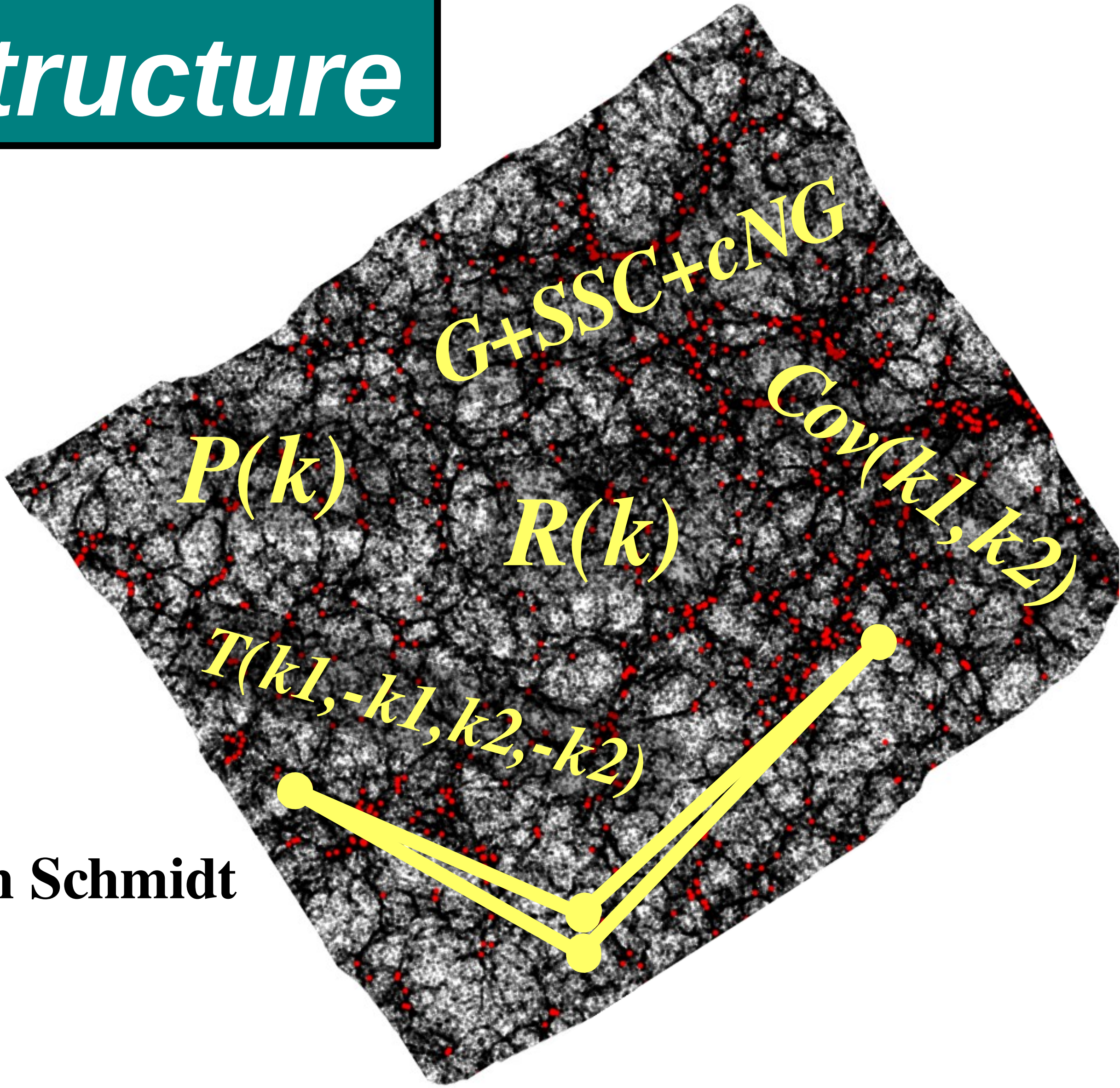
Responses in and on Large Scale Structure



Alexandre Barreira
(MPA)

with Elisabeth Krause & Fabian Schmidt

PTChat Kyoto – April 2019

In this talk ...

1) Response Approach to Perturbation Theory

Barreira, Schmidt , 1703.09212
Barreira, Schmidt , 1705.01092

2) Covariance applications

Barreira, Krause, Schmidt, 1711.07467
Barreira, Krause, Schmidt, 1807.04266
Barreira, 1901.01243

3) Baryonic effects on higher-order N-point functions

Barreira et al 1904.02070

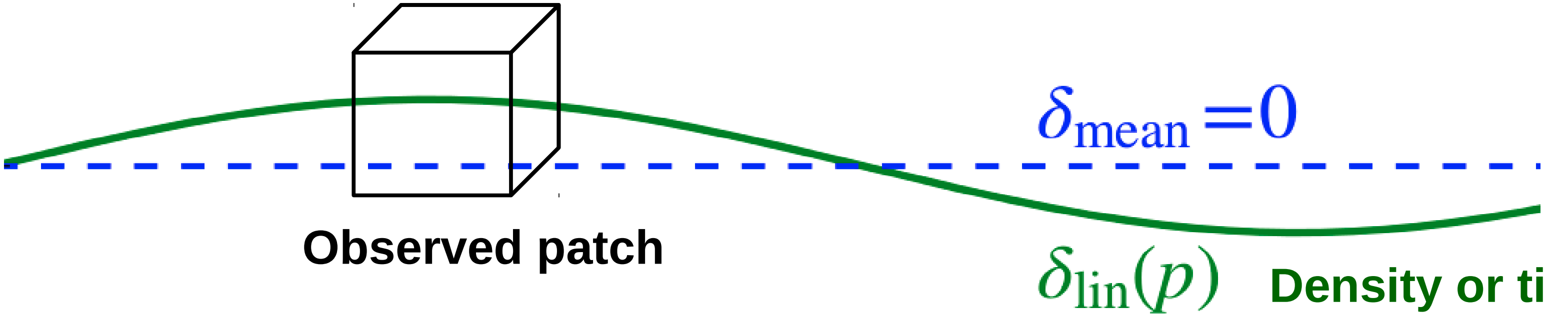
Response Approach to PT

Barreira, Schmidt , 1703.09212
Barreira, Schmidt , 1705.01092

What are responses?

Responses describe how the power spectrum responds to the presence of large-scale perturbations.

$$\boxed{\mathcal{R}_n \equiv \frac{1}{n!P(k)} \frac{\mathrm{d}^n P(\boldsymbol{k}, \delta_1 \cdots \delta_n)}{\mathrm{d}\delta_1 \cdots \mathrm{d}\delta_n}\bigg|_{\delta_a=0}}$$



Density or tidal field perturbation

What are responses?

ctrum responds to the presence
turbations.

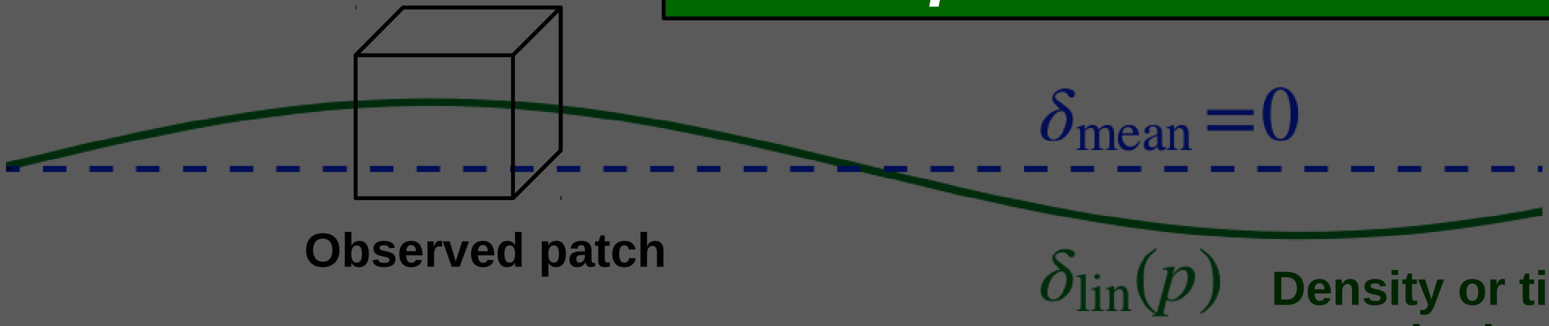
What are they good for?

To “resum” squeezed PT kernels

$$\mathcal{R}_n \equiv \frac{1}{n!P(k)} \frac{\mathrm{d}^n P(\boldsymbol{k}, \delta_1 \cdots \delta_n)}{\mathrm{d}\delta_1 \cdots \mathrm{d}\delta_n} \Bigg|$$

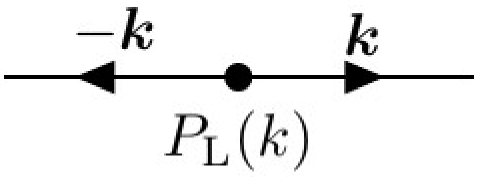
How do we evaluate them?

With separate universe simulations



Density or tidal field perturbation

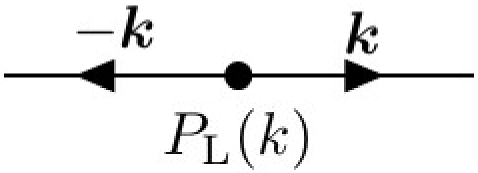
Responses as PT vertices



$$\equiv P_L(k,t)$$

- The **linear** matter power spectrum.

Responses as PT vertices



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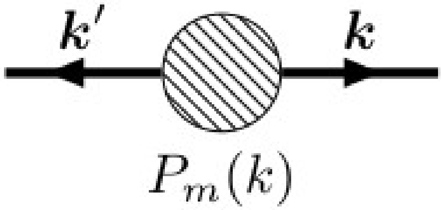

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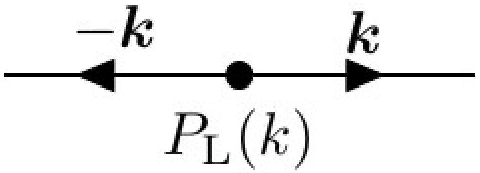
- The **nonlinear** matter power spectrum; the blob describes all nonlinear interactions.

