PERIMETER INSTITUTE

kSZ velocity Reconstruction

Properties from N-body simulation and halo model

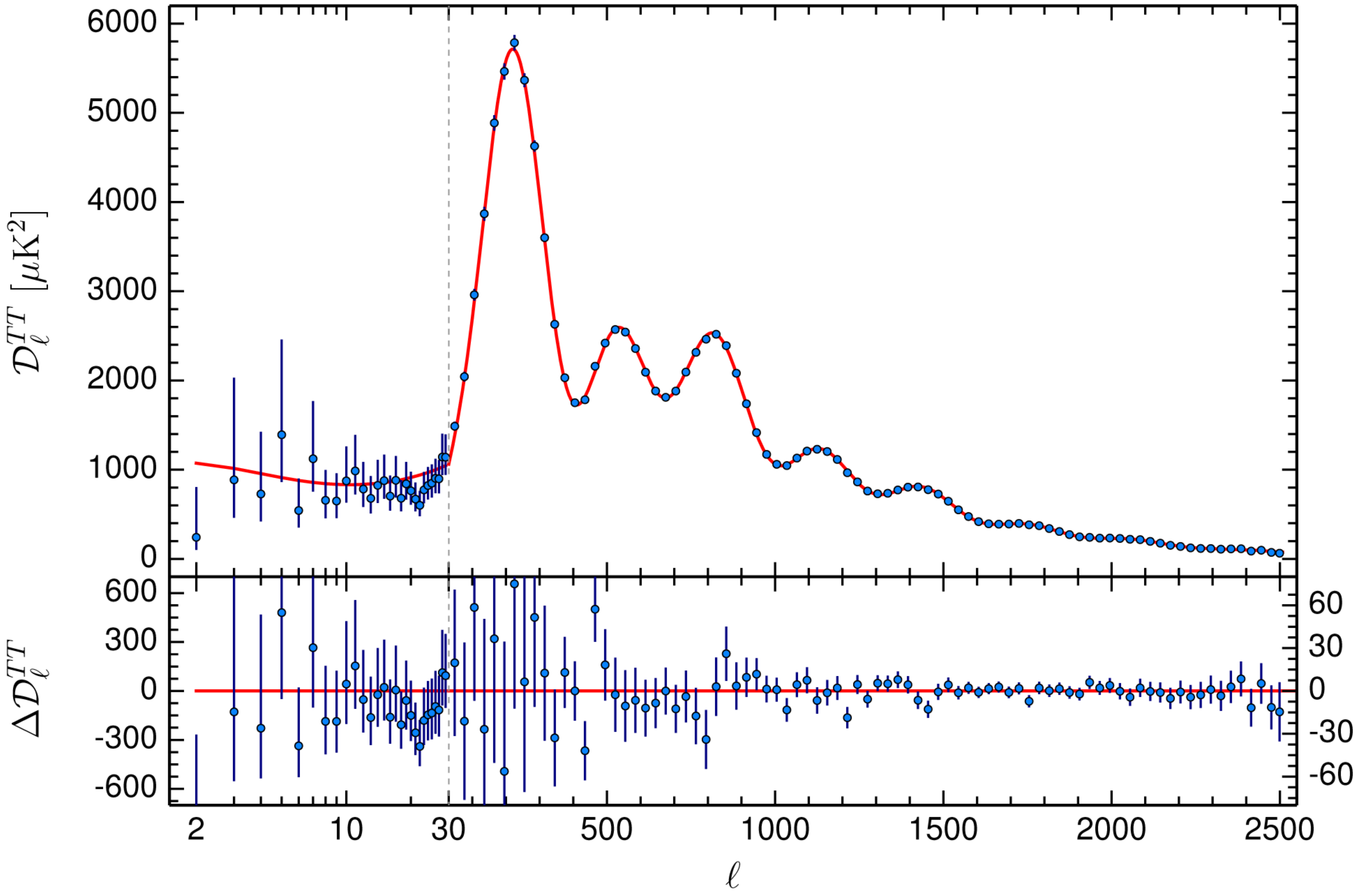
Utkarsh Giri

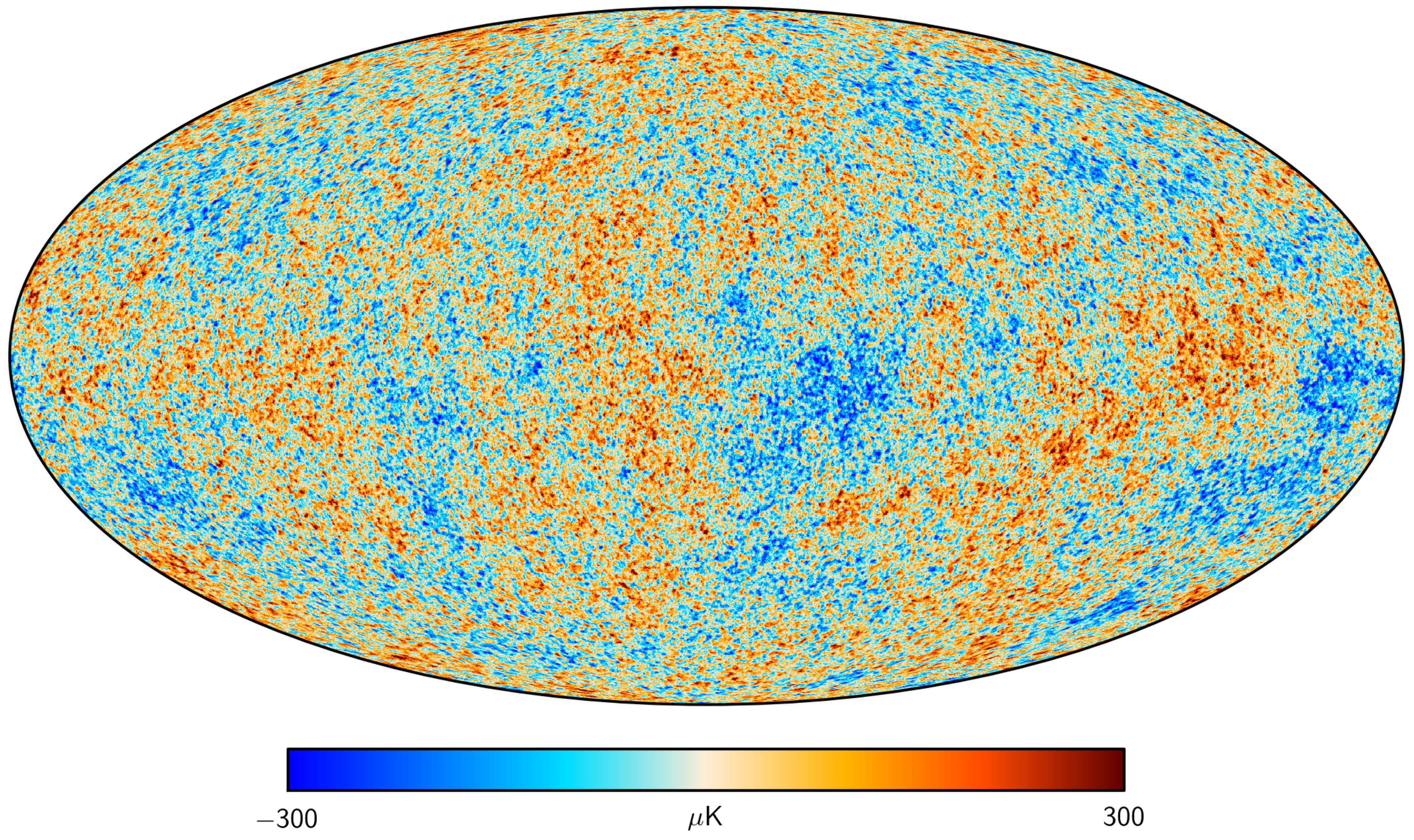
arxiv:2010.07193 **UG** and Kendrick Smith

arxiv:1810.13423 Kendrick Smith, Mat Madhavacheril, Moritz Muchmeyer, Simone Ferraro, **UG**, Matt Johnson

Cosmic Microwave Background

- Radiation from very early epoch
- Enormous source of information
- Helped develop ΛCDM



