Disentangling Modified Gravity and Massive Neutrinos with Intrinsic Shape Alignments of Dark Matter Halos

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in collaboration with

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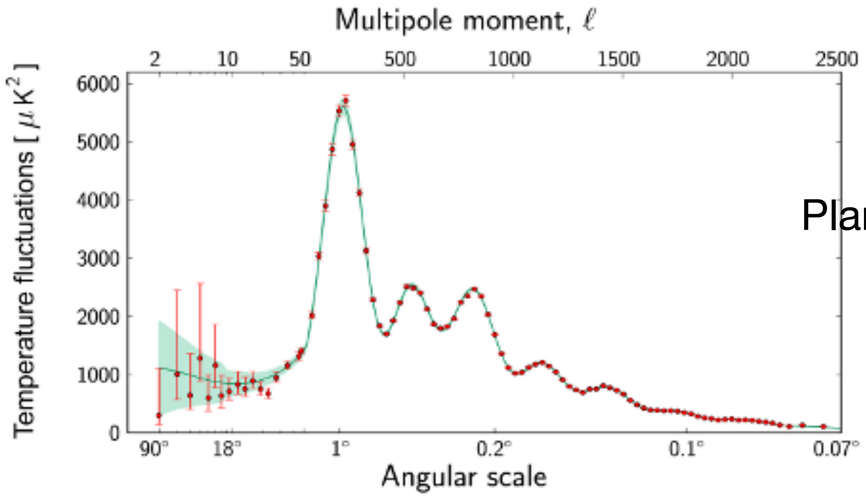
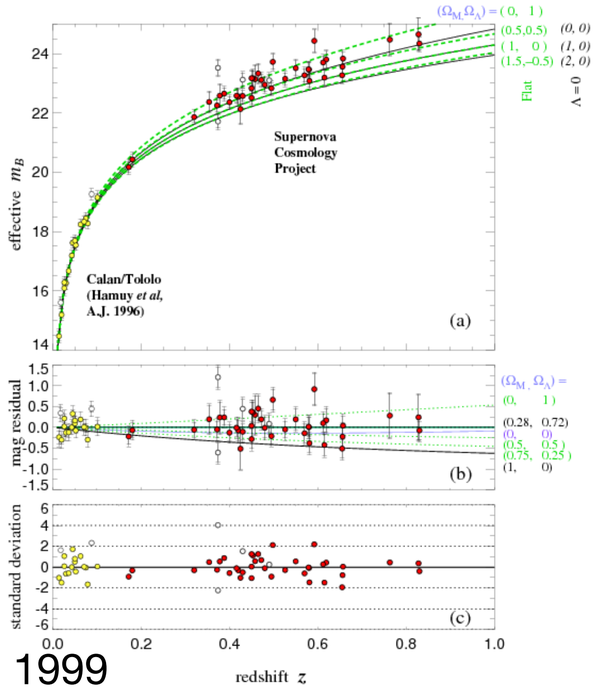
Image Credit: Ralf Kaehler / SLAC National Accelerator Laboratory

EXALTATIONS AND CURSES OF THE ΛCDM COSMOLOGY

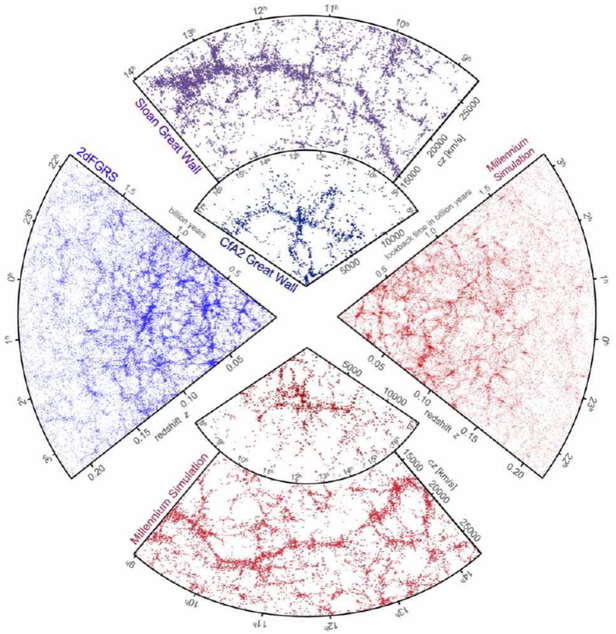
- **Excellent agreements with observations** :
  - The CMB temperature power spectra
  - The matter density power spectra
  - The SNIa temperature-distance relation
  - and many more…
- **Fundamental problems**:
  - The smallness problem of Λ
  - The fine-tuning problem
  - effective but not fundamental …
- **Observational anomalies**:
  - The H_0 and S_8 tensions
  - The DESI results
  - and several more



Planck+13



Perlmutter et al. 1999

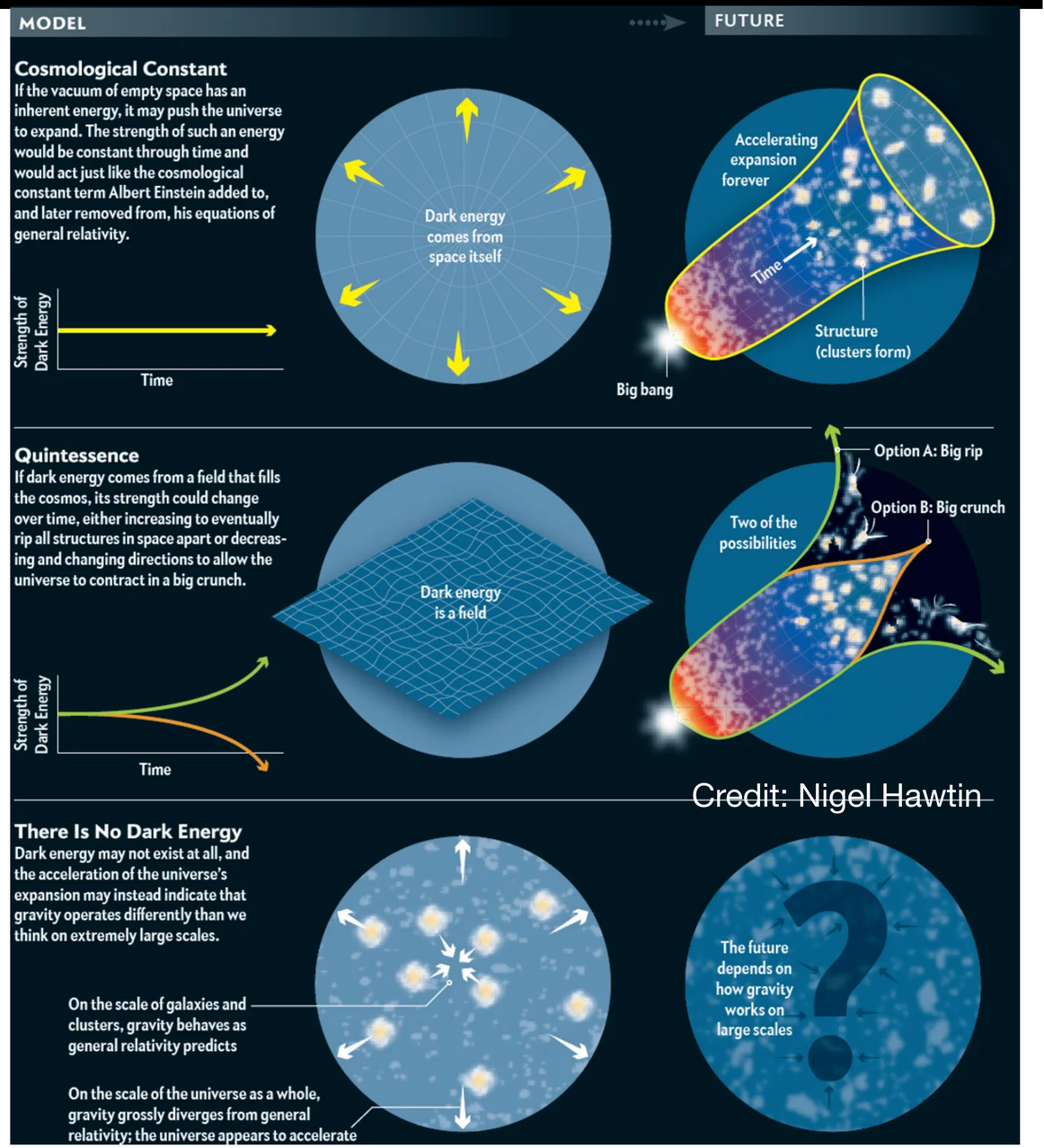


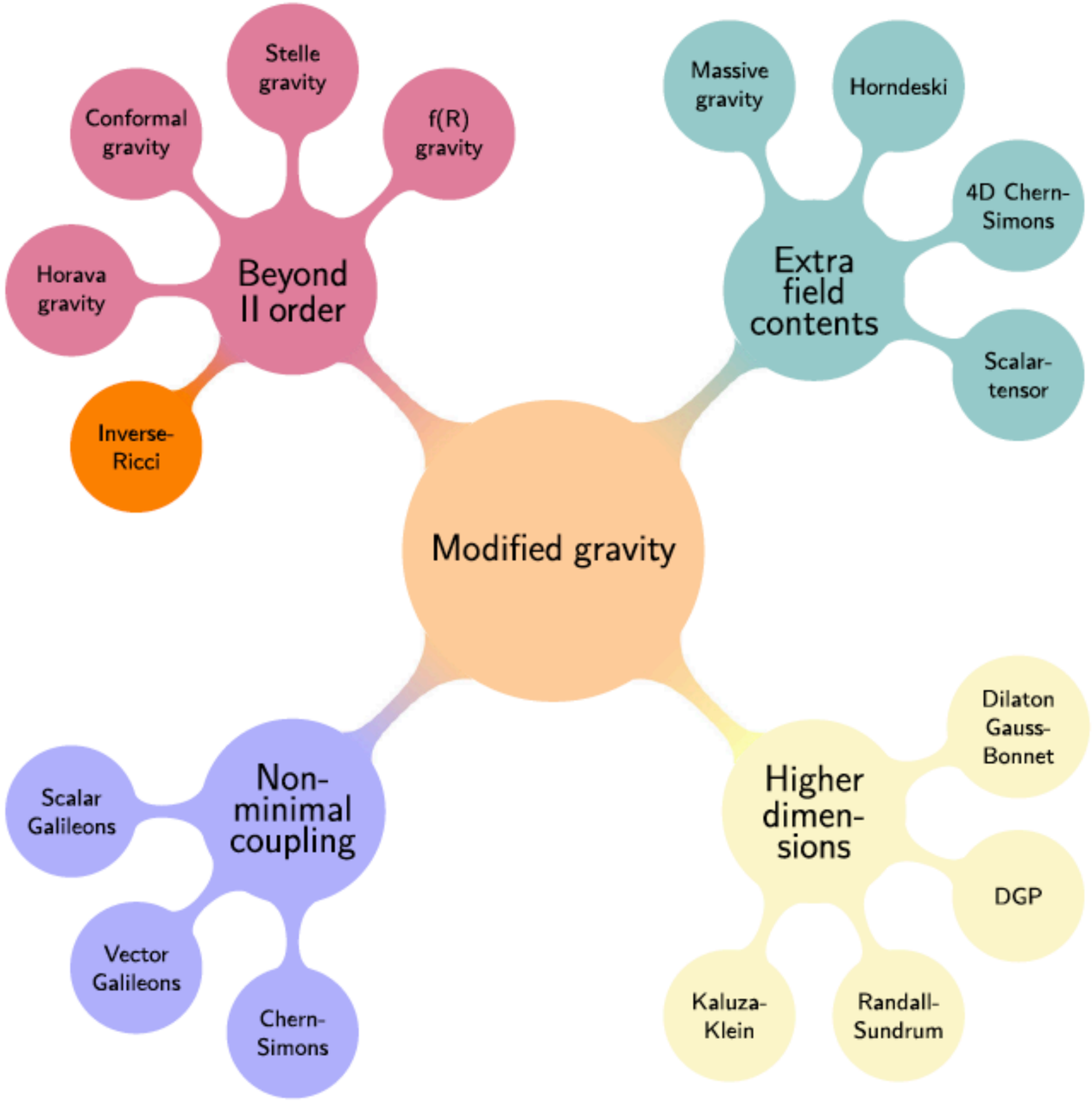
Springel et al 2005

ADVENT of NON-STANDARD COSMOLOGIES

- **Dynamical dark energy models** :
  - The cosmic acceleration is caused not by Λ but by some scalar fields with negative pressure with time-evolving equation of state.

