Cosmology with the kSZ effect: Independent of the optical depth and σ_8

Based on i) Kuruvilla, 2021, arXiv: 2109.13938
ii) Kuruvilla & Aghanim, A&A, 2021, arXiv: 2102.06709

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Kinetic Sunyaev-Zeldovich effect

- Doppler shift of CMB photons scattering off electrons with bulk velocity

$$\left.\frac{\Delta T(\hat{n})}{T_{\rm cmb}}\right|_{\rm kSZ} = -\int {\rm d}l\, \sigma_{\rm T} \left(\frac{\boldsymbol{v}_{\rm e}\cdot\hat{n}}{c}\right) n_{\rm e}$$

- The optical depth, encapsulates all of the information related to the number density of electrons in halos, and shape of the electron profile. It is defined as

$$\tau = \int {\rm d}l\, \sigma_{\rm T}\, n_{\rm e}$$

- The optical depth thus acts as a limiting factor when trying to constrain cosmological parameters. This is known as the optical depth degeneracy. (e.g. Smith et al 18)

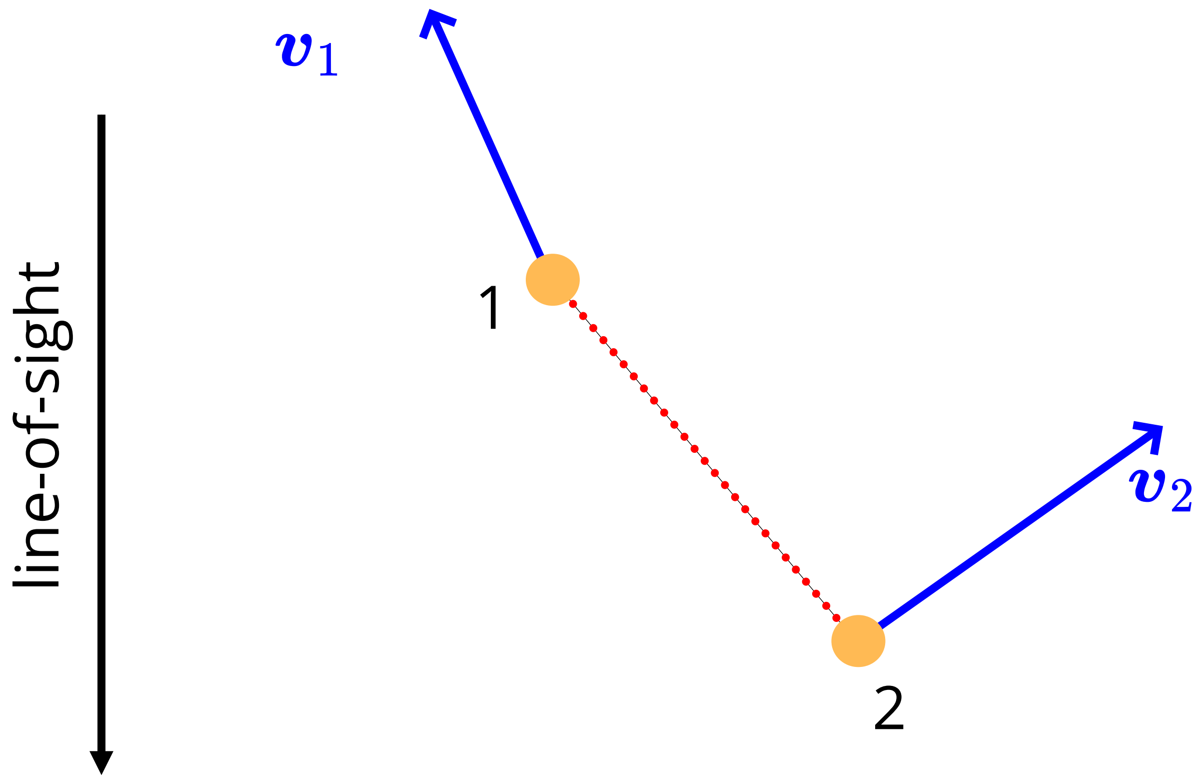
Motivation

Pairwise velocity from kSZ can used to constrain:

- growth rate (Alonso et al. 16)
- neutrino mass (Meuller et al. 14)
- dark energy (Meuller et al. 13)
- ultra-light axions (Farren et al. 21)

Pairwise velocity

$$w_{\mathrm{r}}(r_{12}) = (\boldsymbol{v}_2 - \boldsymbol{v}_1) \cdot \hat{\boldsymbol{r}}_{12}$$



Pairwise velocity

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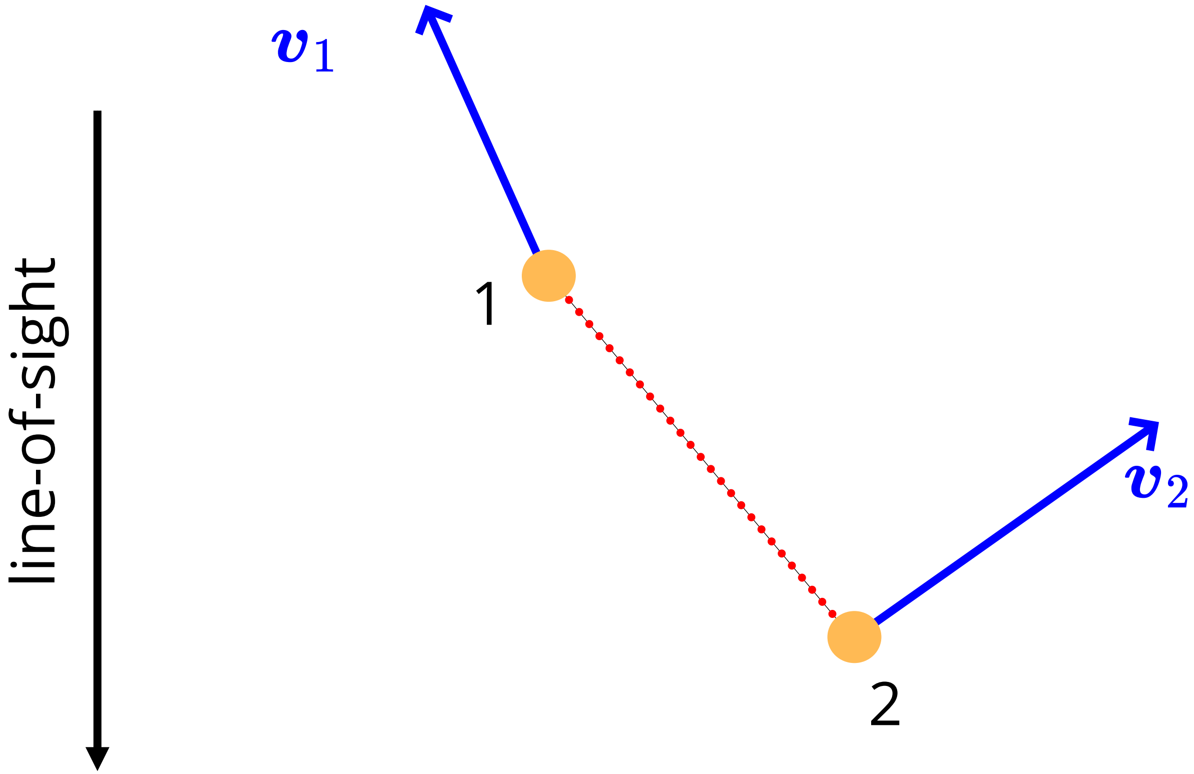
$$\langle \boldsymbol{w}_{12} | \boldsymbol{r}_{12} \rangle_{\mathrm{p}} = \frac{\langle (1+\delta_1)(1+\delta_2)(\boldsymbol{v}_2 - \boldsymbol{v}_1) \rangle}{\langle (1+\delta_1)(1+\delta_2) \rangle}$$



