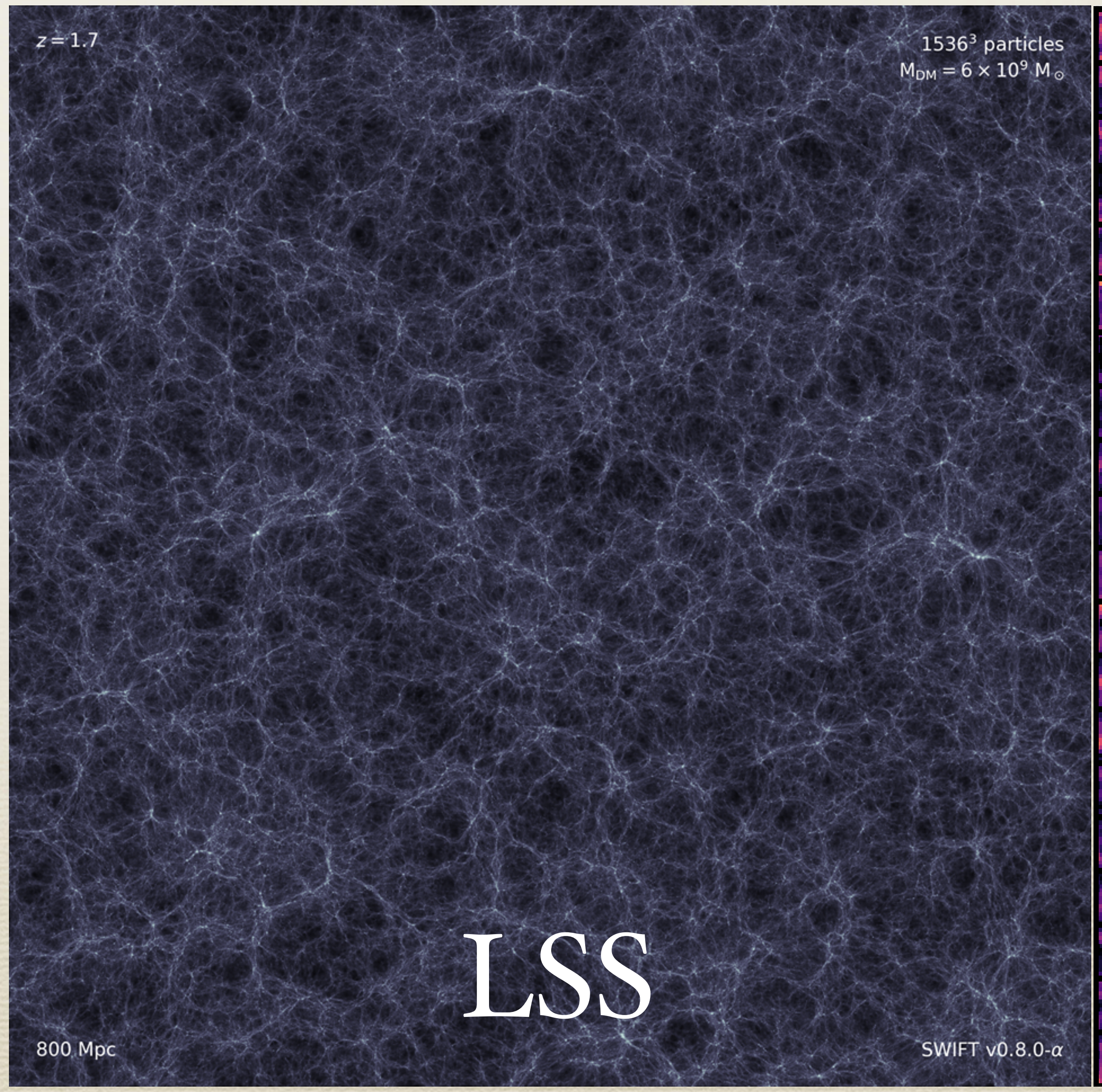
* Small lensing distortions over large patches of the sky.