- **Modified gravity models** :
  - The present cosmic acceleration can be explained without introducing anti-gravitational dark energy by modifying Einstein's general relativity.





credit: https://doi.org/10.1007/s10714-022-02927-2

THE f(R) GRAVITY MODEL

- **A modification of the Einstein-Hilbert action of the form** (Starobinsky80):

$$S = \int \mathrm{d}^4x \sqrt{-g} \left(\frac{R + f(R)}{16\pi G} + \mathcal{L}_{\mathrm{m}} \right),$$

  - $f(R)$: an arbitrary function of the Ricci scalar, R.
  - The scalaron, $|f_{R0}| \equiv |df/dR|_0$, quantifies the strength of the fifth force.

- **The Hu-Sawicki model of $f(R)$ gravity** (Hu-Sawicki07):

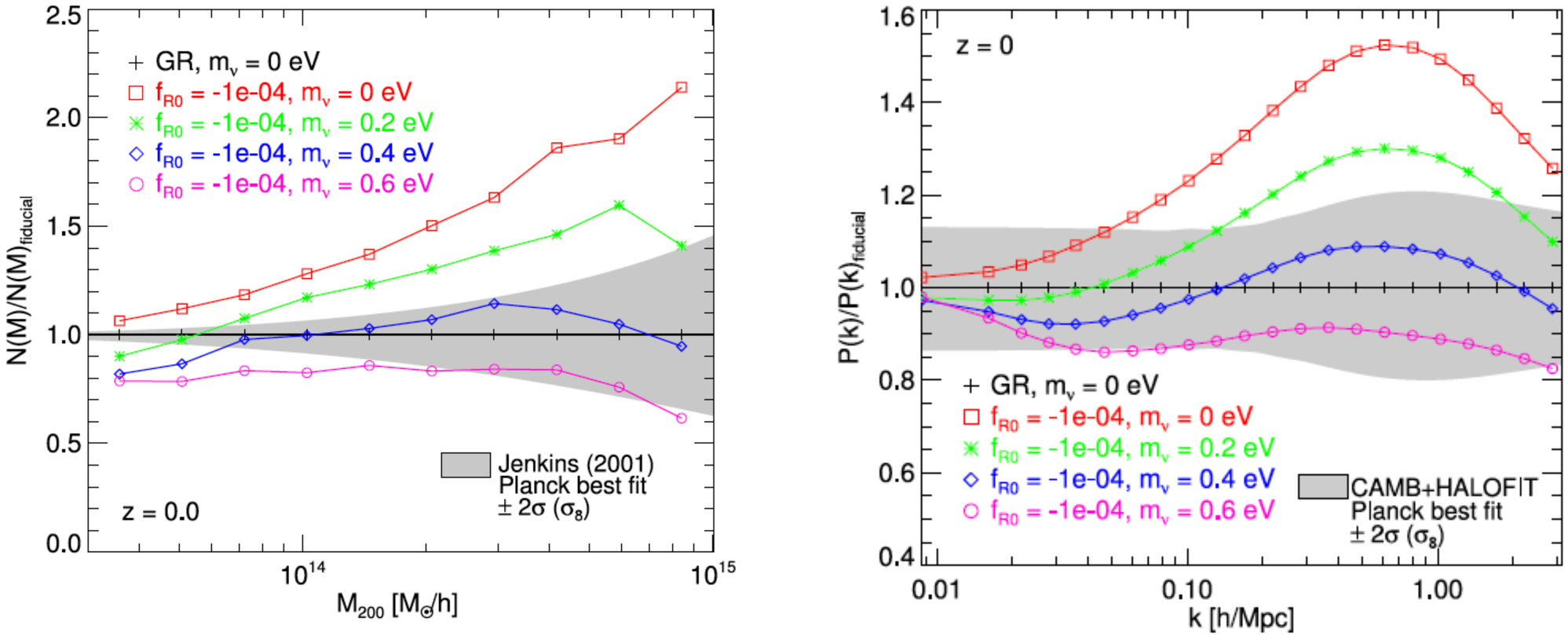
$$f(R) = -m^2 \frac{c_1 \left(\frac{R}{m^2}\right)^n}{c_2 \left(\frac{R}{m^2}\right)^n + 1}, \qquad \text{with } m^2 \equiv H_0^2 \Omega_m$$

  - $\{c_1, c_2, n\}$: non-negative constant free parameters that specify the model.

- **The current observational constraint on the cluster scale**: $|f_{R0}| \lesssim 3.7 \times 10^{-6}$ (Boubekeur et al. 2014)

νCDM + f(R) GRAVITY COSMOLOGY

- It is hard to distinguish between the νCDM+$f(R)$ gravity and ΛCDM cosmologies with the standard diagnostics since the effects of massive neutrinos cancel out those of $f(R)$ gravity:



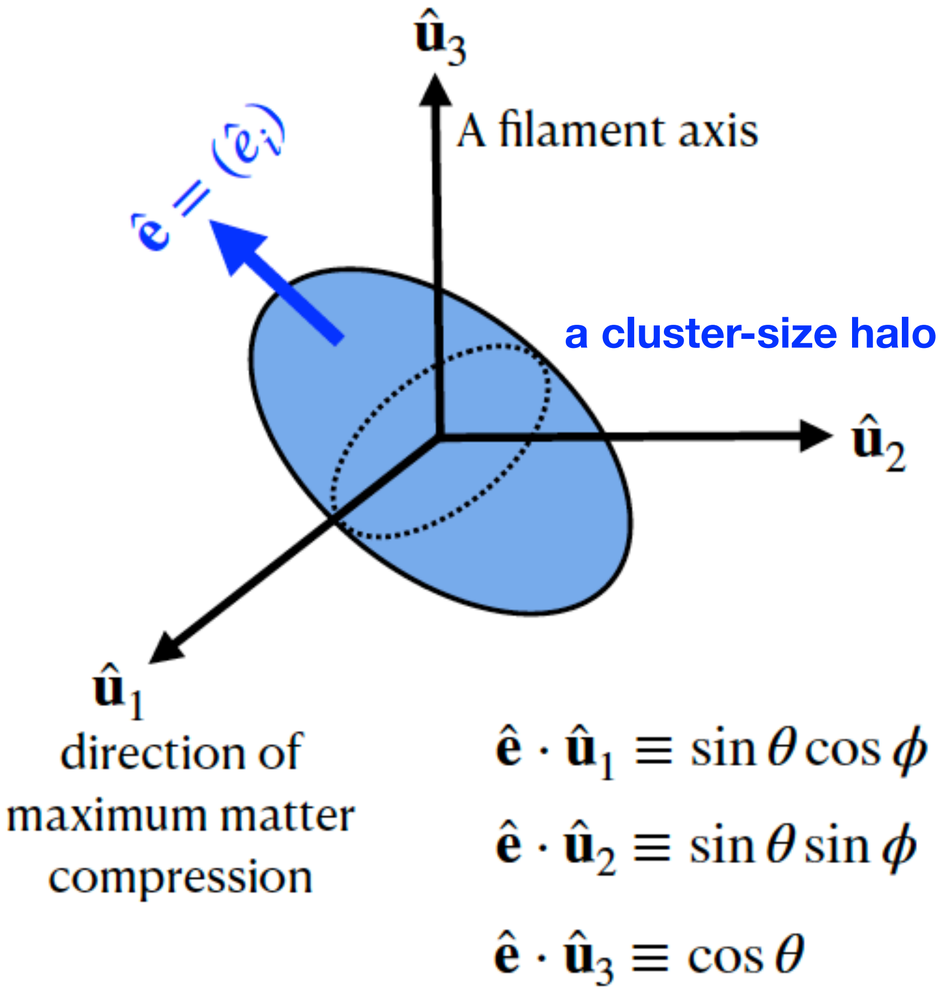
Baldi et al. (2014)

ALIGNMENTS OF HALO SHAPES WITH FILAMENTS

- An analytic model for the intrinsic alignments between the halo shapes and the filament axes (directions of minimum matter compression):

$$\langle \hat{\mathbf{e}}_i \hat{\mathbf{e}}_j | \hat{\mathbf{T}} \rangle = \frac{1 + d_t}{3} - d_t \hat{T}_{ij}$$

$$p(|\cos\theta|) = \frac{1}{2\pi} \int_0^{2\pi} \left[\prod_{n=1}^{3} (1 + d_t - 3 d_t \hat{\lambda}_n) \right]^{-\frac{1}{2}} \times \left(\sum_{l=1}^{3} \frac{|\hat{\mathbf{u}} \cdot \hat{\mathbf{e}}_l|}{1 + d_t - 3 d_t \hat{\lambda}_l} \right)^{-\frac{3}{2}} d\phi.$$



