Title: Squeezing primordial non-Gaussianity out of the matter bispectrum (and trispectrum) with consistency relations

Speakers: Sam Goldstein

Collection/Series: Cosmology and Gravitation

Subject: Cosmology

Date: September 24, 2024 - 11:00 AM

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Abstract:

In this seminar, I will discuss recent progress towards developing robust methods to constrain PNG in the non-linear regime based on the LSS consistency relations — non-perturbative statements about the structure of LSS correlation functions derived from symmetries of the LSS equations of motion. Specifically, I will present non-perturbative models for the squeezed matter bispectrum and collapsed matter trispectrum in the presence of local PNG, as well as in the presence of a more general "Cosmological Collider" signal sourced by inflationary massive particle exchange. Using N-body simulations with modified initial conditions, I will demonstrate that these models yield unbiased constraints on the amplitude of PNG deep into the non-linear regime (k~2 h/Mpc at z=0). Finally, I will discuss how these non-perturbative methods can provide insight into the scale-dependent bias signature associated with the Cosmological Collider scenario.

Squeezing primordial non Gaussianity out of the matter bispectrum (and trispectrum) with consistency relations

Oliver Philcox

J. Colin Hill

Lam Hui

Angelo Esposito

2209.06228
SG, *Esposito, Philcox, Hui, Hill, Scoccimarro, Abitbol*

2310.12959
SG, *Philcox, Hill, Esposito, Hui*

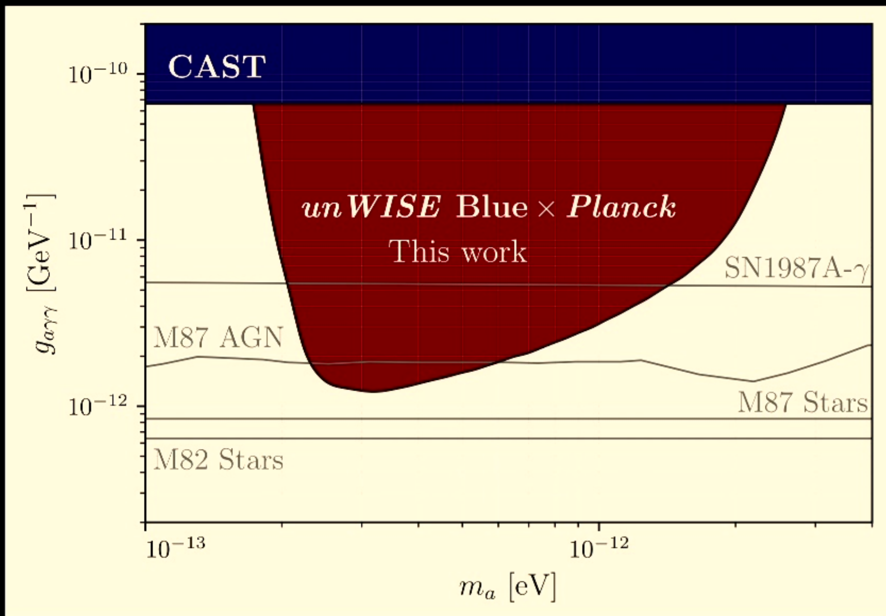
2407.08731
SG, *Philcox, Hill, Hui*

Roman Scoccimarro

Max Abitbol

Sam Goldstein
COLUMBIA UNIVERSITY

Axion bounds from CMBxLSS

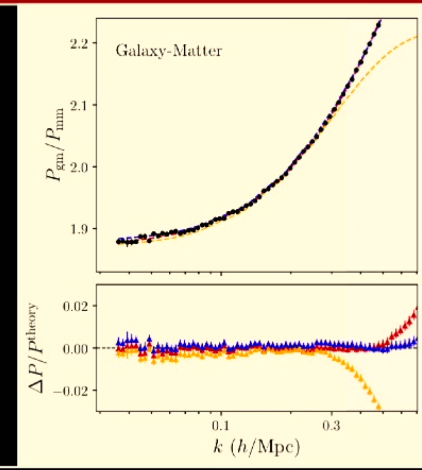


- **SG**, McCarthy, Mondino, Hill, Huang, Johnson 2409.10514 , submitted

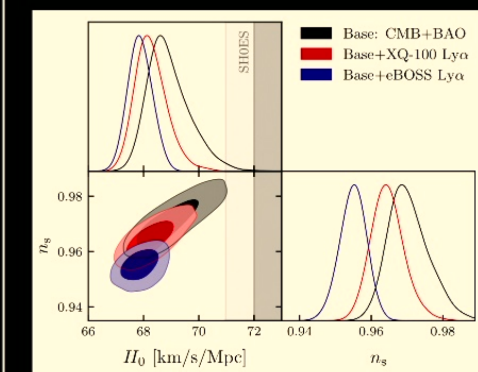
What I won't talk about…

Galaxy-Halo Connection

- Comparing simulations with analytic models for LSS
  - ***Galaxy bias models*: SG**, Pandey, Slosar, Blazek, and Jain, 2111.00501
  - ***Splashback radius***: 2111.06499 and 2105.05914



Lya forest disfavors EDE as a resolution to Hubble tension!



- **SG**, Hill, Iršić, and Sherwin, 2303.00746
  - ***Phys Rev Lett.* 131,** 201001
    - Editors' Suggestion
    - Featured in Physics

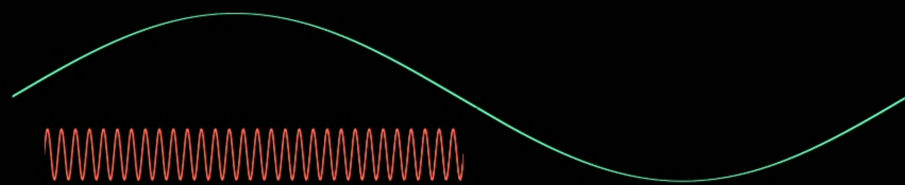
Early Dark Energy and Lya Forest

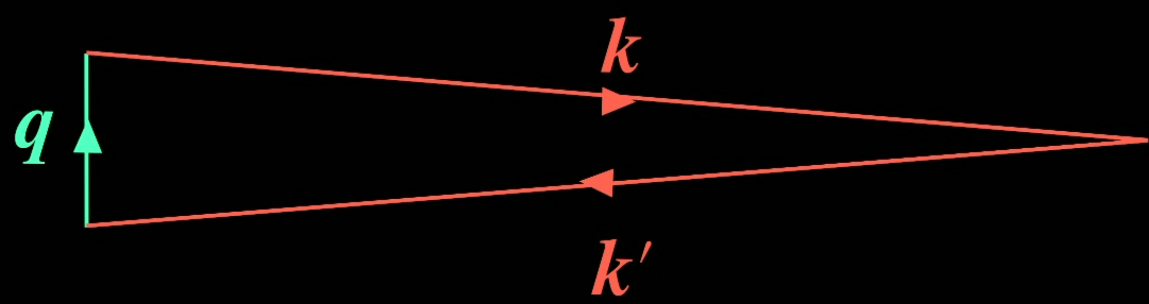
Note / Notation

Correlations between long and short wavelength cosmological perturbations are highly constrained by symmetries

Soft/long wavelength mode:

Hard/short wavelength mode:





"Squeezed" bispectrum ($q \ll k \approx k'$)

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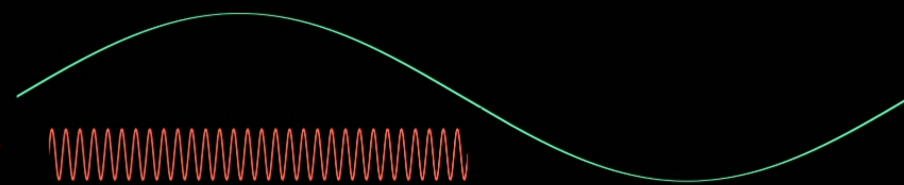