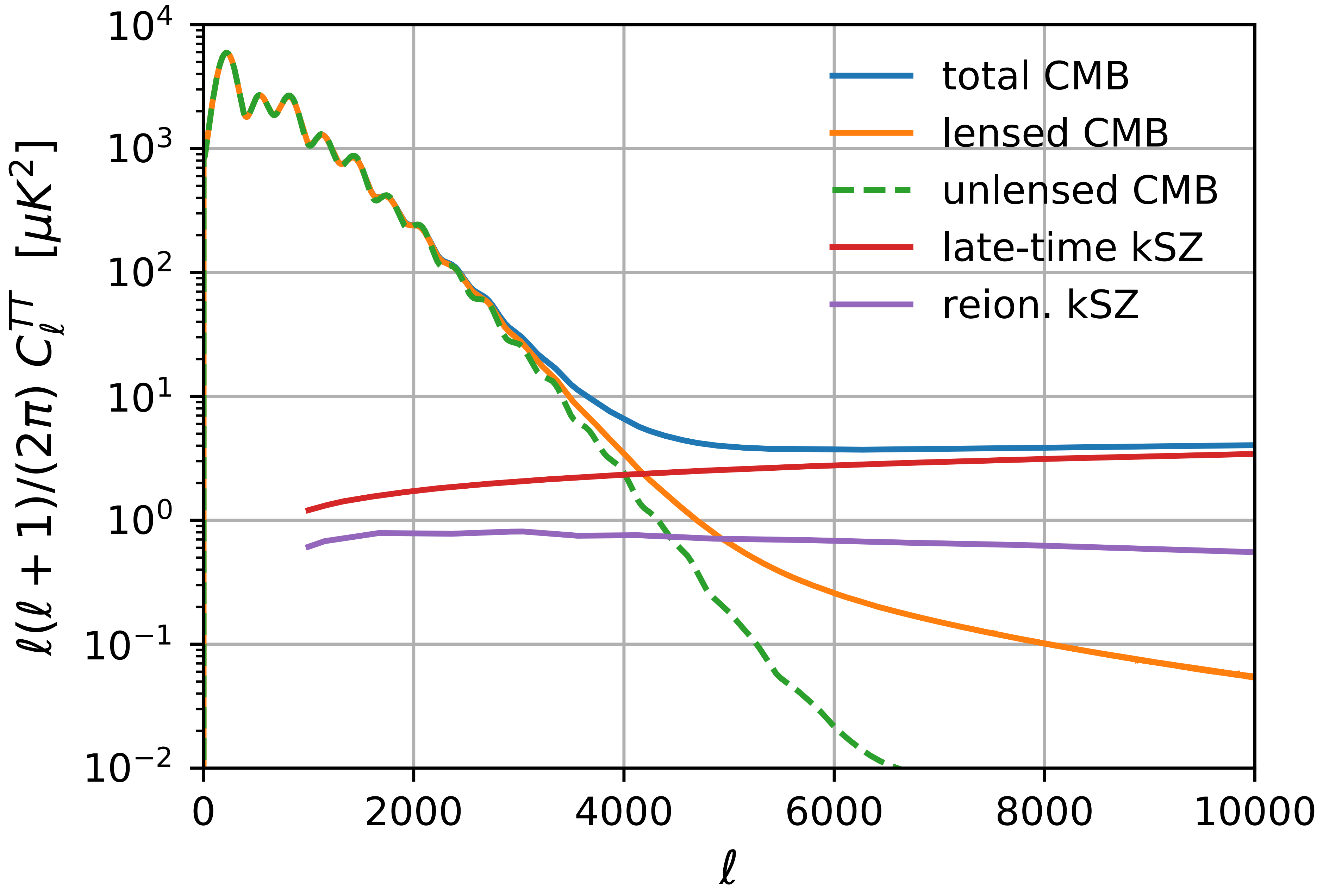


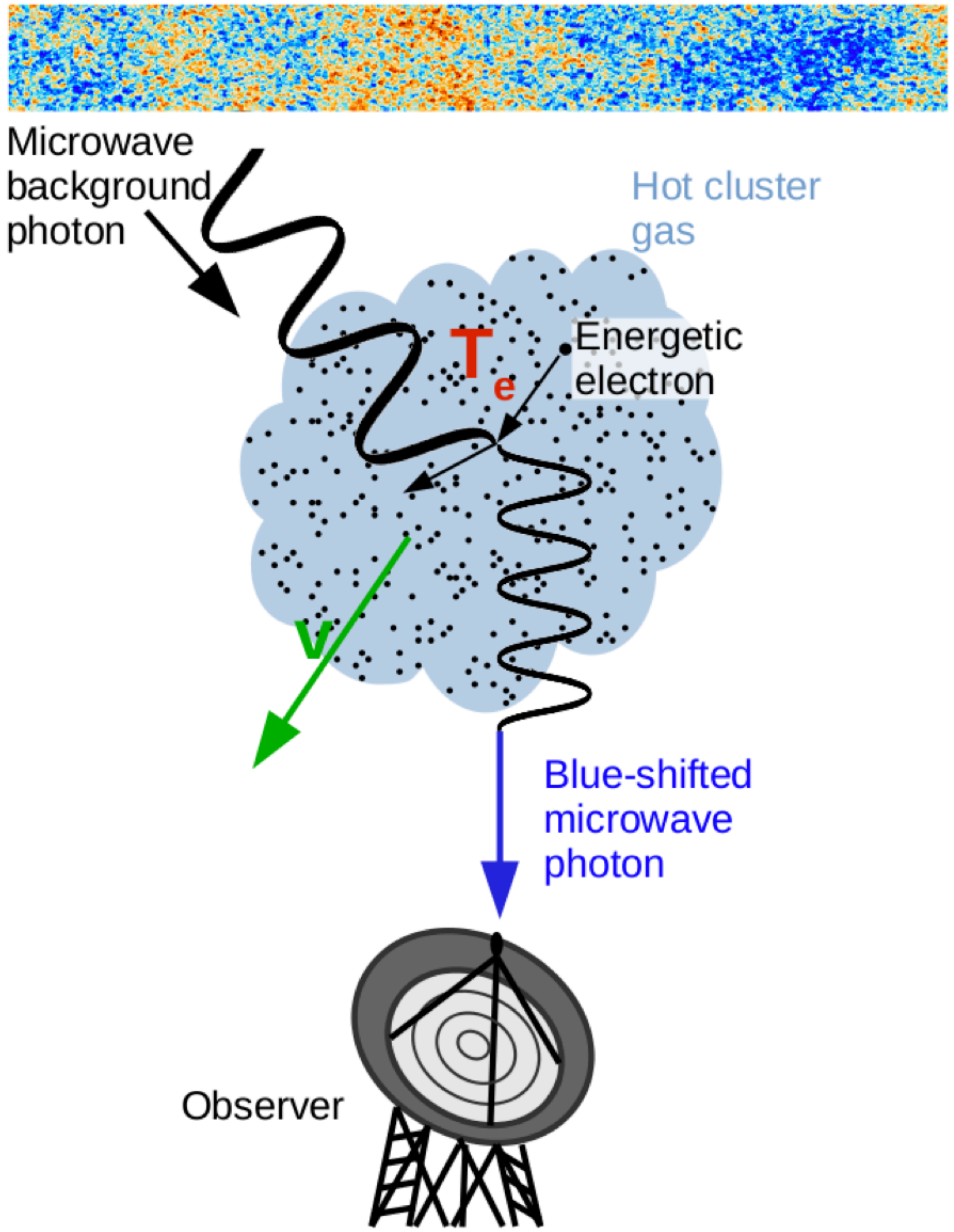
- Most info from gaussian primary anisotropy
- Focus has now shifted to the study of ‘secondary anisotropies’

Kinetic Sunyaev-Zeldovich*

- Sourced by scattering of CMB photons off free electron clouds with bulk radial velocity

$$\frac{\Delta T}{T} \propto \Sigma\, n_e v_r$$





Credit: B Soergel

Bispectrum Formalism

- The kSZ effect induces a bispectrum of the form $\langle \delta_g \delta_g T \rangle$
- The signal-to-noise peaks in the squeezed limit ($k_L \ll k_S$) where

$$\boxed{\langle \delta_g \delta_g T \rangle \propto \frac{P_{gv}(k_L)}{k_L} P_{ge}(k_s)}$$

- Several commonly used kSZ estimators can be derived from the bispectrum.
- The quadratic estimator $\hat{v}_r$ (Deutsch et al. 2017) which reconstructs radial velocity field is particularly well suited for cosmology.

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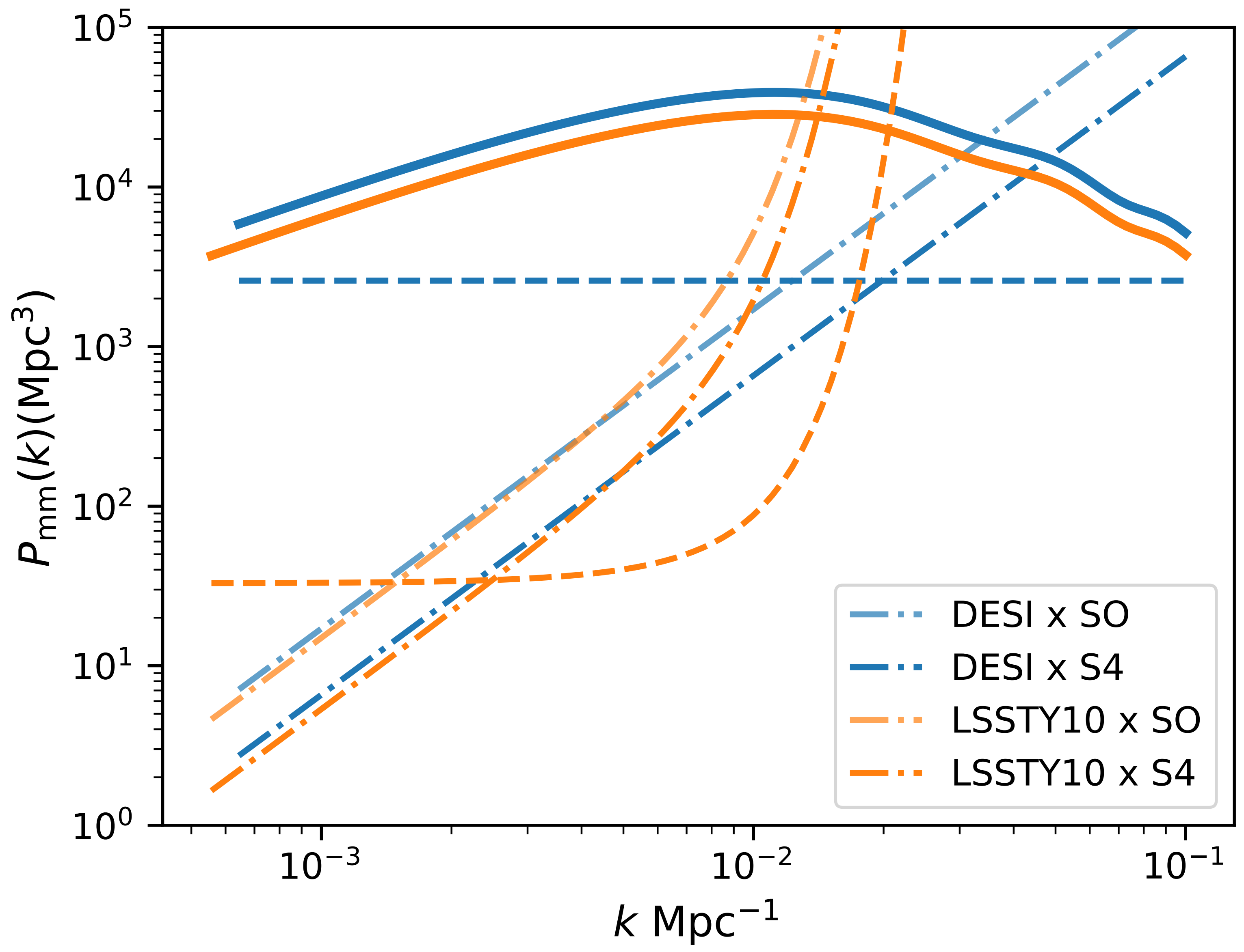
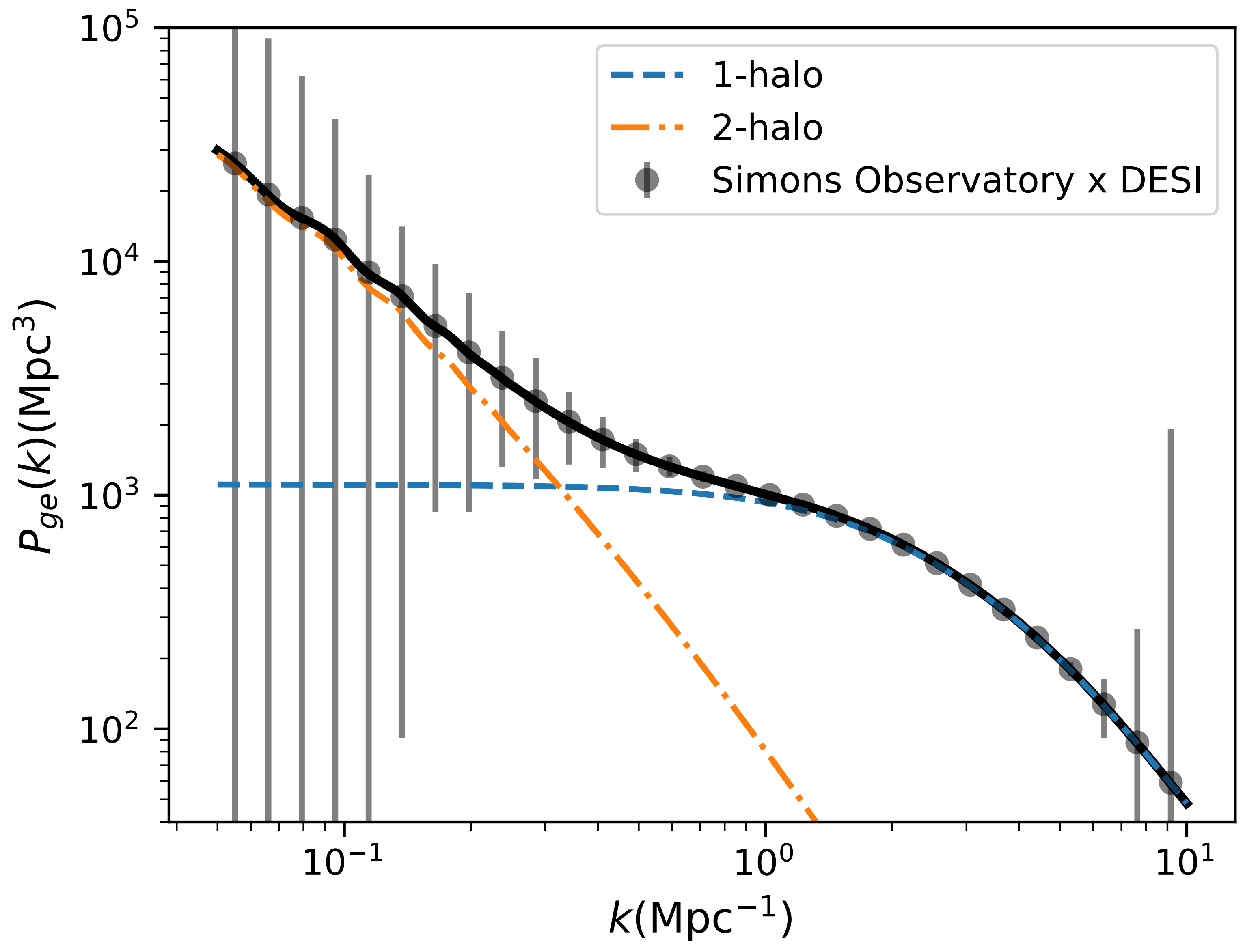
Science Case

Probes both large and small scales with high precision



On large-scales, kSZ constrains Gpc scale modes better than galaxy surveys



On small-scales, kSZ constrains P_{ge} at 1-halo scales with high precision

Gist: kSZ is a very promising tool for both cosmology and astrophysics!