$$\hat{\mathbf{e}} \cdot \hat{\mathbf{u}}_1 \equiv \sin\theta \cos\phi$$

$$\hat{\mathbf{e}} \cdot \hat{\mathbf{u}}_2 \equiv \sin\theta \sin\phi$$

$$\hat{\mathbf{e}} \cdot \hat{\mathbf{u}}_3 \equiv \cos\theta$$

DUAL EFFECTS OF NEUTRINO MASS & $f(R)$ GRAVITY

Massive Neutrinos

Make the cosmic web more anisotropic and thus strengthen the cluster IA

Suppress the filamentary merging and thus weaken the cluster IA

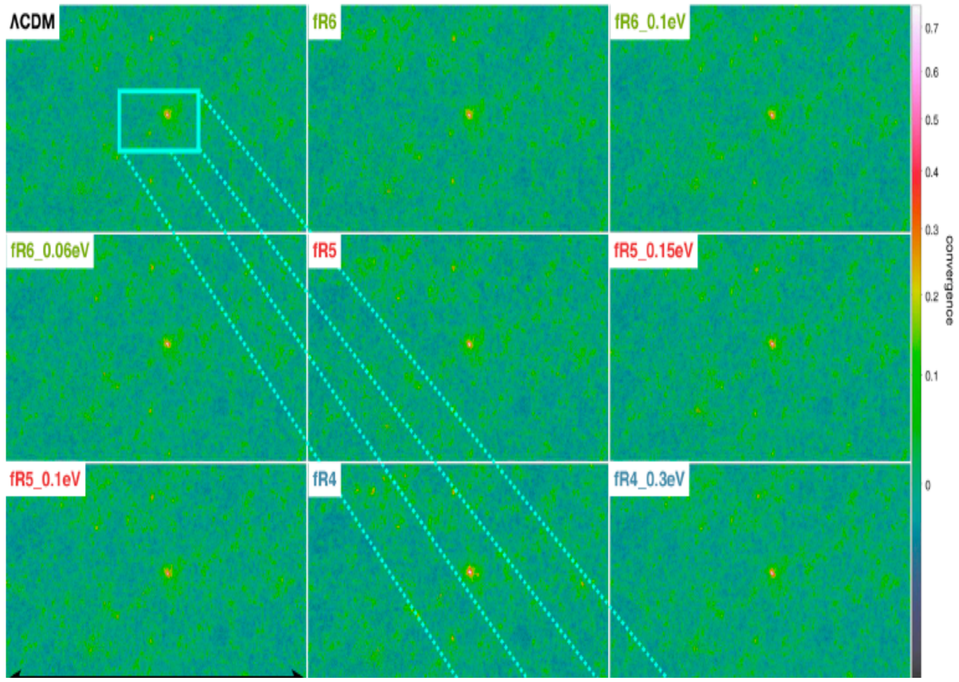
Strong f(R) gravity

Make the cosmic web less anisotropic and thus weaken the cluster IA

Enhance the filamentary merging and thus strengthen the cluster IA

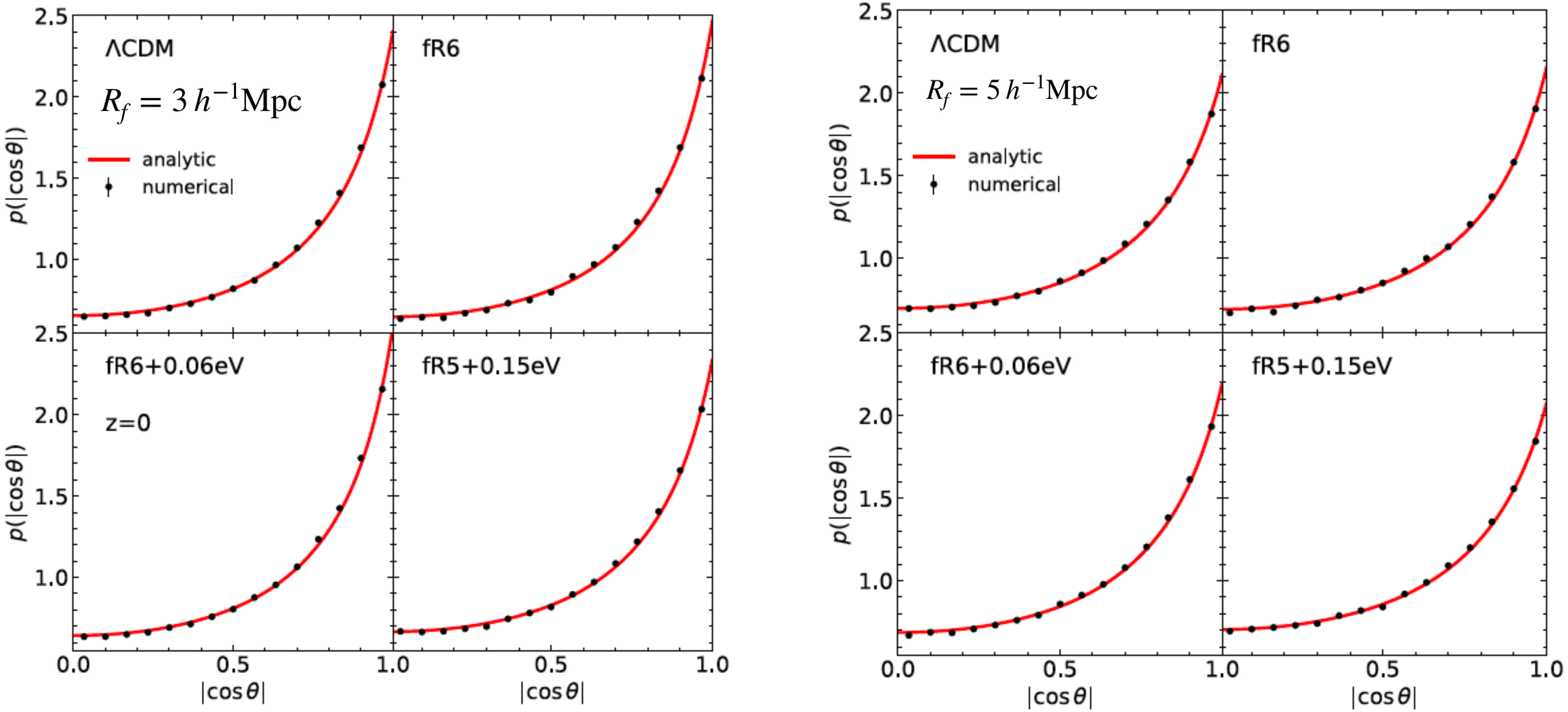
NUMERICAL DATA AND ANALYSIS

- **Dust-grain pathfinder DM only simulations** (Giocoli+18)
  - on a box of $750h^{-3}\mathrm{Mpc}^3$ volume
  - with a total of 768^3 DM particles of individual mass $8.1 \times 10^{10} M_\odot$
  - the MG-Gadget code and the FoF(0.16) halo finder
  - A particle based implementation of massive neutrinos.
- The tidal field reconstructed from the full particle snapshots
- The cluster shapes determined by the inertia momentum tensors.



Model	$\lvert f_{R0}\rvert$	$\sum m_\nu$ (eV)	σ_8
ΛCDM	⋯	0.0	0.847
fR6	10^{-6}	0.0	0.861
fR6+0.06eV	10^{-6}	0.06	0.847
fR5+0.15eV	10^{-5}	0.15	0.864

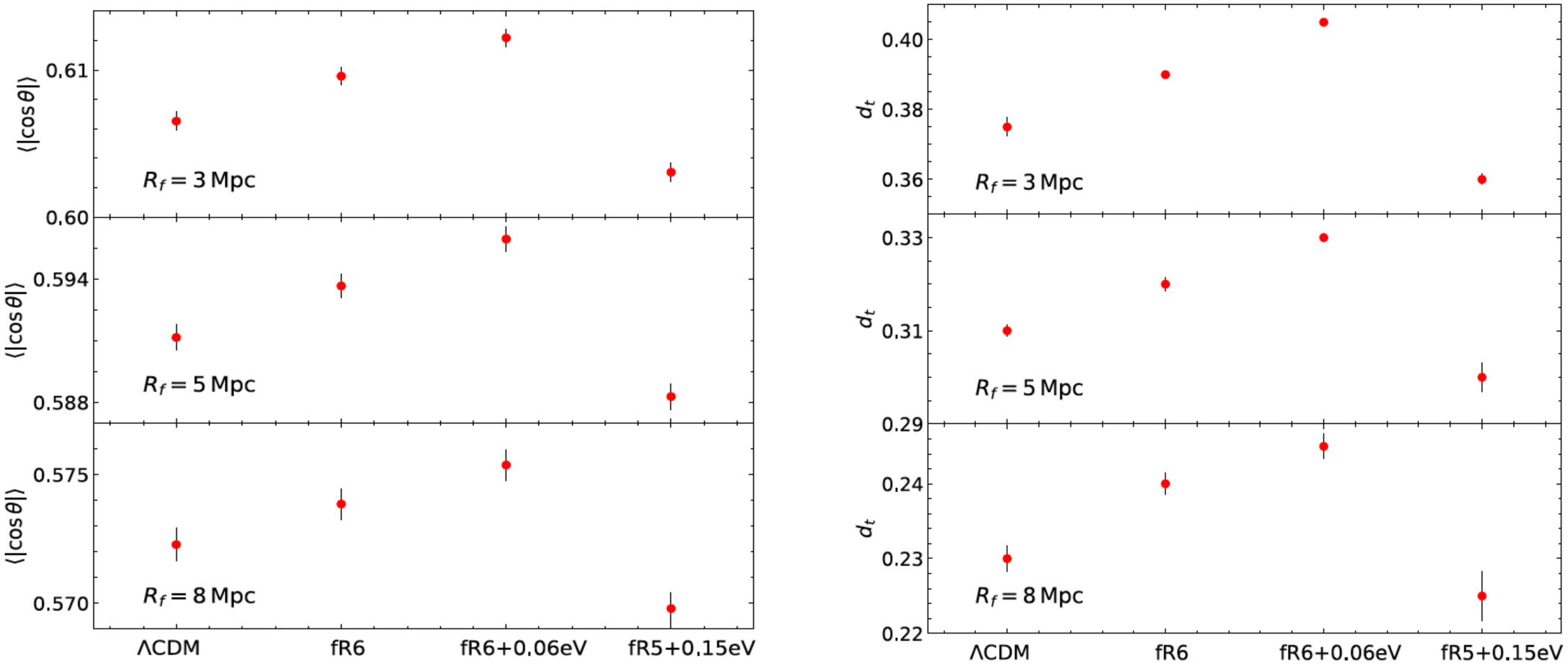
NUMERICAL VS. ANALYTICAL



Lee et al. (2023)

excellent agreements regardless of the smoothing scales!

BREAKING THE DEGENERACY WITH THE SHAPE-FILAMENT ALIGNMENTS



The cluster-filament alignments discriminate the νCDM+$f(R)$ models from the ΛCDM!