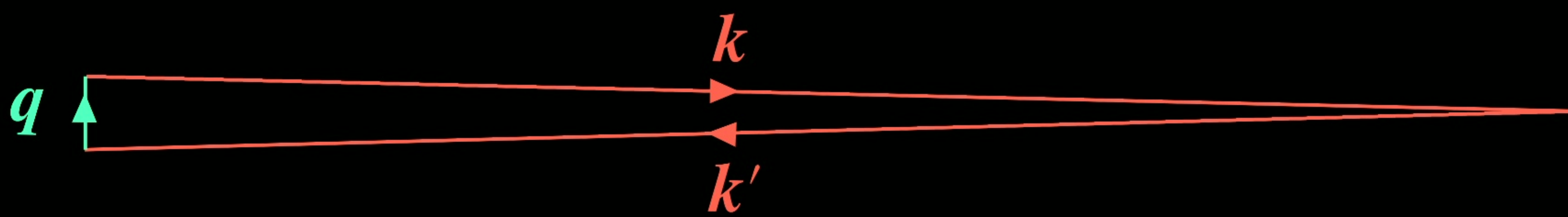

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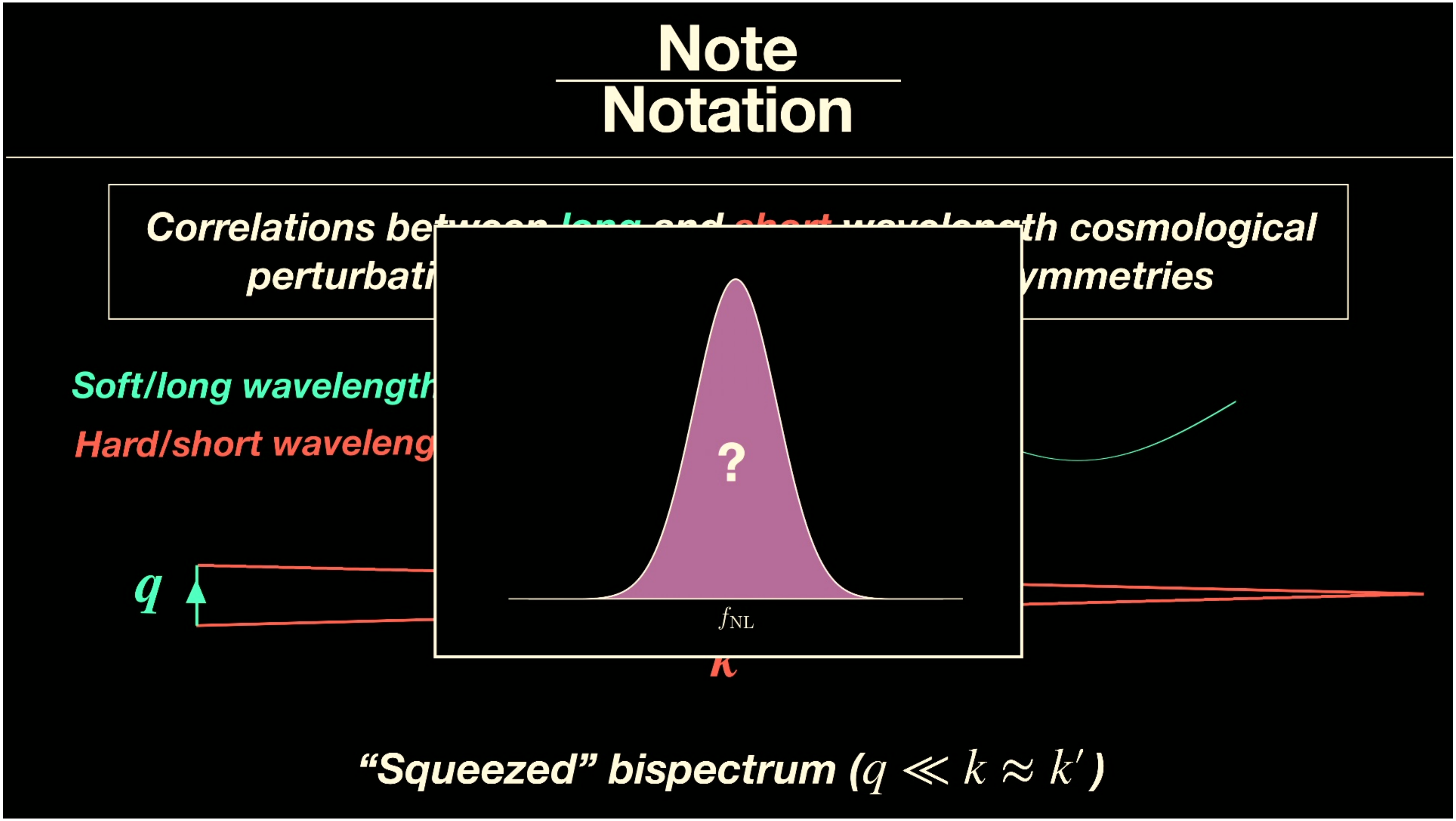
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?
$f_{\rm NL}$
k
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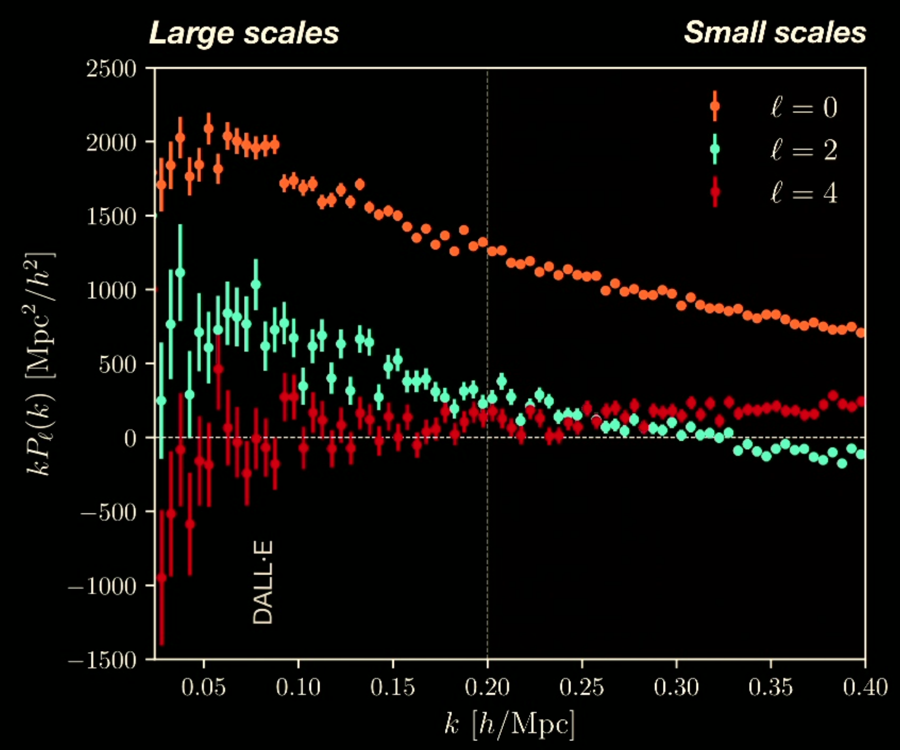
Cosmology with LSS

- Upcoming large-scale structure (LSS) surveys will measure many modes
  - Stress test ΛCDM
  - Provide insight into **initial conditions**
- Theoretical challenge: **non-linearities**
  - Need to exclude small-scale modes from analysis
  - Particularly challenging for non-Gaussian/ higher-order statistics



BOSS galaxy power spectrum multipoles.
(Measurements from Philcox & Ivanov, 2021)

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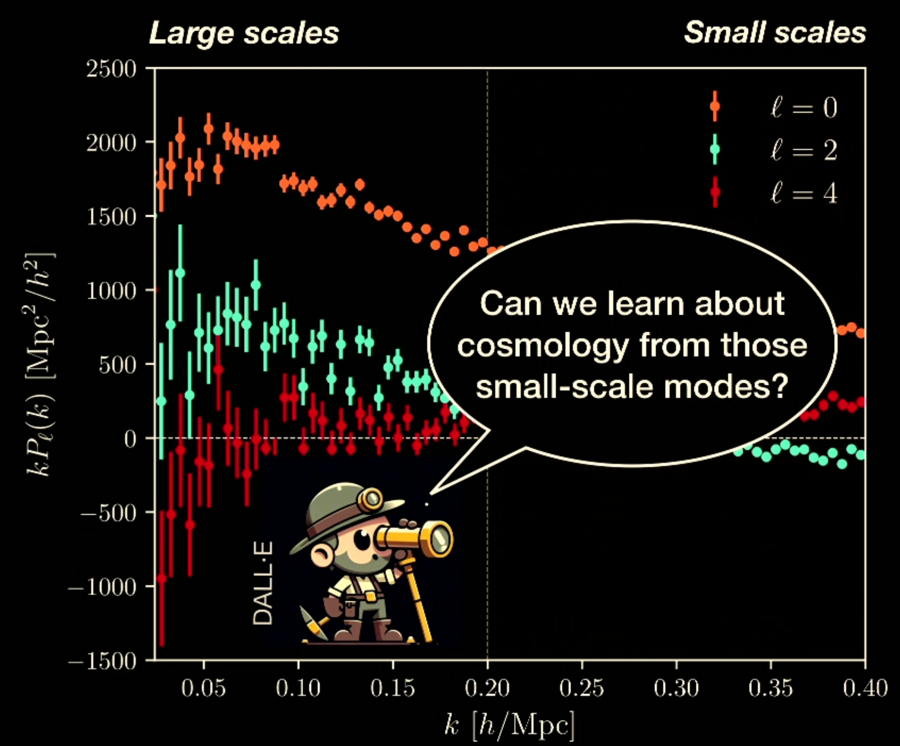