Responses as PT vertices



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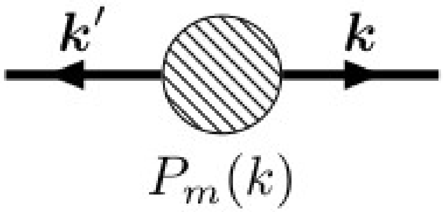

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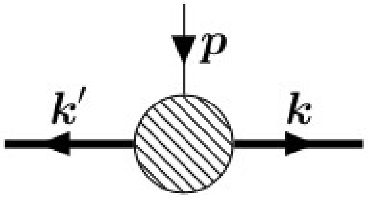
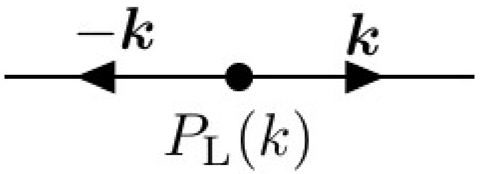
- Interaction of P(k) with a mode **p**



Responses as PT vertices



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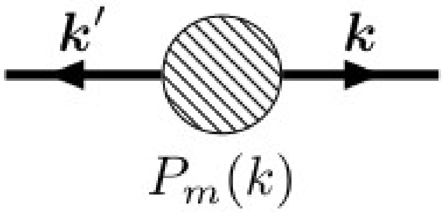

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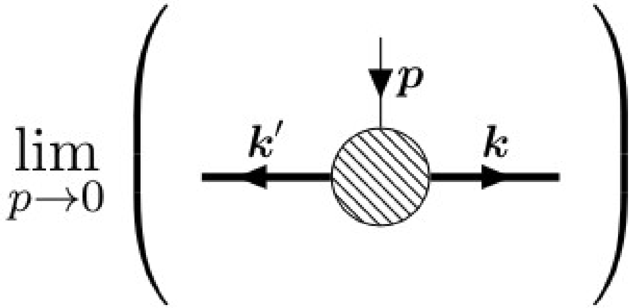

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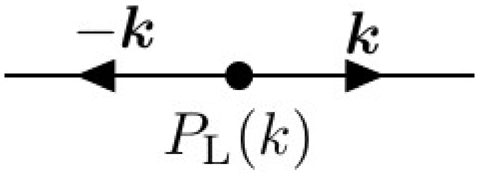

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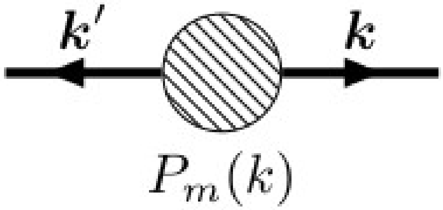

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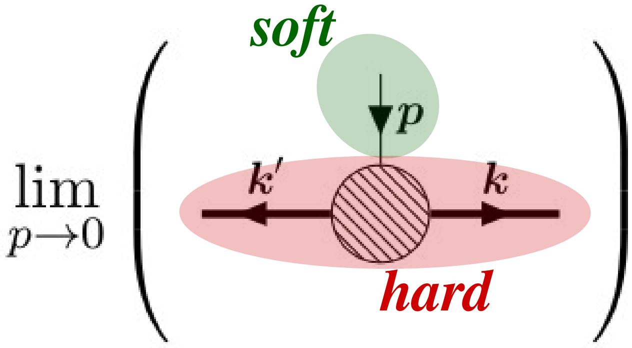
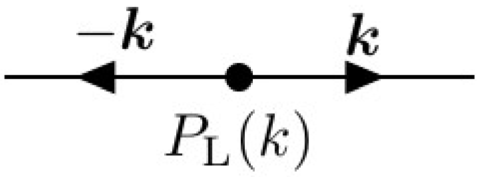


Response interaction

- Interaction of P(k) with a mode **p**

Responses as PT vertices



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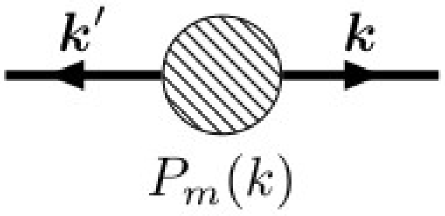

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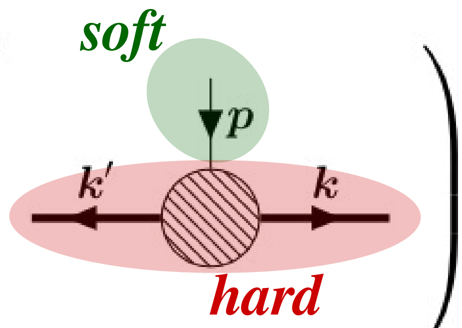


$$\lim_{p\to 0}\left(\quad \right) \equiv \frac{1}{2}\mathcal{R}_1(k;\mu_{\boldsymbol{k},\boldsymbol{p}};t)P_m(k,t)$$

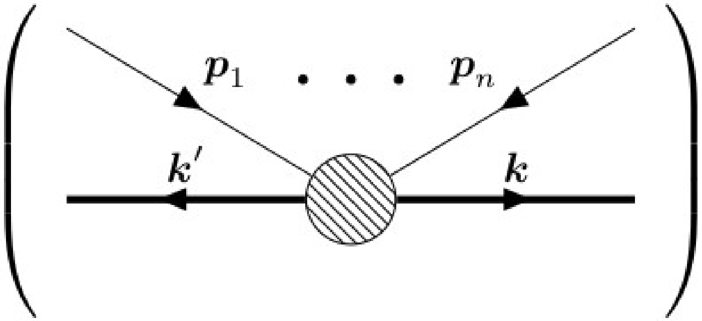
Response interaction

1st order response

Responses as PT vertices

The n-th order response vertex:

the interaction of the power spectrum with N soft modes.



$$\lim_{\{p_a\}\to 0} \left(\quad \right) = \frac{1}{2}\mathcal{R}_n(k;\text{angles})P_m(k)$$

Barreira, Schmidt , 1703.09212

Responses as PT vertices

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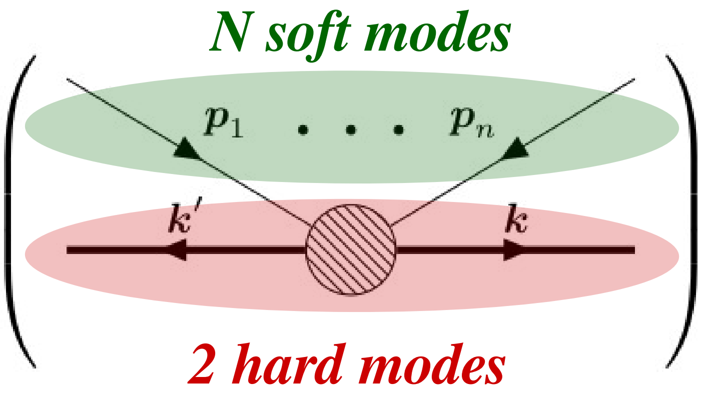
n-th order response



$$\lim_{\{p_a\}\to 0}\left(\;\right) = \frac{1}{2}\mathcal{R}_n(k;\text{angles})P_m(k)$$

Predictive for:

- ***Quasi-linear values of the soft modes, p_n***
- ***Nonlinear values of the hard modes, k,k'***

Barreira, Schmidt , 1703.09212

The Response Recipe

1. Take any N-point function and write all SPT terms.

2. Identify hard-to-soft coupling terms.

3. Replace these SPT kernels by the responses.

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$$\langle\delta(\boldsymbol{k}_1)\delta(\boldsymbol{k}_2)\cdots\delta(\boldsymbol{k}_N)\rangle \quad = \quad \text{Tree Level} \;+\; 1\text{ Loop} \;+\; 2\text{ Loop} \;+\cdots$$

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Evaluate with responses.

Evaluate with SPT kernels

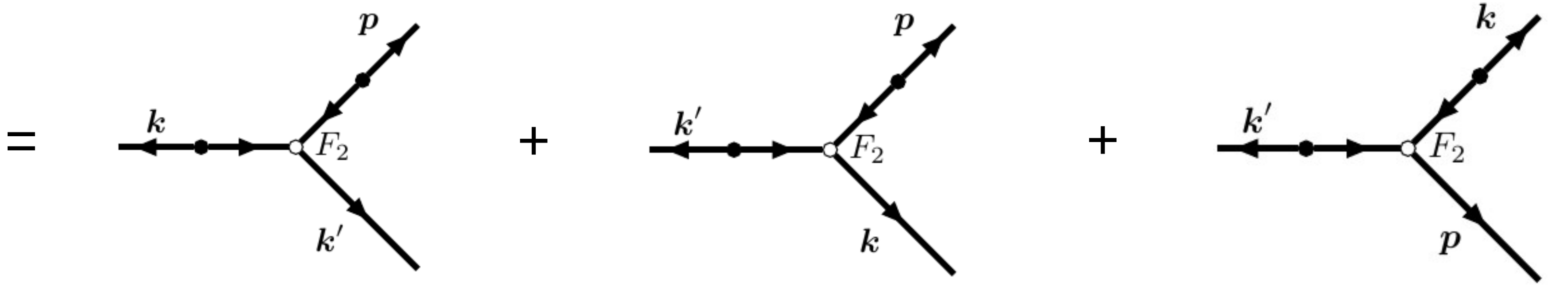
Example 1: Squeezed Bispectrum

$$\langle \delta(\boldsymbol{k})\delta(\boldsymbol{k}')\delta(\boldsymbol{p})\rangle_c$$

hard ***soft***

Example 1: Squeezed Bispectrum

$$\left\langle \underset{\textit{hard}}{\delta(\boldsymbol{k})\delta(\boldsymbol{k}')}\,\underset{\textit{soft}}{\delta(\boldsymbol{p})} \right\rangle_c = 2F_2(\boldsymbol{k},\boldsymbol{p})P_{\rm L}(k)P_{\rm L}(p) \;+\; 2F_2(\boldsymbol{k}',\boldsymbol{p})P_{\rm L}(k')P_{\rm L}(p) \;+\; 2F_2(\boldsymbol{k},\boldsymbol{k}')P_{\rm L}(k)P_{\rm L}(k')$$



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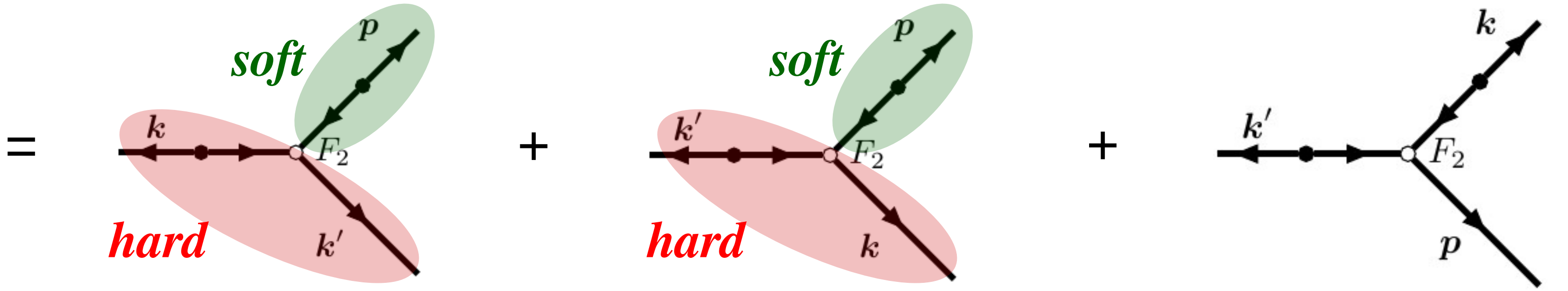

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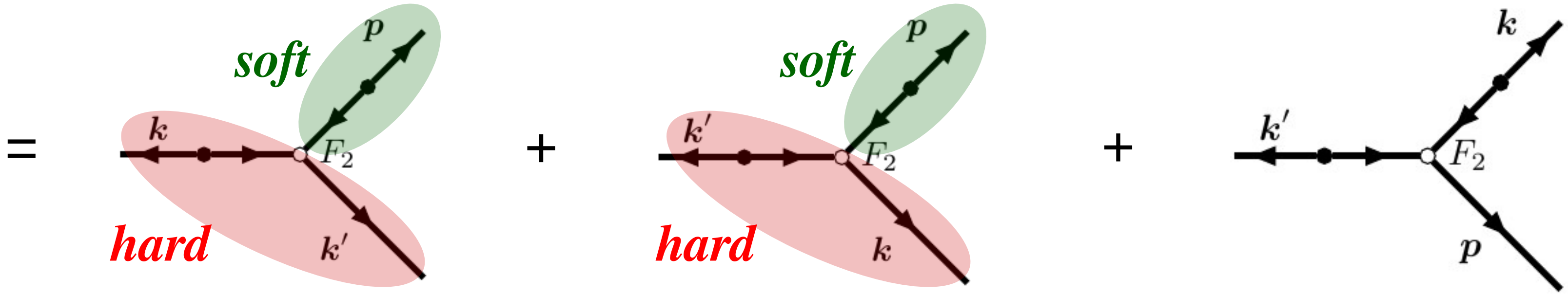
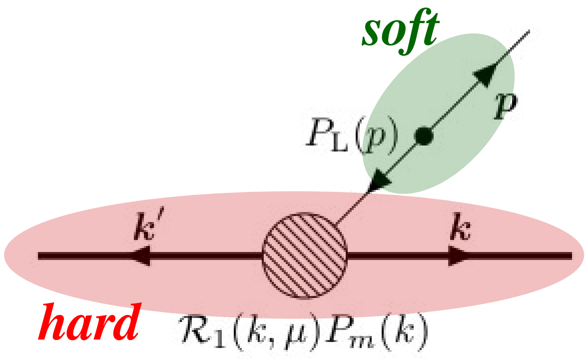


Evaluate with responses



$$+\,(\boldsymbol{k} \leftrightarrow \boldsymbol{k}') = \mathcal{R}_1(k,\mu_{\boldsymbol{k},\boldsymbol{p}})P_m(k)P_{\rm L}(p)$$

Valid for nonlinear k,k' .