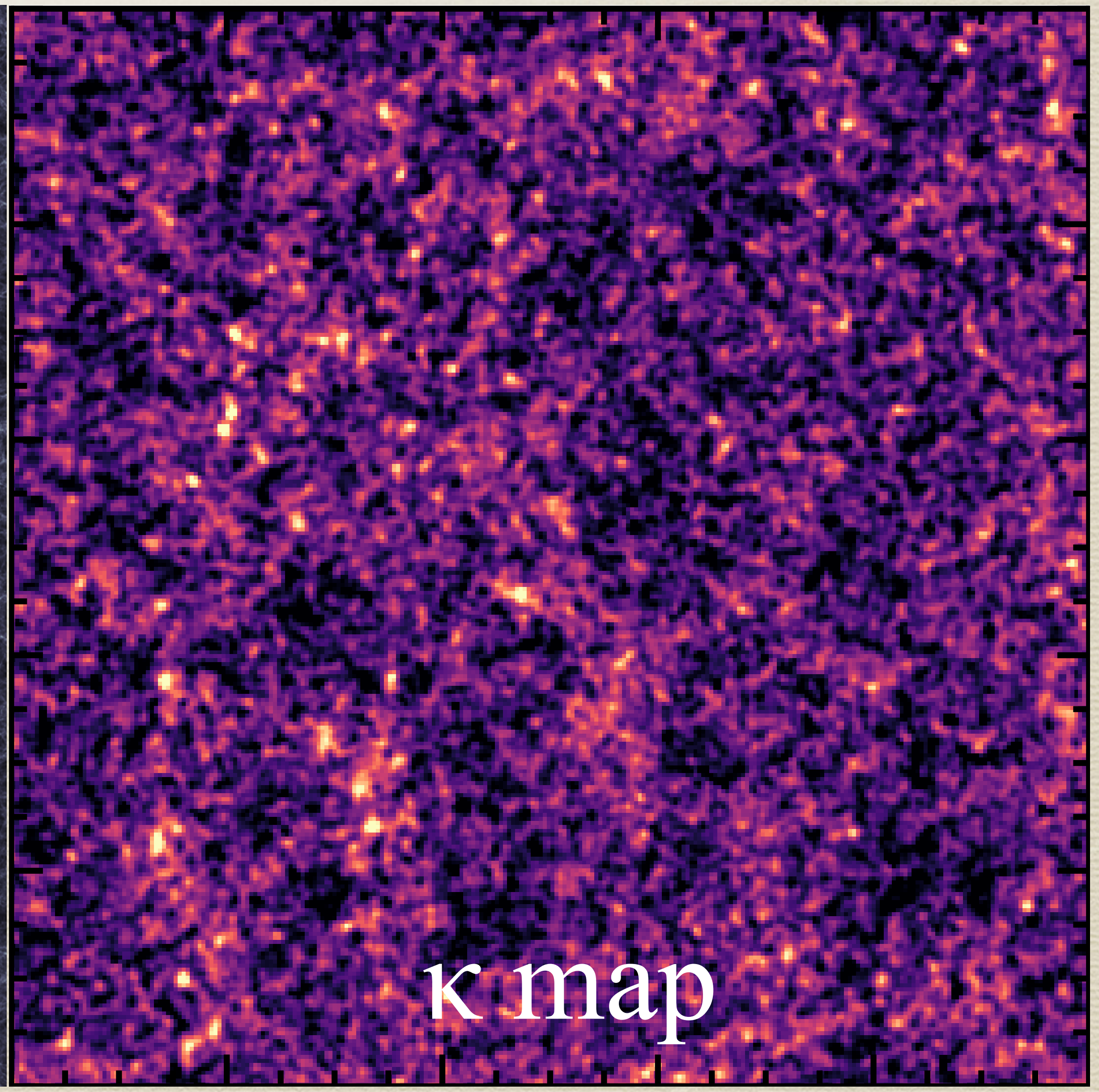
* Corresponds closely to projected total density field.

* $\kappa > 0$ = over-density
  $\kappa < 0$ = under-density

* Use $\nu = \kappa / \sigma$ since $\kappa << 1$, where σ is the noise rms.