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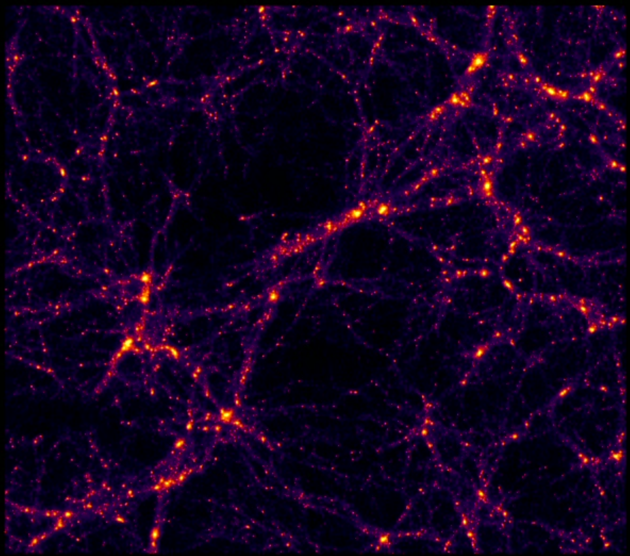
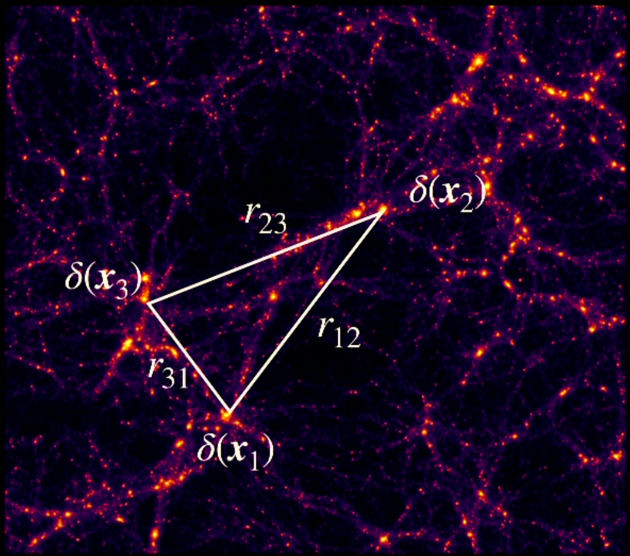
Non-linearities in LSS



Goal: Constrain cosmology from $\delta(\boldsymbol{x}) = \frac{\rho(\boldsymbol{x}) - \bar{\rho}}{\bar{\rho}}$

Non-linearities in LSS

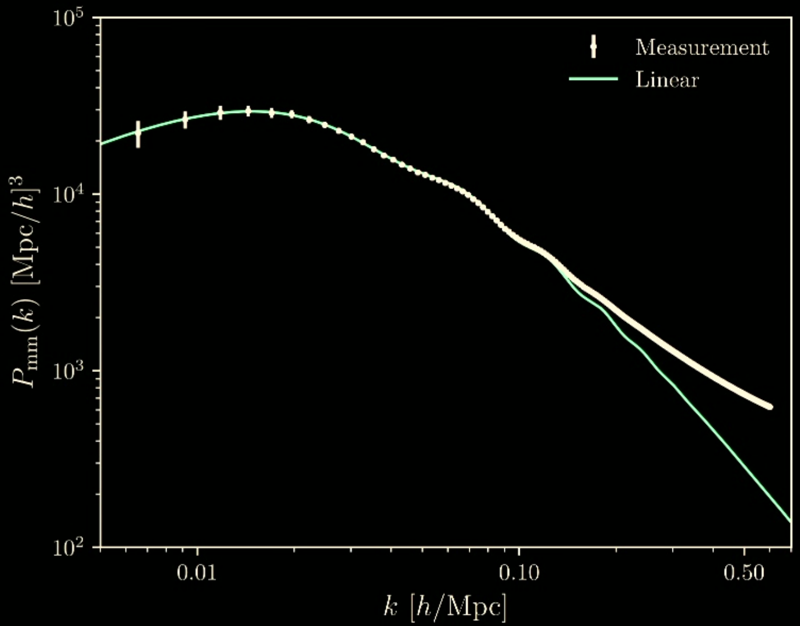
- Compress field into its correlation functions



$$\xi_n(\boldsymbol{x}_1, \ldots \boldsymbol{x}_n) \equiv \langle \delta(\boldsymbol{x}_1) \ldots \delta(\boldsymbol{x}_n) \rangle_c$$

Non-linearities in LSS

- Compress field into its correlation functions
  - Power spectrum is lossless if field is Gaussian
- Need to model correlation functions with theory



$$\langle \delta(\boldsymbol{k})\delta(\boldsymbol{k}')\rangle \equiv (2\pi)^3 \delta_D(\boldsymbol{k}+\boldsymbol{k}')P(k)$$

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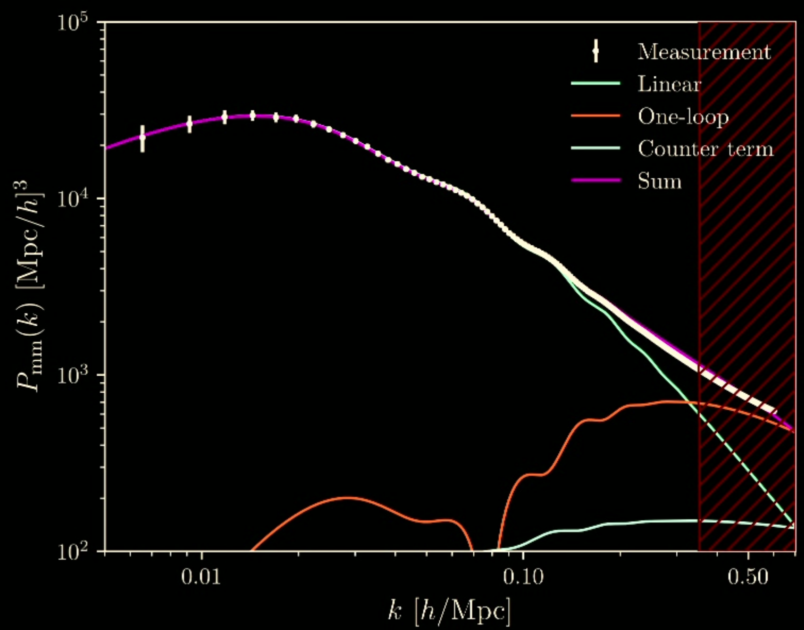

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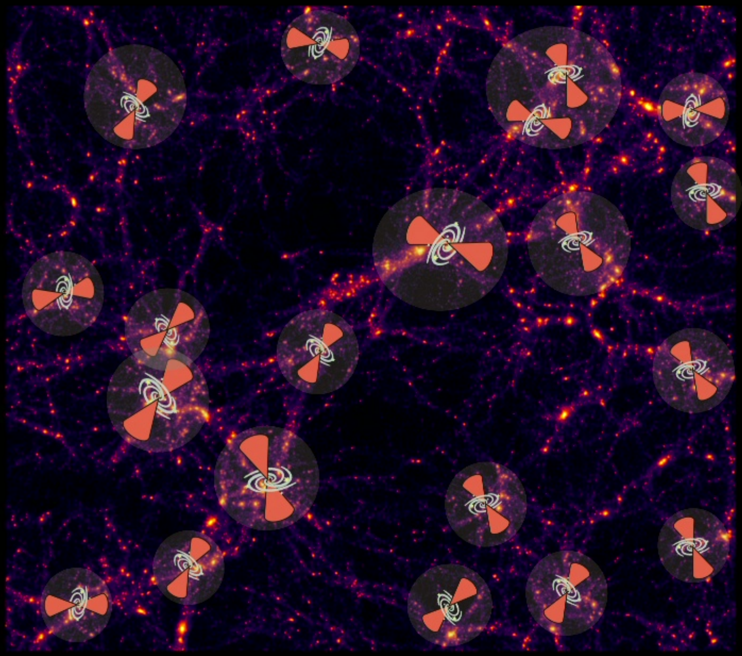