CLUSTER SHAPE-SHAPE ALIGNMENTS

- The spatial correlations of $(\hat{T}_{ij})$ create the shape-shape alignments of cluster-size halos:

$$\eta(r) = \langle |\hat{\boldsymbol{u}}(\boldsymbol{x}) \cdot \hat{\boldsymbol{u}}(\boldsymbol{x}+\boldsymbol{r})|^2 \rangle - \frac{1}{3},$$

$$\simeq g_1 \frac{\xi(r;R_f)}{\sigma^2(R_f)} + g_2 \left[\frac{J_3(r;R_f)}{\sigma^2(R_f)} - \frac{J_5(r;R_f)}{\sigma^2(R_f)} \right]$$

where

$$\xi(r) = \frac{1}{2\pi^2} \int_0^\infty P(k) W^2(k,R_f) \frac{\sin kr}{kr} k^2 dk,$$

$$J_3(r) \equiv \frac{3}{r^3} \int_0^r \xi(r') r'^2 dr'^2,$$

$$J_5(r) \equiv \frac{5}{r^5} \int_0^r \xi(r') r'^4 dr'^4,$$

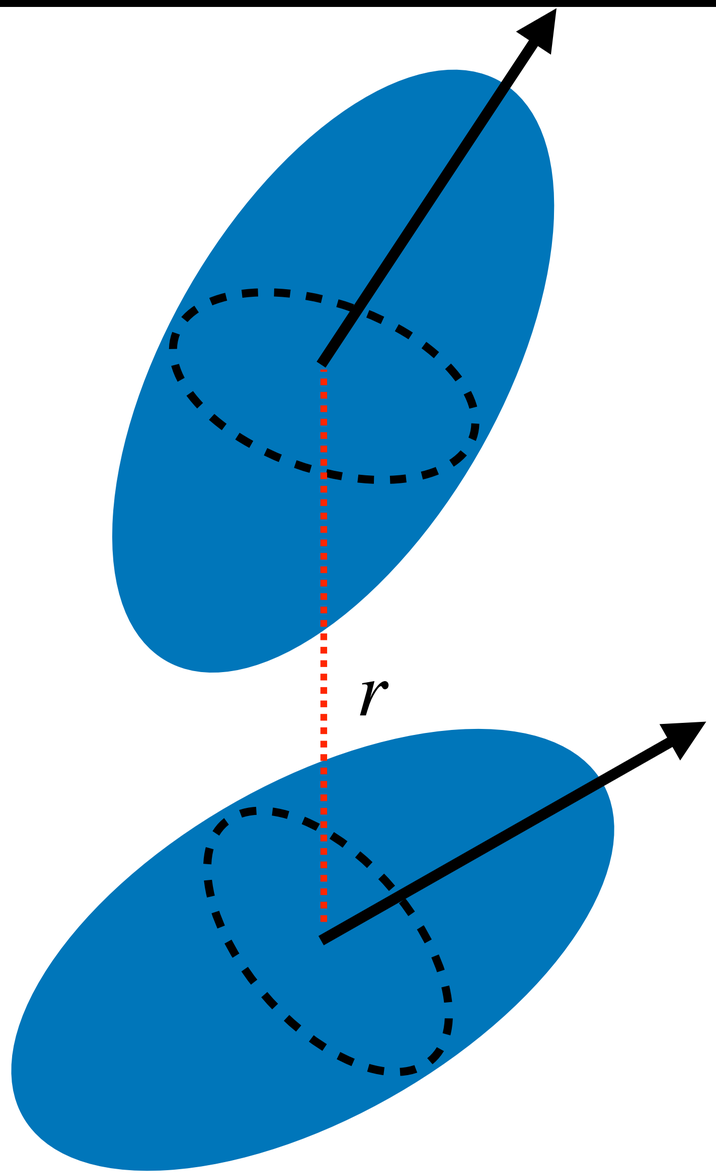
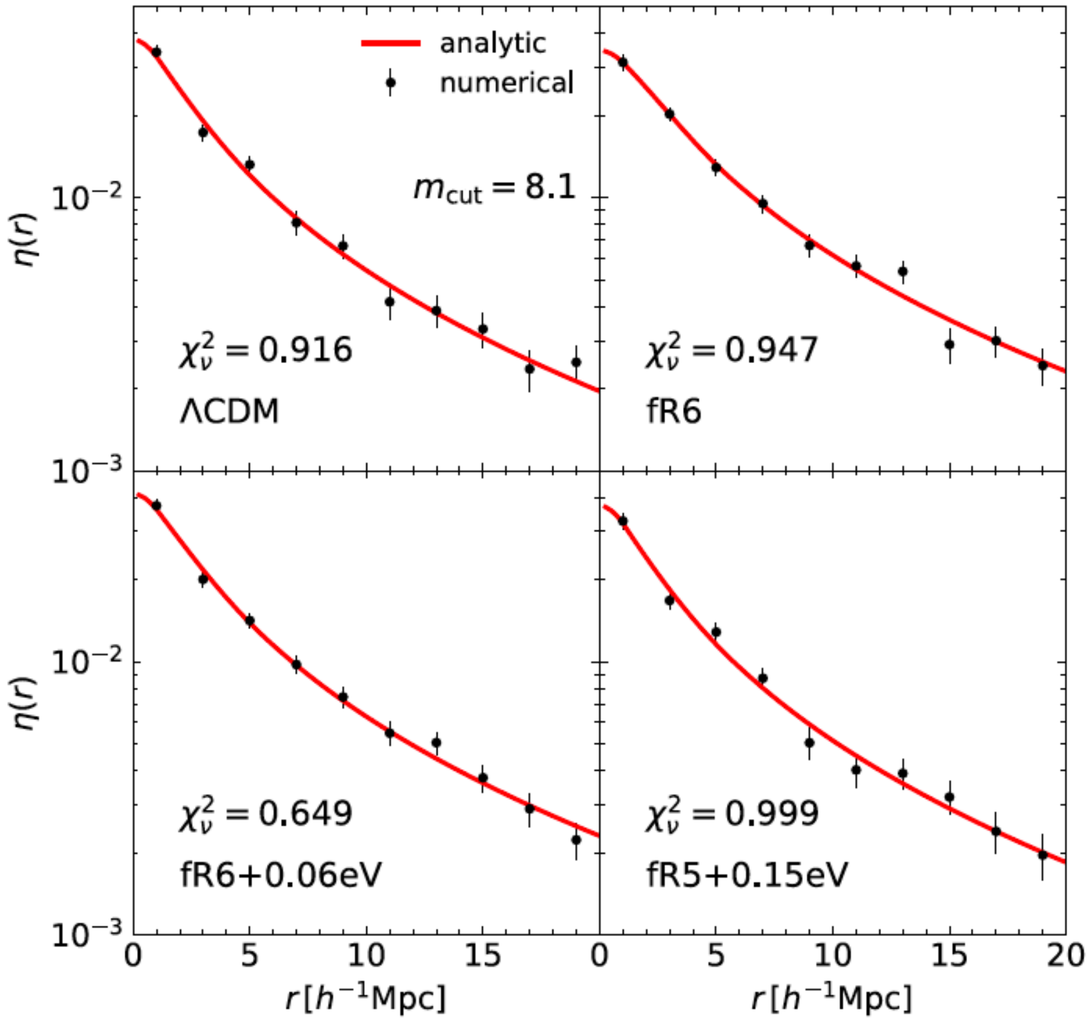
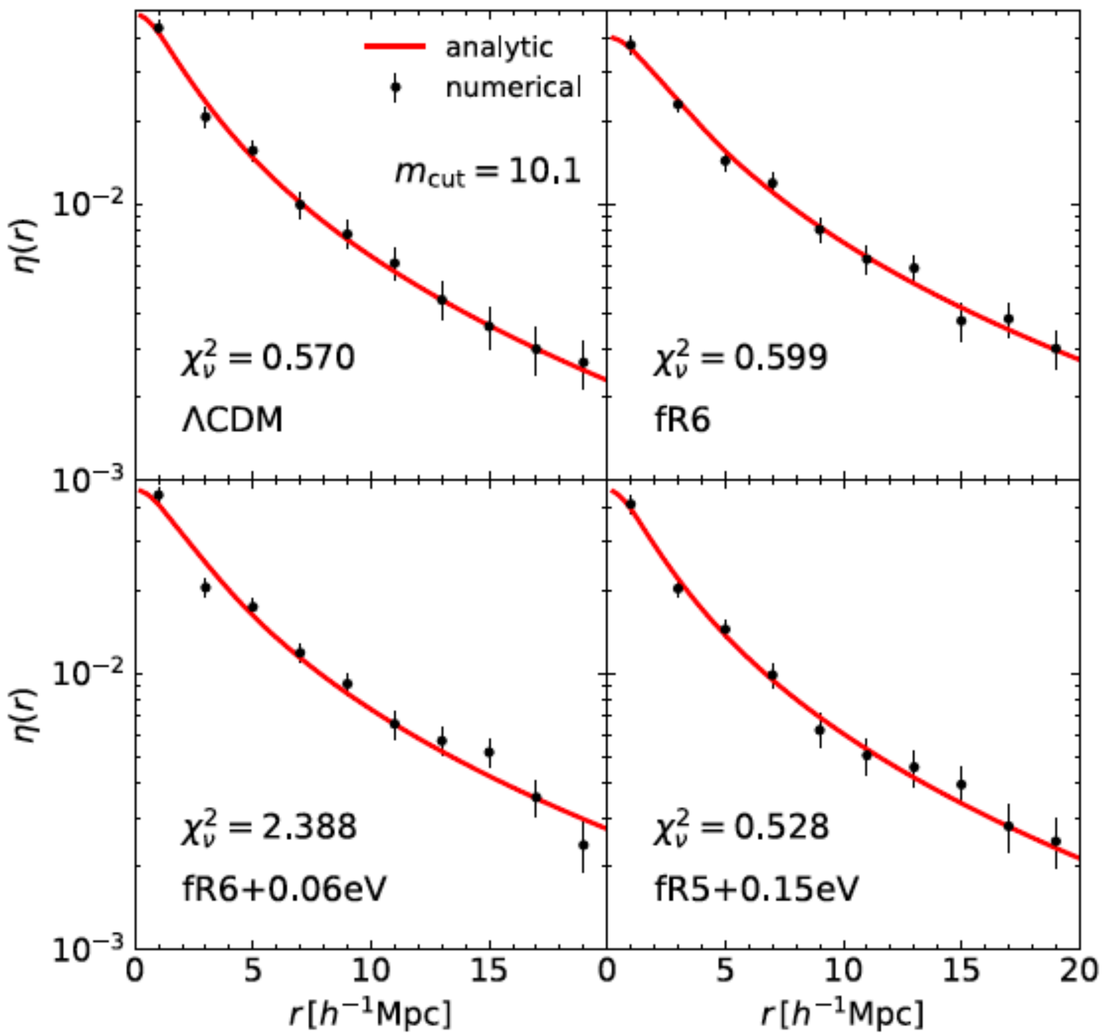


Table 1
Numbers of Selected Group/Cluster Halos for each Cosmology

Model	$\lvert f_{R0} \rvert$	$\sum m_\nu$ (eV)	σ_8	$N_{8.1}$	$N_{10.1}$	$N_{\rm sync}$
ΛCDM	⋯	0.0	0.847	217567	159969	208500
fR6	10^{-6}	0.0	0.861	242418	176106	208500
fR6+0.06eV	10^{-6}	0.06	0.847	238003	173164	208500
fR5+0.15eV	10^{-5}	0.15	0.864	226161	168259	208500