Pairwise velocity

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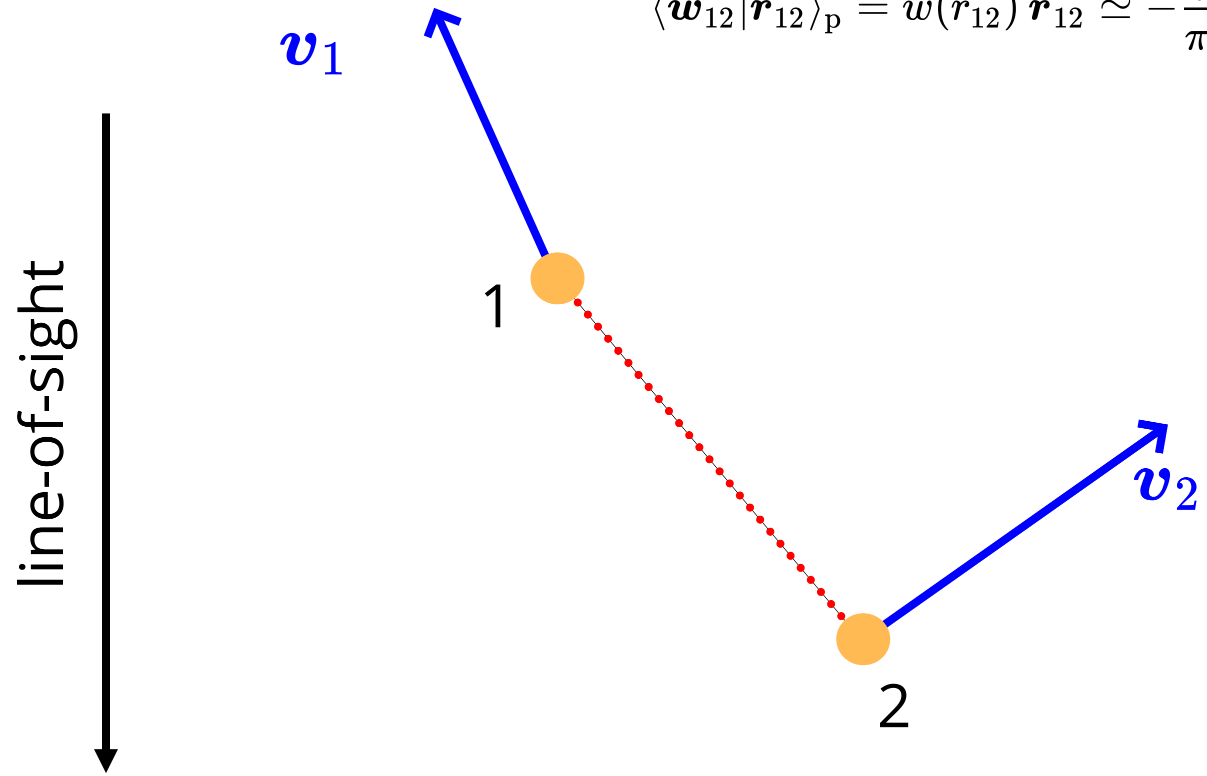
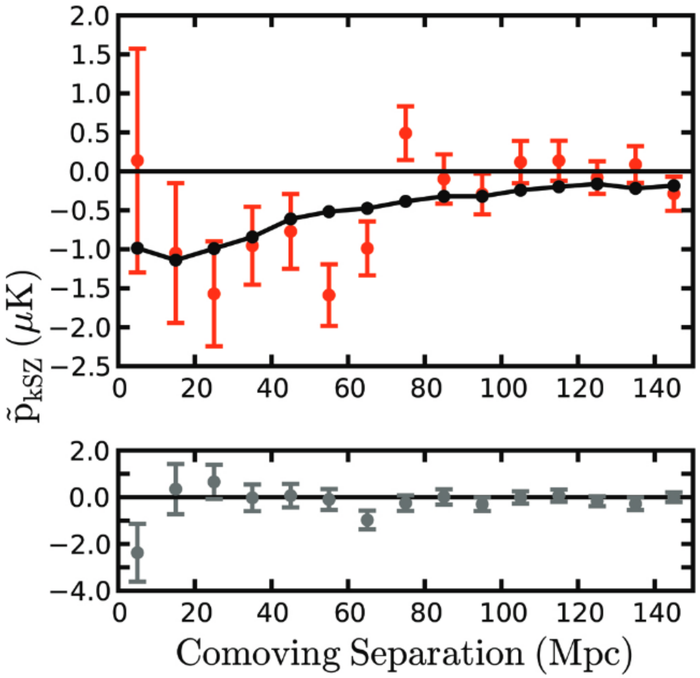
$$\langle \boldsymbol{w}_{12} | \boldsymbol{r}_{12} \rangle_{\rm p} = \bar{w}(r_{12})\, \hat{\boldsymbol{r}}_{12} \simeq -\frac{f}{\pi^2}\, \hat{\boldsymbol{r}}_{12} \int_0^\infty k\, j_1(k r_{12})\, P(k)\, {\rm d}k$$

(Fisher 94)



- The first significant detection of the kinetic Sunyaev-Zeldovich (kSZ) effect was achieved through the mean pairwise mean velocity.

(Hand et al. 12)



(Hand et al. 12)

$$\frac{\Delta T^{\mathrm{kSZ}}(r_{12})}{T_{\mathrm{cmb}}} \simeq -\tau \frac{\bar{w}(r_{12})}{c}$$

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Table 1. Recent measurements of the kinetic Sunyaev-Zeldovich effect with cross-correlations of various tracers of large-scale structure.

Method	Reference	kSZ data	Tracer type	Tracer data	Significance
Pairwise temperature difference	Hand et al. (2012)[a]	ACT	Galaxies (spec-z)	BOSS III/DR9	$2.9\,\sigma$
	Planck Collaboration Int. XXXVII (2016)	*Planck*	Galaxies (spec-z)	SDSS/DR7	1.8–$2.5\,\sigma$
	Hernández-Monteagudo et al. (2015)	WMAP	Galaxies (spec-z)	SDSS/DR7	$3.3\,\sigma$
	Soergel et al. (2016)	SPT	Clusters (photo-z)	1-yr DES	$4.2\,\sigma$
	De Bernardis et al. (2017)	ACT	Galaxies (spec-z)	BOSS/DR11	3.6–$4.1\,\sigma$
	Sugiyama et al. (2018)[b]	*Planck*	Galaxies (spec-z)	BOSS/DR12	$2.45\,\sigma$
	Li et al. (2018)[b]	*Planck*	Galaxies (spec-z)	BOSS/DR12	$1.65\,\sigma$

(source: Planck LIII, A&A, 617, A48, 2018)

- One of the most recent measurement is using the ACT DR5 data with a 5.4 sigma detection. (Calafut et al. 21)

- Future CMB experiments like Simons Observatory and CMB-S4 is expected to measure the pairwise velocity with S/N of 100+

(e.g. Sugiyama et al. 18)

Can we generalise it to three-point statistics?