Example 1: Squeezed Bispectrum

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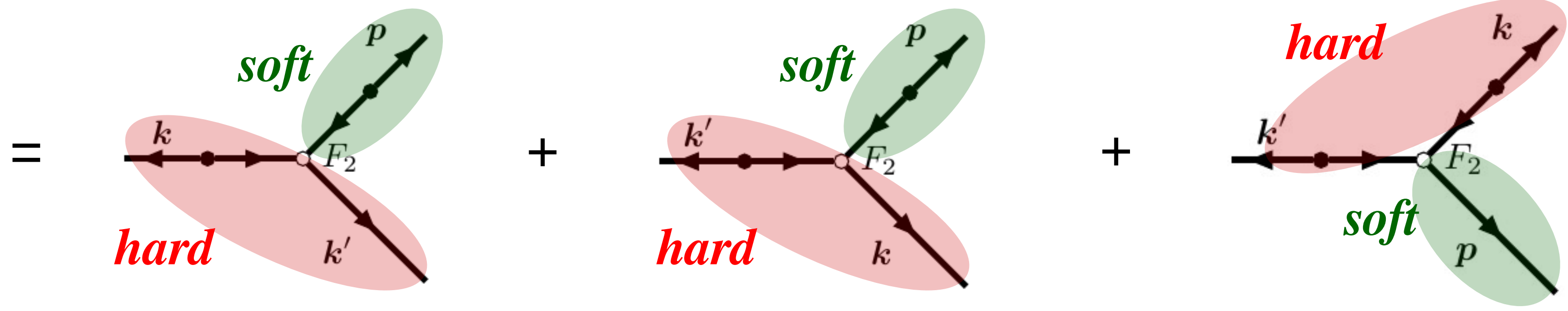
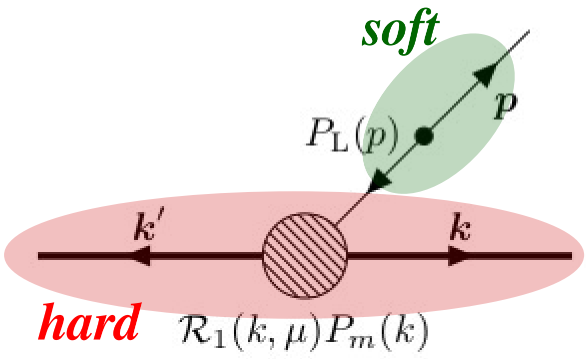


~ (p/k)^2

Evaluate with responses



$$+\,(\boldsymbol{k} \leftrightarrow \boldsymbol{k}') = \mathcal{R}_1(k, \mu_{\boldsymbol{k},\boldsymbol{p}})P_m(k)P_\mathrm{L}(p)$$

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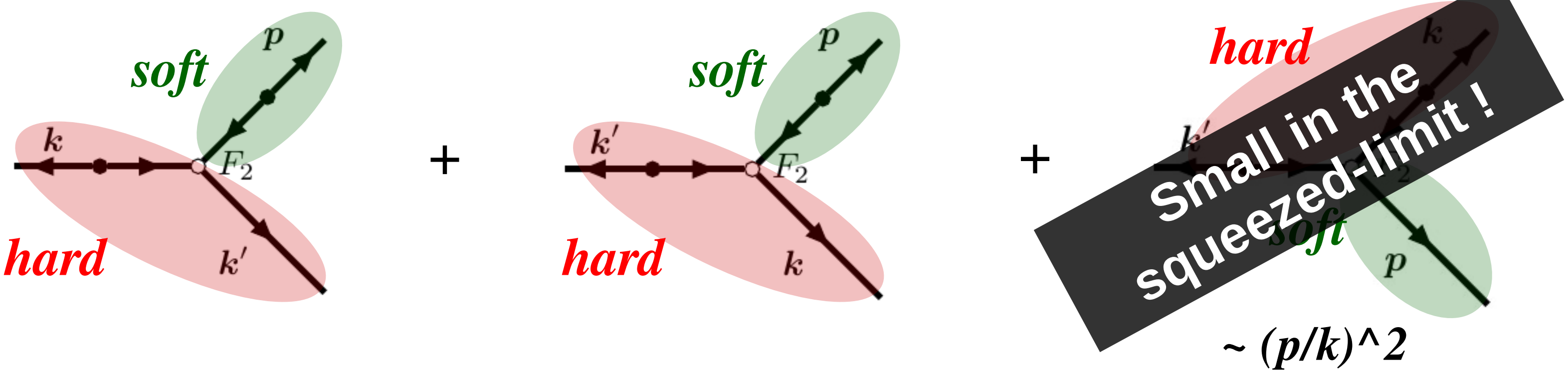
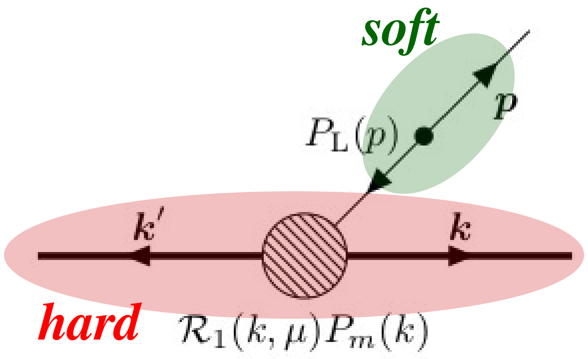
hard *soft*

= 

Small in the squeezed-limit !

~ (p/k)^2

Evaluate with responses



$$+ \, (\boldsymbol{k} \leftrightarrow \boldsymbol{k}') = \mathcal{R}_1(k,\mu_{\boldsymbol{k},\boldsymbol{p}})P_m(k)P_{\rm L}(p)$$

Valid for nonlinear k,k' .

Example 1: Squeezed Bispectrum

$$\lim_{p\to 0}\ \left\langle \underbrace{\delta(\boldsymbol{k})\delta(\boldsymbol{k}')}_{\text{hard}}\underbrace{\delta(\boldsymbol{p})}_{\text{soft}} \right\rangle_c$$

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$$2\Big[F_2(\boldsymbol{k},\boldsymbol{p})P_{\rm L}(k)+F_2(\boldsymbol{k}',\boldsymbol{p})P_{\rm L}(k')\Big]P_{\rm L}(p)$$

All modes p,k,k' must be linear

With Standard Perturbation Theory

$$\lim_{p\to 0}\ \Big\langle \underbrace{\delta(\boldsymbol{k})\delta(\boldsymbol{k}')}_{\text{hard}}\underbrace{\delta(\boldsymbol{p})}_{\text{soft}}\Big\rangle_c$$

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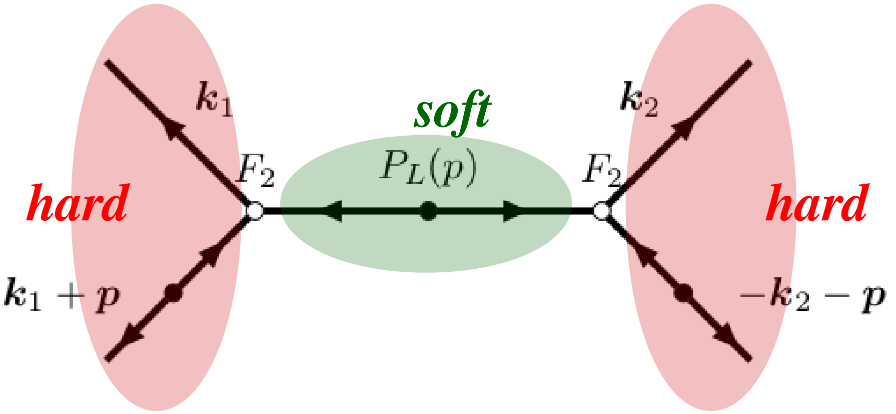
With responses

Result is valid for linear p, ***but any nonlinear k, k' !***

$$\mathcal{R}_1(k,\mu_{\boldsymbol{k},\boldsymbol{p}})P_m(k)P_{\rm L}(p)$$

Example 2: SSC

$$\mathrm{Cov}\Big[\underset{\text{hard}}{P_m(\boldsymbol{k}_1)}, \underset{\text{hard}}{P_m(\boldsymbol{k}_2)}\Big] \supset$$

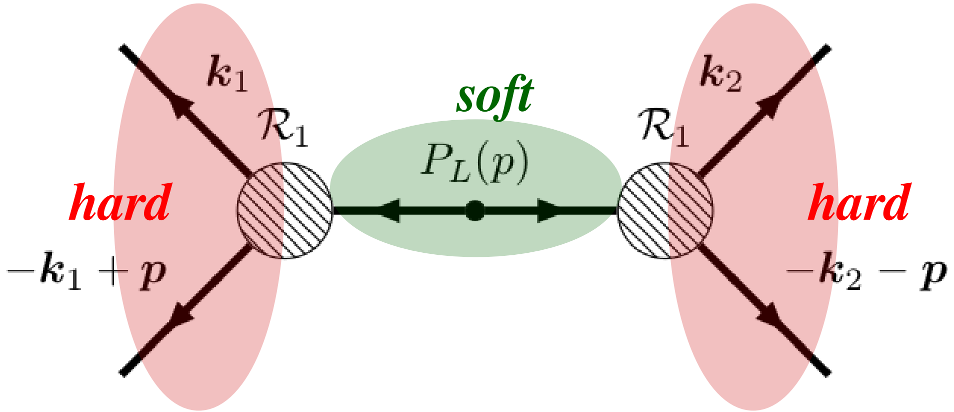


"Internal" response interactions

↓

Approach not limited to squeezed N-pt functions

Evaluate with responses



$$= \mathcal{R}_1(k_1, -\mu_{\boldsymbol{p},\boldsymbol{k}_1})\mathcal{R}_1(k_2, \mu_{\boldsymbol{p},\boldsymbol{k}_2})P_m(k_1)P_m(k_2)P_\mathrm{L}(p)$$

Two 1st order responses →

Separate Universe Simulations

The response approach requires simulation measurements of

P_m

Power spectrum
“Normal” simulations.

$\mathcal{R}_n$

Responses
Separate Universe Simulations

Separate Universe Simulations

Write the response in terms of all possible local gravitational observables

$$\mathcal{R}_n = \sum_{\mathcal{O}} R_{\mathcal{O}}(k)\ \mathcal{K}^{(n)}_{\mathcal{O},\text{large scale}}$$

Separate Universe Simulations

Write the response in terms of all possible local gravitational observables

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$\downarrow$

All possible configurations of large-scale density/tidal fields;

Given by perturbation theory.

Separate Universe Simulations

Write the response in terms of all possible local gravitational observables

$$\mathcal{R}_n = \sum_{\mathcal{O}} R_{\mathcal{O}}(k)\ \mathcal{K}^{(n)}_{\mathcal{O},\text{large scale}}$$

Measure the response to each specific large-scale configuration;

What we will get from simulations.

All possible configurations of large-scale density/tidal fields;

Given by perturbation theory.