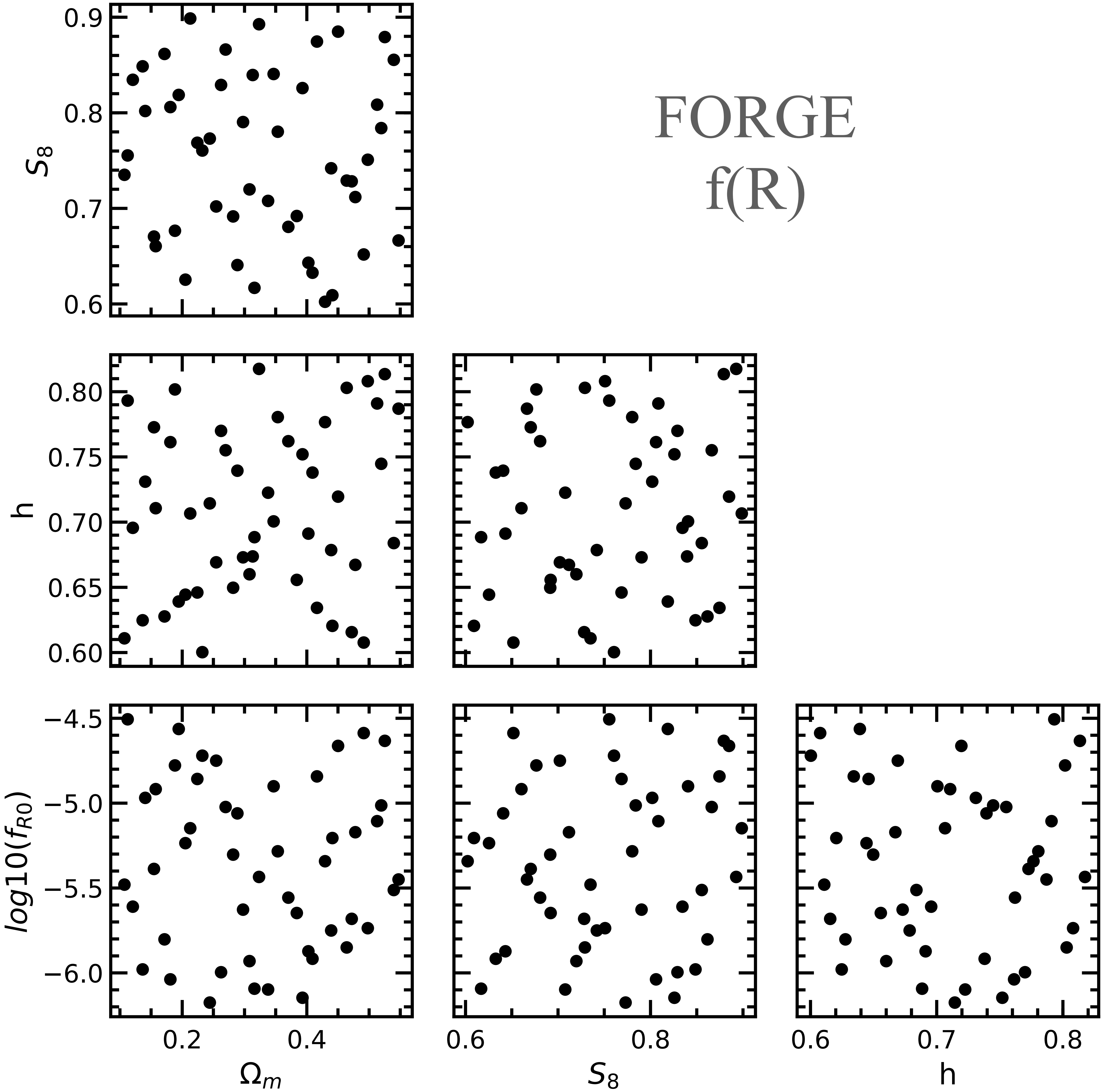
Large scale structure	**Weak lensing**
Clusters	WL peaks
Filaments	Ridges
Walls	-
Voids	WL Voids & minima