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Quadratic Estimator $\hat{v}_r$

- Modulation of small-scale δ_e by a large-scale v_r

$$T_{ksz}(l) \approx v_r(k_L)\delta_e(k_S) \implies \langle \delta_g(k_S) T(l) \rangle_{fix\ k_L} \propto v_r(k_L)$$

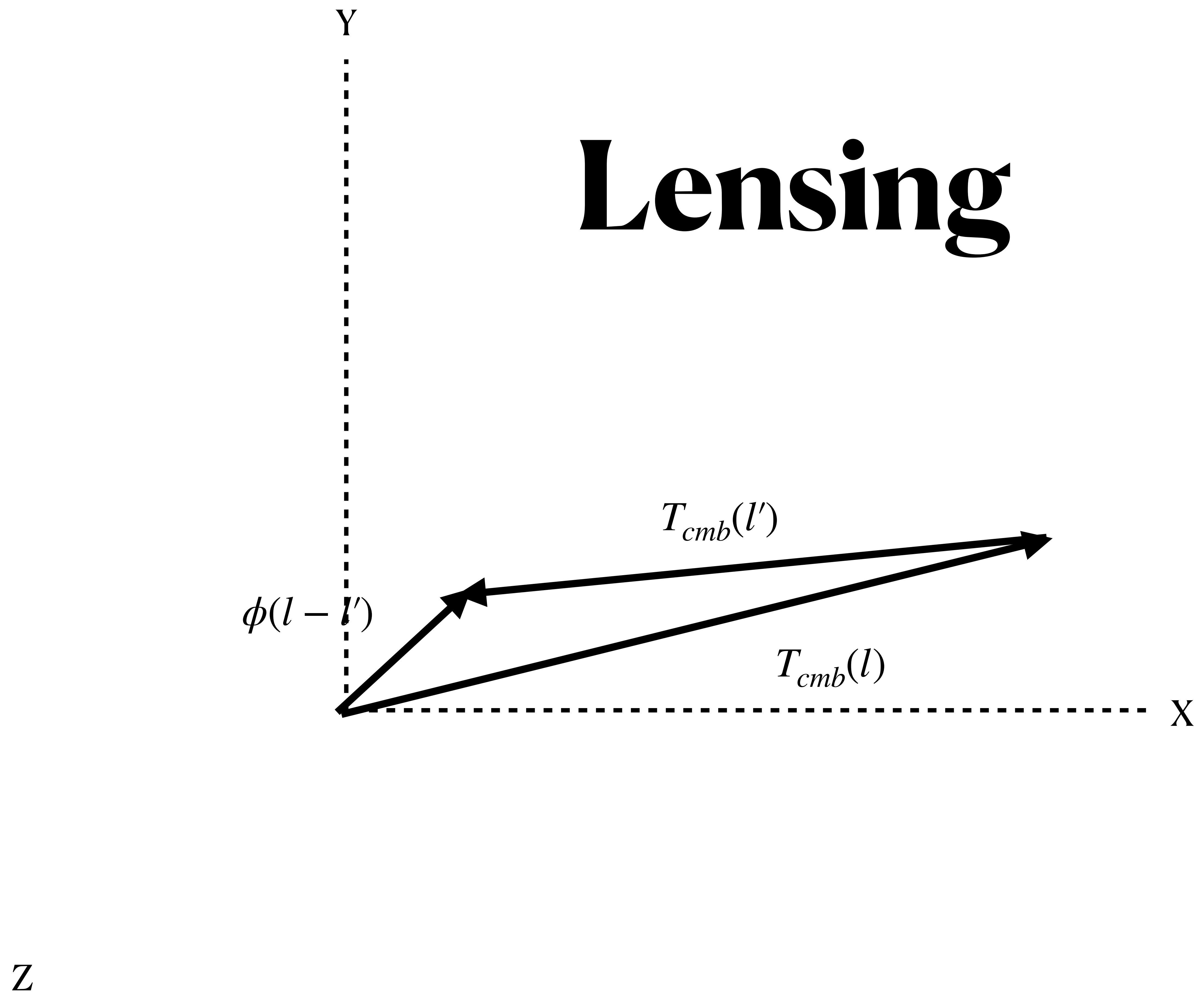
- QE reconstructs radial velocity v_r by combining CMB map with galaxy surveys with optimal filters and summing over small-scales.

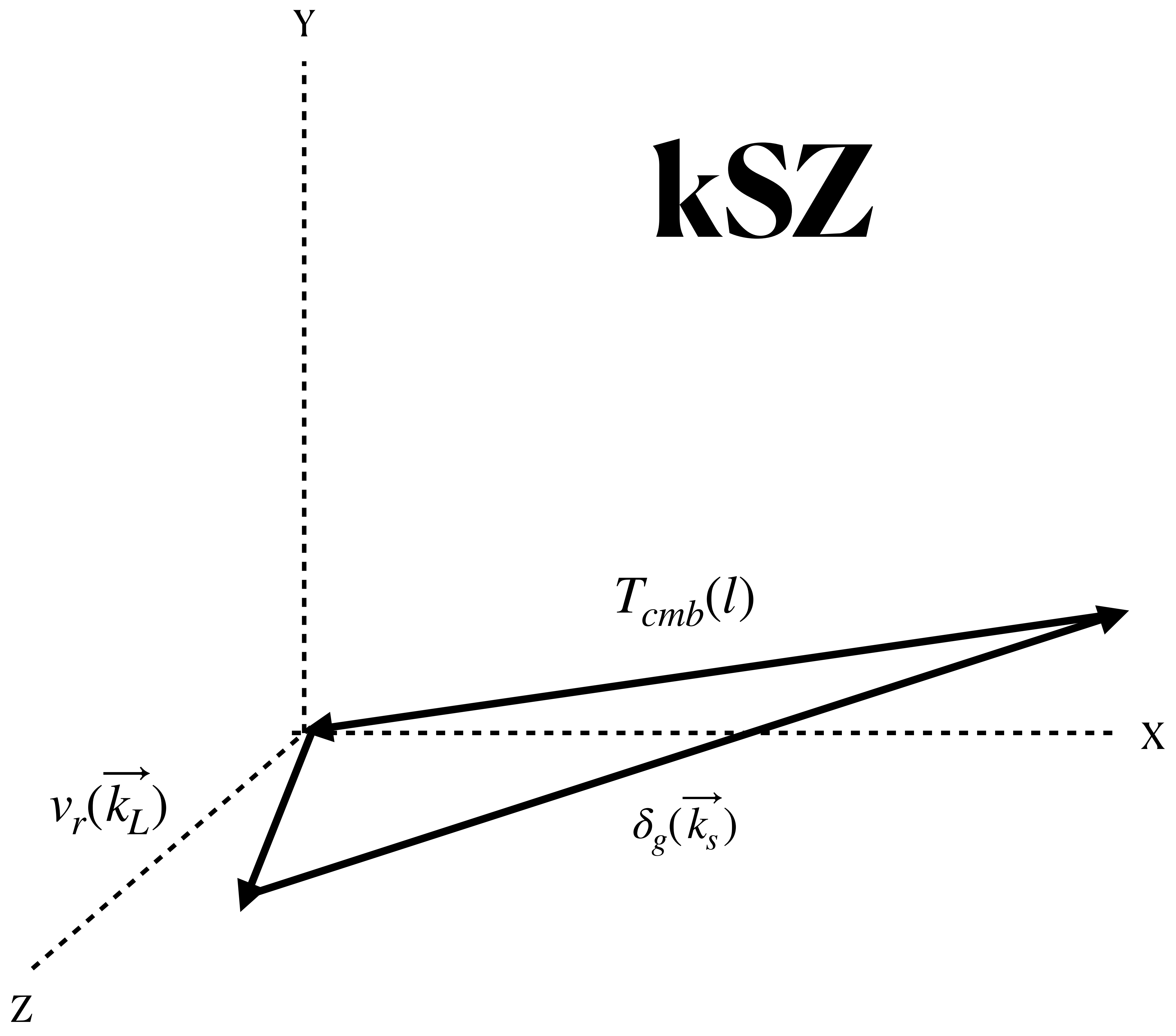
$$\hat{v}_r(k_L) = N_{v_r}(k_L)\frac{K_*}{\chi_*^2}\int \frac{d^3k_S}{(2\pi)^3}\frac{d^2l}{(2\pi)^2}\frac{P_{ge}(k_S)}{P_{gg}^{tot}(k_s)C_l^{TT,tot}}\delta_g^*(k_S)T^*(l)\,(2\pi)^3\delta^3\left(k_L + k_S + \frac{l}{\chi_*}\right)$$

- Reconstruction noise, or N^0-bias (nomenclature motivated by CMB lensing)

$$N_{v_r}^0(k_L) = \frac{\chi_*^4}{K_*^2}\left[\int \frac{d^3k_S}{(2\pi)^3}\frac{d^2l}{(2\pi)^2}\frac{P_{ge}(k_S)^2}{P_{gg}^{tot}(k_S)C_l^{TT,tot}}(2\pi)^3\delta^3\left(k_L + k_S + \frac{l}{\chi_*}\right)\right]^{-1}$$

QE: Lensing vs kSZ geometry





Reconstruction with simulations

- The scales involved are:

$$l \sim 5000;\ \ k_L \ll \frac{l}{\chi_*} \approx 0.01\ \mathrm{Mpc}^{-1};\ k_S \sim \mathcal{O}(1)\ \mathrm{Mpc}^{-1}$$

- We use Quijote simulations : Box-size = 1 h^{-1}Gpc ; Particles=1024^3; z=2

- $\delta_g = \delta_h$ (assuming one galaxy per halo, leads to DESI like shot noise)

- $T_{sim} = T_{kSZ} + T_{primary} + T_{noise}$ (assuming Electrons trace DM ($\delta_e = \delta_m$))

$$T_{noise}(l) = s_w^2 exp\left[\frac{-l(l+1)\theta_{fwhm}^2}{8ln2}\right]; \mathrm{s_w} = 0.5\ \mu\mathrm{k\ arcmin};\quad \theta_{\mathrm{fwhm}} = 1\ \mathrm{arcmin}$$

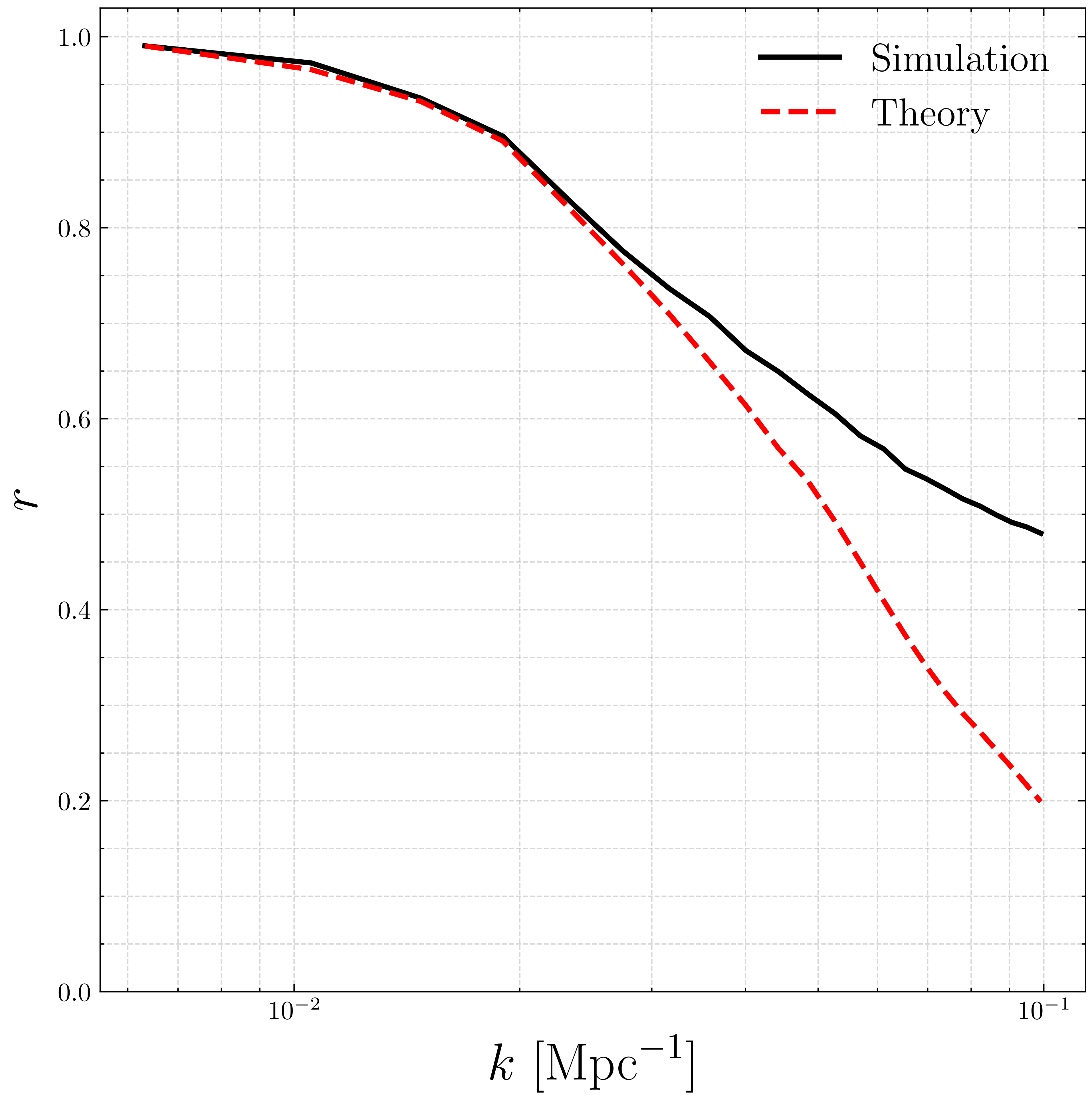
- Reconstruct radial velocity with quadratic estimator $v_r \sim \delta_h \times T_{sim}$