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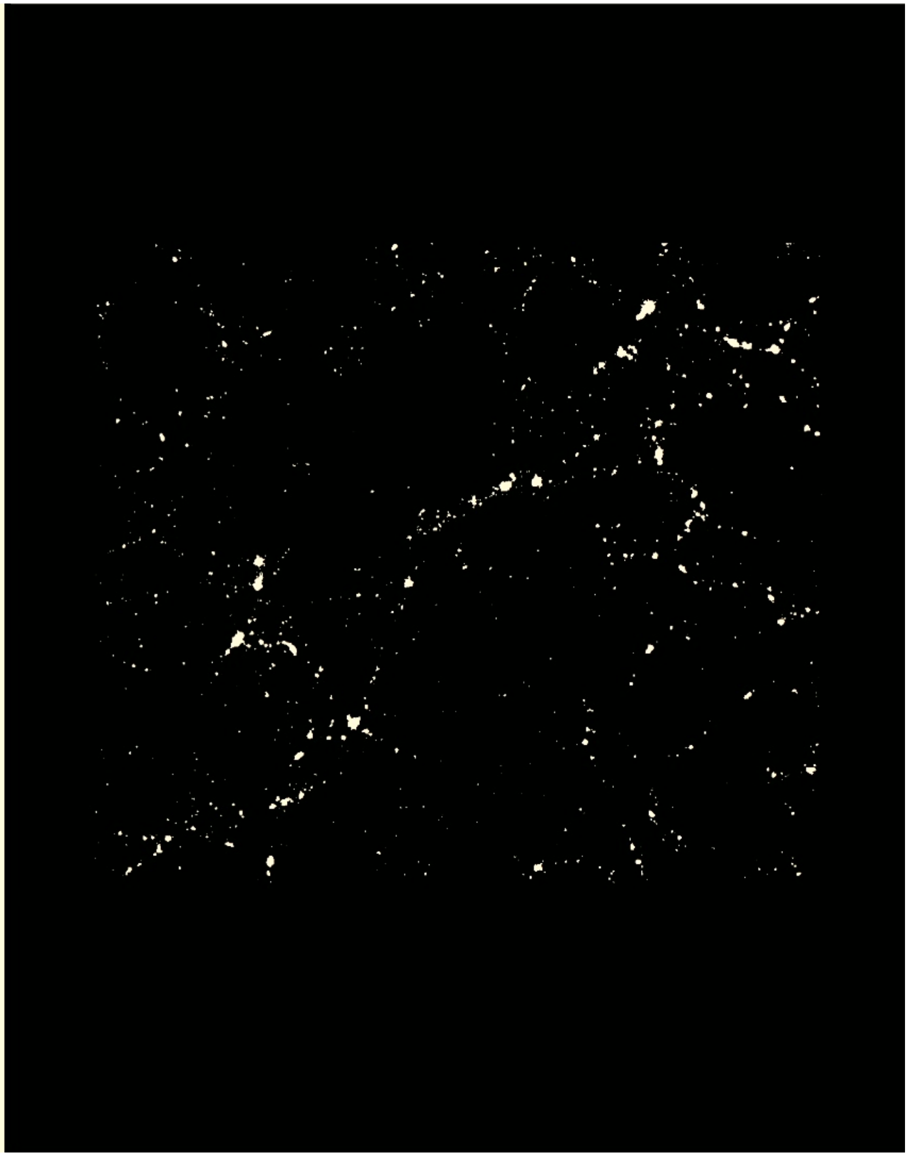
- Observational limitations
  - Generally observe biased tracers
  - Redshift space distortions



Non-linearities in LSS

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What to do when we cannot use perturbation theory?

Non-linearities in LSS

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What to do when we cannot use perturbation theory?

Let there be ***freedom from perturbations*** with respect to the things which come from the external cause; and let there be justice in the things ***done by symmetries.***

Marcus Aurelius ~170 AD

Let there be ***freedom from perturbations*** with respect to the things which come from the external cause; and let there be justice in the things ***done by symmetries.***

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Ward identities from QFT

Consistency relations/soft theorems

How do symmetries constrain cosmological correlators?

- ***Translational invariance:***

$$\implies \langle \mathcal{O}(\boldsymbol{k_1})\ldots\mathcal{O}(\boldsymbol{k_n})\rangle = (2\pi)^3\delta_D\left(\sum_a \boldsymbol{k_a}\right)\langle \mathcal{O}(\boldsymbol{k_1})\ldots\mathcal{O}(\boldsymbol{k_n})\rangle'$$

- ***Rotational symmetry:***

$$\implies \langle \mathcal{O}(\boldsymbol{k_1})\ldots\mathcal{O}(\boldsymbol{k_n})\rangle' = F(\boldsymbol{k_i}\cdot\boldsymbol{k_j})$$

- *Examples*:
  - Power spectrum: $\langle \delta(\boldsymbol{k_1})\,\delta(\boldsymbol{k_2})\rangle = (2\pi)^3\delta_D(\boldsymbol{k_1}+\boldsymbol{k_2})\,P(k_1)$
  - Bispectrum: $\langle \delta(\boldsymbol{k_1})\,\delta(\boldsymbol{k_2})\delta(\boldsymbol{k_3})\rangle = (2\pi)^3\delta_D(\boldsymbol{k_1}+\boldsymbol{k_2}+\boldsymbol{k_3})\,B(k_1,k_2,k_3)$
  - Trispectrum: $\langle \delta(\boldsymbol{k_1})\,\delta(\boldsymbol{k_2})\delta(\boldsymbol{k_3})\delta(\boldsymbol{k_4})\rangle = (2\pi)^3\delta_D(\boldsymbol{k_1}+\boldsymbol{k_2}+\boldsymbol{k_3}+\boldsymbol{k}_4)\,T(k_1,k_2,k_3,k_4,k_{12},k_{23})$

What about more general symmetries?

LSS Consistency relations

- Equations of motion for δ_m, v_m, Φ

$$\frac{\partial \delta}{\partial \tau} + \nabla \cdot [(1+\delta)\boldsymbol{v}] = 0 \qquad \text{(conservation of mass)}$$

$$\frac{\partial \boldsymbol{v}}{\partial \tau} + \mathscr{H}\boldsymbol{v} + [\boldsymbol{v} \cdot \nabla]\boldsymbol{v} = -\nabla\Phi \qquad \text{(conservation of momentum)}$$

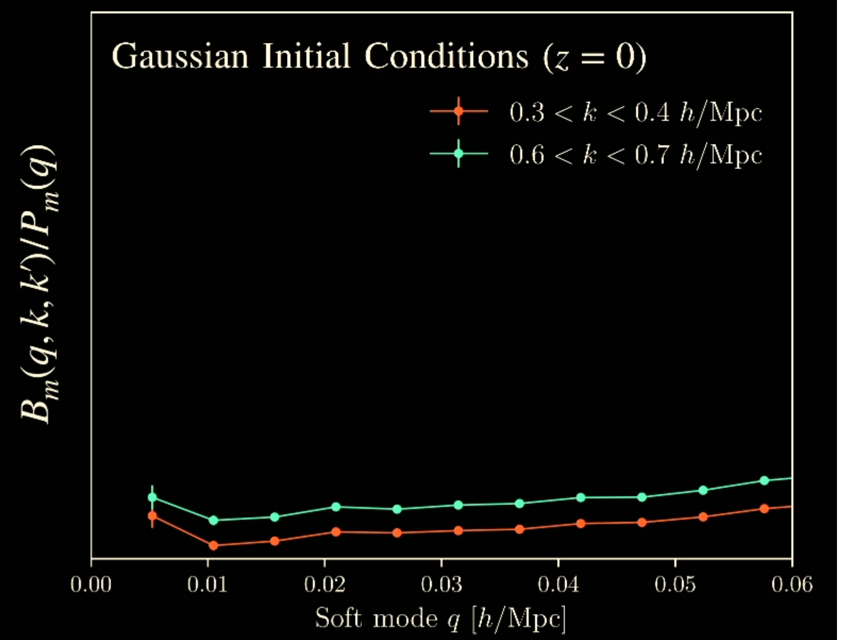
$$\nabla^2 \Phi = \frac{3}{2}\Omega_m \mathscr{H}^2 \delta \qquad \text{(Poisson equation)}$$

- Possess the following symmetry:

1. *Shift in gravitational potential*: $\Phi \mapsto \Phi + \kappa(\eta)$
2. *Time-dependent translation*: $\boldsymbol{x} \mapsto \boldsymbol{x} + \boldsymbol{n}(\eta)$

$$\Phi \to \Phi - (\mathscr{H}\boldsymbol{n}' + \boldsymbol{n}'') \cdot \boldsymbol{x}, \quad \boldsymbol{v} \to \boldsymbol{v} + \boldsymbol{n}'$$

$\Longrightarrow$



$$\lim_{q \to 0} \left[\frac{B(q,k,k')}{P(q)} \right]$$ has no $(1/q)^\alpha$ poles

Kehagias & Riotto 2012; Peloso & Pietroni, 2013

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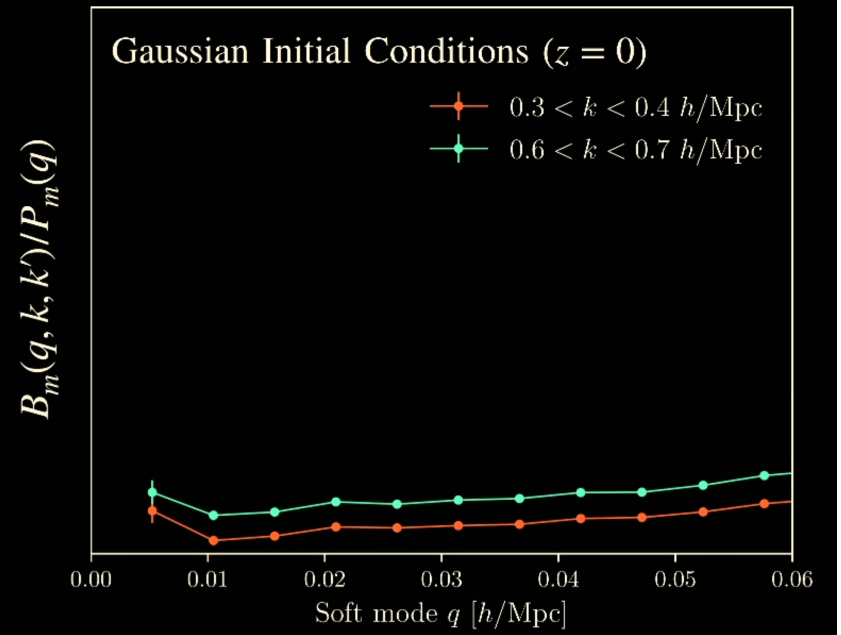