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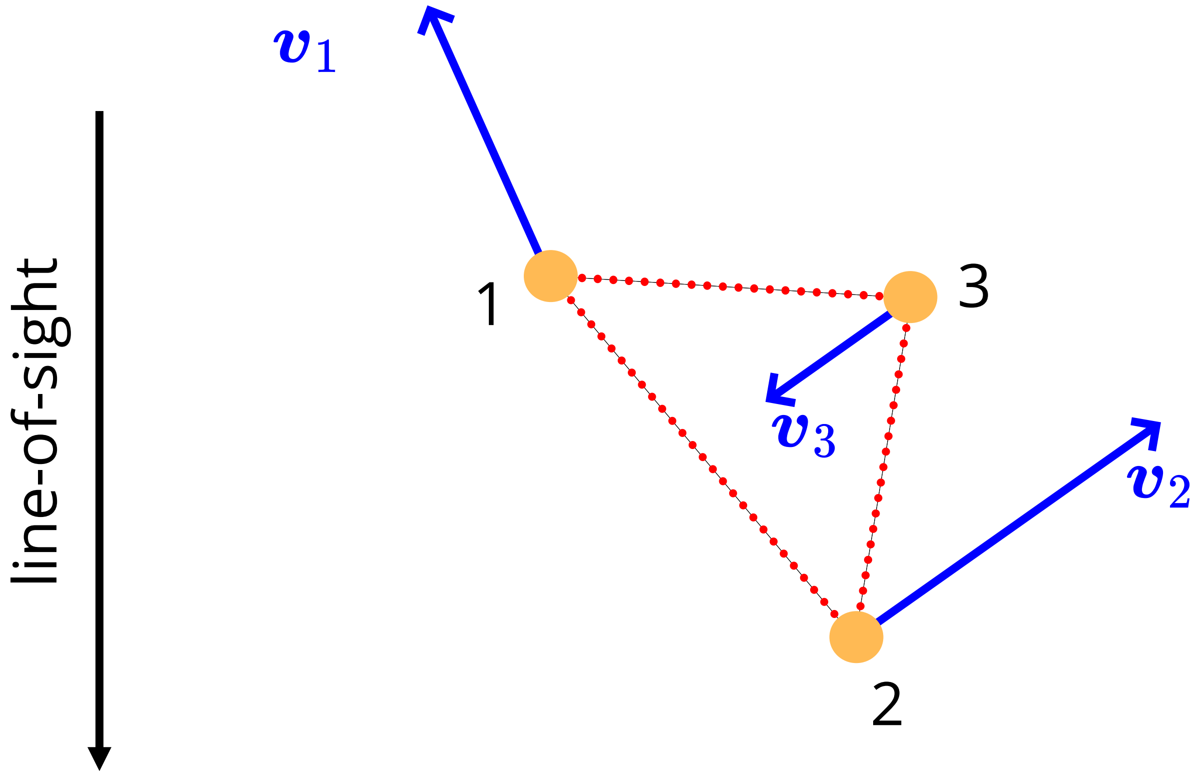
Can we generalise it to three-point statistics?

Yes we can!

Three-point relative velocity

(First introduced in Kuruvilla & Porciani, JCAP, 2020)



$$R_{12}(r_{12}, r_{23}, r_{31}) = (\boldsymbol{v}_2 - \boldsymbol{v}_1) \cdot \hat{\boldsymbol{r}}_{12}$$

$$R_{23}(r_{12}, r_{23}, r_{31}) = (\boldsymbol{v}_3 - \boldsymbol{v}_2) \cdot \hat{\boldsymbol{r}}_{23}$$

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How do we measure the three-point relative velocity statistics in this work?

Quijote suite of simulations

- The Quijote simulations is a suite of 44,100 full N-body simulations run using Gadget 3.

  (Villaescusa-Navarro et al. 20)

- Boxes of 1 Gpc/h and contains 512^3 CDM (+neutrino) particles.

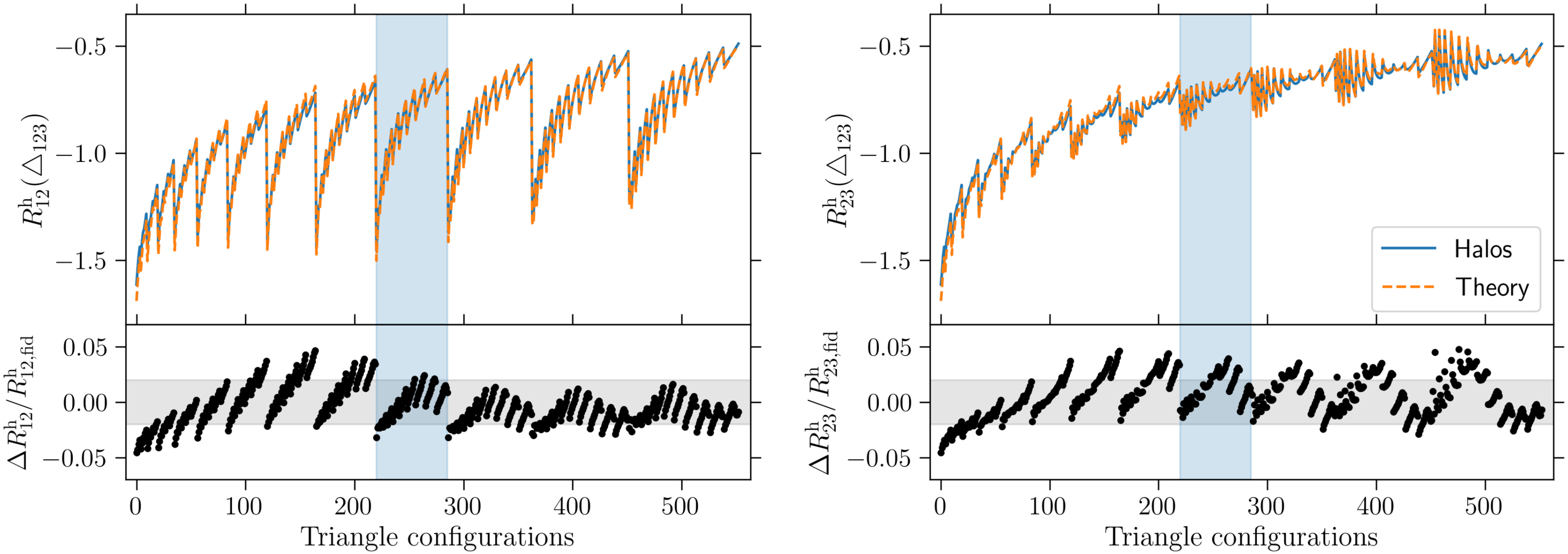
- 15000 realisations of the fiducial cosmology.

- Additional sets of 500 realisations where only cosmological parameter is varied.