Separate Universe Simulations

$$\mathcal{R}_1 \longrightarrow \underbrace{R_1(k)}_{\text{Response to overdensity}}\overbrace{\delta(\boldsymbol{p})}^{\text{Large-scale overdensity}} + \underbrace{R_K(k)}_{\text{Response to tidal field}}\overbrace{\hat{k}^i\hat{k}^j K_{ij}(\boldsymbol{p})}^{\text{Large-scale tidal field}}$$

Separate Universe Simulations

Nitty-gritty: Li et al (1401.0385) ; Wagner et al (1409.6294); Baldauf et al (1511.01465) Schmidt et al (1803.03274);

$$\mathcal{R}_n = \sum_{\mathcal{O}} R_{\mathcal{O}}(k)\, \mathcal{K}^{(n)}_{\mathcal{O},\mathrm{large\ scale}}$$

Response to specific perturbations

All possible configurations of large-scale density/tidal fields;

Separate Universe Simulations

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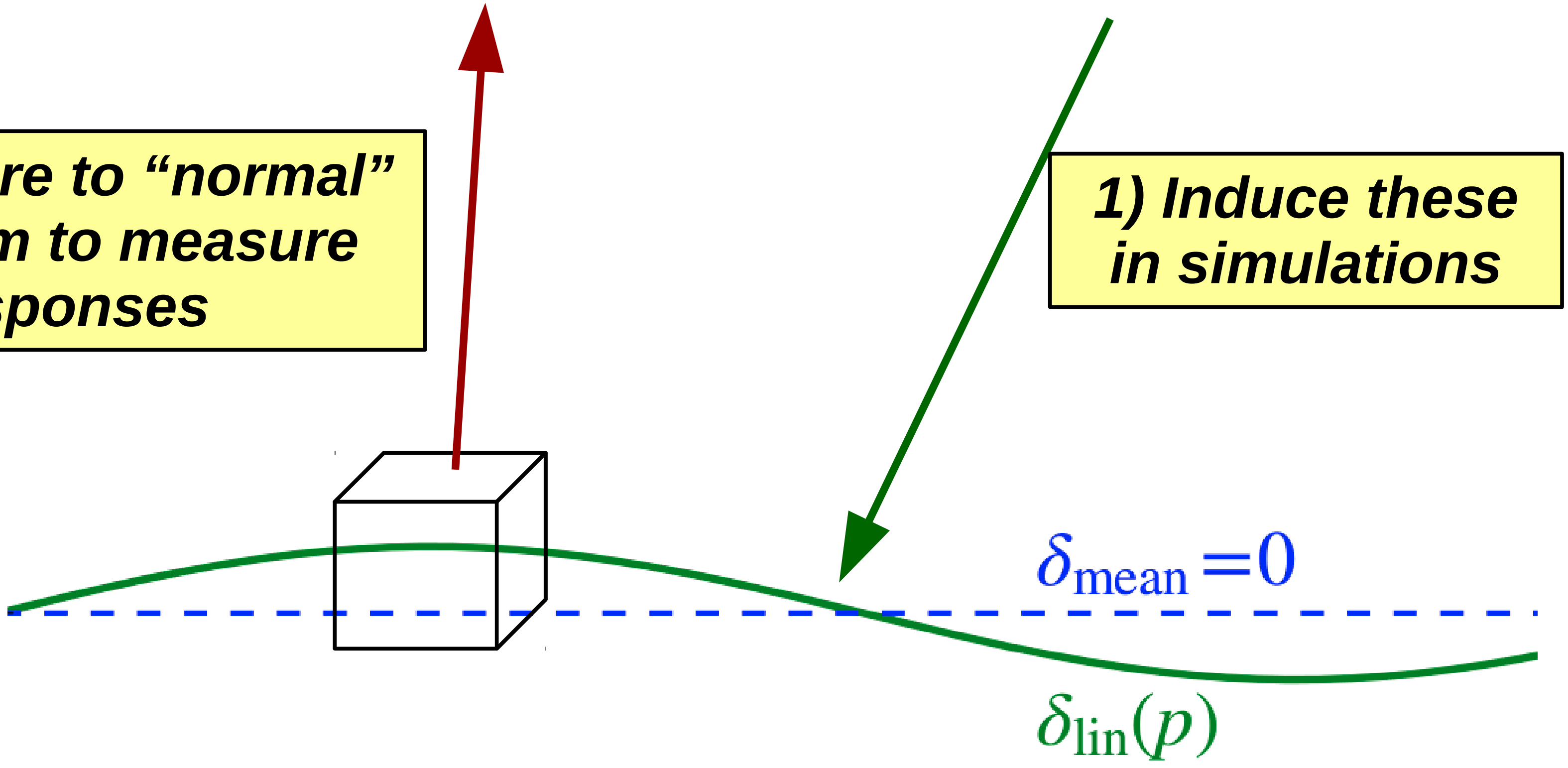


2) Compare to "normal" spectrum to measure responses

1) Induce these in simulations

Separate Universe Simulations

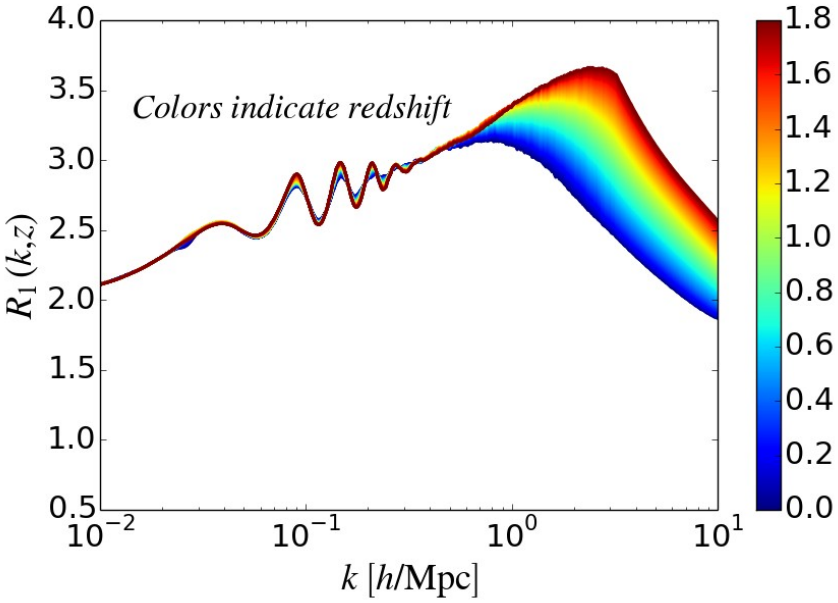
$$P_m(\boldsymbol{k},\boldsymbol{x}) = P_m(k)\left[1 + R_1(k)\delta(\boldsymbol{x}) + R_K(k)\hat{k}^i\hat{k}^j K_{ij}(\boldsymbol{x})\right]$$

Separate Universe Simulations

$$P_m(\boldsymbol{k},\boldsymbol{x}) = P_m(k)\left[1 + R_1(k)\delta(\boldsymbol{x}) + R_K(k)\hat{k}^i\hat{k}^j K_{ij}(\boldsymbol{x})\right]$$

Response to overdensity

Li et al (1401.0385) ; Wagner et al (1409.6294)



Separate Universe Simulations

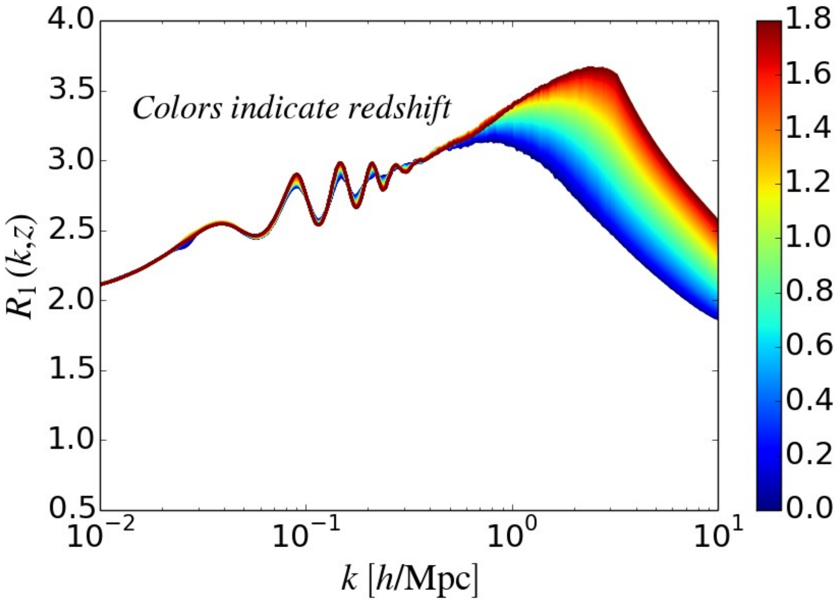
$$P_m(\boldsymbol{k},\boldsymbol{x}) = P_m(k)\left[1 + R_1(k)\delta(\boldsymbol{x}) + R_K(k)\hat{k}^i\hat{k}^j K_{ij}(\boldsymbol{x})\right]$$

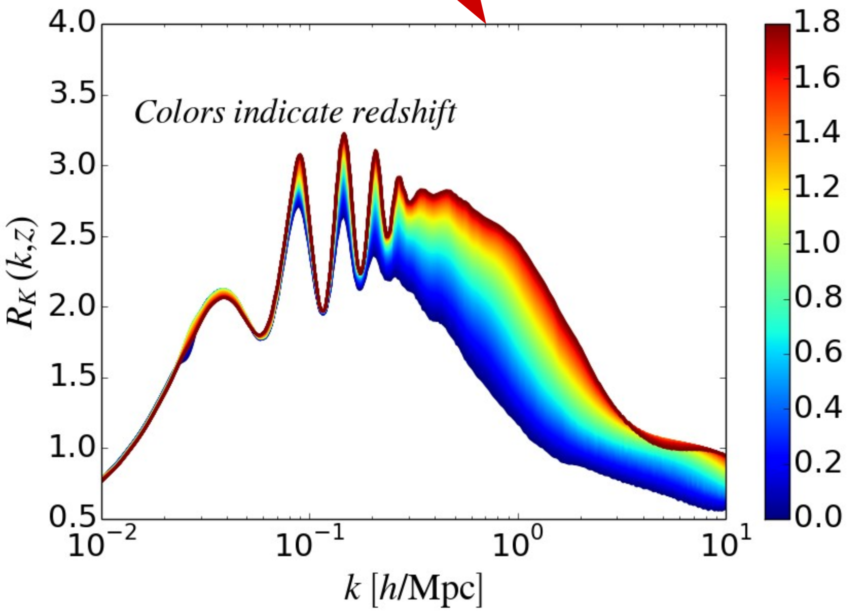
Response to overdensity

Li et al (1401.0385) ; Wagner et al (1409.6294)

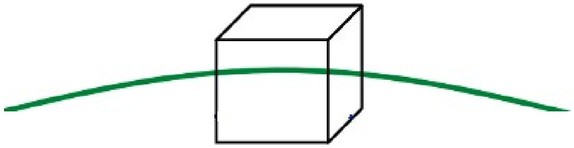
Response to tidal field

Schmidt et al (1803.03274)

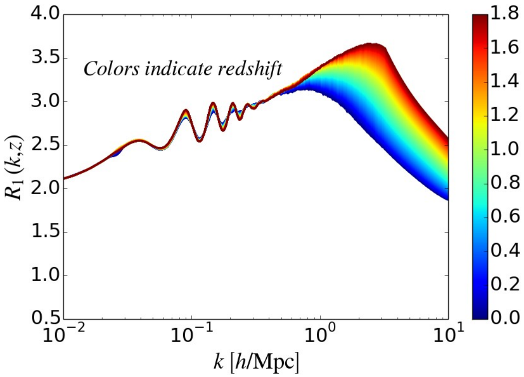




To keep in mind ...



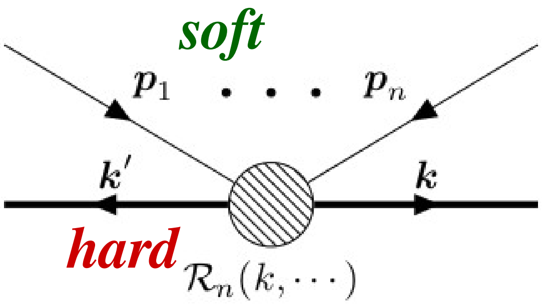
Separate Universe Simulations



Measure the “response” of the power spectrum to long-modes.