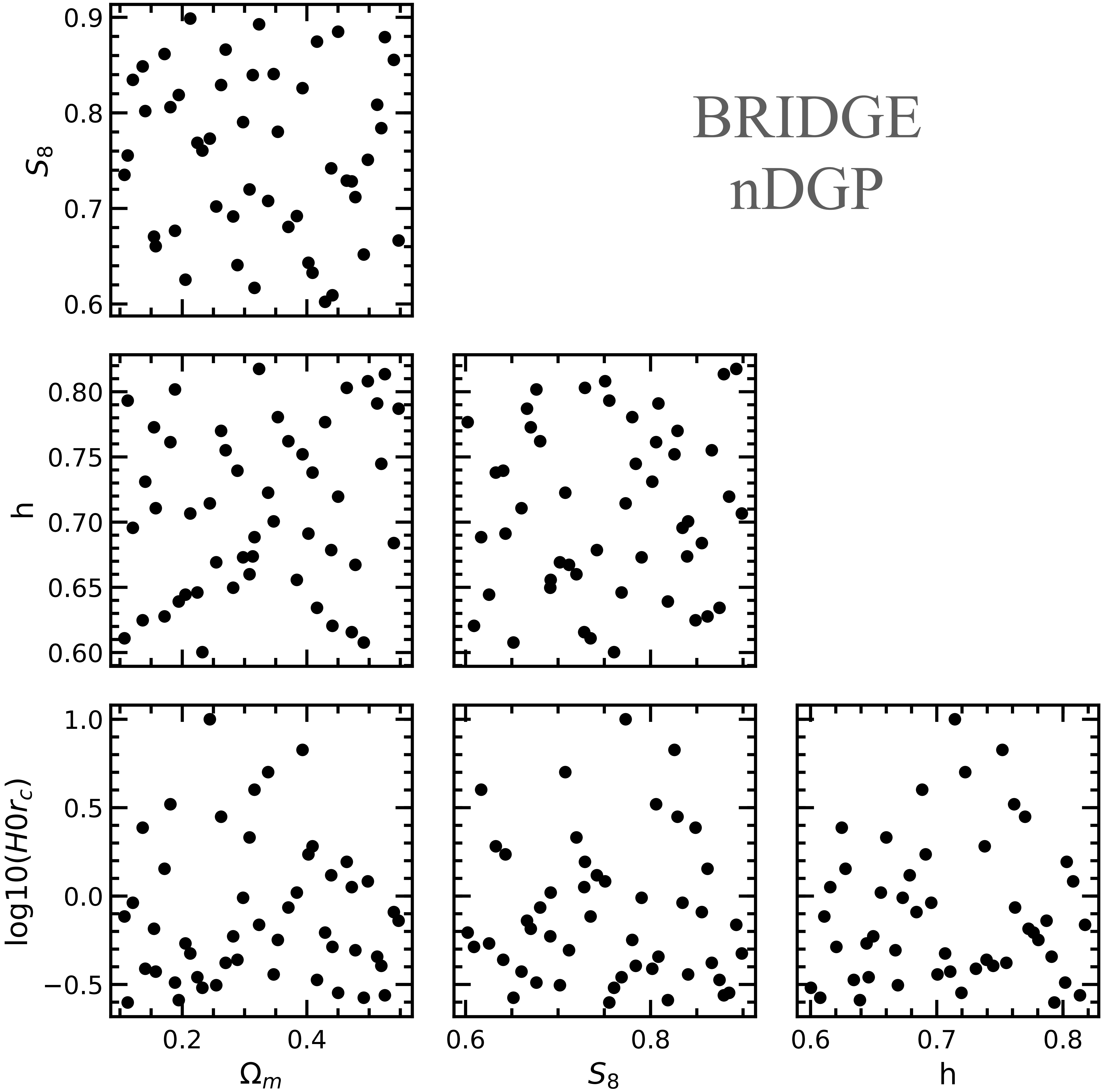


Modified gravity simulations

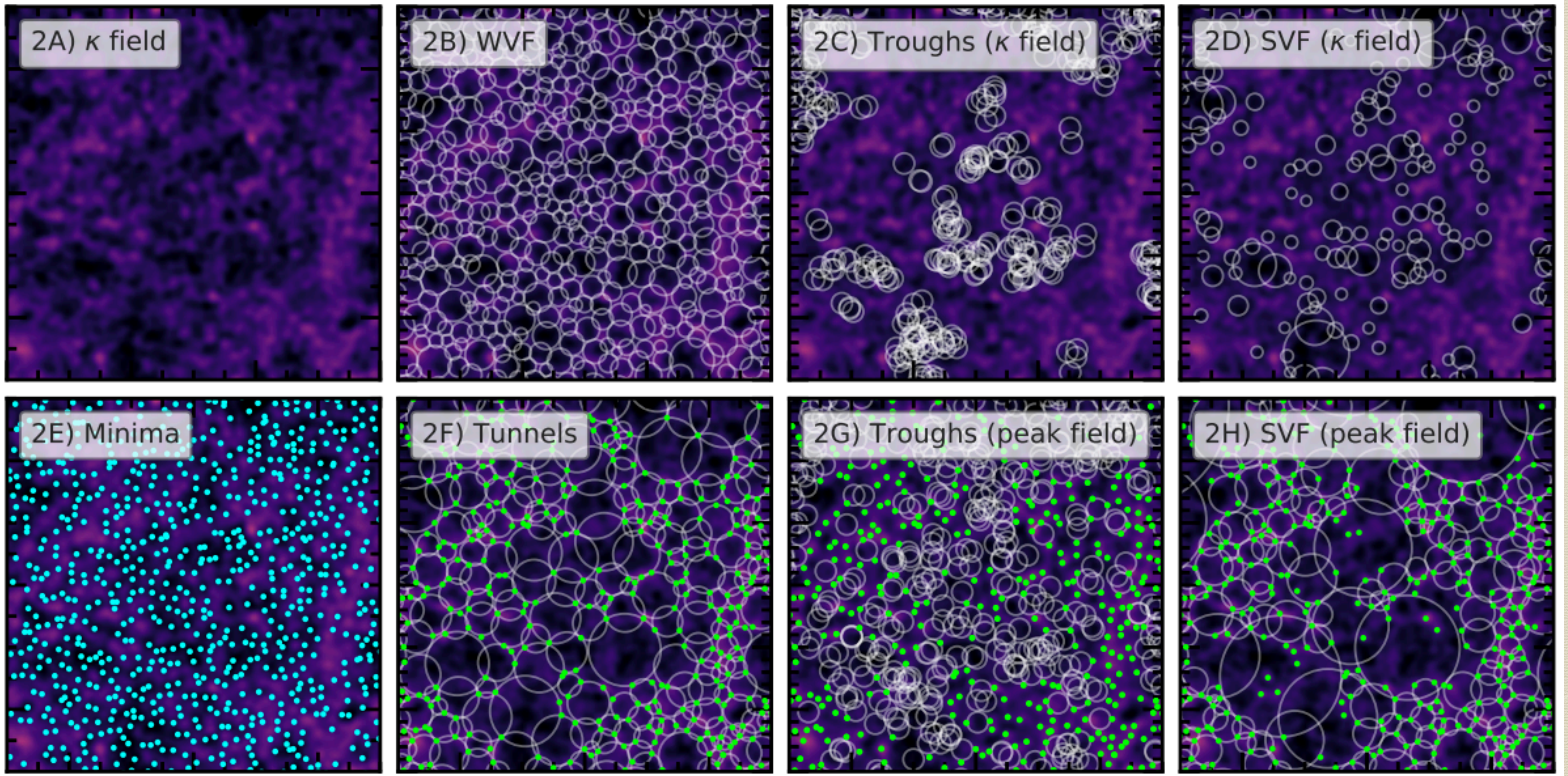
FORGE
f(R)