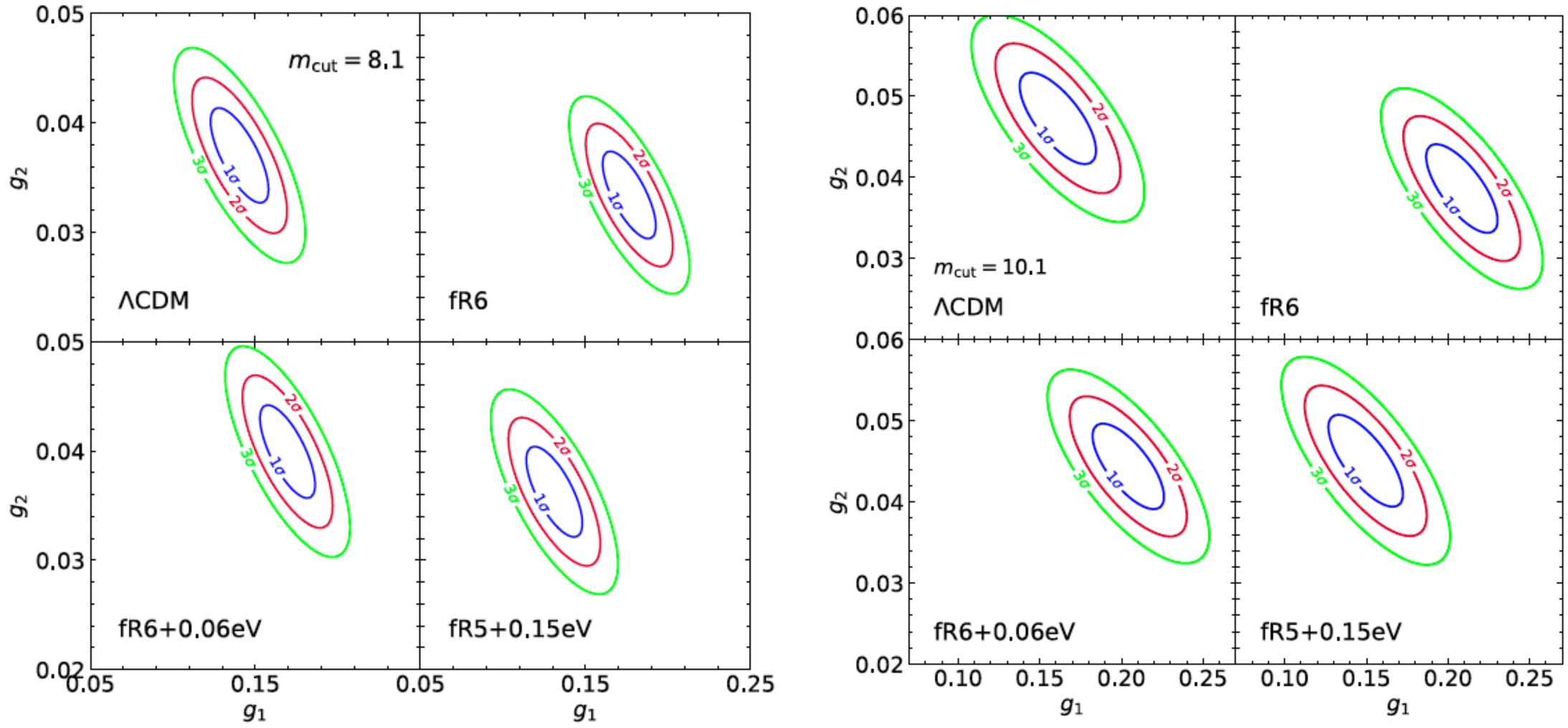
NUMERICAL VS. ANALYTICAL





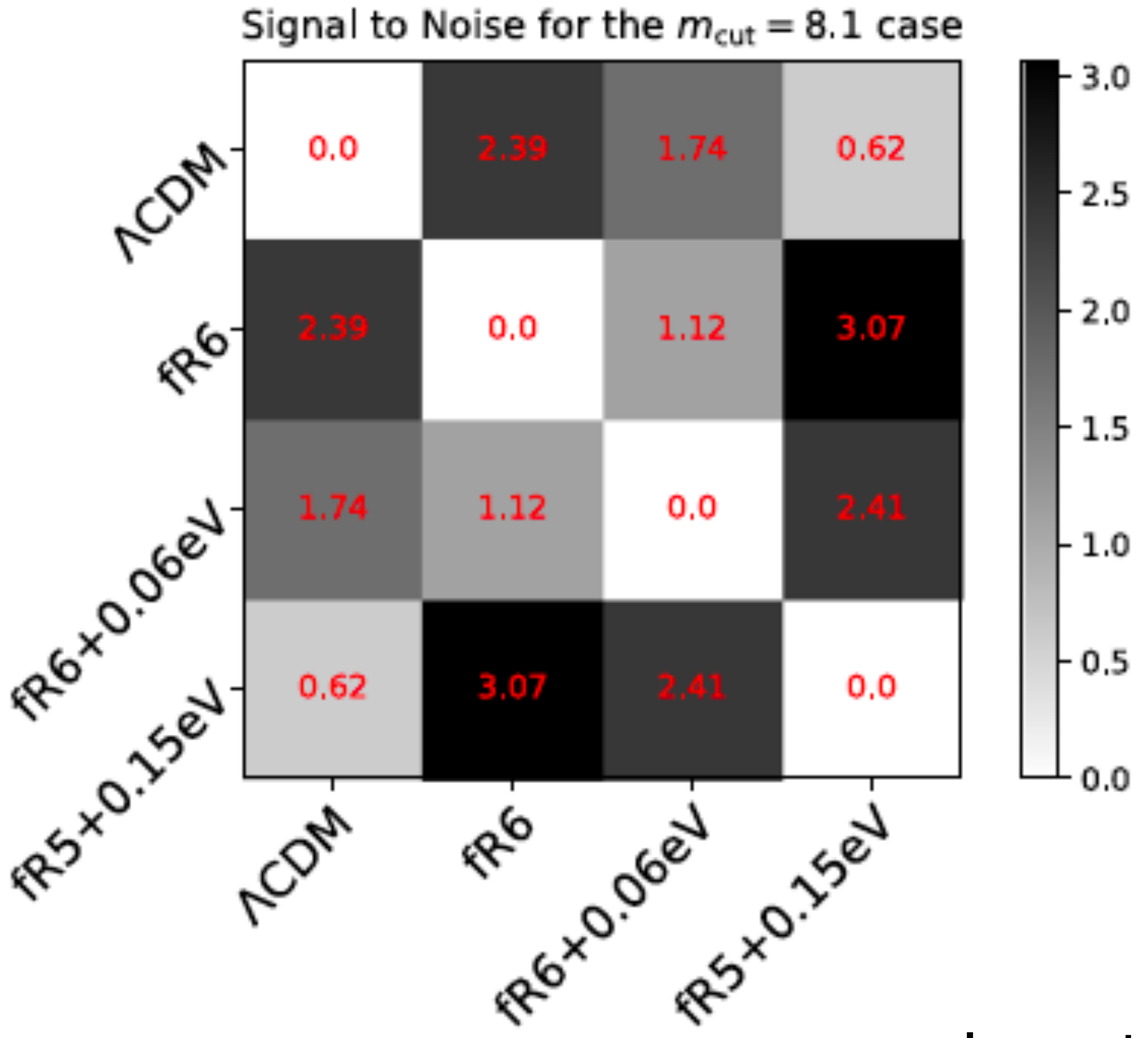
excellent agreements regardless of the mass-cut

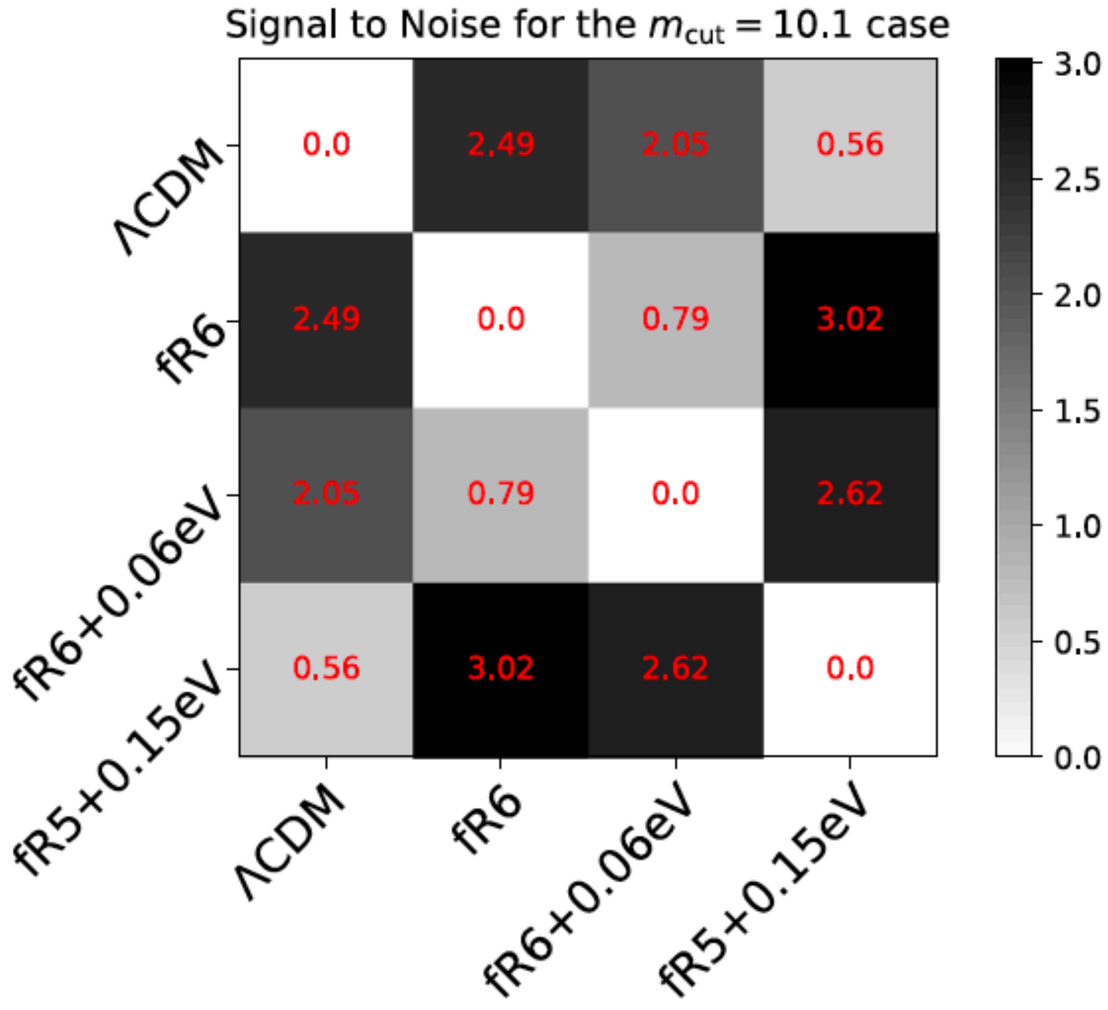
BREAKING THE DEGENERACY WITH THE SHAPE-SHAPE ALIGNMENTS



The cluster shape-shape alignments discriminate the νCDM+$f(R)$ models from the ΛCDM.