Halos - Mean relative velocity between pairs in a triplet

Triangular configurations: $50 \leq r_{31} \leq r_{23} \leq r_{12} \leq 120\ h^{-1}\mathrm{Mpc}$

Minimum halo mass: $M_{\mathrm{h}} > 5 \times 10^{13}\ h^{-1} M_{\odot}$



$$R^{\mathrm{h}}_{ij}(\triangle_{123}, M_{\mathrm{h}}) = b(M_{\mathrm{h}})\, R_{ij}(\triangle_{123})$$

Halos - Mean relative velocity between pairs in a triplet

$$\langle \boldsymbol{w}_{12} | \triangle_{123} \rangle_{\mathrm{t}} = \frac{\langle (1+\delta_1)(1+\delta_2)(1+\delta_3)(\boldsymbol{v}_2 - \boldsymbol{v}_1) \rangle}{\langle (1+\delta_1)(1+\delta_2)(1+\delta_3) \rangle}$$

$$\simeq \langle \delta_1 \boldsymbol{v}_2 \rangle - \langle \delta_2 \boldsymbol{v}_1 \rangle + \langle \delta_3 \boldsymbol{v}_2 \rangle - \langle \delta_3 \boldsymbol{v}_1 \rangle$$

$$= \bar{w}(r_{12})\, \hat{\boldsymbol{r}}_{12} - \frac{1}{2} \left[\bar{w}(r_{23})\, \hat{\boldsymbol{r}}_{23} + \bar{w}(r_{31})\, \hat{\boldsymbol{r}}_{31} \right]$$

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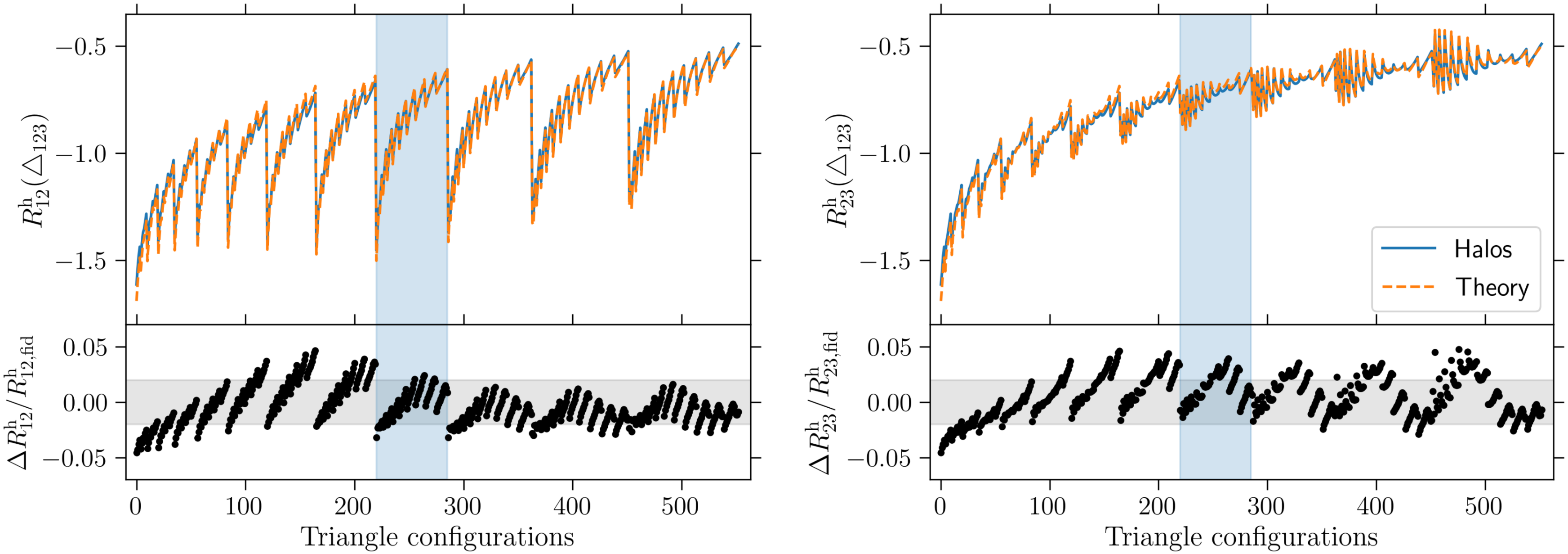

$$R_{12}(\triangle_{123}) = \bar{w}(r_{12}) - \frac{1}{2}\left[\bar{w}(r_{23})\ \cos\chi - \bar{w}(r_{31})\ \frac{r_{12}+r_{23}\cos\chi}{\sqrt{r_{12}^2+r_{23}^2+2r_{12}r_{23}\cos\chi}}\right]$$

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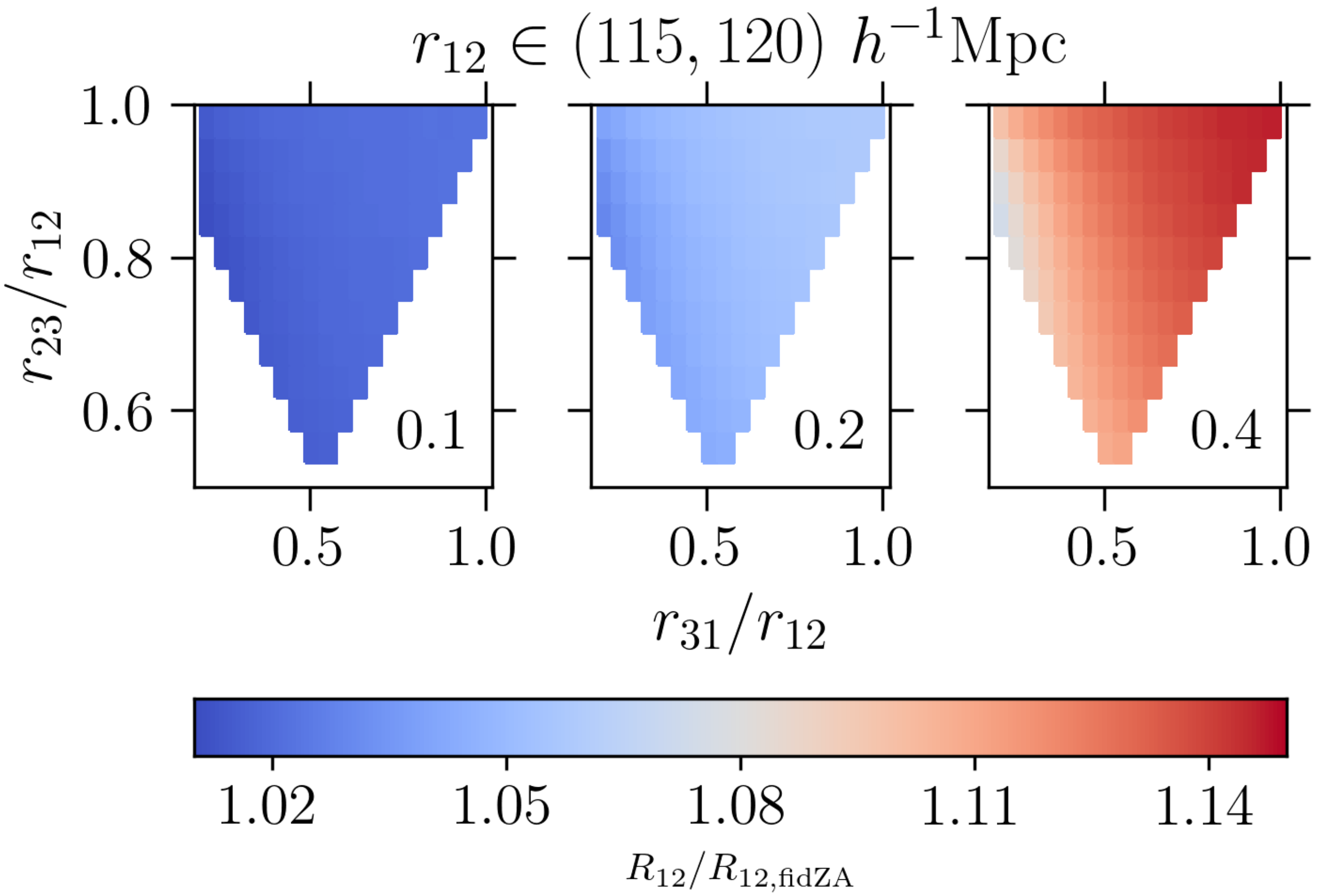
Can we use the relative velocity statistics to constrain cosmology?