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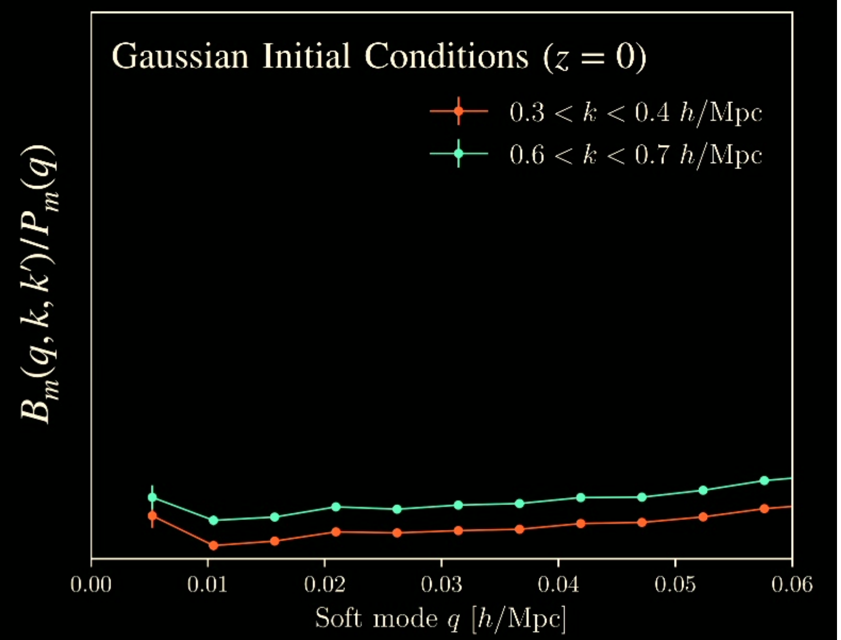

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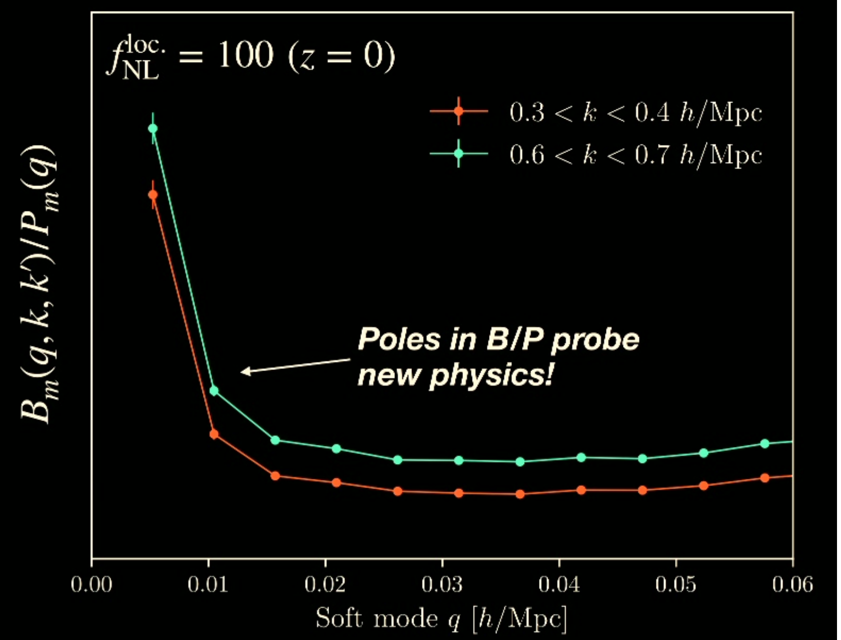

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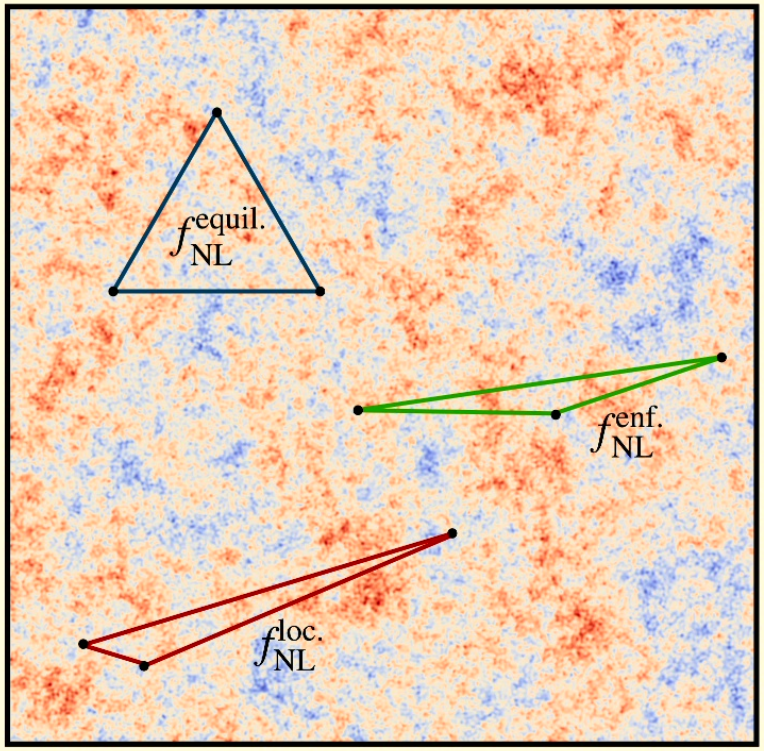
Primordial non-Gaussianity (PNG)

- What is the **physics** responsible for origin of structure?
- Single-field slow roll inflation (SFI) -> ~Gaussian IC's
  - More interesting scenarios produce PNG
- Classify with shapes of bispectrum
  - *Inflaton self-interactions:* $f_{\rm NL}^{\rm equil.}$
  - *Vacuum state:* $f_{\rm NL}^{\rm enf.}$
  - *Multiple light fields:* $f_{\rm NL}^{\rm loc.}$

$$\Phi(\boldsymbol{x}) = \phi_G(\boldsymbol{x}) + f_{\rm NL}^{\rm loc.}\left(\phi_G^2(\boldsymbol{x}) - \langle\phi_G^2(\boldsymbol{x})\rangle\right)$$

Komatsu & Spergel, 2001



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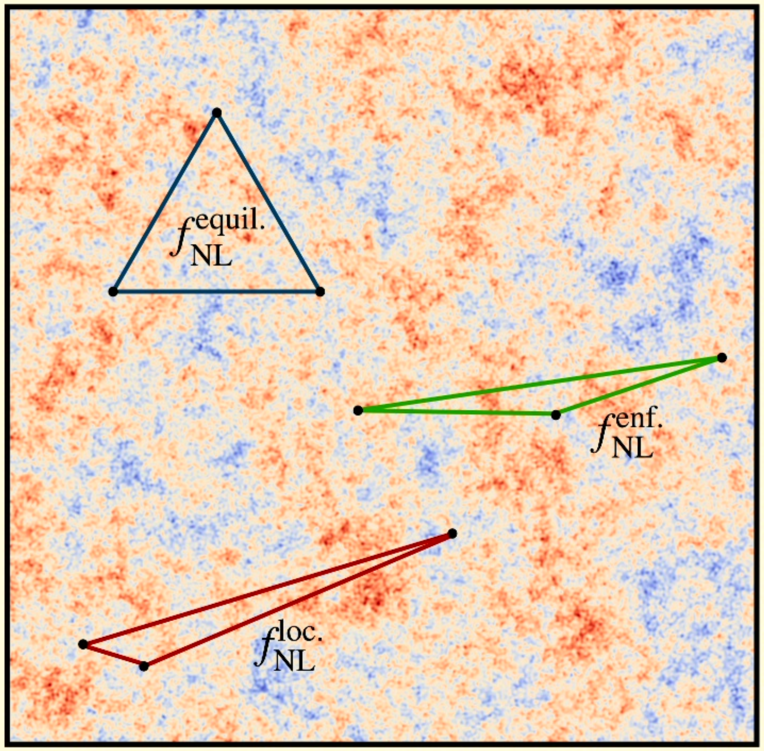
$f_{\rm NL}^{\rm loc.} \neq 0$ would rule out single-field inflation

Maldacena, 2002; Creminelli & Zaldarriaga, 2004



The cosmological collider

- Massive **scalars** during inflation have characteristic squeezed bispectrum

$$\lim_{k_1 \ll k_2 \approx k_3} B_\Phi(k_1,k_2,k_3) = 4 f_{\rm NL}^{\Delta} \left(\frac{k_1}{k_2}\right)^{\Delta} P_\Phi(k_1) P_\Phi(k_2)$$

- Power-law depends on **mass:** $\Delta = 3/2 - \sqrt{9/4 - m^2/H^2}$

(Arkani-Hamed & Maldacena, 2015)

1 - Massless ($m \ll H; \ \Delta \approx 0$):