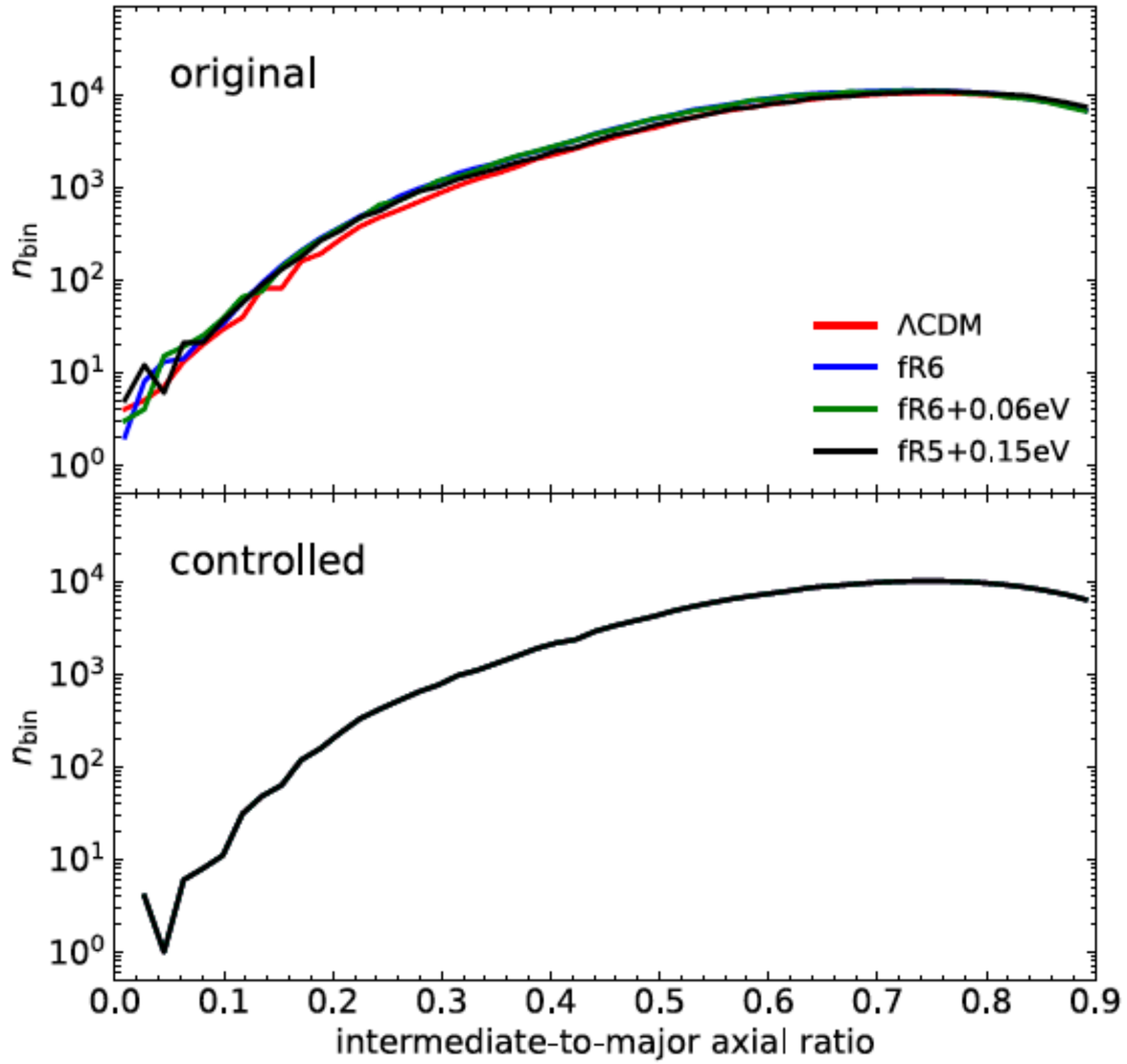
STATISTICAL SIGNIFICANCE

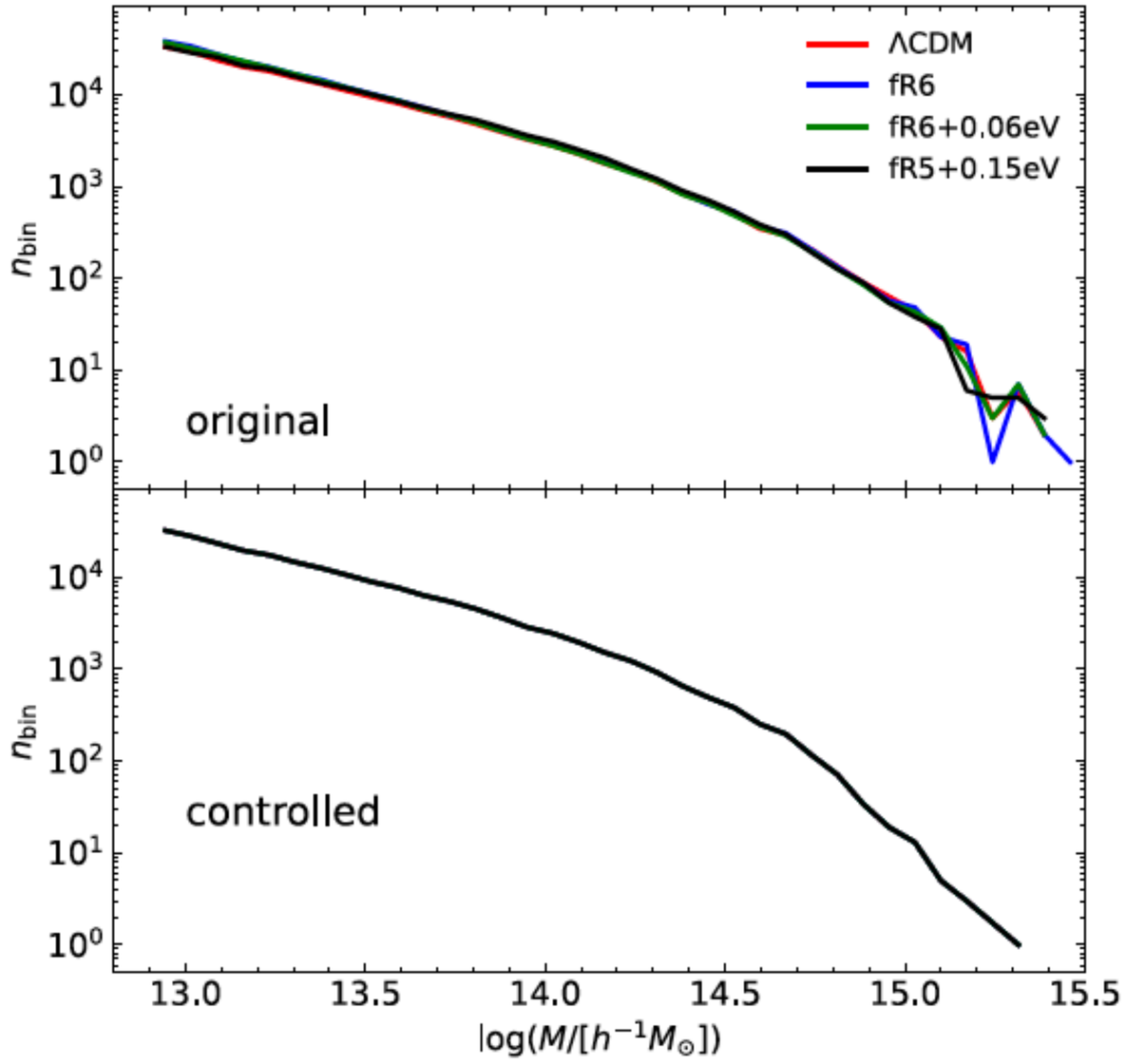




Lee et al. (2023)

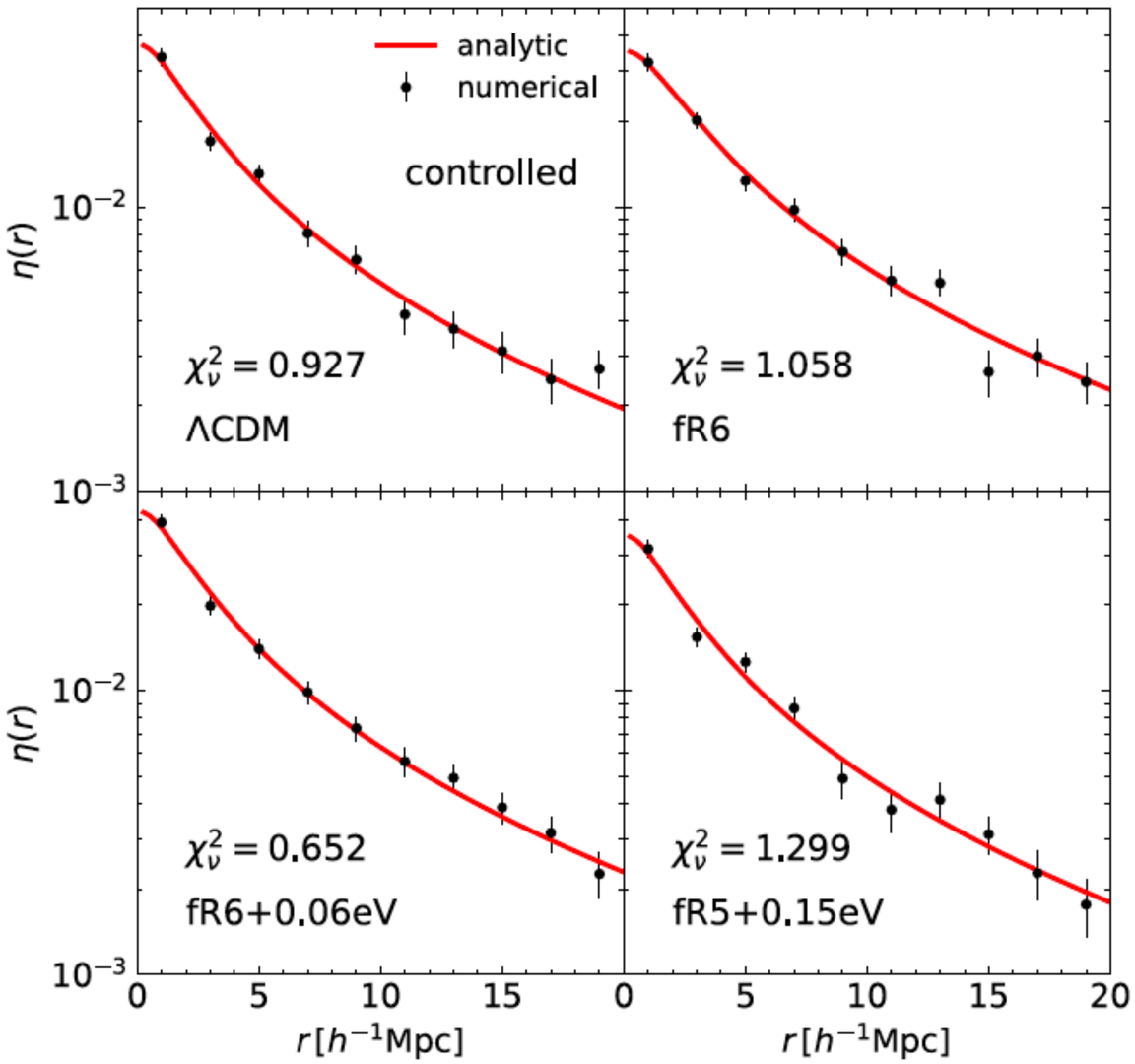
CONTROLLING THE MASS AND AXIAL-RATIO DIFFERENCES