Halos - Mean relative velocity between pairs in a triplet

- Fisher matrix formalism
- Compute the covariance matrix for the relative velocity statistics using 15,000 simulations from the Quijote suite.
- Derivatives also computed directly using the Quijote suite.

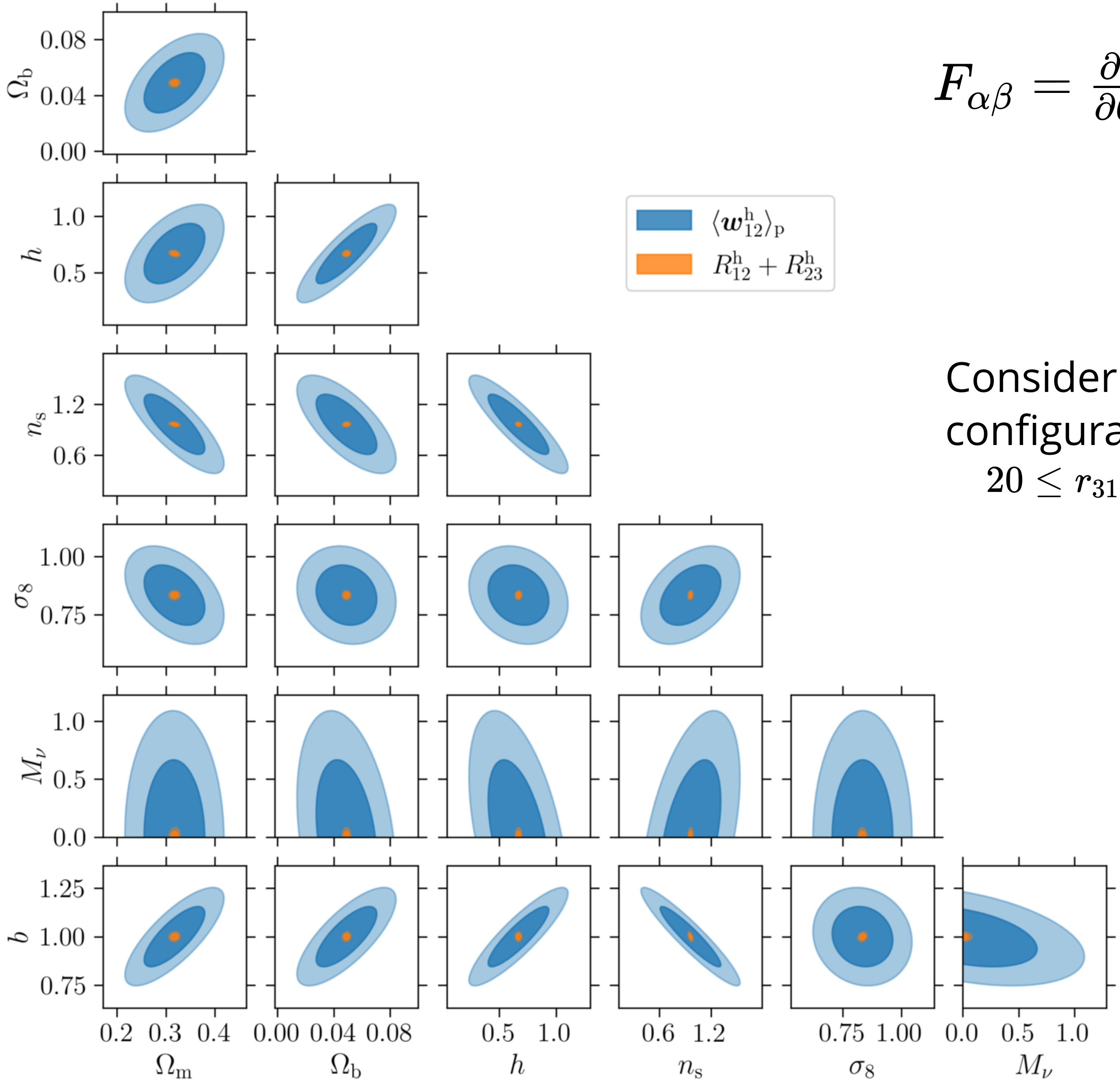
- This work runs parallel to the quantification of the information content from the halo redshift-space bispectrum using the Quijote suite. (Hahn et al. 20)

Effect of massive neutrinos



(JK & Aghanim 21)

$$F_{\alpha\beta} = \frac{\partial \boldsymbol{S}}{\partial \theta_\alpha} \cdot \hat{\mathbf{C}}^{-1} \cdot \frac{\partial \boldsymbol{S}^{\mathsf{T}}}{\partial \theta_\beta}$$



$$F_{\alpha\beta} = \frac{\partial \boldsymbol{S}}{\partial \theta_\alpha} \cdot \hat{\mathbf{C}}^{-1} \cdot \frac{\partial \boldsymbol{S}^{\mathsf{T}}}{\partial \theta_\beta}$$

Considering all triangular configurations:

$$20 \leq r_{31} \leq r_{23} \leq r_{12} \leq 120$$

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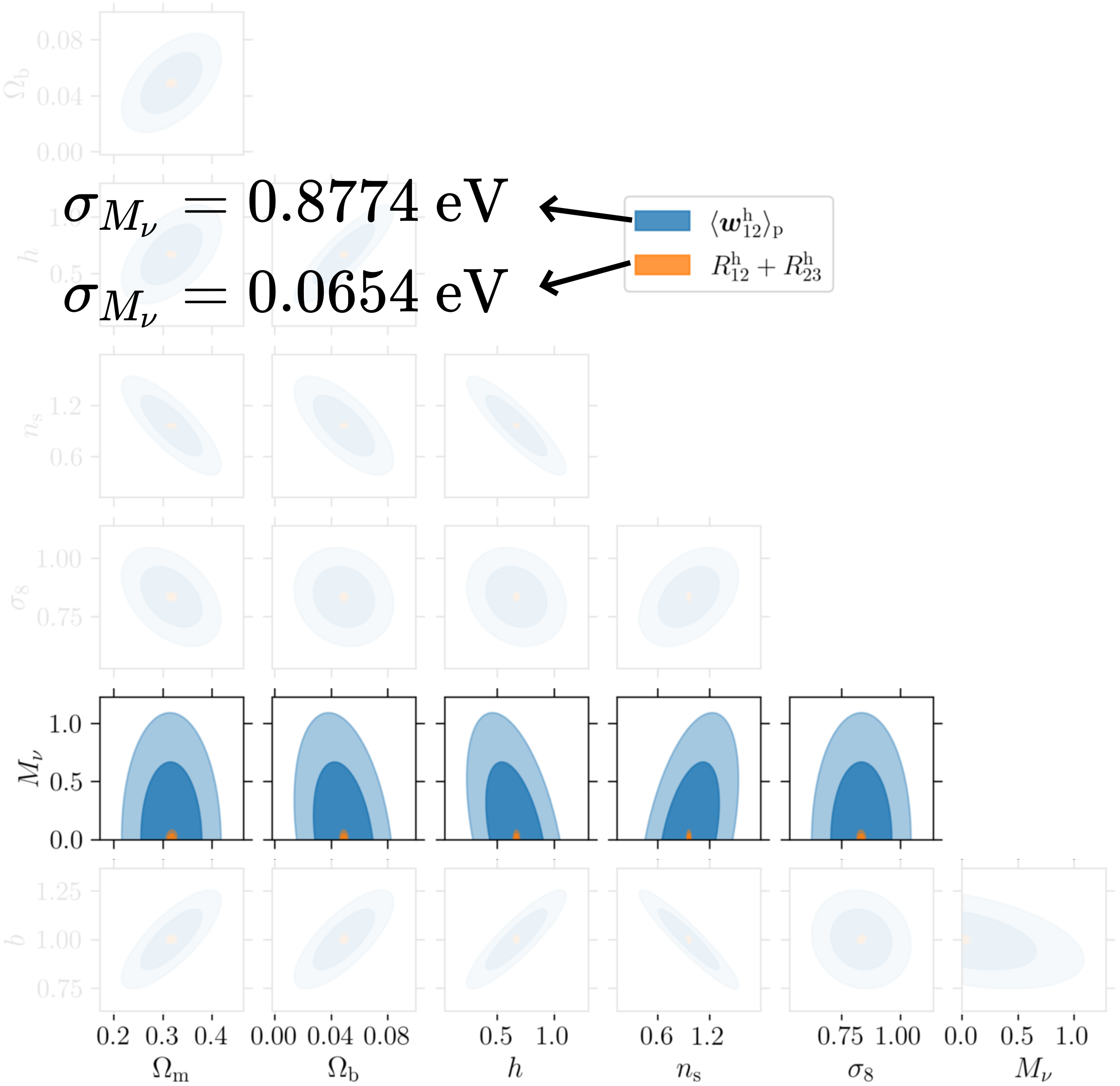
$$\sigma_{M_\nu} = 0.8774\ \mathrm{eV}$$