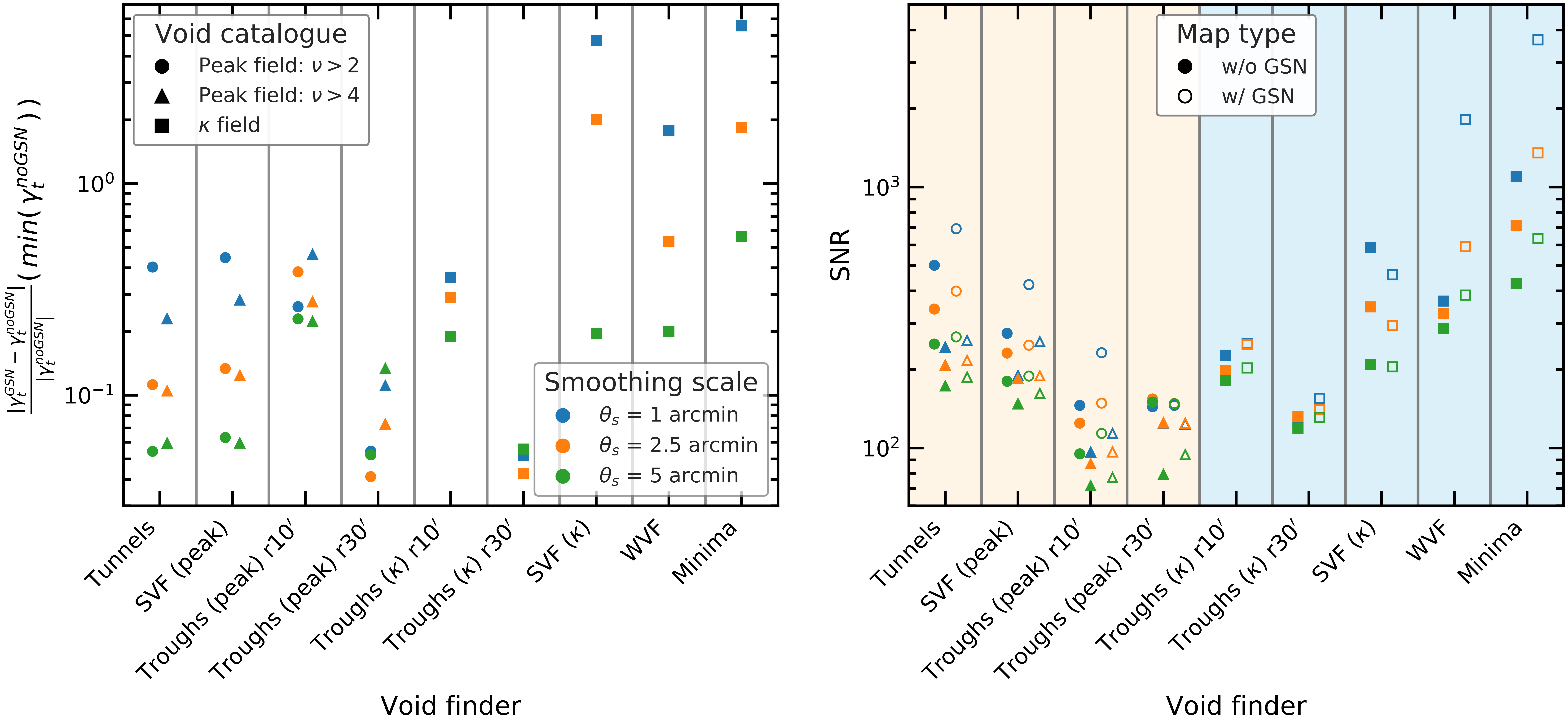
BRIDGE
nDGP



Different void finders