Responses

They are squeezed resummed PT vertices



N-point functions in the nonlinear regime.

Lensing covariances

Barreira, Krause, Schmidt, 1711.07467
Barreira, Krause, Schmidt, 1807.04266
Barreira, 1901.01243

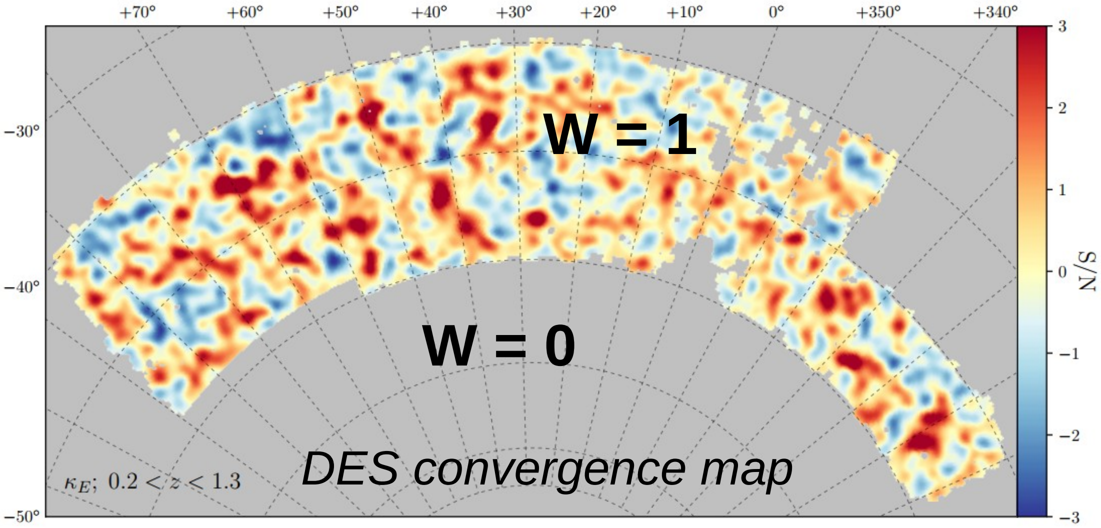
The covariance decomposition

- **Windowed lensing convergence**

$$\kappa_{\mathcal{W}}(\boldsymbol{\theta}) = \mathcal{W}(\boldsymbol{\theta})\kappa(\boldsymbol{\theta})$$

- **Estimator of its power spectrum**

$$\hat{C}_\kappa(\boldsymbol{\ell}) = \frac{\tilde{\kappa}_{\mathcal{W}}(\boldsymbol{\ell})\tilde{\kappa}_{\mathcal{W}}(-\boldsymbol{\ell})}{\Omega_{\mathcal{W}}}$$



e.g. Takada&Hu (1302.6994)

- **Covariance matrix of the estimator**

$$\mathrm{Cov}_\kappa\left(\hat{C}_\kappa(\boldsymbol{\ell}_1), \hat{C}_\kappa(\boldsymbol{\ell}_2)\right) = \left\langle \hat{C}_\kappa(\boldsymbol{\ell}_1)\hat{C}_\kappa(\boldsymbol{\ell}_2)\right\rangle - \left\langle \hat{C}_\kappa(\boldsymbol{\ell}_1)\right\rangle\left\langle \hat{C}_\kappa(\boldsymbol{\ell}_2)\right\rangle$$

$$= \underbrace{\mathrm{Cov}^G_\kappa(\boldsymbol{\ell}_1, \boldsymbol{\ell}_2)}_{\text{Gaussian}} + \underbrace{\mathrm{Cov}^{cNG}_\kappa(\boldsymbol{\ell}_1, \boldsymbol{\ell}_2)}_{\text{Connected non-Gaussian}} + \underbrace{\mathrm{Cov}^{SSC}_\kappa(\boldsymbol{\ell}_1, \boldsymbol{\ell}_2)}_{\text{Super-sample}}$$

Connected non-Gaussian term : cNG

- Describes the **coupling of different Fourier modes due to nonlinear structure formation** (given by the parallelogram matter trispectrum).

$$\boxed{\mathrm{Cov}_{\kappa}^{cNG}(\boldsymbol{\ell}_1, \boldsymbol{\ell}_2) = \frac{1}{\Omega_{\mathcal{W}}} \int \mathrm{d}\chi \frac{[g(\chi)]^4}{\chi^6} T_m(\boldsymbol{k}_{\ell_1}, -\boldsymbol{k}_{\ell_1}, \boldsymbol{k}_{\ell_2}, -\boldsymbol{k}_{\ell_2})}$$

$$\boldsymbol{k}_{\ell} = \frac{\boldsymbol{\ell} + 1/2}{\chi}$$

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$$\boldsymbol{k}_\ell = \frac{\boldsymbol{\ell}+1/2}{\chi}$$

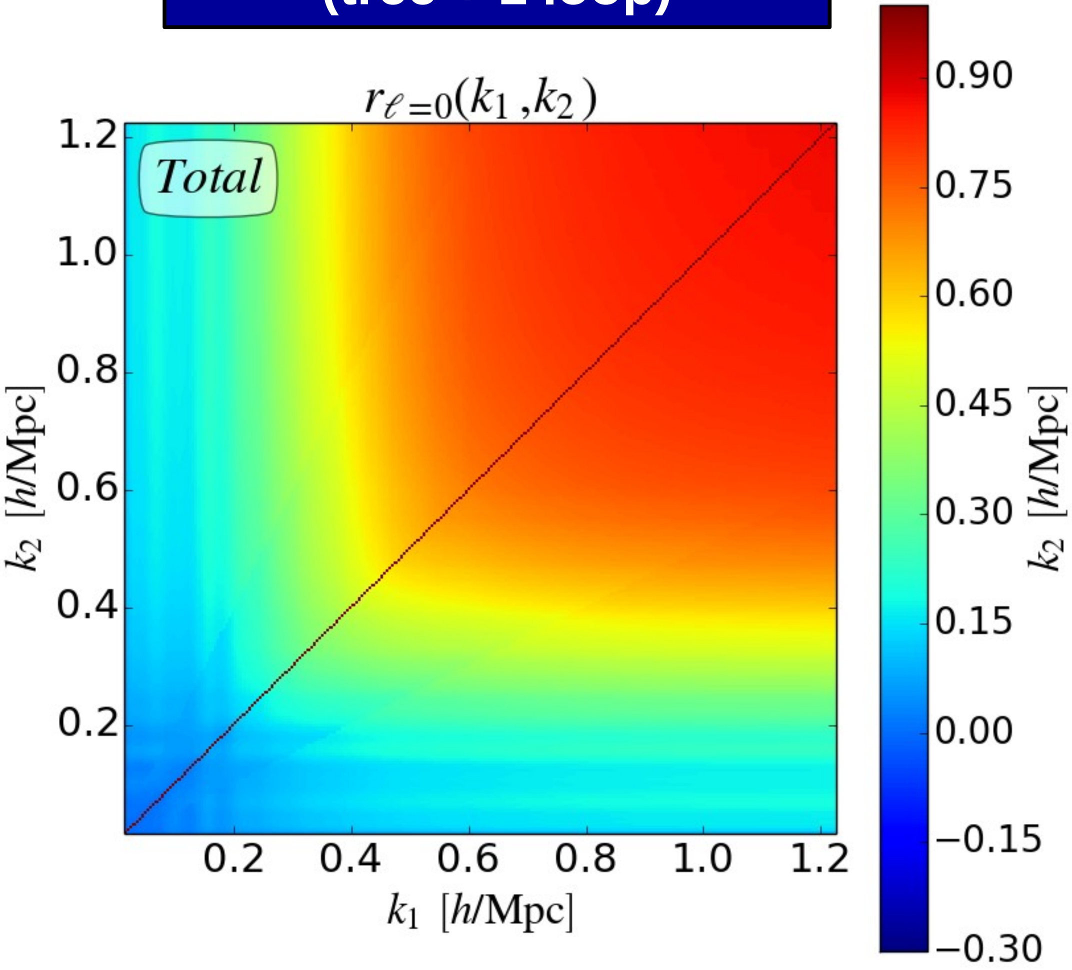
LOS projection

Parallelogram Trispectrum

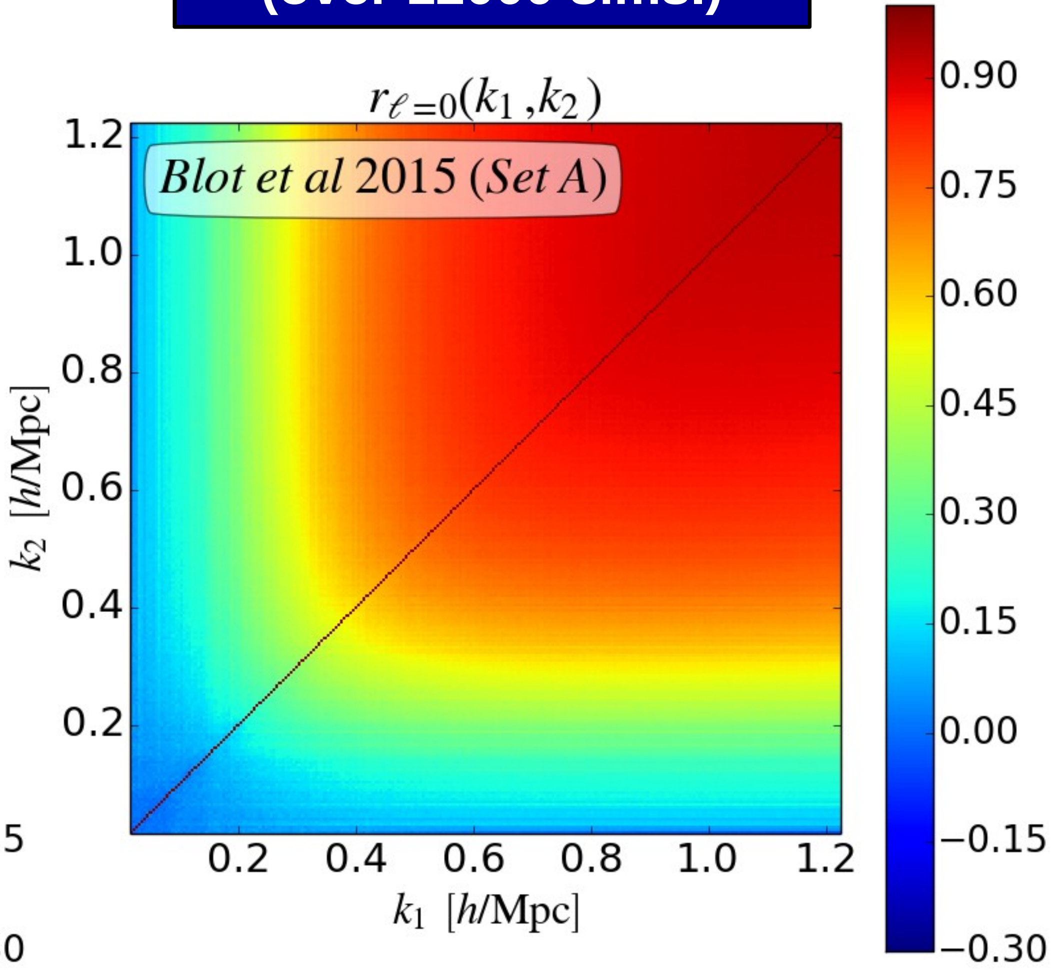
Evaluate it with the response approach.

cNG : response vs simulations

Response approach
(tree + 1 loop)