$$\sigma_{M_\nu} = 0.0654\ \mathrm{eV}$$



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But is this really competitive with clustering statistics?

Summary statistics	Matter density	Baryon density	Hubble parameter (h)	Spectral index	Sigma 8	Summed neutrino mass (eV)
mean relative velocity	0.0091	0.0024	0.0226	0.0221	0.0156	0.0655
power spectrum multipoles	**2.6**	**4.8**	**4.9**	**5.7**	**2.3**	**4.5**
bispectrum monopole	**1.2**	**1.7**	**1.7**	**1.5**	**0.9**	**0.8**

(Hahn et al. 20)

* Numbers within the orange box denotes the factor of improvement of 1 sigma constraint from three-point relative velocity with respect to the corresponding clustering statistics.

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What about the optical depth degeneracy?

We saw earlier that $\frac{\Delta T^{\mathrm{kSZ}}(r_{12})}{T_{\mathrm{cmb}}} \simeq -\tau \frac{\bar{w}(r_{12})}{c}$ thus $\Delta T^{\mathrm{kSZ}} \propto \tau f \sigma_8^2$

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- One of the attempt to break this degeneracy has been proposed by using fast radio bursts (FRB).

(Madhavacheril et al. 19)

- However we introduce a new statistic which is independent of optical depth, and also sigma 8.

(Kuruvilla 2021)

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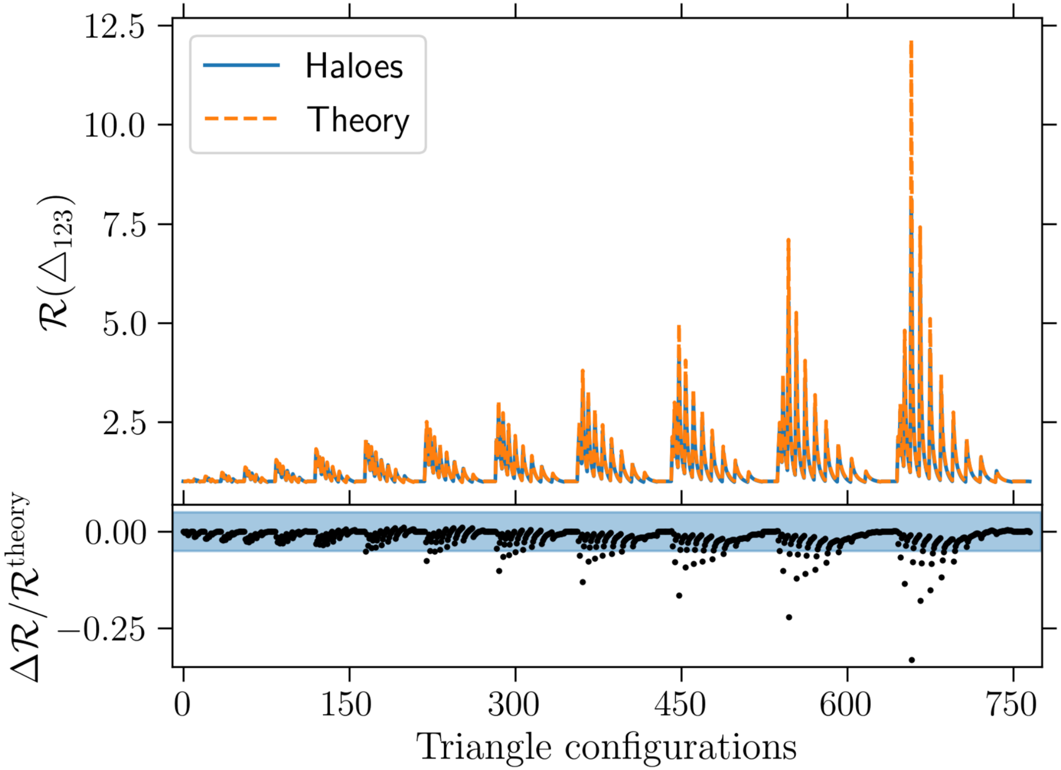
(Kuruvilla 2021)

$$\mathcal{R}(\triangle_{123}) = \frac{\Delta T^{\rm kSZ}_{12}(\triangle_{123})}{\Delta T^{\rm kSZ}_{23}(\triangle_{123})} \equiv \frac{R^{\rm h}_{12}(\triangle_{123})}{R^{\rm h}_{23}(\triangle_{123})} = \frac{R_{12}(\triangle_{123})}{R_{23}(\triangle_{123})}$$