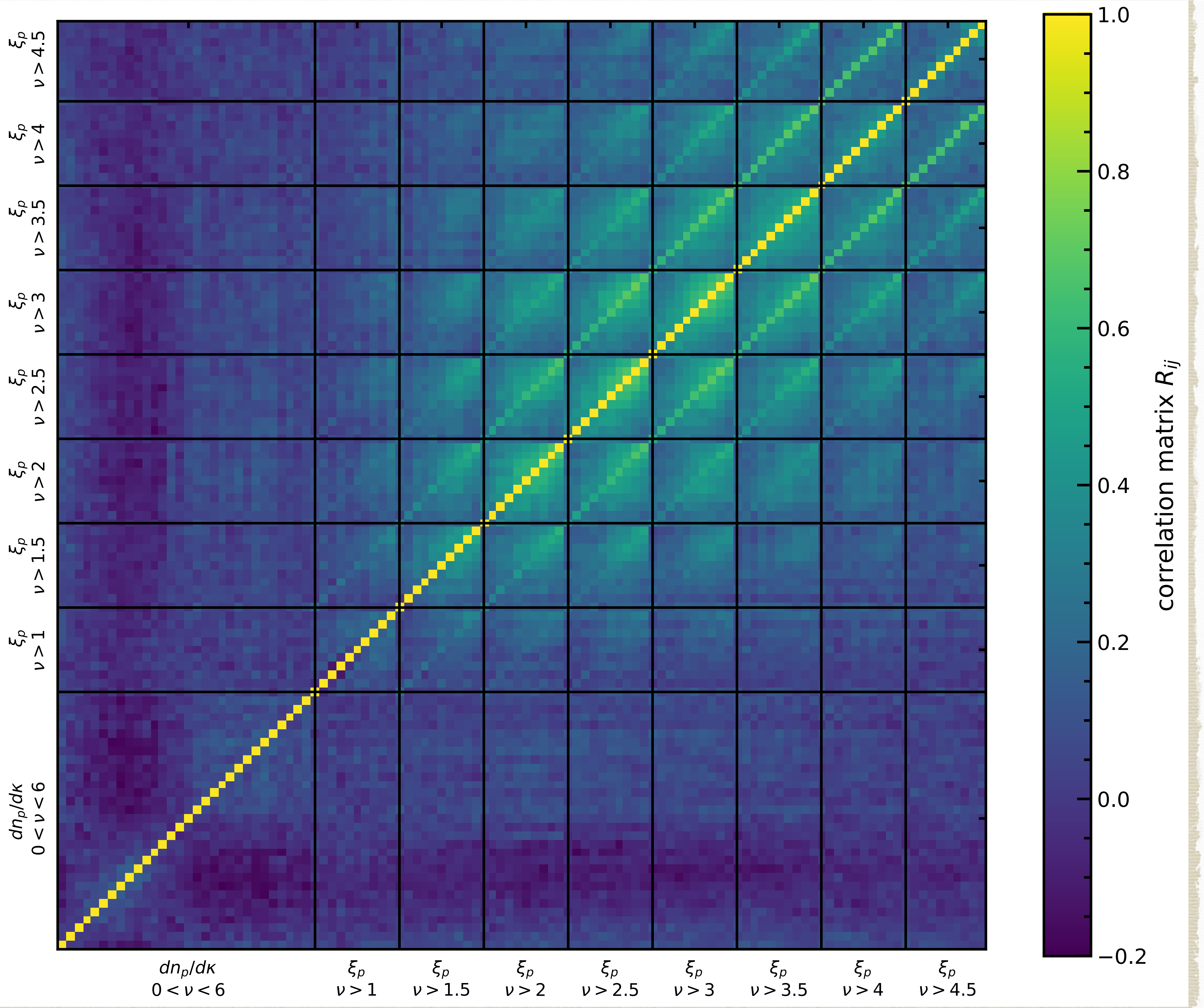


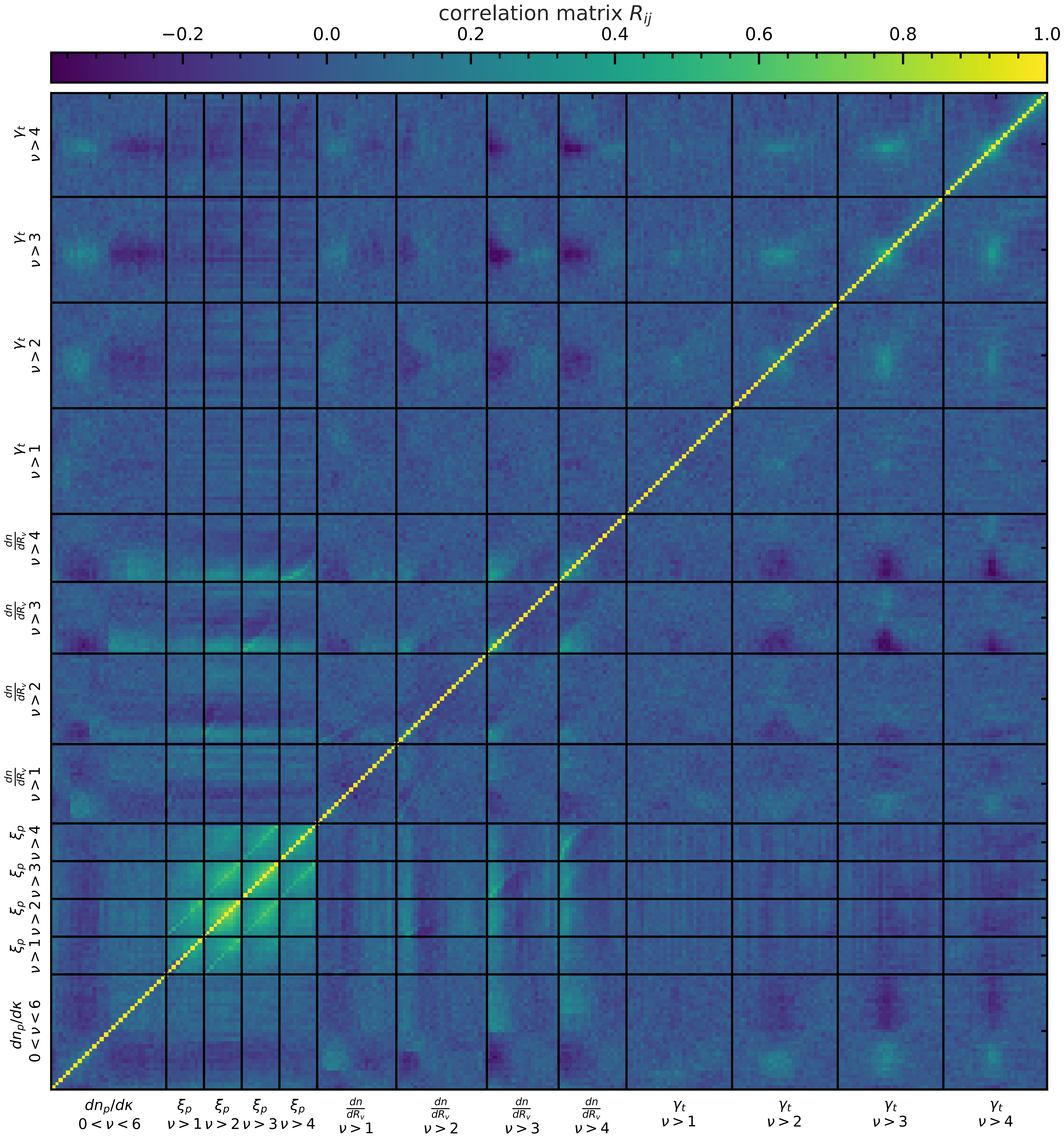
Which void finder is best?