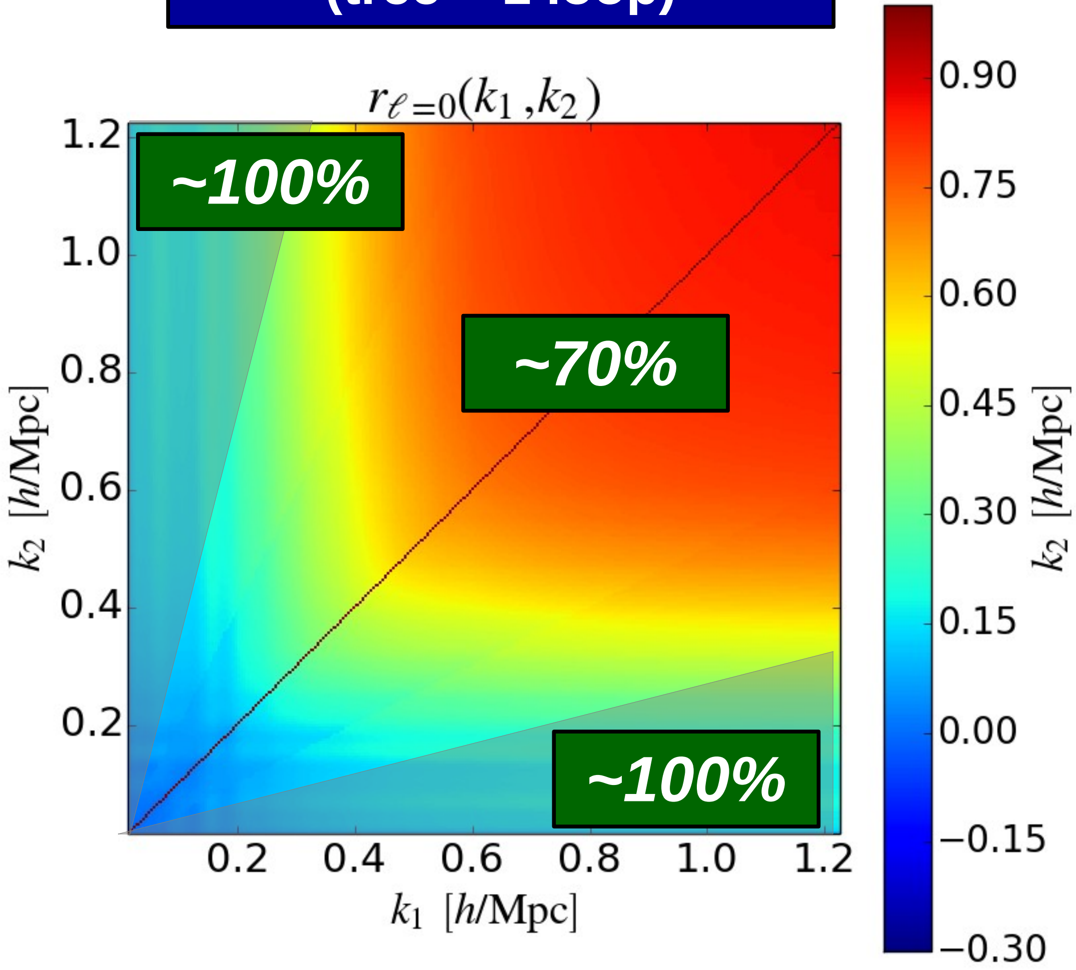


Ensemble method
(over 12000 sims.)



cNG : response vs simulations

Response approach
(tree + 1 loop)

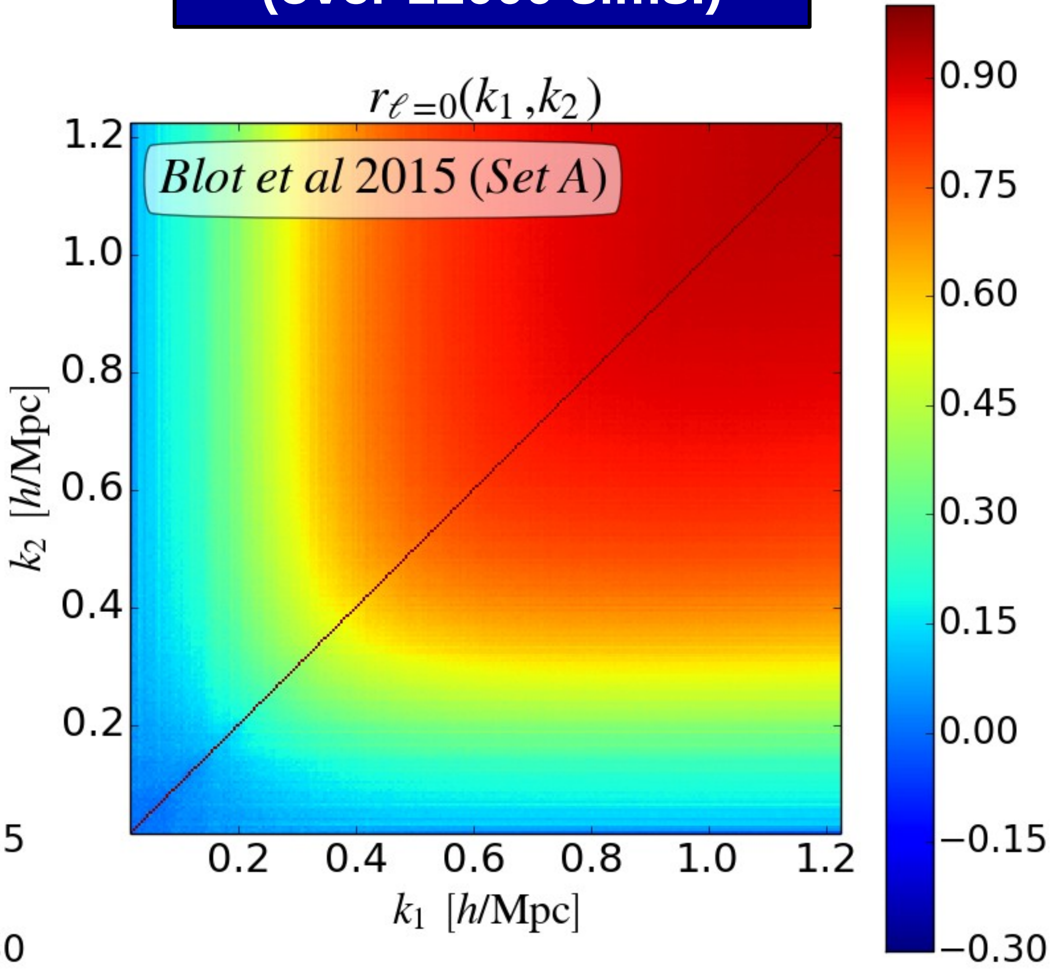


~100%

~70%

~100%

Ensemble method
(over 12000 sims.)



The super-sample term : SSC

- Describes the coupling of modes inside the survey with **unobserved modes outside the survey**.

Hamilton et al (0511416)
Takada&Bridle (0705.0163)
Takada&Hu (1302.6994)
Barreira et al (1711.07467)

$$\begin{aligned}\mathrm{Cov}_{\kappa}^{SSC}(\boldsymbol{\ell}_1,\boldsymbol{\ell}_2) \;=\; & \frac{1}{\Omega_{\mathcal{W}}^2}\int \mathrm{d}\chi \frac{[g(\chi)]^4}{\chi^6}\int \frac{\mathrm{d}^2\boldsymbol{\ell}}{(2\pi)^2}|\tilde{\mathcal{W}}(\boldsymbol{\ell})|^2\mathcal{R}_1(\boldsymbol{k}_{\boldsymbol{\ell}_1},\mu_{\boldsymbol{\ell}_1,\boldsymbol{\ell}})\mathcal{R}_1(\boldsymbol{k}_{\boldsymbol{\ell}_2},\mu_{\boldsymbol{\ell}_2,\boldsymbol{\ell}}) \\ & \times P_m(\boldsymbol{k}_{\ell_1})P_m(\boldsymbol{k}_{\ell_2})P_L(\boldsymbol{k}_{\ell})\end{aligned}$$

Note: This expression assumes Limber for the super-survey modes, which is only accurate up to 10% for Euclid/LSST. Beyond Limber SSC expressions exist however (Barreira, Krause, Schmidt , arXiv:1711.07467).

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LOS projection

Window function

1st order responses

$$\mathrm{Cov}_{\kappa}^{SSC}(\boldsymbol{\ell}_1,\boldsymbol{\ell}_2) = \frac{1}{\Omega_{\mathcal{W}}^2}\int \mathrm{d}\chi \frac{[g(\chi)]^4}{\chi^6}\int \frac{\mathrm{d}^2\boldsymbol{\ell}}{(2\pi)^2}|\tilde{\mathcal{W}}(\boldsymbol{\ell})|^2 \mathcal{R}_1(\boldsymbol{k}_{\ell_1},\mu_{\boldsymbol{\ell}_1,\boldsymbol{\ell}})\mathcal{R}_1(\boldsymbol{k}_{\ell_2},\mu_{\boldsymbol{\ell}_2,\boldsymbol{\ell}})$$
$$\times P_m(\boldsymbol{k}_{\ell_1})P_m(\boldsymbol{k}_{\ell_2})P_L(\boldsymbol{k}_{\ell})$$

Power spectra

Responses fully specify the SSC term

Note: This expression assumes Limber for the super-survey modes, which is only accurate up to 10% for Euclid/LSST. Beyond Limber SSC expressions exist however (Barreira, Krause, Schmidt , arXiv:1711.07467).

Lensing covariance summary

$$\mathrm{Cov}_\kappa(\boldsymbol{\ell}_1, \boldsymbol{\ell}_2) \quad = \quad \mathrm{Cov}_\kappa^{G} \quad + \quad \mathrm{Cov}_\kappa^{cNG} \quad + \quad \mathrm{Cov}_\kappa^{SSC}$$

Lensing covariance summary

Understood ! ✓

✓ **Understood !**

$$\mathrm{Cov}_\kappa(\boldsymbol{\ell}_1, \boldsymbol{\ell}_2) = \boxed{\mathrm{Cov}_\kappa^{G}} + \mathrm{Cov}_\kappa^{cNG} + \boxed{\mathrm{Cov}_\kappa^{SSC}}$$

Lensing covariance summary

Understood ! ✓

Understood ! ✓

$$\mathrm{Cov}_{\kappa}(\boldsymbol{\ell}_1, \boldsymbol{\ell}_2) = \mathrm{Cov}_{\kappa}^{G} + \mathrm{Cov}_{\kappa}^{cNG} + \mathrm{Cov}_{\kappa}^{SSC}$$

Responses capture most of it,
but do we even need it ?

The unimportance of the cNG term for future surveys

Euclid-like lensing setup

Barreira, Krause, Schmidt
1807.04266

- Tomographic convergence power spectrum
  10 tomographic bins
- 20 ell bins in [20, 5000]
- Mask: spherical cap 15000 deg^2
- Source density: 30 / arcmin^2

$$\boxed{\mathcal{L}(w_0) \propto \exp\left[-\frac{1}{2}\left(\overrightarrow{Theory}-\overrightarrow{Data}\right)\mathbf{Cov}^{-1}\left(\overrightarrow{Theory}-\overrightarrow{Data}\right)\right]}$$

What is the impact of different matrices on parameter constraints ?