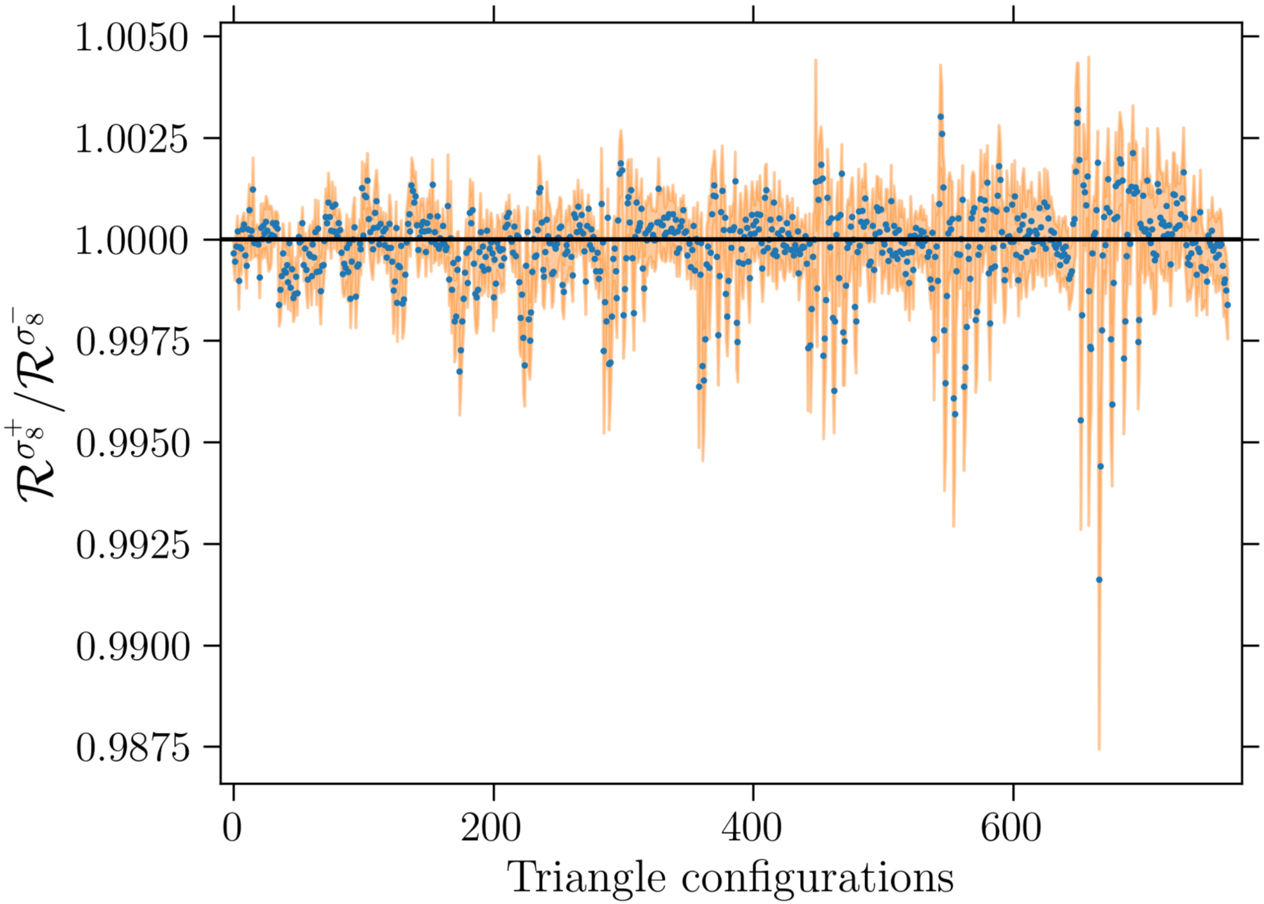
Triangular configurations: $40 \leq r_{31} \leq r_{23} \leq r_{12} \leq 120\ h^{-1}\mathrm{Mpc}$

Minimum halo mass: $M_\mathrm{h} > 5 \times 10^{13}\ h^{-1} M_\odot$



(Kuruvilla 2021)

Independent of σ_8



Thus can completely circumvent the summed neutrino mass - sigma 8 degeneracy.