Covariance

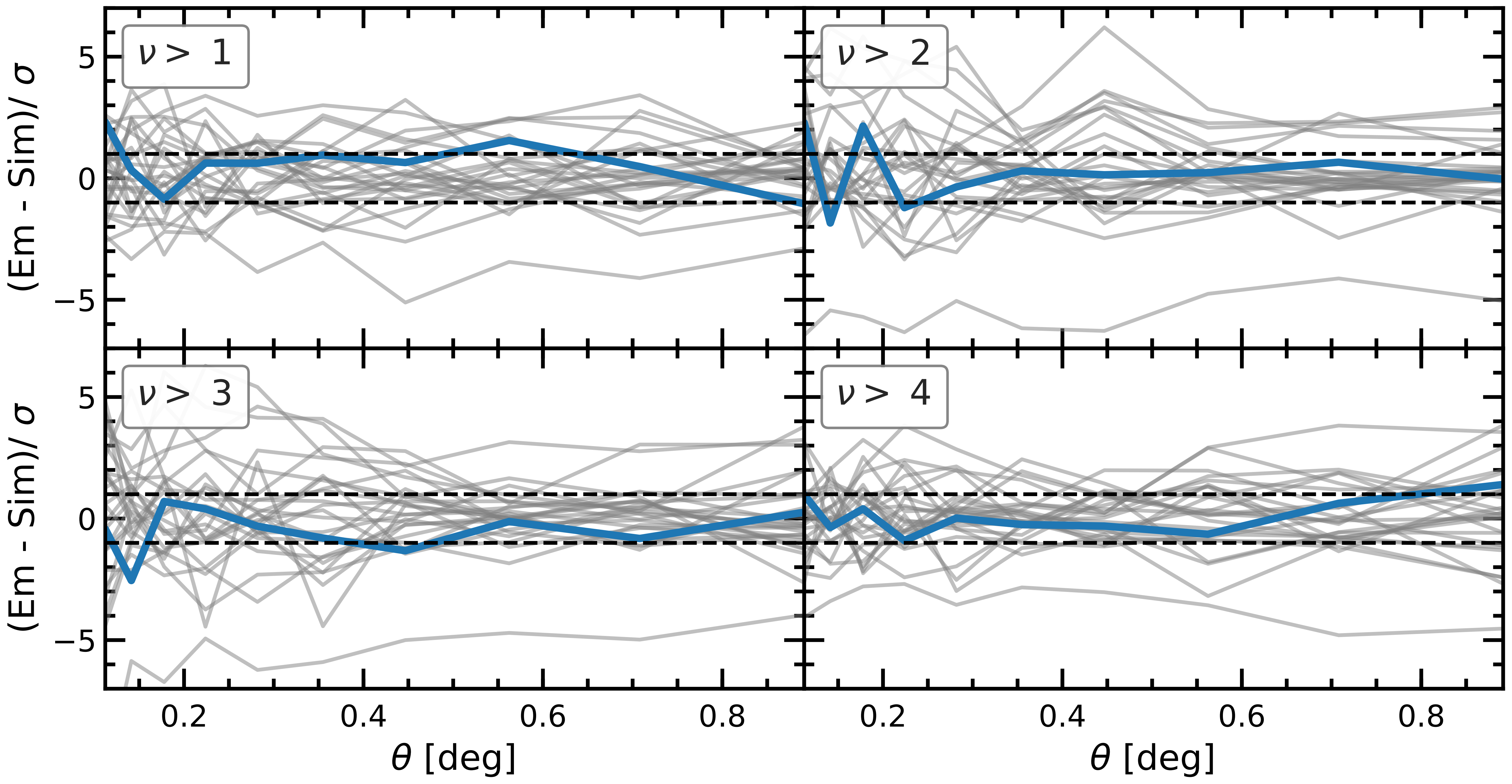
* PA + P2PCF full covariance

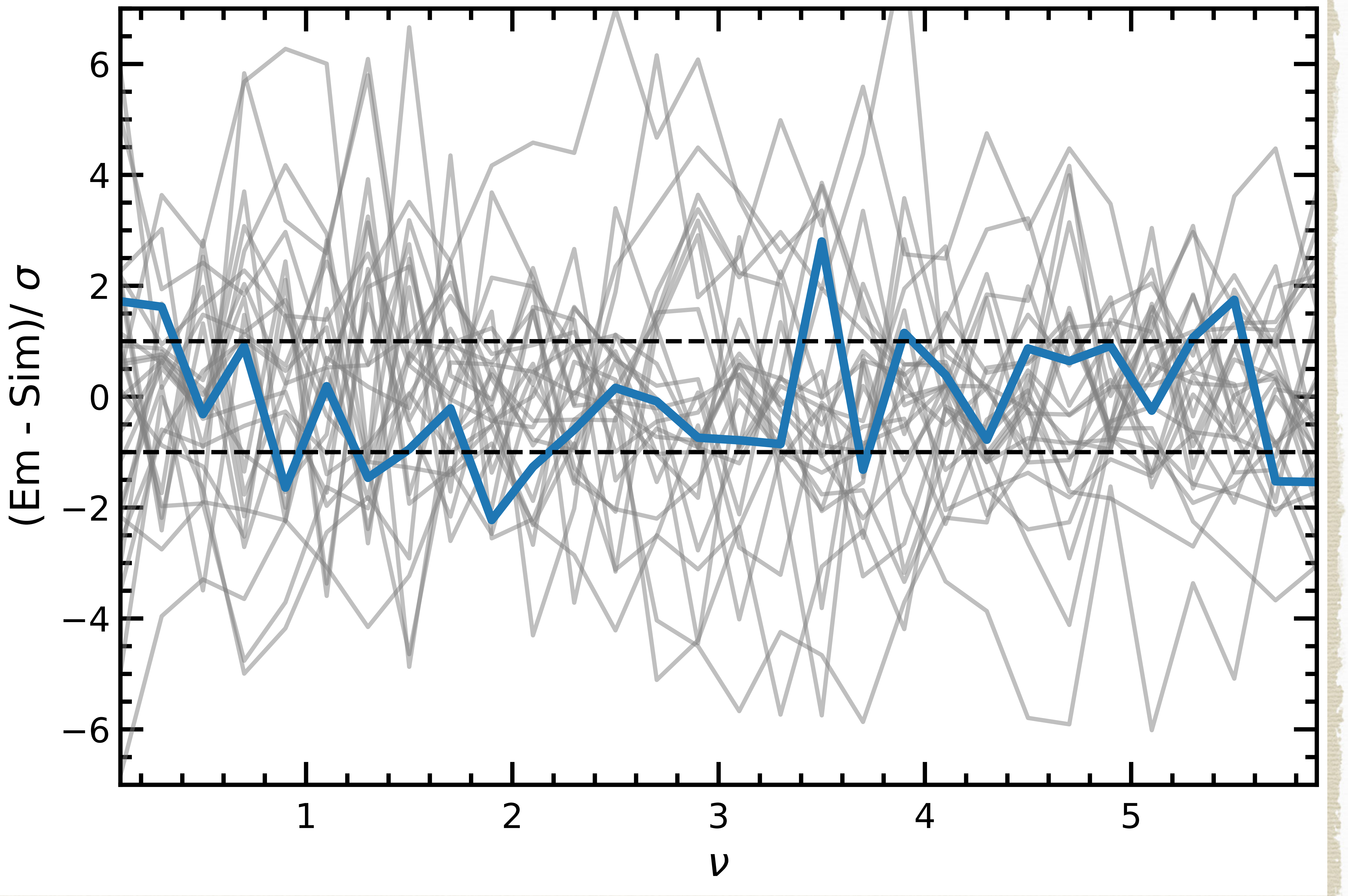




correlation matrix R_{ij}
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
$dn_p/d\kappa$ $0 < \nu < 6$
ξ_p $\nu > 1$
ξ_p $\nu > 2$
ξ_p $\nu > 3$
ξ_p $\nu > 4$
$\frac{dn}{dR_v}$ $\nu > 1$
$\frac{dn}{dR_v}$ $\nu > 2$
$\frac{dn}{dR_v}$ $\nu > 3$
$\frac{dn}{dR_v}$ $\nu > 4$
γ_t $\nu > 1$
γ_t $\nu > 2$
γ_t $\nu > 3$
γ_t $\nu > 4$

Peak emulator accuracy





* WL void emulator accuracy