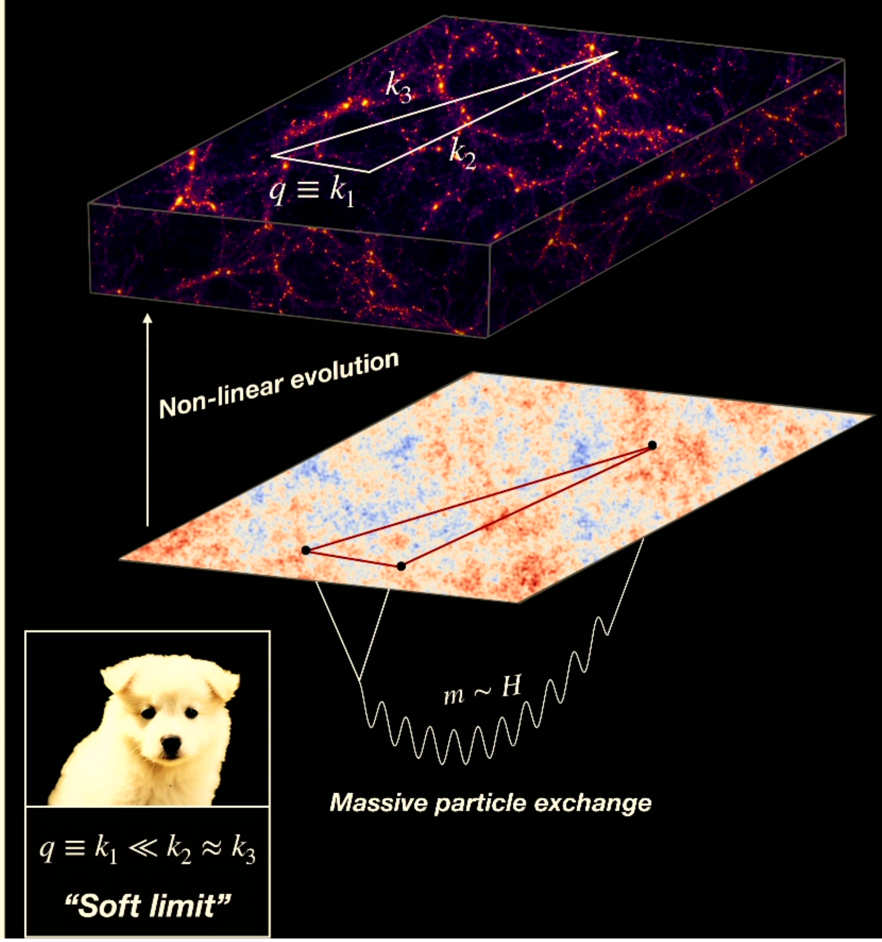
- Local non-Gaussianity ($f_{\rm NL}^{\Delta} = f_{\rm NL}^{\rm loc.}$)/multi-field inflation

2 - Massive-ish ($0 < m/H \leq 3/2; \ 0 < \Delta \leq 3/2$):

- Power-law scaling (quasi-single field)
  - Interpolates between $f_{\rm NL}^{\rm loc.}$ and $f_{\rm NL}^{\rm eq.}$

3 - Massive-er ($m/H \geq 3/2$; $\Delta \in \mathbb{C}$):

- Oscillatory bispectra

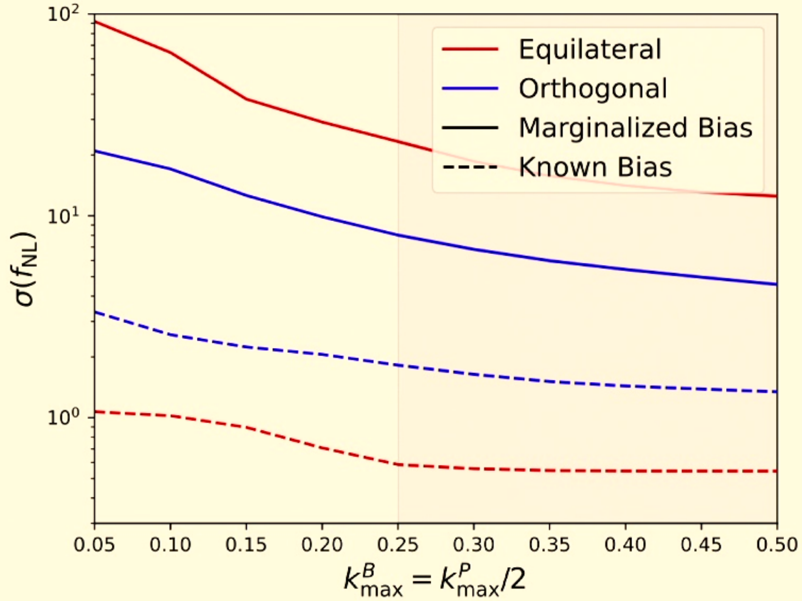


Observational Status of PNG Constraints

- Best constraints on PNG currently come from CMB
  - $f_{\rm NL}^{\rm loc.} = -0.9 \pm 5.1$
  - $f_{\rm NL}^{\rm equil.} = -26 \pm 47$
  - $f_{\rm NL}^{\rm ortho.} = -38 \pm 24$

Planck 2018 constraints on PNG

- Near-term/next generation CMB experiments will only improve by a factor of ~2-3 (nice job *Planck*!)
- We ***need*** LSS(xCMB?) to search for PNG



Megamapper Forecasts on PNG *(Cabass++2023)*

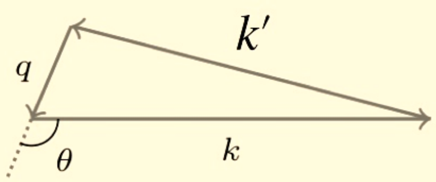
Recap

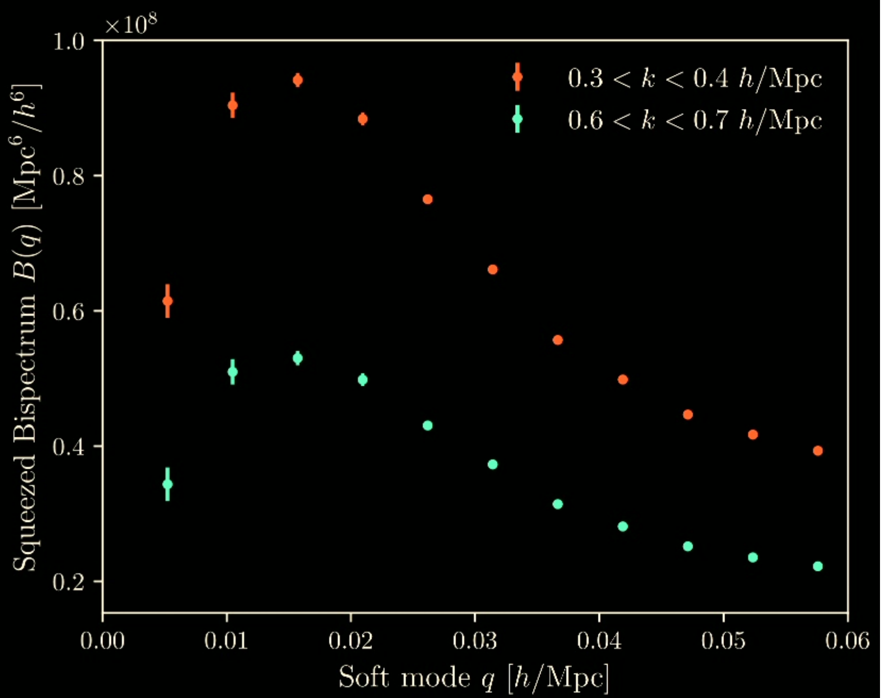
- LSS datasets are excellent probe of cosmology, **but** difficult to model on small scales *(e.g.,* non-linear nuisances+baryonic bewilderments…)
  - Consistency relations place robust, *non-perturbative* constraints on LSS correlators in the non-linear regime
- Consistency relations **can be violated** in multi-field inflation models/ cosmological collider scenario

Can we use consistency relations violation to search for PNG with LSS measurements at smaller scales?

Measurements

- Measure soft power spectrum ($\hat{P}_m(q)$)
- **Angle averaged** squeezed bispectrum
  - $\hat{B}(q, k_{\text{min}}, k_{\text{max}}) = \int d\Omega_{\boldsymbol{k}}\, B(q, k, k')$
  - Average over wide k-bin for hard modes





Measurements of angle averaged squeezed bispectrum as a function of the soft mode for two different hard momenta bins.