Results: Correlation

- Correlation between reconstructed field and true velocity field tells us about the quality of reconstruction.
- The correlation coefficient is given by

$$r_{sim} = \frac{P_{v_r \hat{v}_r}}{\sqrt{P_{v_r v_r}}\sqrt{P_{\hat{v}_r \hat{v}_r}}}$$

- For $k < 0.01\ \mathrm{Mpc}^{-1}$, $\boxed{r_{sim} \geq 97\,\%}$
- $r \to 100\,\%$ is highly desirable for cosmological applications.
- r_{sim} agrees well with leading-order theory, but not exactly=> **extra noise terms**

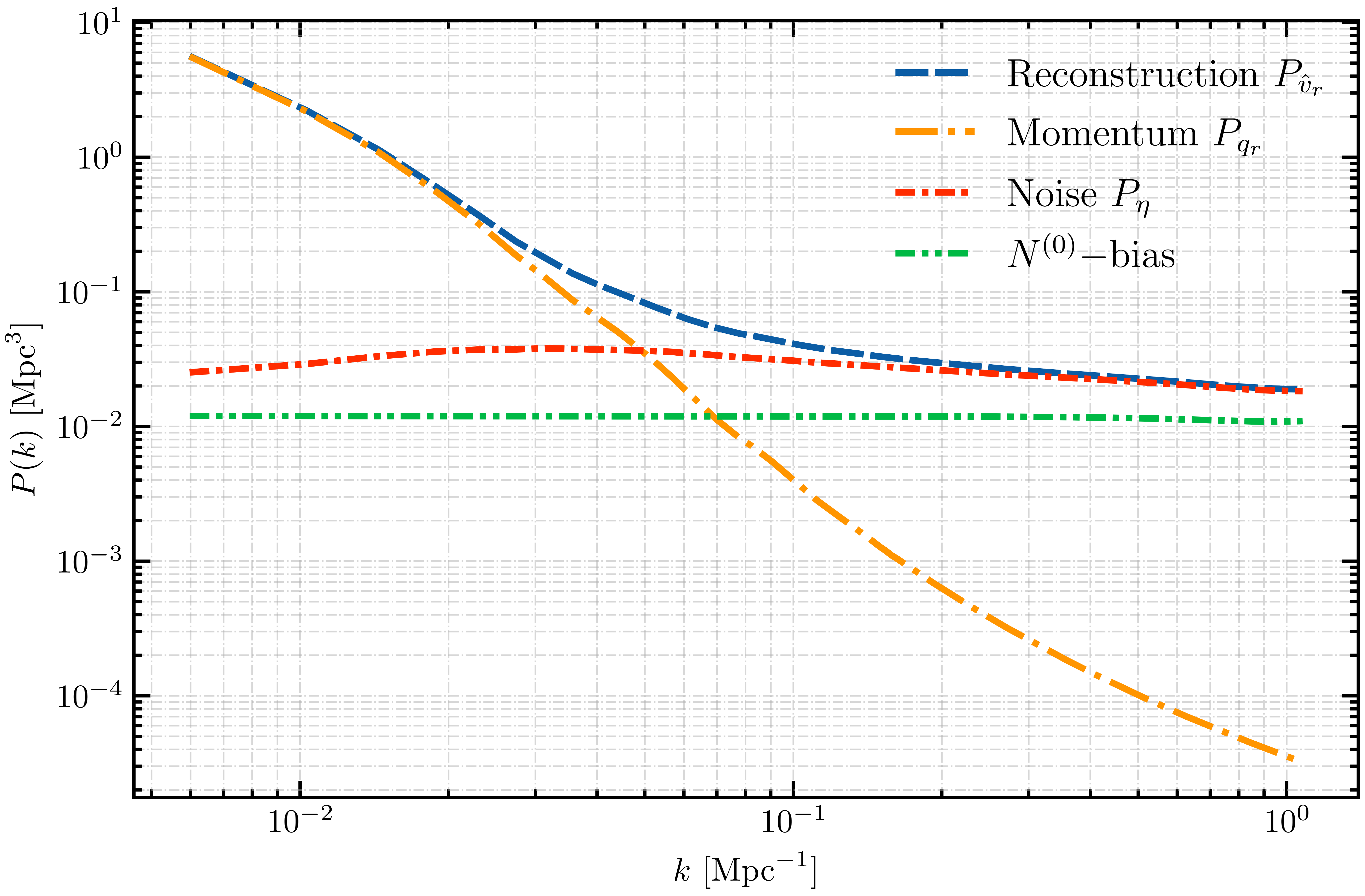


Power spectrum

- The reconstructed power spectrum agrees well with the radial velocity powerspectrum at $k < 0.02\ \mathrm{Mpc}^{-1}$
- Excess **Residual noise** seen

$$\boxed{\text{Power spectrum}(\hat{v}_r - v_r^{true}) \ > N^{(0)}}$$

- The excess noise needs to be modelled for precision cosmology.
- Unaccounted noise can bias parameter inference when analyzing data.



- We revisit the full noise calculation using halo model

Revisiting noise calculation

- Schematically, QE in underlying fields can be represented as

$$\hat{v}_r \sim \delta_g T \sim (\delta_g(T_{kSZ} + T_{other})) \sim \delta_g(\delta_e v_r + T_{other}) \sim (\delta_g \delta_e v_r) + (\delta_g T_{other})$$

- Powerspectrum :

$$P_{\hat{v}_r}(\mathbf{k}_L) = \underbrace{\langle \delta_g \delta_g \rangle \langle T_{\rm other} T_{\rm other} \rangle + (\delta_g v_r \delta_e)(\delta_g v_r \delta_e)}_{N^{(0)}} + \underbrace{(\delta_g v_r \delta_e)(\delta_g v_r g \delta_e)}_{P_{vv}} + \underbrace{(\delta_g v_r \delta_e)(\delta_g v_r \delta_e)}_{N^{(1)}} + \underbrace{\langle (\delta_g v_r \delta_e)(\delta_g v_r \delta_e) \rangle_{ng}}_{N^{(3/2)}}$$

- $N^{(1)} - bias$: Expressed in closed form integral expression. Can also be estimated by doing Monte-Carlo over clever contractions of gaussian realization. **Subdominant!**

- $N^{(3/2)} - bias$:
  - Comes from non-gaussian nature of underlying fields.
  - Integral over 6-point function which we model using the halo model.

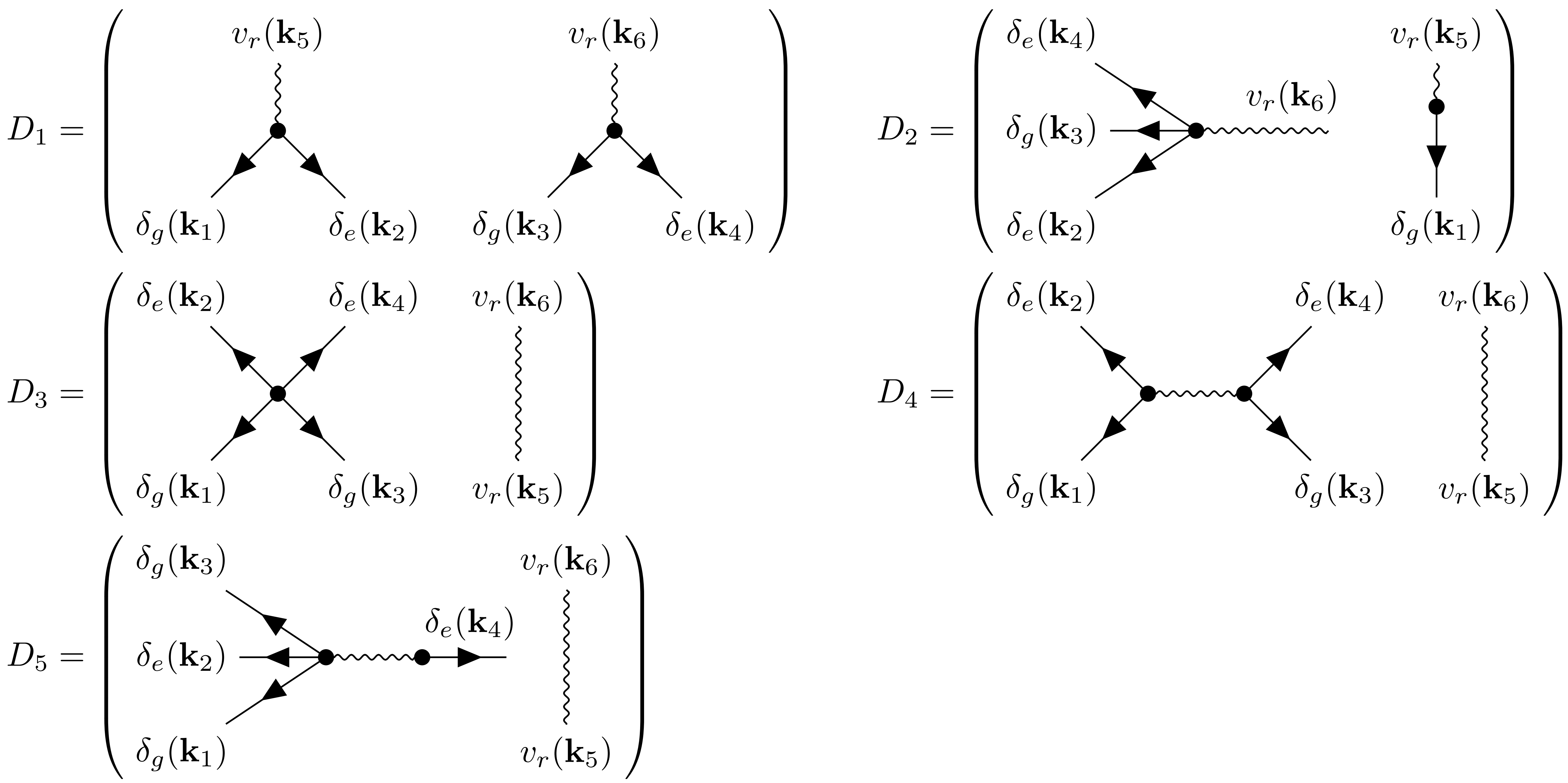
$N^{(3/2)}$-bias

- An integral over the 6-point term $\langle \delta_g(k_1)\delta_e(k_2)\delta_g(k_3)\delta_e(k_4)v_r(k_5)v_r(k_6)\rangle_{ng}$
- We assume v_r is a linear-scale field
- We develop Feynman diagram rules for calculation of higher-point function in the halo model.
- 22 terms in total!