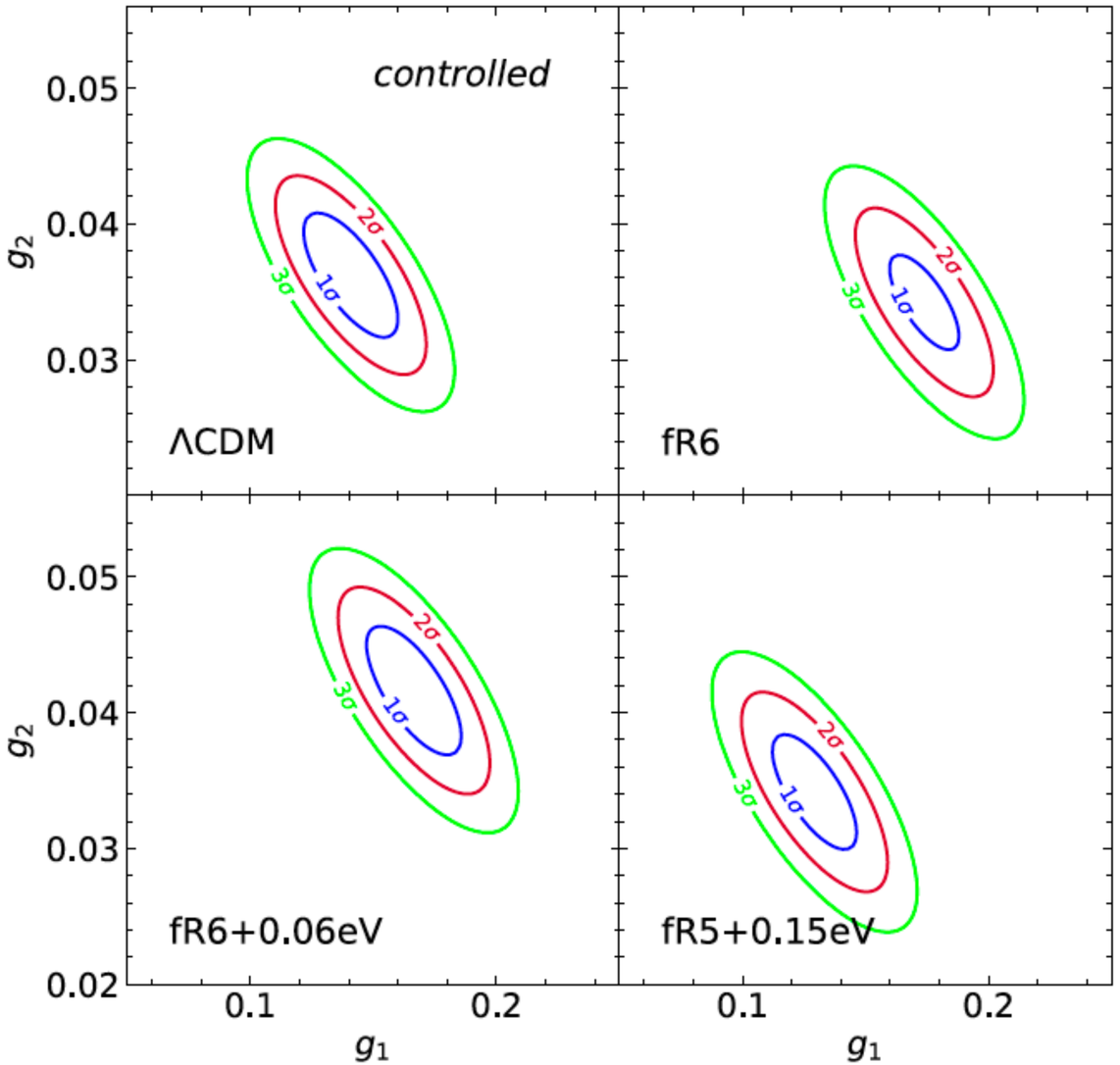




Lee et al. (2023)

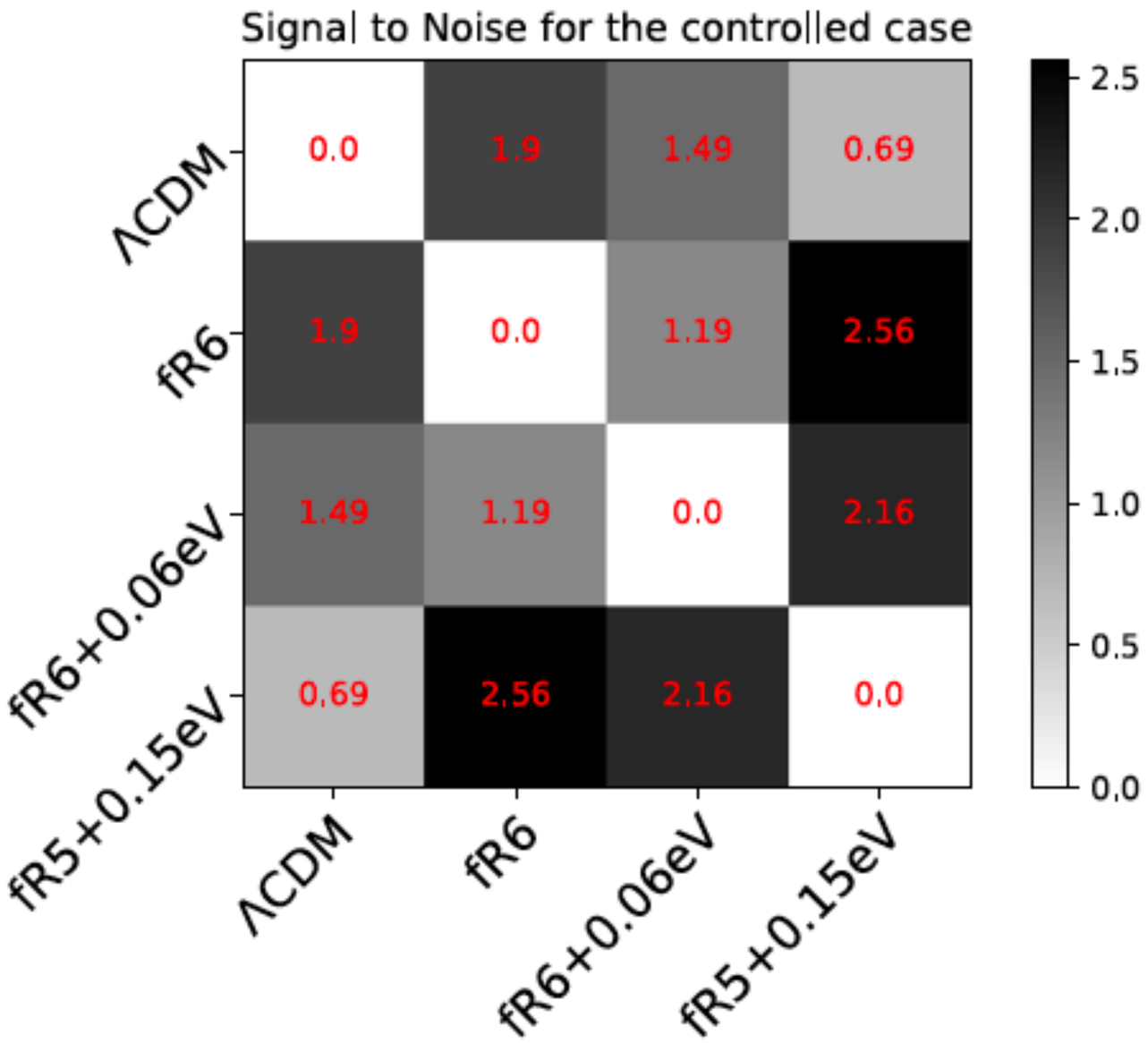
NUMERICAL VS. ANALYTICAL FROM THE CONTROLLED SAMPLES





good agreements even when the controlled samples are used!

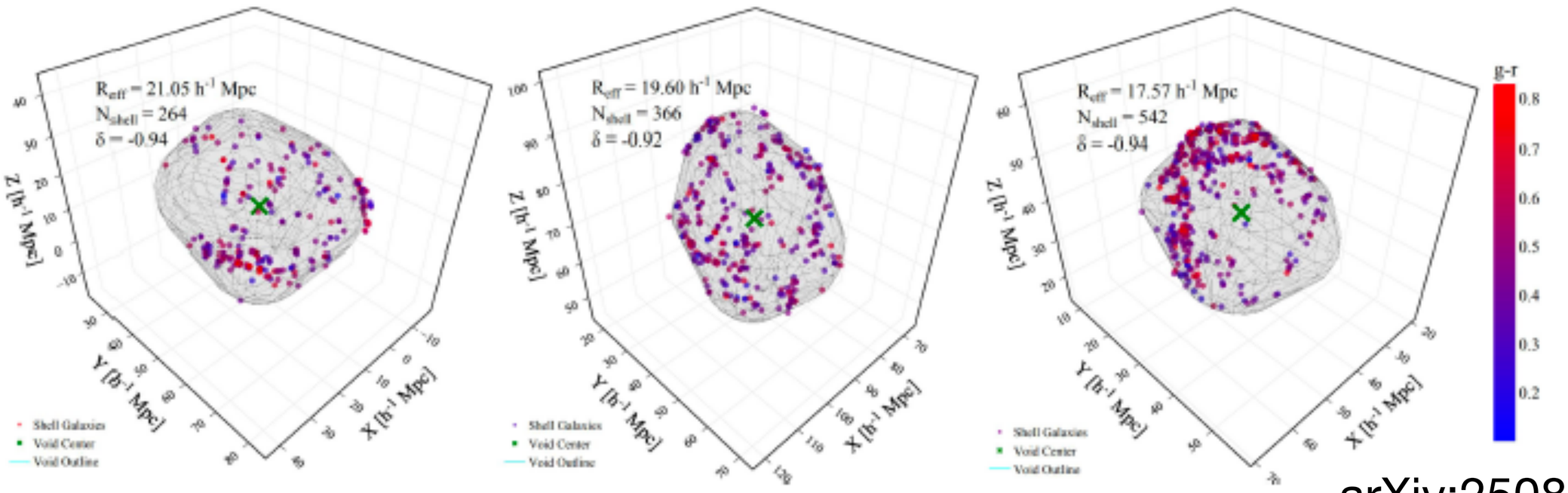
SIGNIFICANCE FROM THE CONTROLLED SAMPLES