Non-perturbative model for the squeezed bispectrum

- Let's derive the leading order $f_{\rm NL}$ contribution to the **squeezed** matter bispectrum
- Squeezed bispectrum ($q \ll k$) is described by **modulation** of small scale power spectrum to long wavelength gravitational potential Φ_L

$$\lim_{q \ll k_{\rm NL}, k} B_m(q, k, k') = \lim_{q \ll k_{\rm NL}, k} \langle \delta_m(\boldsymbol{q}) \delta_m(\boldsymbol{k}) \delta_m(\boldsymbol{k}') \rangle',$$

(Non-perturbative see, e.g., Lewis, 1107.5431)

$$= \langle \delta_m(\boldsymbol{q}) P_m(k \,|\, \Phi_L) \rangle' = P_{\Phi_L m}(q) \frac{\partial P_m(k)}{\partial \Phi_L(q)},$$

$$= \frac{3\Omega_{m0} H_0^2}{2q^2 T(q) D_{\rm md}(z_q)} P_m(q) \frac{\partial P_m(k)}{\partial \Phi_L(q)}.$$

From Poisson's equation

Adding in gravitational non-Gaussianity

- Squeezed bispectrum ($q \ll k$) is **modulation** of small-scale power spectrum by a long-wavelength gravitational potential $\Phi_L(\mathbf{x})$.
  - Contributions from PNG are associated with $\partial P_m(k)/\partial \Phi_L(q)$
  - Contributions from gravitational non-Gaussianity modeled using response approach

(e.g., Valageas 13; Chiang+17; Esposito+19; Biagetti+22; Giri+23)

$$\lim_{q \ll k_{\rm NL}, k} B_m(q, k, k') = \frac{3\Omega_{m0} H_0^2}{2q^2 T(q) D_{\rm md}(z)} P_m(q) \left(\frac{\partial P_m(k)}{\partial \Phi_L(q)} \right) + \left(\bar{a}_0 + \bar{a}_2 \frac{q^2}{k^2} \right) P_m(q) P_m(k)$$

Consistency relations violating term

Gravitational term (protected by symmetry)

$\bar{a}_0$ and $\bar{a}_2$ are nuisance params describing non-linear physics (similar to bias params!)

- **How to estimate this *non-linear* potential derivative?**

Separate universe prediction for $\partial P_m(k)/\partial\Phi_L(q)$

- Split perturbation into long (L) and short (S)

$$\phi(\boldsymbol{x}) = \Phi_L(\boldsymbol{x}) + \Phi_S(\boldsymbol{x})$$

~Constant=background

- For local PNG, $\Phi_L(\boldsymbol{x})$ modulates $\Phi_S(\boldsymbol{x})$
- Same as local rescaling of amplitude of $P^{\rm lin}(k)$

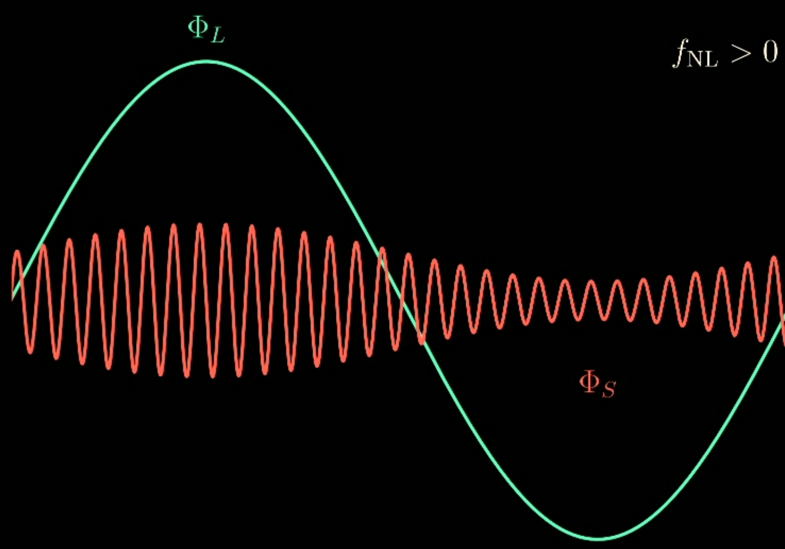
$$\sigma_8^{\rm loc.}(\boldsymbol{x}) = (1 + 2f_{\rm NL}\Phi_L(\boldsymbol{x}))\sigma_8$$

(e.g., Giri, Münchmeyer, Smith 2305.03070)

- PNG is just a modification of the ICs!

$$\frac{\partial P_m(k)}{\partial \Phi_L(q)} = 2f_{\rm NL}\frac{\partial P_m(k)}{\partial \log\sigma_8}\bigg|_{\rm SU}$$

(Dalal+07, Slosar+08, Desjacques+08)



$$\Phi = \Phi_L + f_{\rm NL}(\Phi_L^2 - \langle\Phi_L\rangle^2) + (1 + 2f_{\rm NL}\Phi_L)\Phi_S + f_{\rm NL}(\Phi_S^2 - \langle\Phi_S^2\rangle)$$

Mode Coupling

Separate universe prediction for $\partial P_m(k)/\partial\Phi_L(q)$

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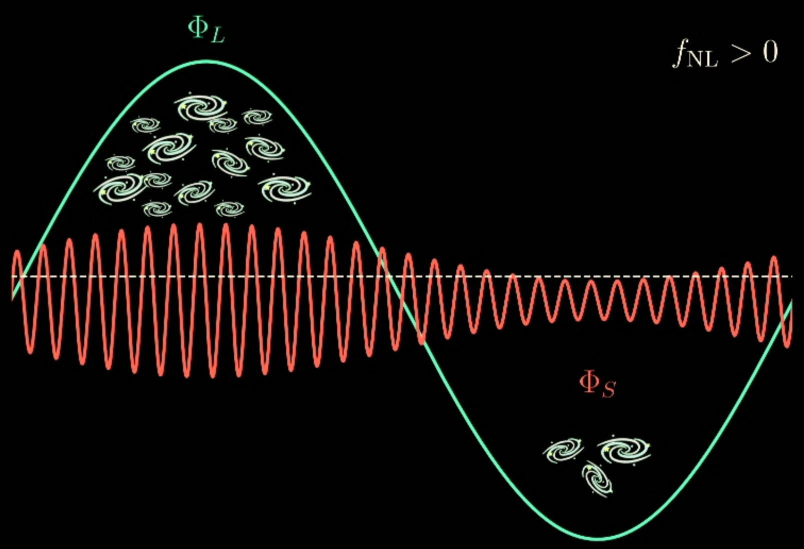


"Scale-dependent" bias
Dalal+08/Matarrese+08/
Slosar+08/Desjacques+08

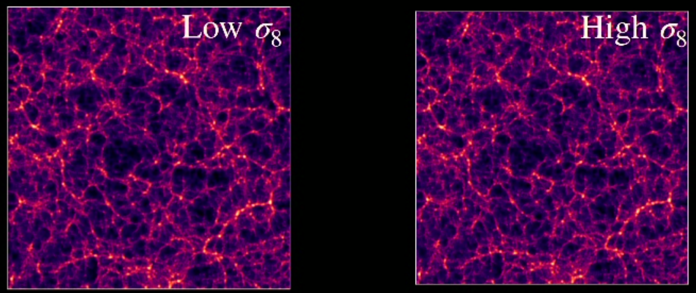
Separate universe (*continued*)

- For local PNG, we have

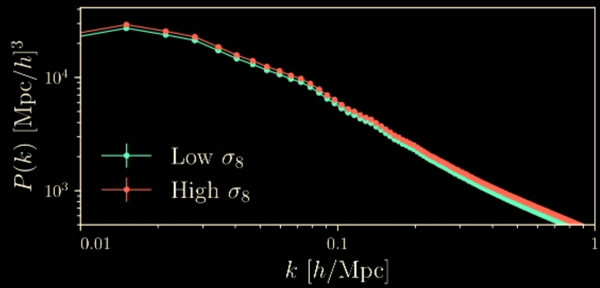
$$\frac{\partial P_m(k)}{\partial \Phi_L(q)} = 2f_{\mathrm{NL}} \frac{\partial P_m(k)}{\partial \log \sigma_8}\bigg|_{\mathrm{SU}}$$

- **a): How do we compute this?**
  - Run sims with modified $P^{\mathrm{lin.}}(k)$ and finite difference the late-time power spectra
- **b): Why is this useful?**
  - Relatively cheap to estimate from sims

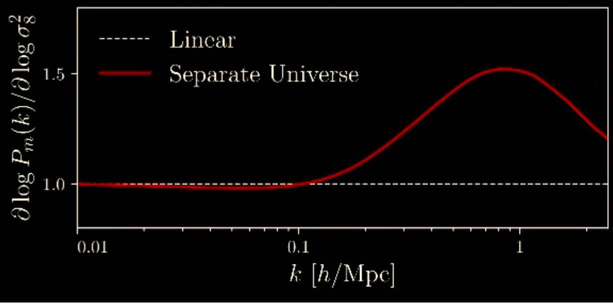
(i) Run sims with modified ICs



(ii) Compute $P_{mm}(k)$ from simulation output



(iii) Finite difference to get logarithmic derivative



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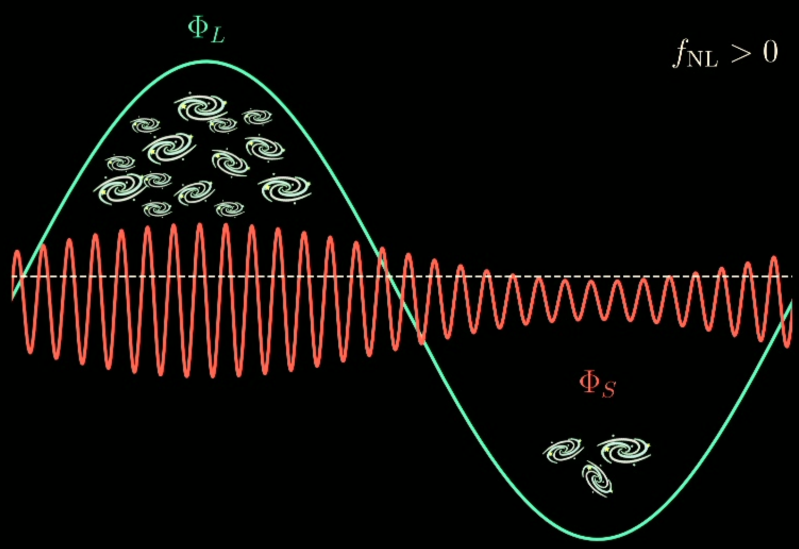
$$\frac{\partial P_m(k)}{\partial \Phi_L(q)} = 2f_{\mathrm{NL}} \frac{\partial P_m(k)}{\partial \log \sigma_8}\bigg|_{\mathrm{SU}}$$