The unimportance of the cNG term for future surveys

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Barreira, Krause, Schmidt
1807.04266

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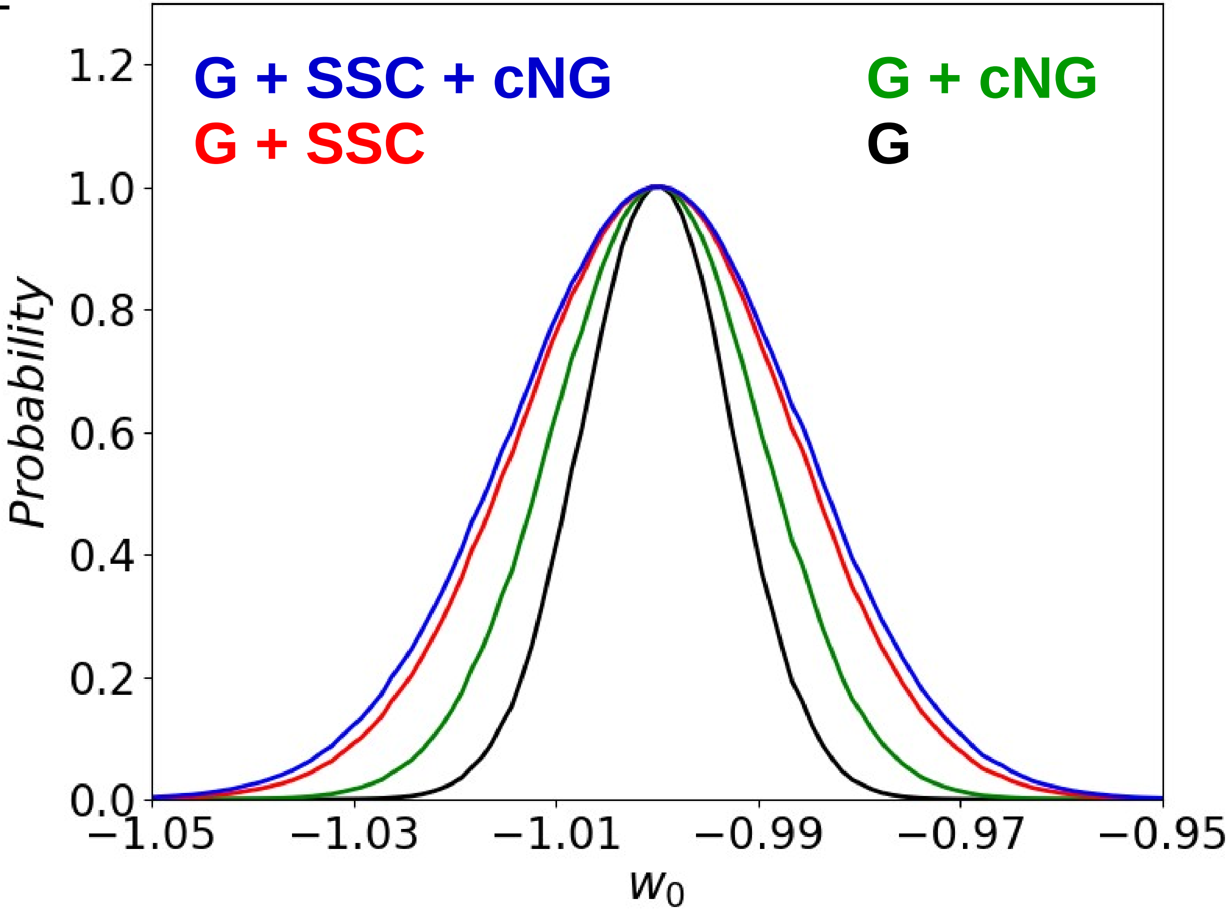
Assumes no systematics,
→ conservative.

Relative to G+SSC, cNG increases error by only 6% .

cNG has also a small impact on parameter biases.



The unimportance of the cNG term for future surveys

Euclid-like lensing setup

- Tomographic convergence power spectrum
  10 tomographic bins
- 20 ell bins in [20, 5000]

Barreira, Krause, Schmidt
1807.04266

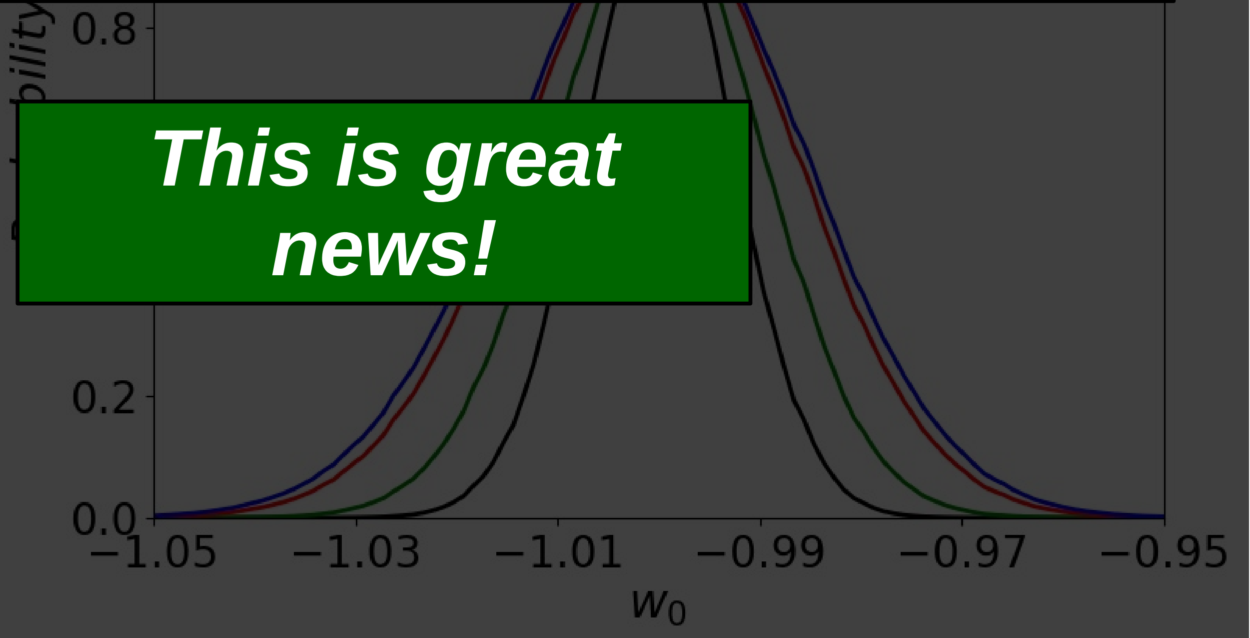
Assumes no systematics,

The cNG is the hardest-to-evaluate covariance term,
but it is also the smallest …

… accuracy of analytical methods is likely sufficient for lensing.

increases error by only 6% .

cNG has also a small impact on parameter biases.



This is great news!

Squeezed bispectrum covariance

Barreira (arXiv:1901.01243)

- Squeezed bispectrum

$$B_i = B_m(k_i, k_i', s_i), \quad s_i \ll k_i, k_i'$$

- Covariance decomposition

Negligible

$$\mathrm{Cov}\Big(B_1, B_2\Big) = \mathrm{Cov}^{PPP} + \mathrm{Cov}^{BB} + \mathrm{Cov}^{TP} + \mathrm{Cov}^{SSC} + \mathrm{Cov}^{cNG}$$

Fully given by P(k) and its responses

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Barreira (arXiv:1901.01243)

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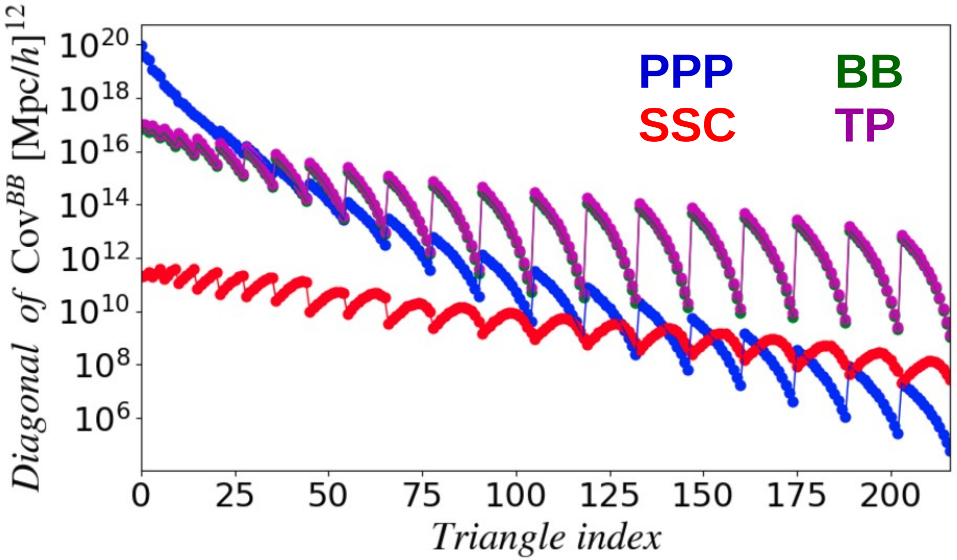
Fully given by P(k) and its responses



Analytical calculation of the sq. bispectrum covariance.

The SSC term is negligible !

(Okay to skip from f_nl forecasts)

Baryons and higher-order statistics

Barreira et al 1904.02070

Baryonic effects on N-point functions

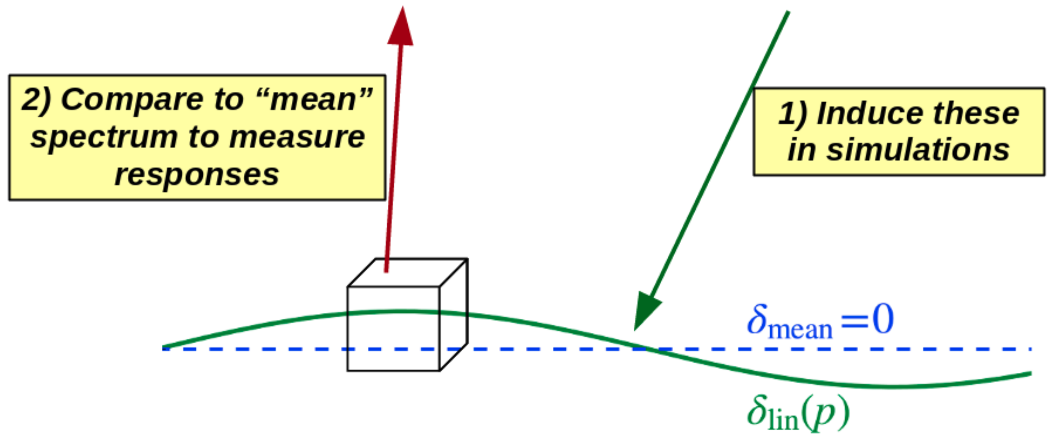
Separate Universe Simulations with IllustrisTNG

**with the
TNG collaboration**

$$\mathcal{R}_n = \sum_{\mathcal{O}} R_{\mathcal{O}}(k)\, \mathcal{K}^{(n)}_{\mathcal{O},\mathrm{large\ scale}}$$