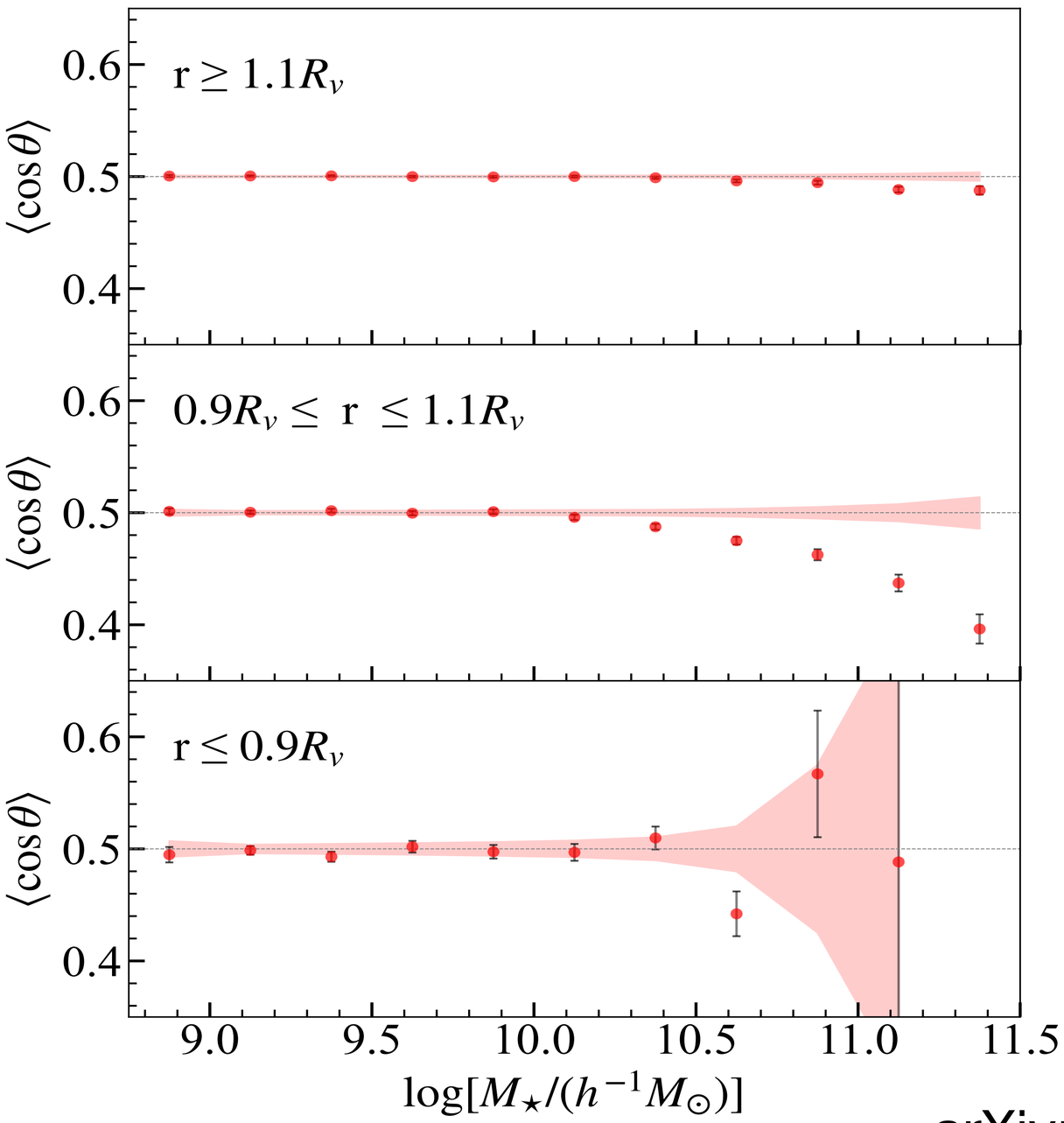
Lee et al. (2023)

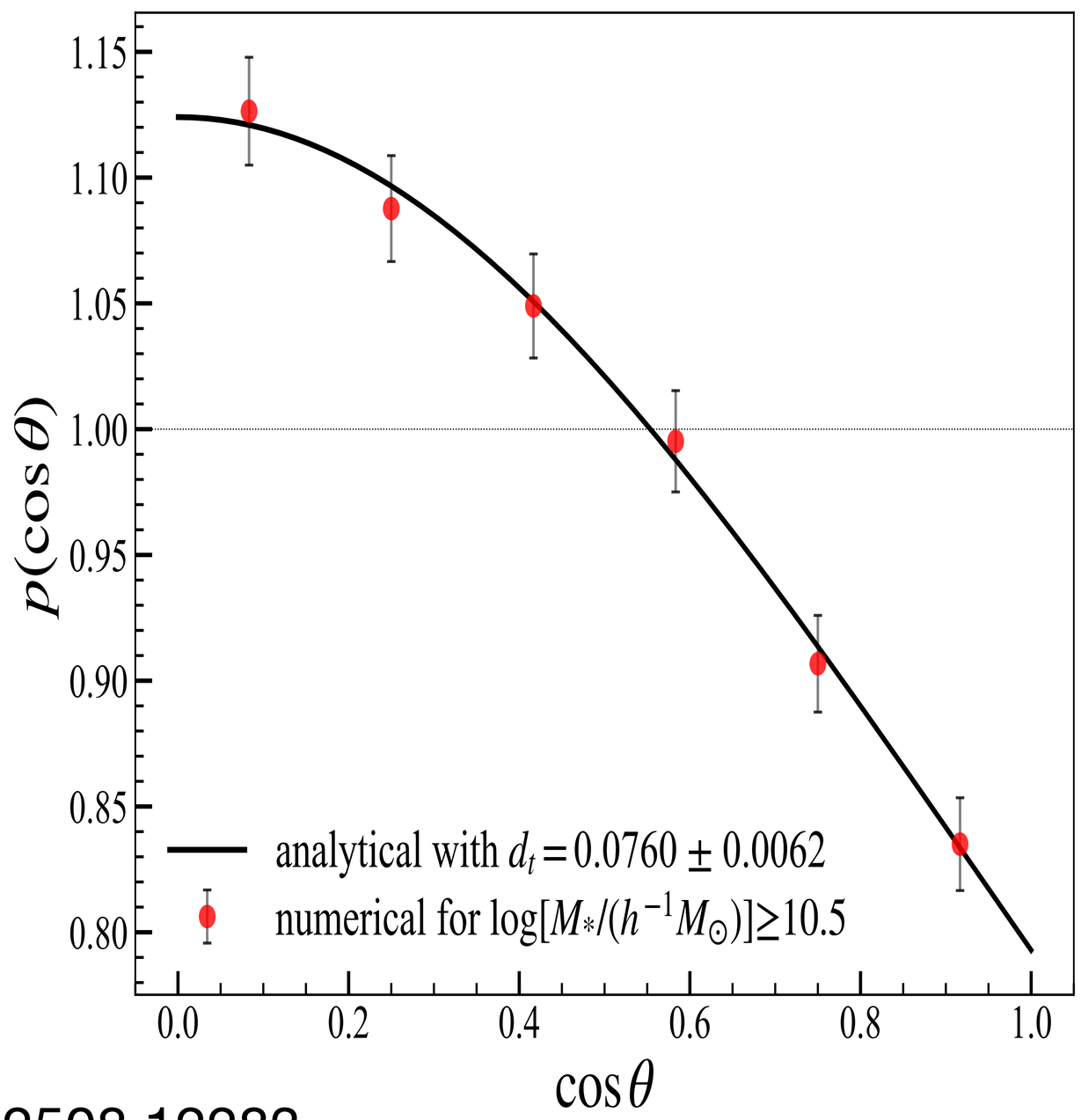
ALIGNMENTS OF GALAXY SHAPES ON VOID SURFACES

- The alignments between the shapes of the galaxies on void surfaces and the directions toward the void centers are also investigated.
  - The voids are identified from the IllustrisTNG300-1 simulations with the help of the Void-Finder algorithm.
  - The galaxy shapes are determined from the stellar components of TNG subhalos.



arXiv:2508.12283





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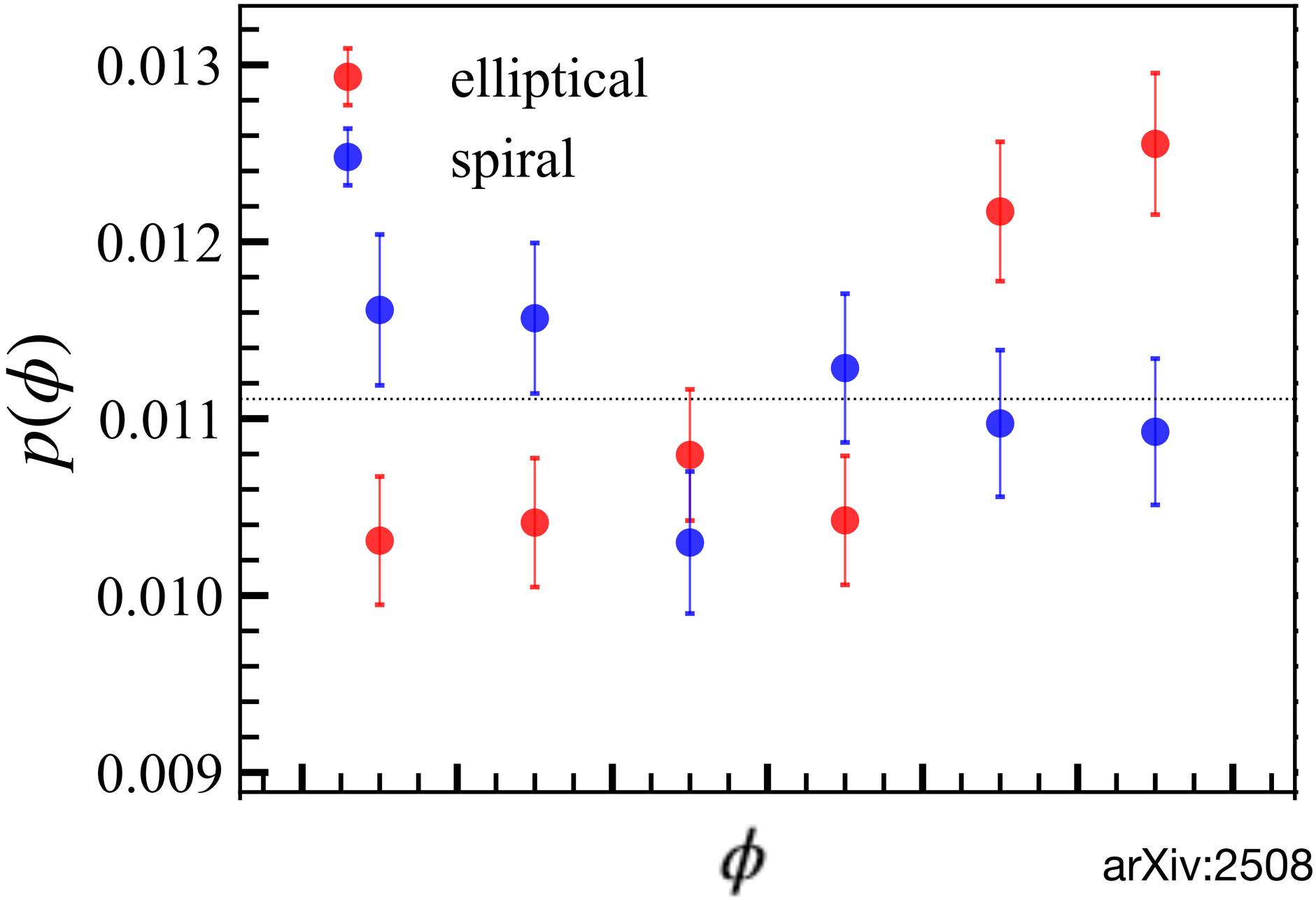

arXiv:2508.12283

SUMMARY AND CONCLUSION

- The intrinsic alignments between the cluster halo shapes and principal axes of the large-scale tidal fields have been found to be in principle break the degeneracies between the νCDM+$f(R)$ gravity and ΛCDM cosmologies:
  - not observationally feasible due to the difficulties in the measurements of 3D cluster shapes.

- The intrinsic alignments between the stellar shapes of void surface galaxies and the directions toward the void centers have been found to be significant:
  - observationally quite feasible.
  - necessary to see whether or not it can also break the cosmological degeneracy.
    - hydrodynamical simulations for non-standard cosmologies required.