Integration:

- Considerations: Shot noise dominant on small scales + velocity being on linear scales $\implies$ 3/22 terms significant

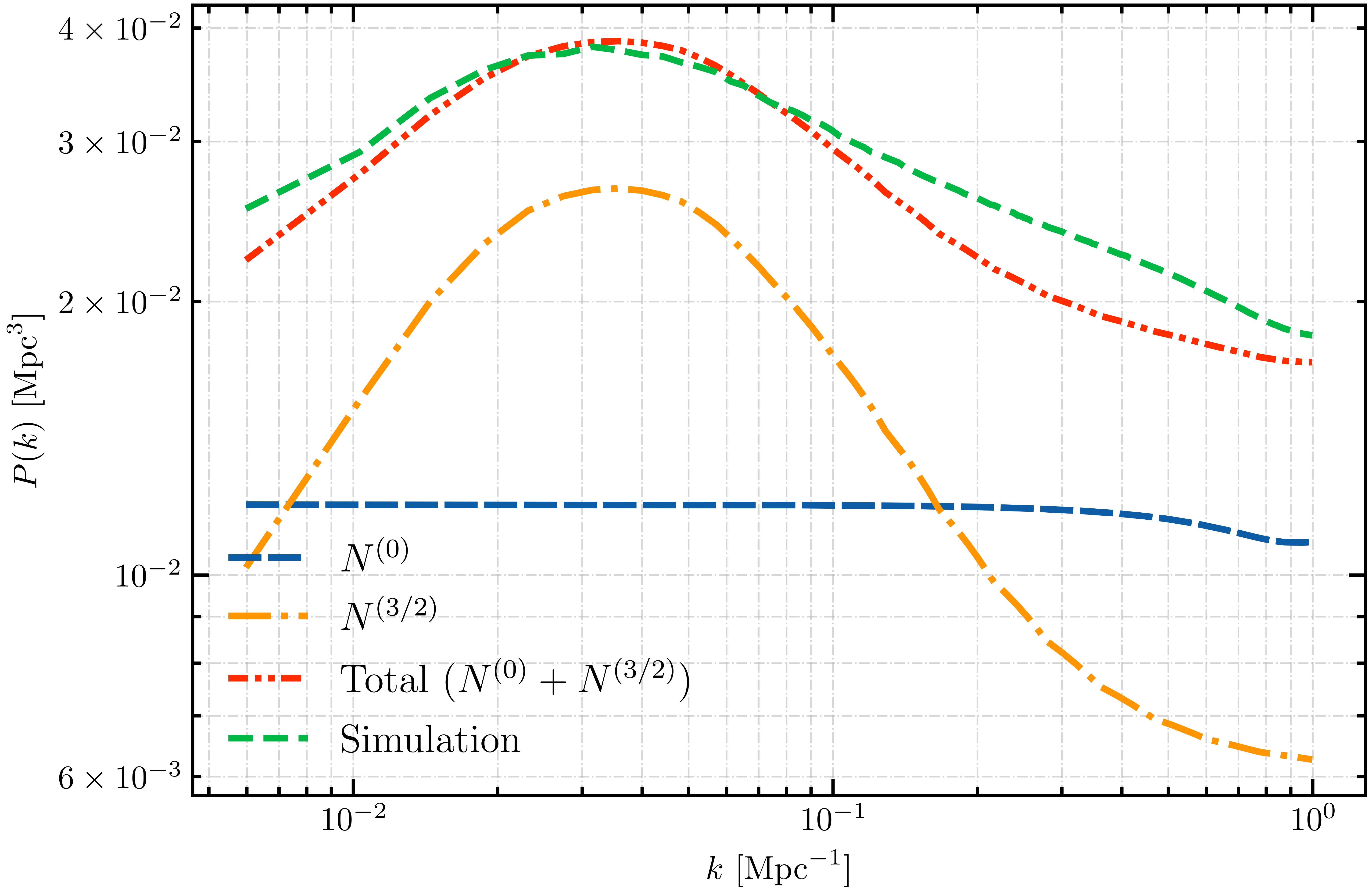
Diagrammatic Representation



D1, D3, D4 contribute

Reconstruction Noise

- We find that our halo model calculation (with some approximations) is able to explain the excess noise in both magnitude and shape.



Application

Primordial Non-Gaussianity

- Phenomenological parameterization of non-gaussianity.

$$\Phi_{NG} = \Phi_G + f_{NL}[\langle \Phi_G^2 \rangle - \langle \Phi_G \rangle^2]$$

- Dalal et. al. 2008 showed that $f_{NL} \neq 0$, adds a scale-dependent bias term to galaxy bias

$$\boxed{b_h = b_g + \frac{2 f_{NL} \delta_c (b_g - 1)}{\alpha(k)}}$$

- Seljak (2009): Use multiple tracers to achieve sample variance cancellation (SVC).
- **Requirement** : High correlation between tracers (we have r>0.97)

Our Likelihood Model

- We build a **mode based** likelihood using large-scale modes of halo density and velocity fields
- Our data vector: $D = [\delta_h^k, \hat{v}_r^k]$
- 3-parameter likelihood model: $\mathscr{L}(b_g, b_v, f_{NL}) \propto exp\left(-\dfrac{D^T C^{-1} D}{2} \right)$

where. $$C = \begin{pmatrix} P_{hh} + \frac{1}{n_g} & P_{hv} \\ P_{hv} & P_{vv} + N^{(0)} \end{pmatrix}$$

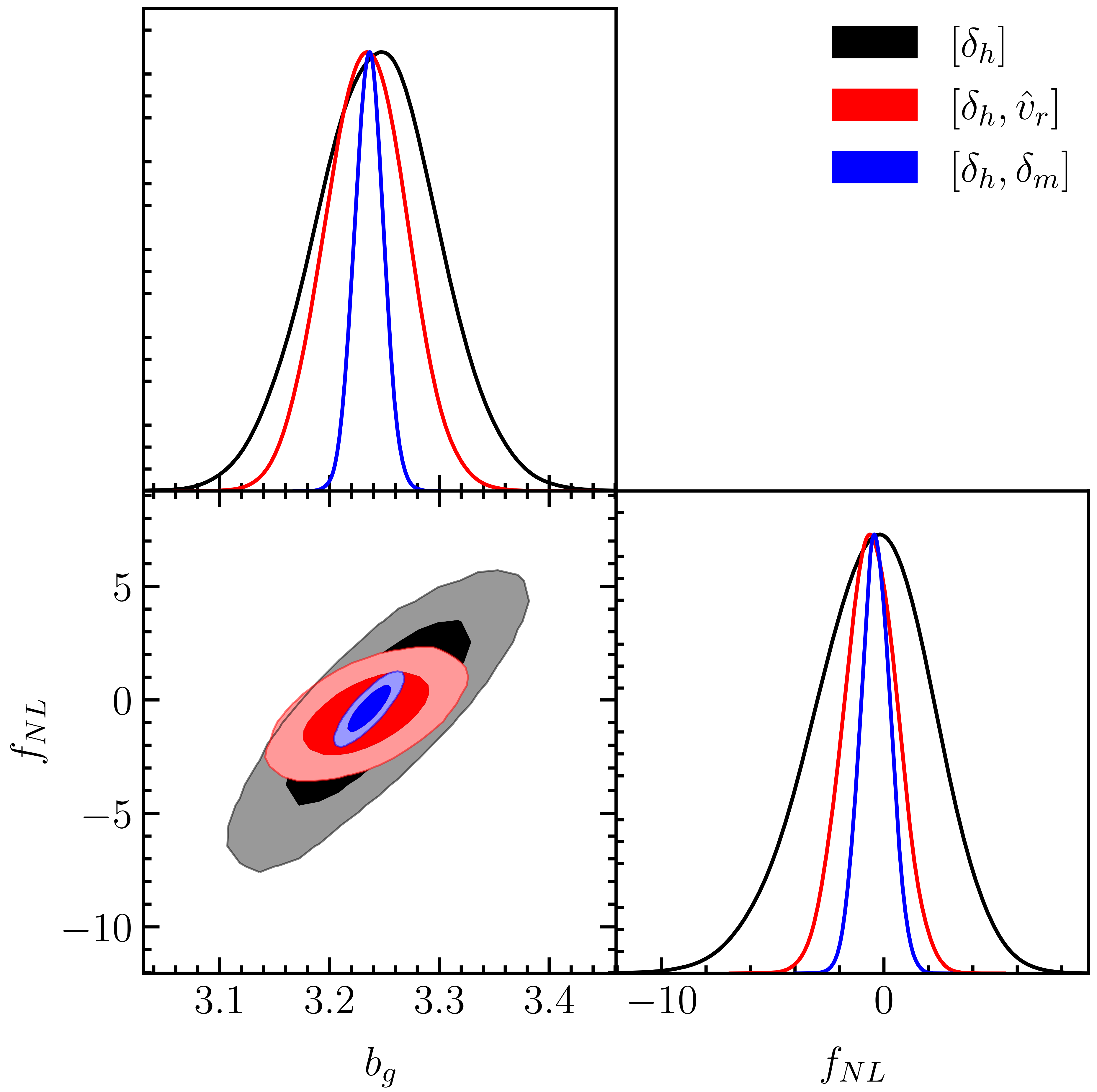
$$P_{hv} = \left(b_v \frac{k_r faH}{k^2} \right) \left(\frac{b_g + 2f_{NL}(\delta_c - 1)}{\alpha(k)} \right) P_{mm}(k)$$

$$P_{hh} = \left(b_g + \frac{2f_{NL}\delta_c(b_g - 1)}{\alpha(k)} \right)^2 P_{mm}(k)$$