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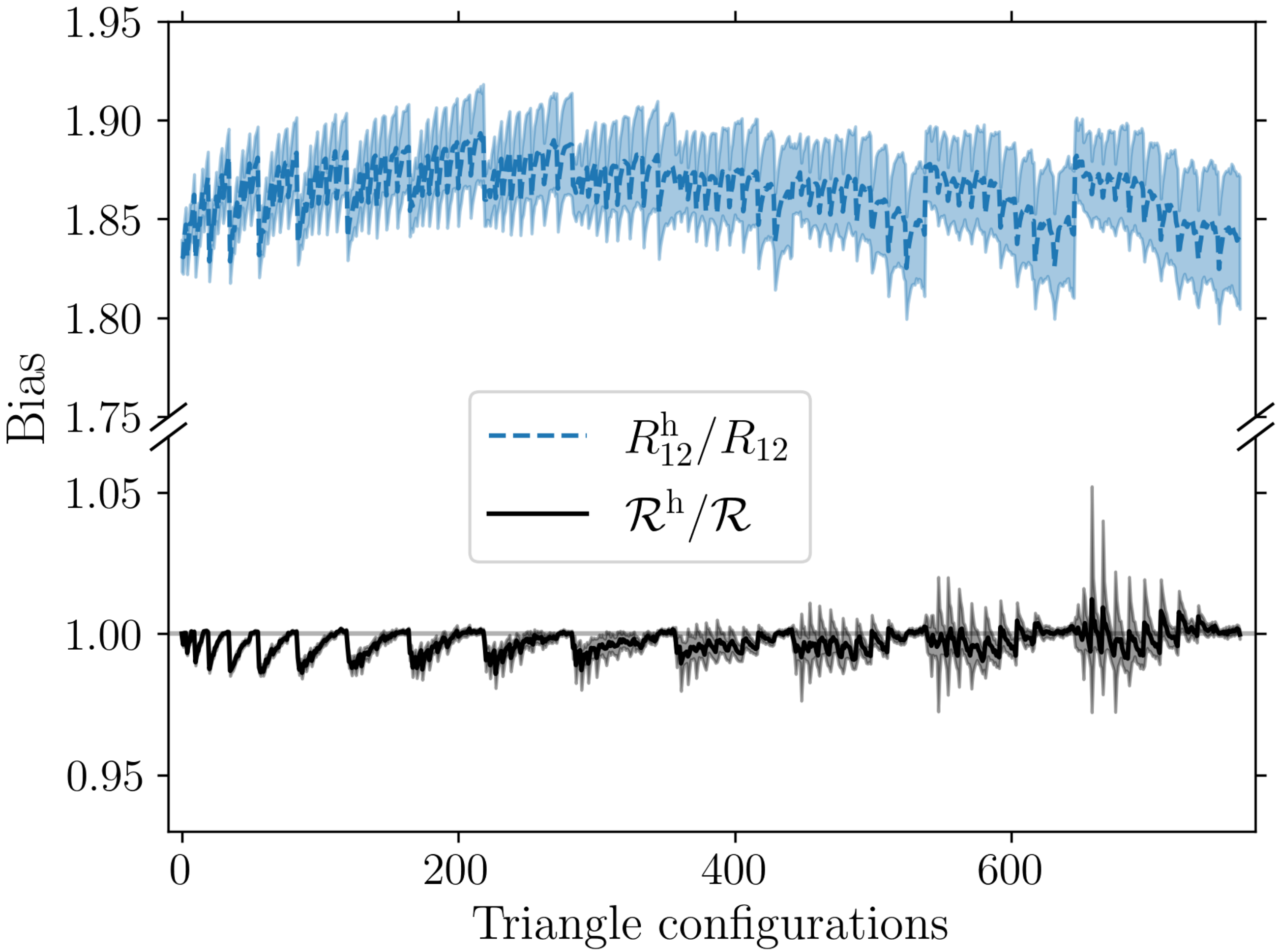
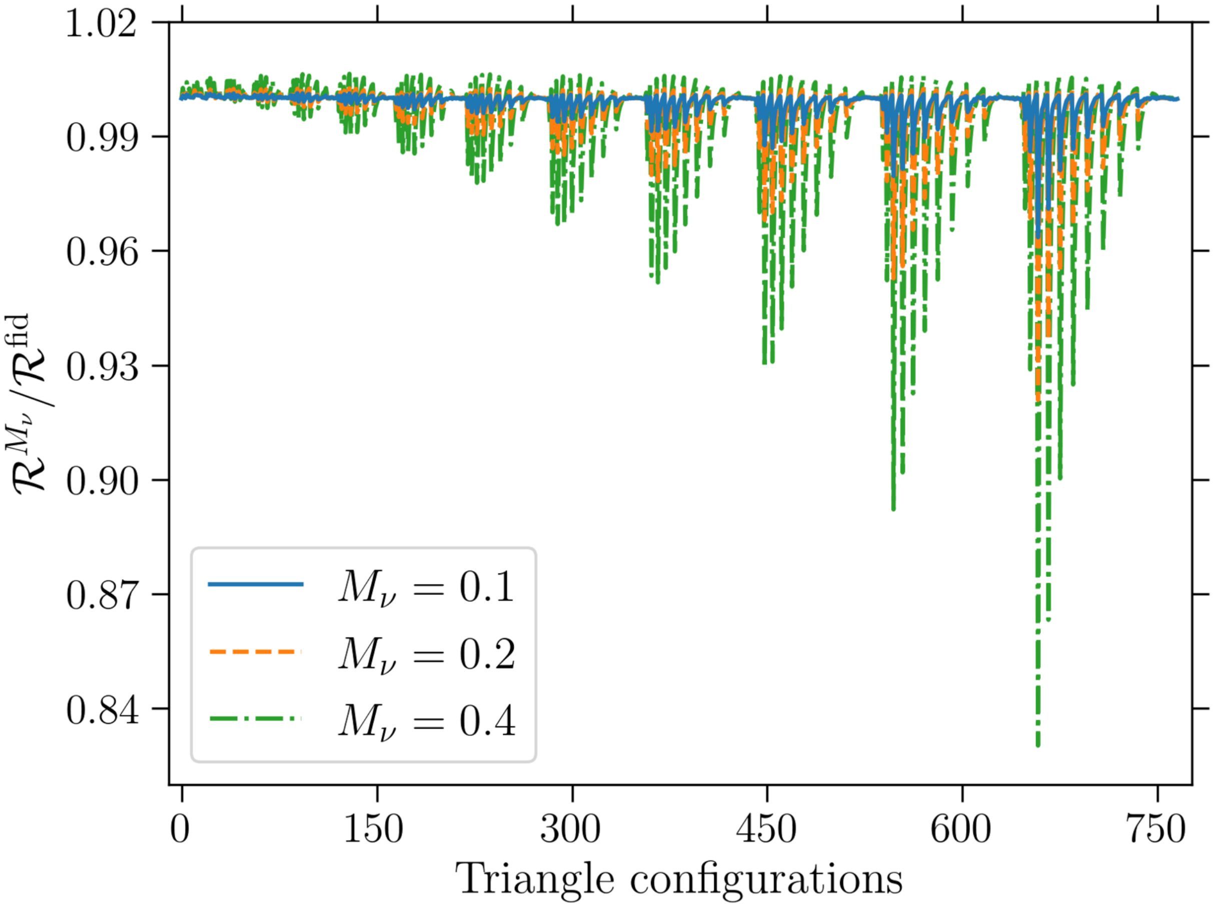
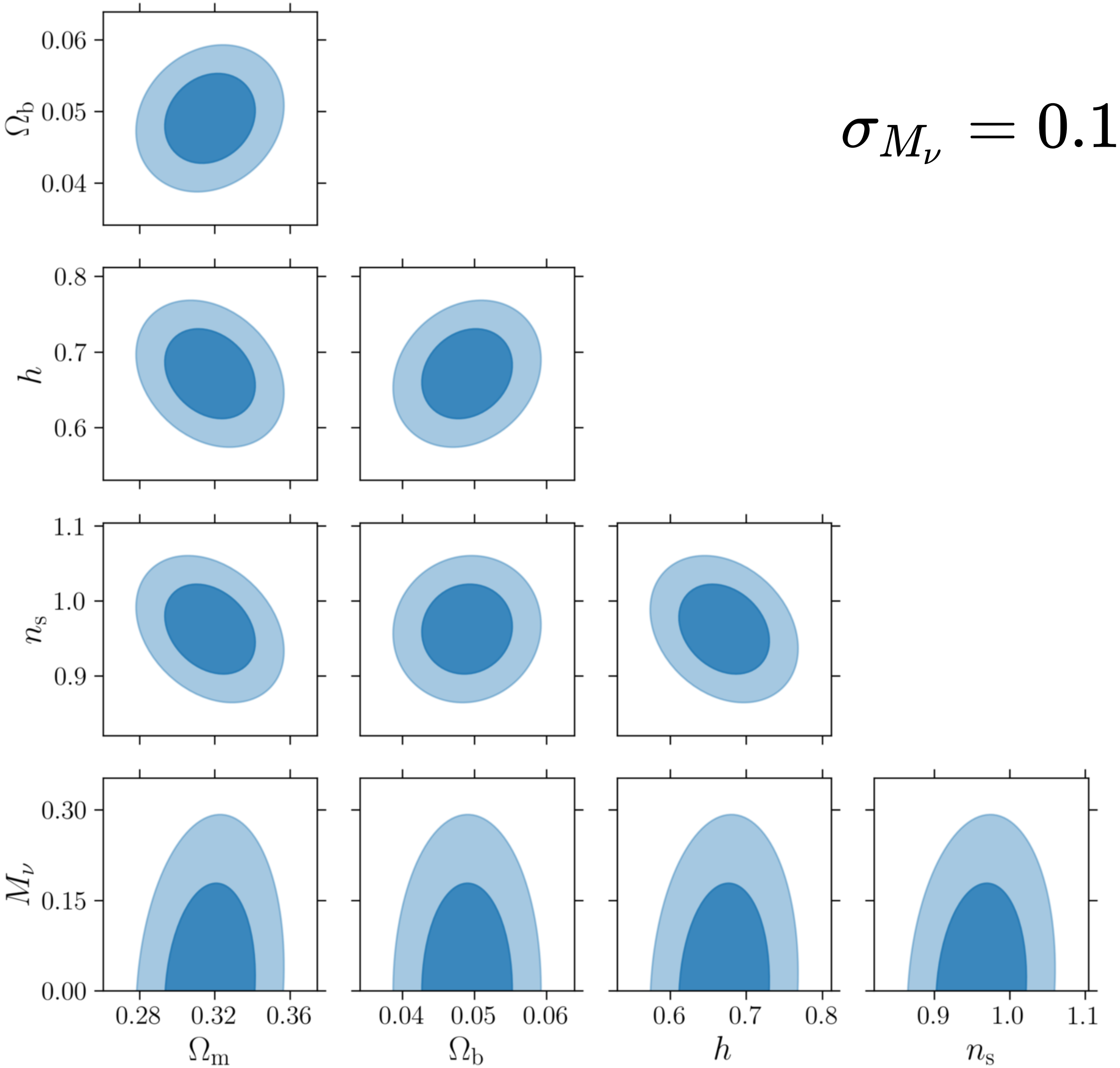
(Nearly) scale independent bias for the new statistic



Effect of summed neutrino mass





$$\sigma_{M_\nu} = 0.1175 \text{ eV}$$

Improvement factor for $\mathcal{R}$

$$\{\Omega_{\rm m}, \Omega_{\rm b}, h, n_{\rm s}, M_\nu\}$$

- Factor of improvement of **{6.2, 7.6, 9.8, 12.9, 8.87}** respectively over the mean pairwise velocity.
- **{2.3, 3.6, 4.5, 5.4, 5.7}** when comparing against the constraints from power spectrum from Hahn et al. 20.
- **{1.8, 2.9, 3.2, 3.1, 1.8}** when comparing against the constraints using bispectrum from Hahn et al. 20.
- However when comparing against $R_{12} + R_{23}$, the constraints are reduced by a factor of about 1.4.

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Future prospects

- To develop an estimator, like for the pairwise velocity, which will enable to measure the mean radial relative velocities (using los velocities from kSZ).

- To understand what would be the expected S/N for the three-point relative velocities from the future CMB surveys.

Conclusions

- Cosmological constraints from the mean three-point relative velocity statistics are competitive with those obtained from the bispectrum, while having sizeable improvements with respect to the power spectrum.

  (Kuruvilla & Aghanim 2021)

- Introduced a new statistic which enables to constrain the summed neutrino mass independent of optical depth and sigma 8.

  (Kuruvilla 2021)

Thank you for listening!