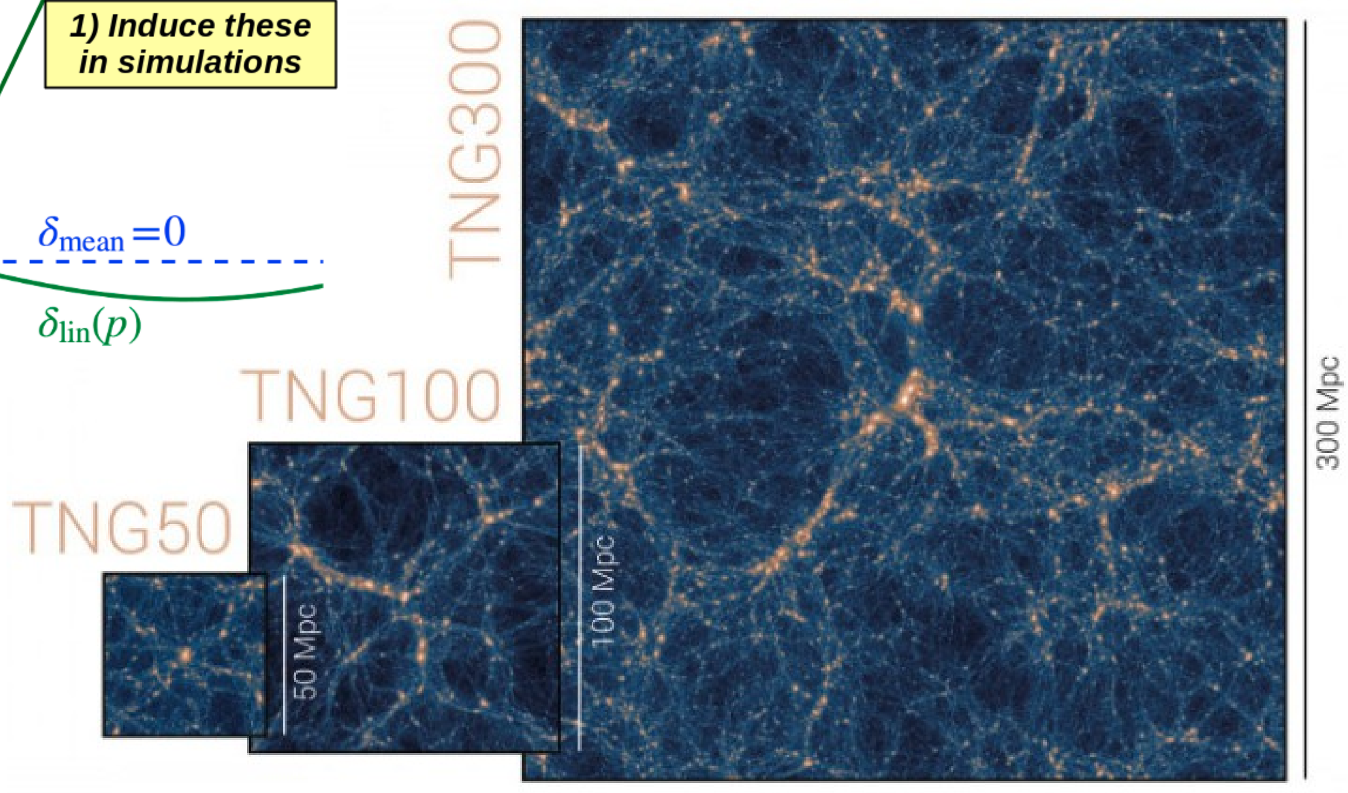
Response to specific perturbations

Large-scale density/tidal perturbations



2) Compare to "mean" spectrum to measure responses

1) Induce these in simulations



Barreira+ 1904.02070

Baryonic effects on N-point functions

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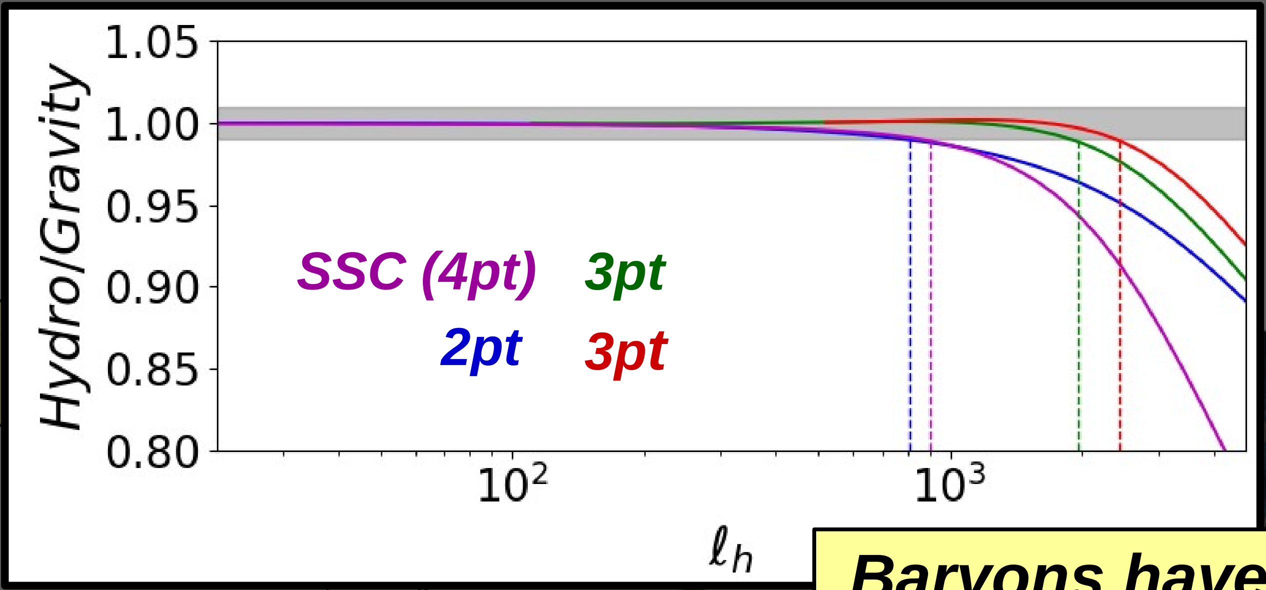
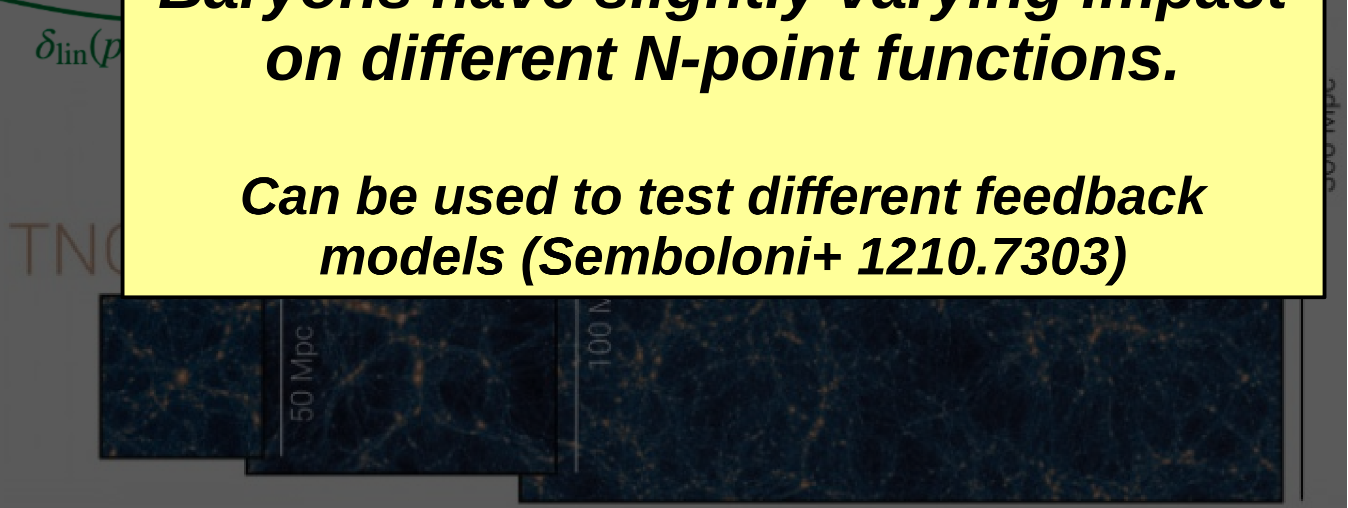




Baryons have slightly varying impact on different N-point functions.

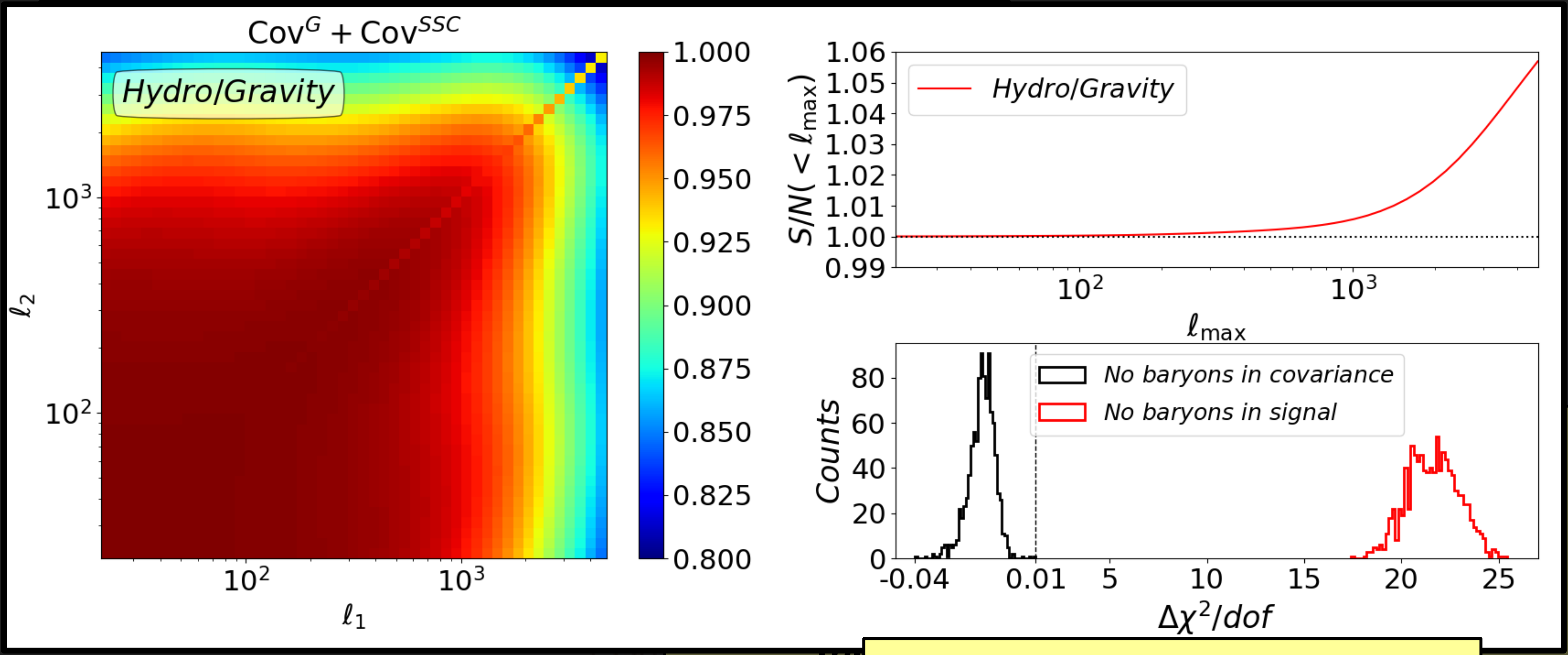
Can be used to test different feedback models (Semboloni+ 1210.7303)

Barreira+ 1904.02070

Baryonic effects on N-point functions

Baryons actually lower the covariance matrix !

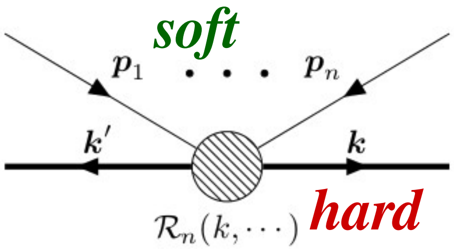
Ignoring baryons is conservative on errors bars!



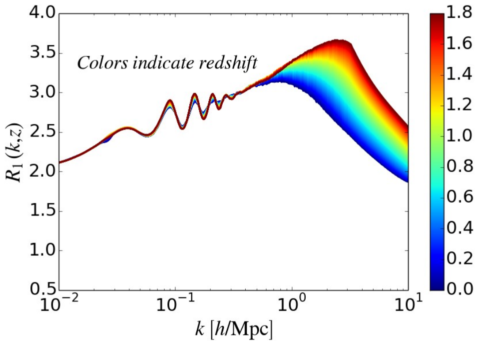
Baryons have small impact on goodness-of-fit !

Barreira+ 1904.02070

Summary



Responses as resummed squeezed PT vertices



Existing applications

Covariance of 2pt functions.

Baryons and N-pt functions.

Covariance of the sq. bispectrum.