$$P_{vv} = \left(b_v \frac{k_r faH}{k^2} \right)^2 P_{mm}(k)$$

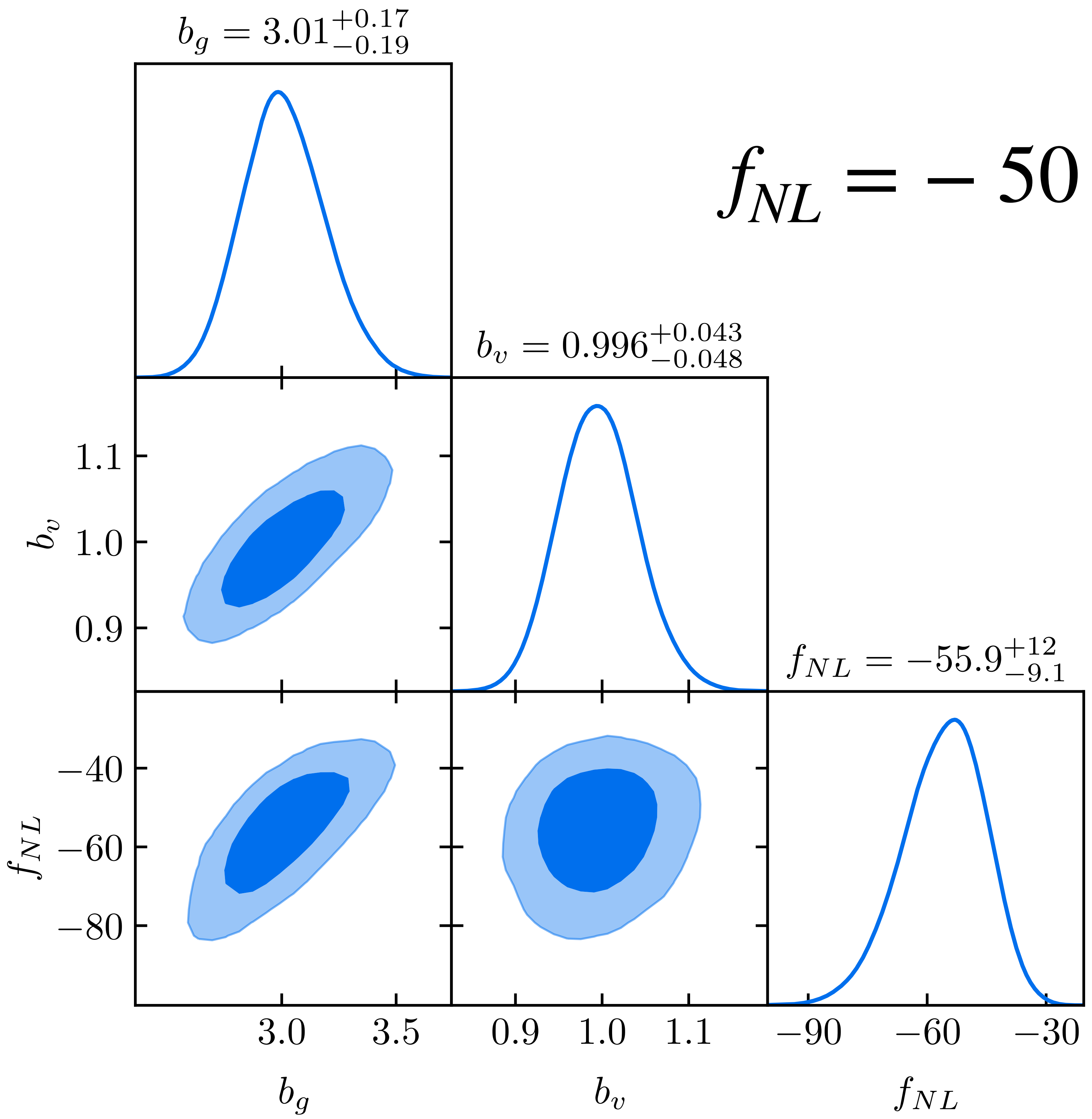
$f_{NL} = 0$ case

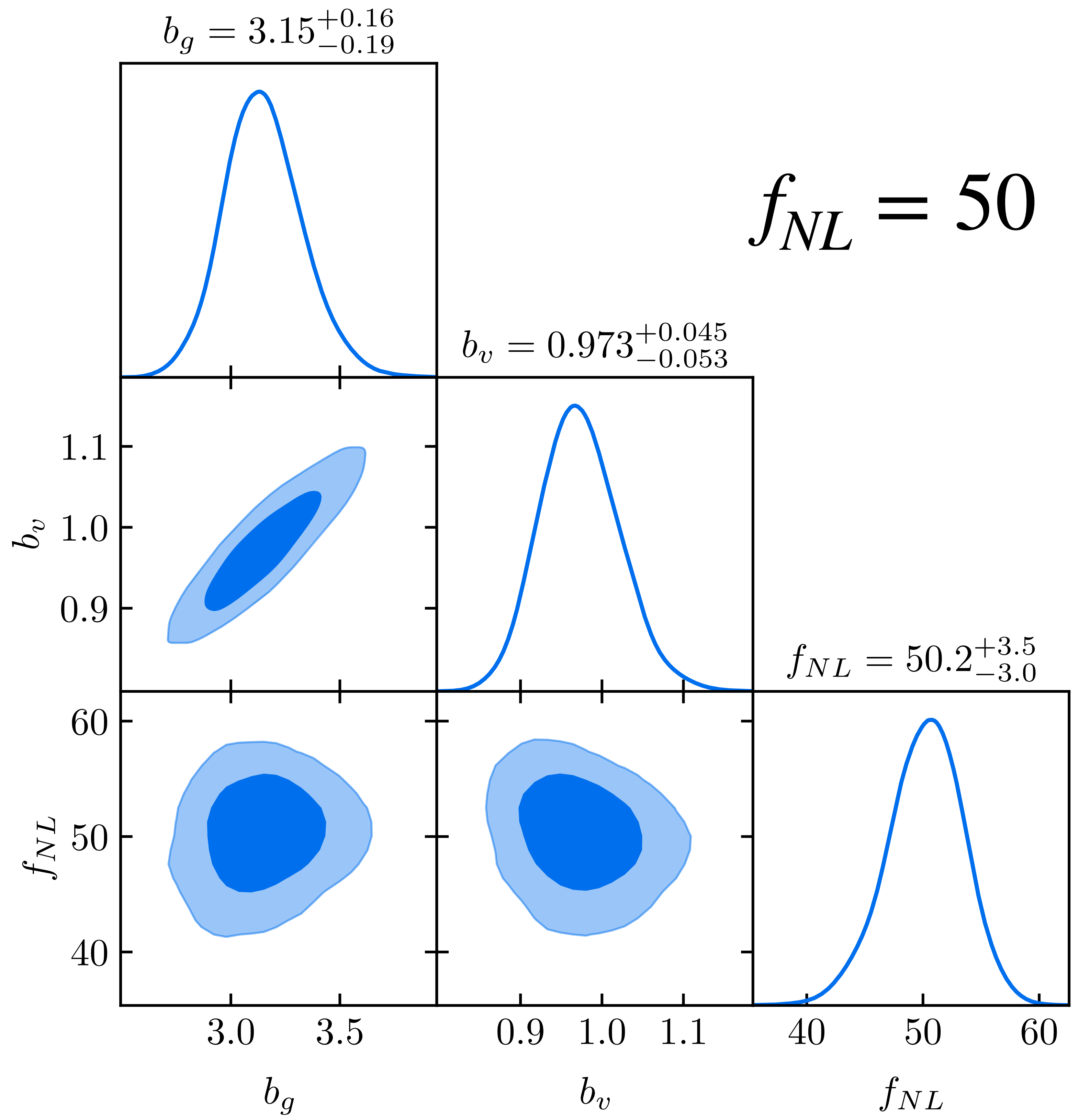
- We compose a joint likelihood from the 100 high resolution simulations.
- Recover unbiased $f_{NL} = 0$ when using reconstructed velocity fields.
- Improves constraints relative to halo-only treatment which shows sample variance cancellation is happening.
- Reconstruction+SVC works!



$f_{NL} \neq 0$ case

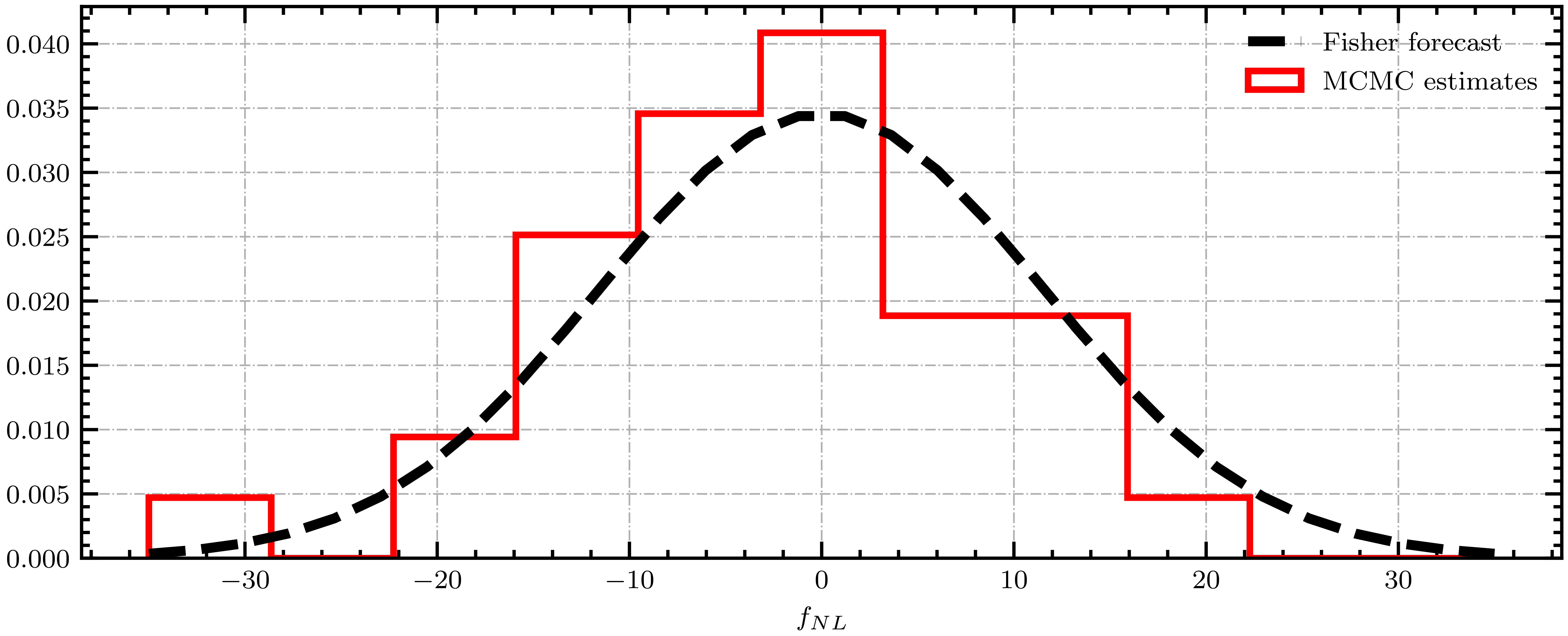
- We study 4 GADGET-2 simulations with non-gaussian potential ($f_{NL} \neq 0$)
- Here again we recover unbiased estimates of f_{NL}





Fisher analysis

- Results from ensemble of 100 simulations with $f_{NL} = 0$ agrees with gaussian Fisher estimate within few percent.
- This validates the gaussian likelihood model thus demonstrating another desirable quality of reconstructed field.

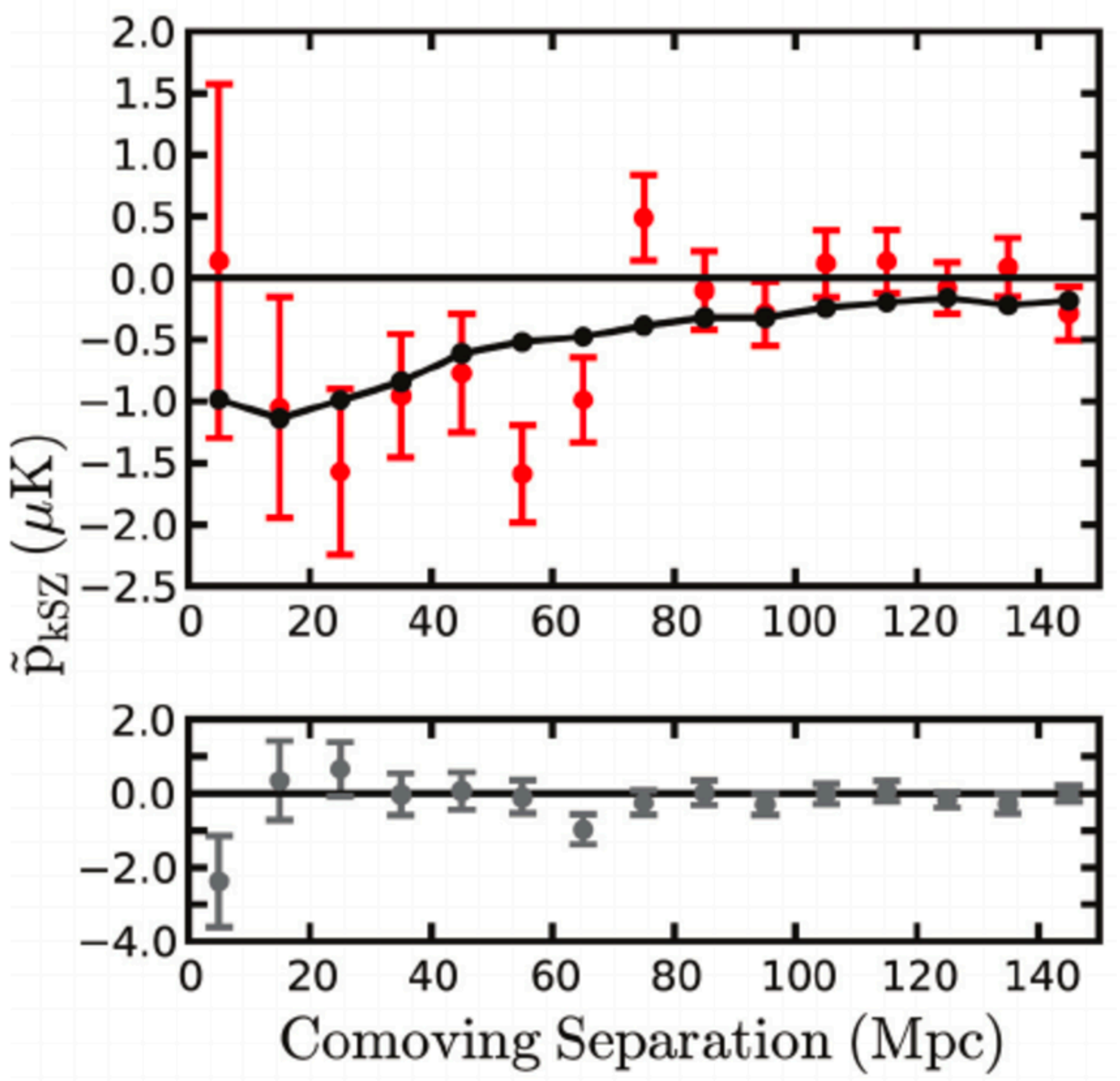


Conclusion

- We show using simulations that kSZ velocity reconstruction works!
- High correlation with linear velocity is achieved.
- Powerspectrum has new additional noise terms: $N^{(1)}$ and $N^{(3/2)}$
- $N^{(3/2)}$-bias is of the same order as $N^{(0)}$-bias, must be included in analysis.
- We derive the non-gaussian 6-point $N^{(3/2)}$-bias in the halo model
- Our 'end-to-end' MCMC pipeline shows that using a gaussian likelihood model we can achieve SVC and improve constraints on f_{NL} using kSZ velocity!
- Lots of avenues to pursue in the near future!!

kSZ estimators

- A lot of effort has been put into developing estimators.
- Several seemingly different cross-correlation estimators have been designed
  - Pairwise estimator
  - Velocity template
  - **Velocity reconstruction**
  - …
- They have been successful in detecting the kSZ signal at a few sigma



Pairwise kSZ detection from Hand et. al. 2012

Results: Bias

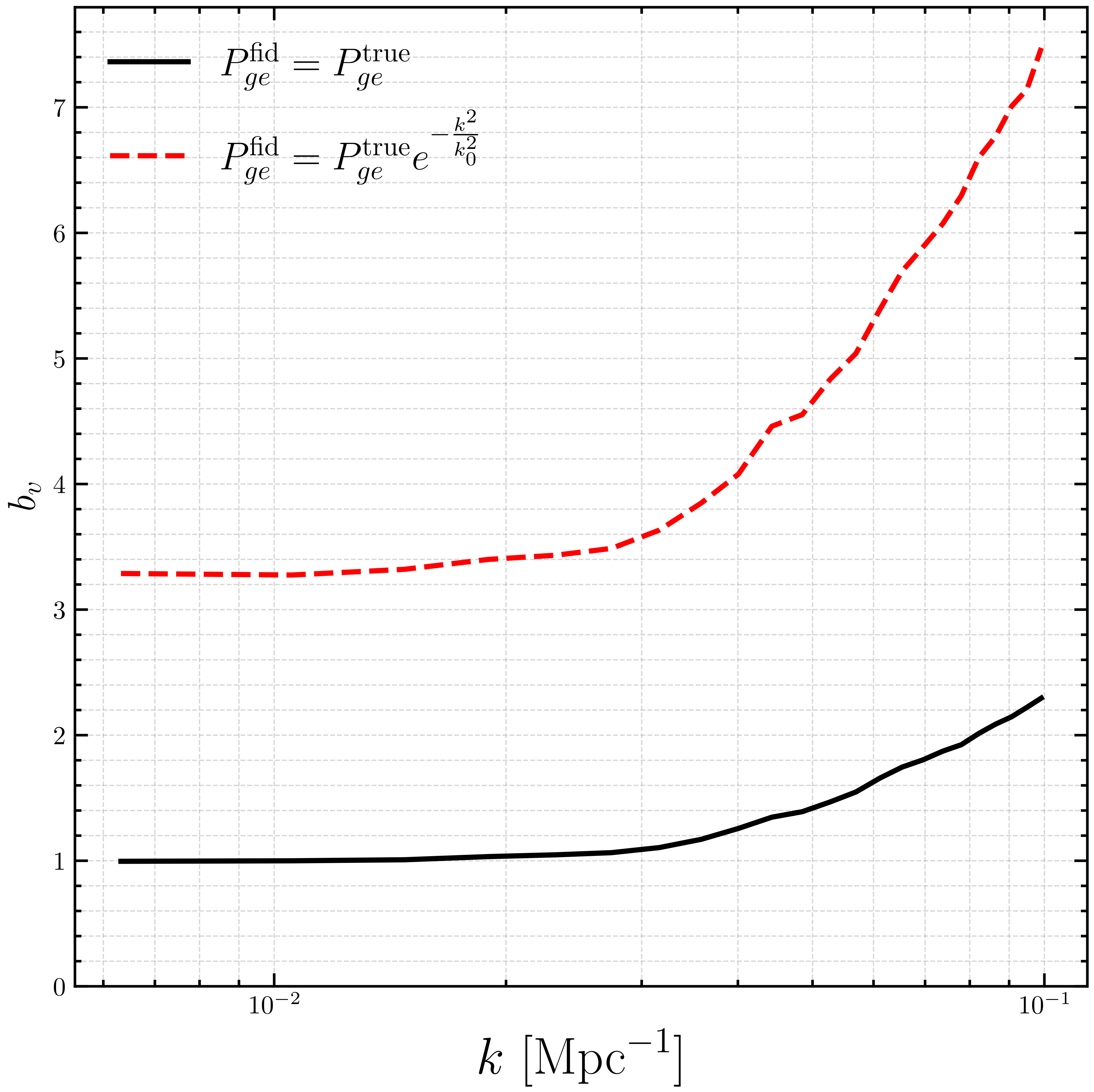
- The estimator reconstructs
$$\langle v_r \rangle = b_v v_r^{true} \quad \text{(at LO)}$$
- Bias reflects uncertainty in modelling electron-halo connection aka optical-depth degeneracy

$$b_v = \frac{\int dk_s F(k_s) P_{ge}^{fid}(k_s)}{\int dk_s F(k_s) P_{ge}^{true}(k_s)}$$ **[arXiv:1810.13423]**

- Bias estimate from simulations is

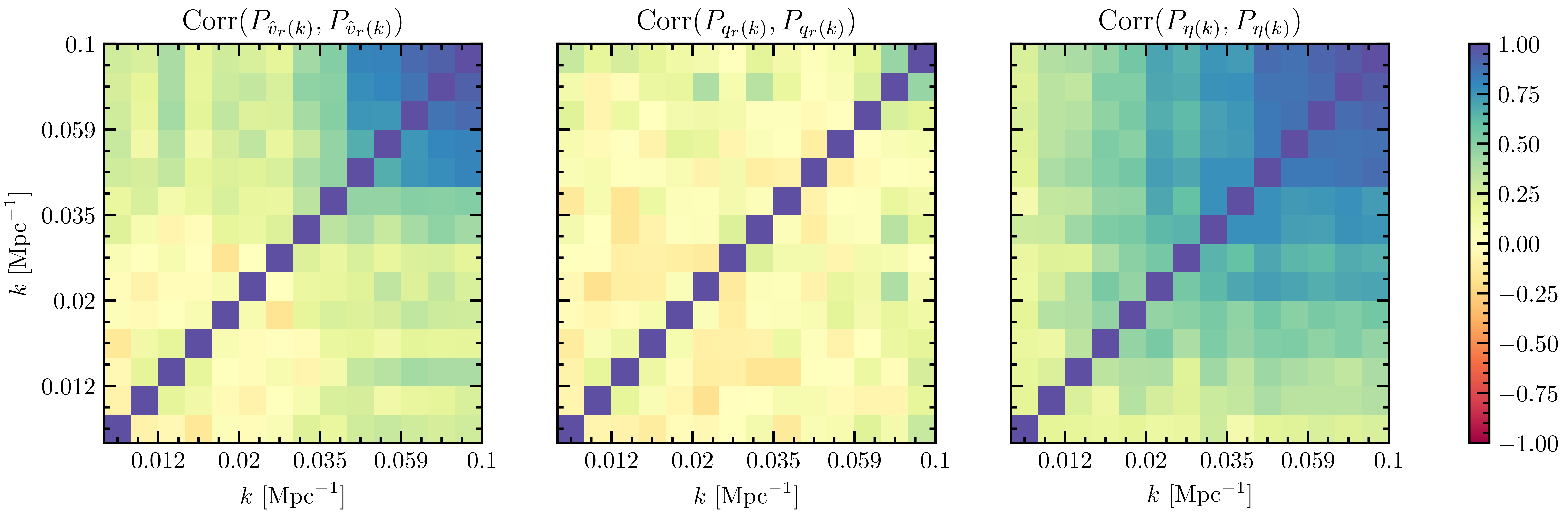
$$b_v = \frac{P_{v_r \hat{v}_r}}{P_{v_r v_r}}$$

- For $k \sim 0.01\ \text{Mpc}^{-1}$,
$b_v \to 1$ when $P_{ge}^{fid} = P_{ge}^{true}$



Powerspectrum Covariance

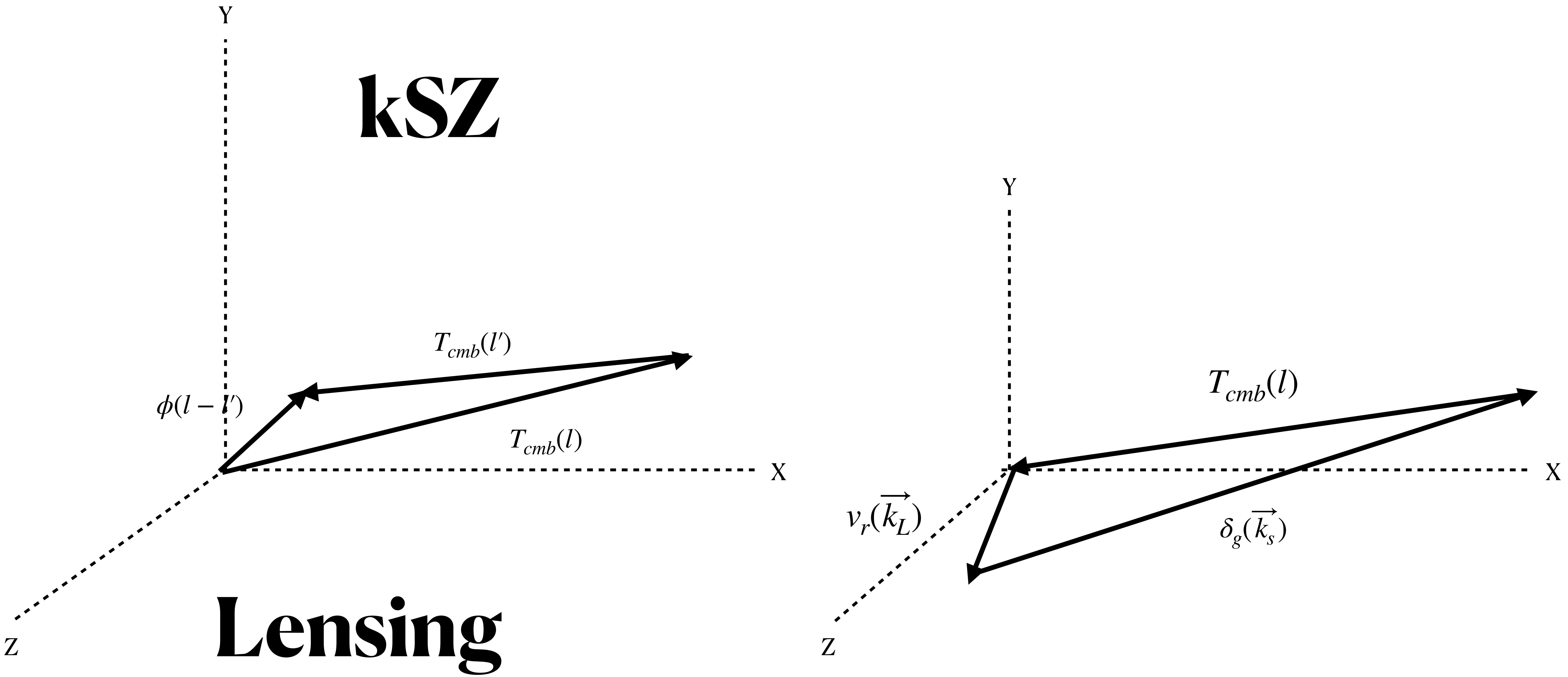
- For a gaussian field, $Corr(i,j) = \delta^K_{i,j}$



- We find that

$$Corr(i,j) = \delta^K_{i,j}$$
$$\approx \mathcal{O}(1) @ k > 0.03\ \mathrm{Mpc}^{-1}$$

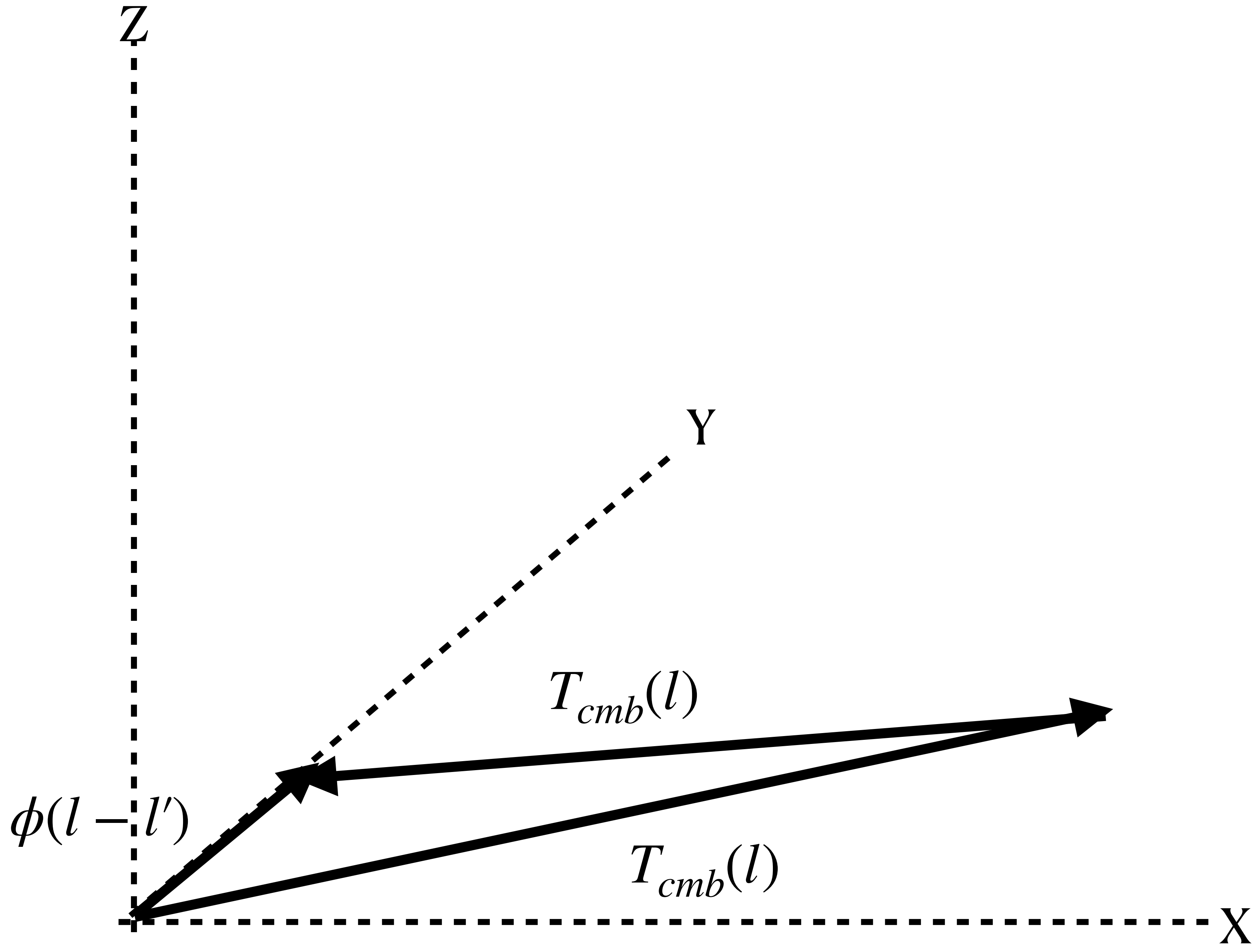
QE: Lensing vs kSZ geometry

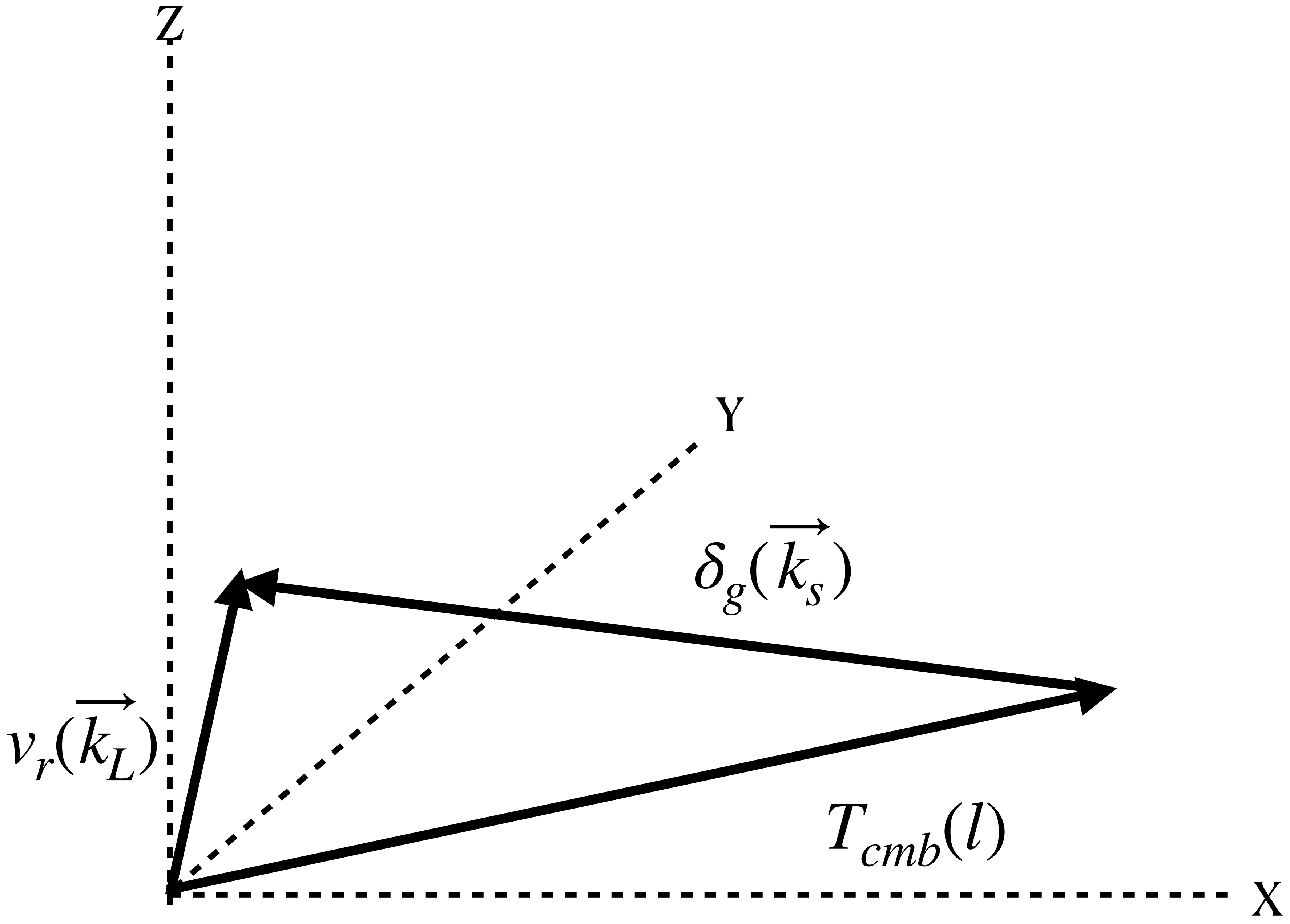


Kinetic Sunyaev-Zeldovich

- So far detected in cross-correlation with LSS at a few-σ
- High significance detection imminent thus potentially enabling very interesting science.
- A lot of effort has been put into developing estimators
- Various estimators:
  - Pairwise estimator [Hand et. al. 2012 and references therein]
  - Velocity template [Ho et. al. 2008, Schaan et. al. 2020]
  - **Velocity quadratic estimator** [Terrana et. al. 2016, Cayuso et. al. 2017]

QE: Lensing vs kSZ geometry





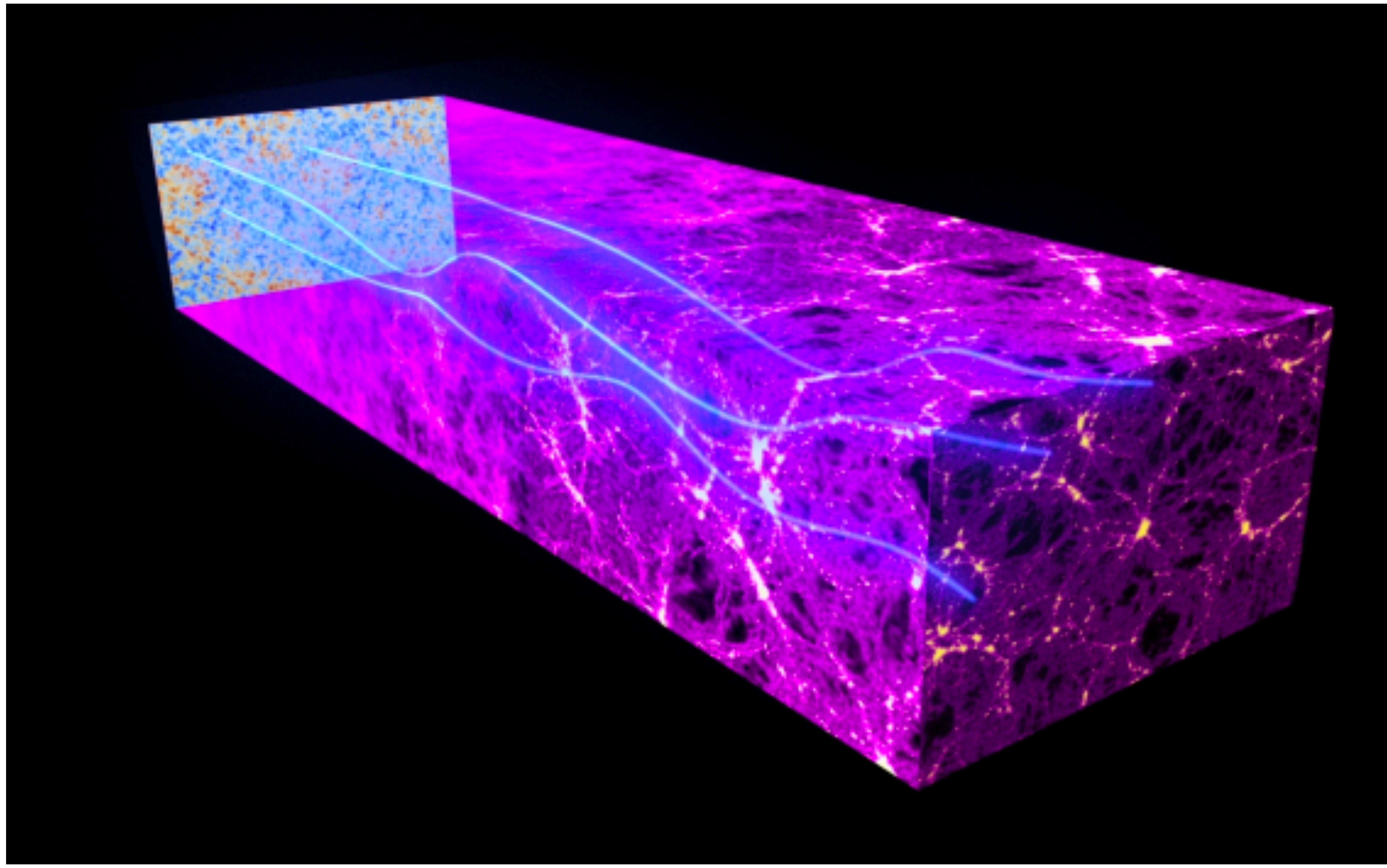
Lensing

kSZ

Implication for upcoming surveys:

Secondary Anisotropies

- Sourced by scattering of CMB off intervening structure between the surface of last scattering and us.
- Examples include:
  - CMB lensing   [Sensitive to Ω_m, Σm_ν, σ_8]
  - Sunyaev-Zeldovich (SZ) effect
    - Thermal Sunyaev-Zeldovich(tSZ)
    - Kinetic Sunyaev-Zeldovich (kSZ)
      - Patchy kSZ
      - **Late-time kSZ**



Sample Variance Cancellation

- Seljak 2009: For a phenomenon like primordial non-gaussianity that affects the clustering of tracers, instead of looking at its signature in the powerspectrum of stochastic tracer field which suffers from fundamental sample variance, one can instead look at the relative clustering bias of 2 tracers which circumvents sample variance limit and allows for arbitrary precision in principle. This is the idea of sample variance cancellation(SVC)
-

Velocity Quadratic Estimator

- New probe of LSS cosmology
- Offers a neat way of using kSZ effect for cosmological studies
- Extremely useful in constraining physics which affects largest-scales
- Can probe models of DE, modified gravity and sum of neutrino mass modulo optical depth degeneracy.
- One application we explore: Constraining primordial non-gaussianity

Velocity Quadratic Estimator

- Modulation of small-scale δ_e by a large-scale v_r

$$T(l) \approx T_{cmb}(l) + v_r(k_L)\delta_e(k_S)$$

- Implies

$$\langle \delta_g(k_S) T(l) \rangle_{fix\ k_L} \propto v_r(k_L)$$

- In words, one can combine CMB map with galaxy surveys at small-scales to reconstruct large-scale radial velocity modes.

- The scales involved are:

$$l \sim 5000$$

$$k_L \ll \frac{l}{\chi_*} \approx 0.01\ \mathrm{Mpc}^{-1}$$

$$k_S \sim \mathcal{O}(1)\ \mathrm{Mpc}^{-1}$$

Revisiting Noise calculation

Simulations

- Quijote Simulations [Villaescusa-Navarro 2019]:
  - N-body simulations with gaussian initial condition using GADGET-2
  - Box-size=1 h^{-1}Gpc ; Particles=1024^3
- Our ansatz:
  - Snapshot geometry; $\delta_g = \delta_h; \delta_e = \delta_m$

$$N(l) = s_w^2 exp\left[\frac{-l(l+1)\theta_{fwhm}^2}{8ln2}\right]; \mathrm{s_w} = 0.5\ \mu\mathrm{k\ arcmin}; \quad \theta_{\mathrm{fwhm}} = 1\ \mathrm{arcmin}$$

- $T_{sim} = T_{primary} + T_{kSZ} + T_{noise}$

Primordial Non-Gaussianity

- A model for non-gaussianity

$$\Phi_{NG} = \Phi_G + f_{NL}[\langle \Phi_G^2 \rangle - \langle \Phi_G \rangle^2]$$

- $f_{NL} = 0$ under simple models of inflation. Single-field slow roll inflation with canonical kinetic terms and Bunch-Davies vaccua.
- Multi-field inflation induces non-zero f_{NL}
- $f_{NL} \neq 0$ induces non-zero bispectrum under squeezed configuration in CMB
- Also induces bispectrum in LSS modulo late-time non-gaussianity