(Dalal+07, Slosar+08, Desjacques+08)



"Scale-dependent" bias

Dalal+08/Matarrese+08/Slosar+08/Desjacques+08

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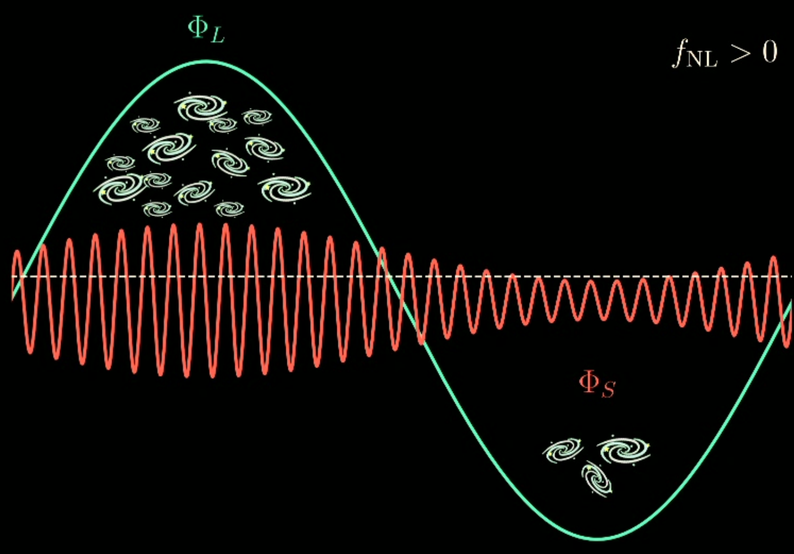


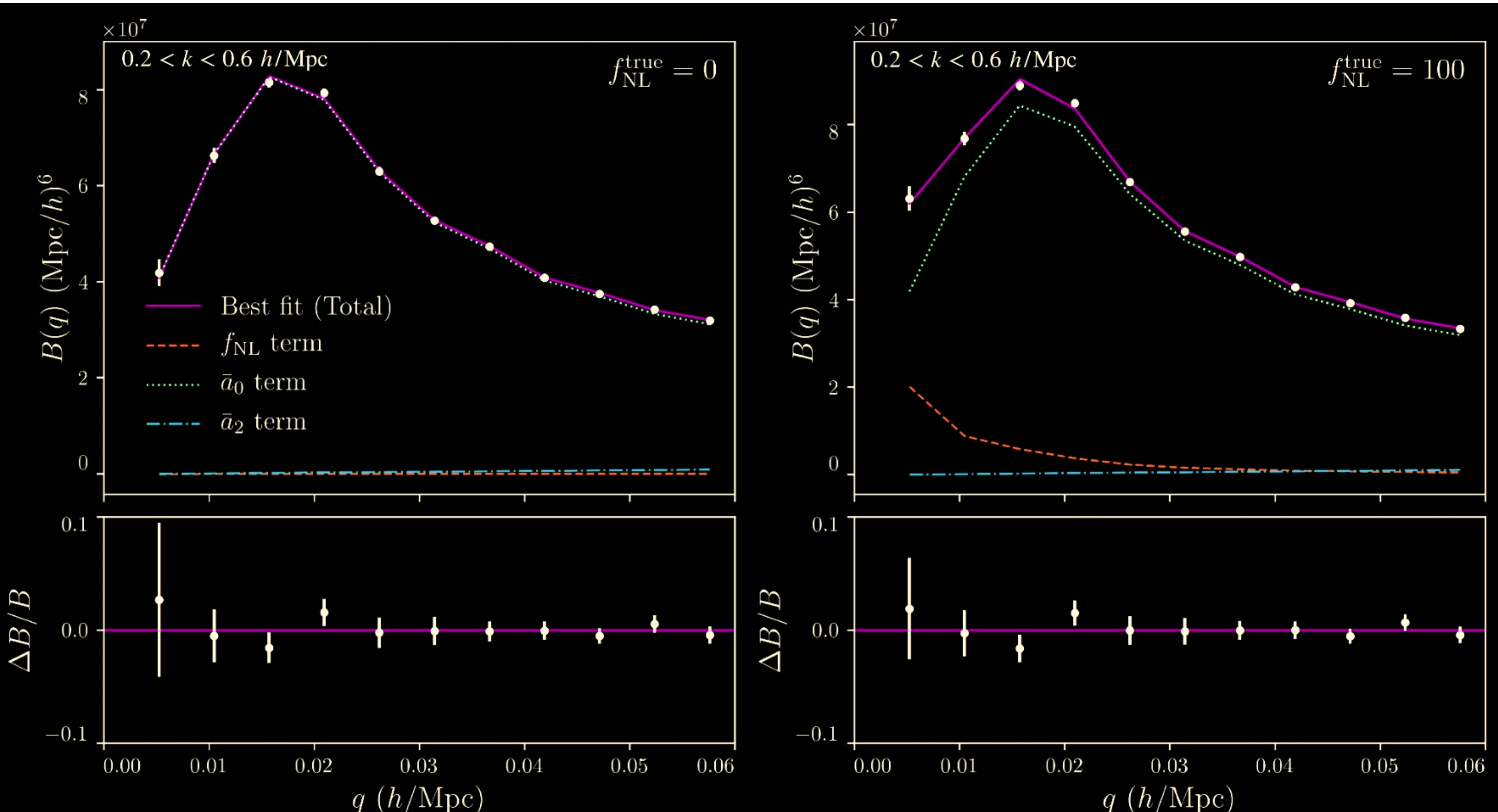
"Scale-dependent" bias
Dalal+08./Matarrese+08/
Slosar+08/Desjacques+08

Putting it all together

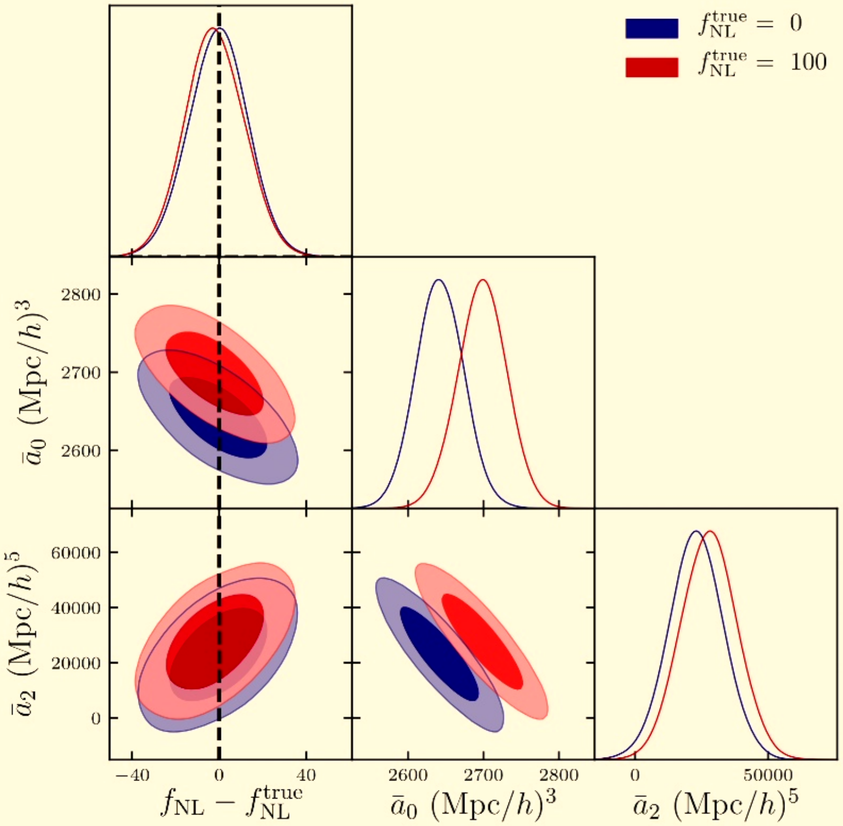
- Model for non-linear squeezed matter bispectrum is

$$\lim_{q \ll k_{\rm NL}, k} B_m(q,k,k') = \left[\frac{6\Omega_{m0}H_0^2}{q^2 T(q) D_{\rm md}(z)} \frac{\partial \log P_m(k)}{\partial \log \sigma_8^2} \bigg|_{\rm SU} f_{\rm NL} + \bar{a}_0 + \bar{a}_2 \frac{q^2}{k^2} \right] P_m(q) P_m(k)$$

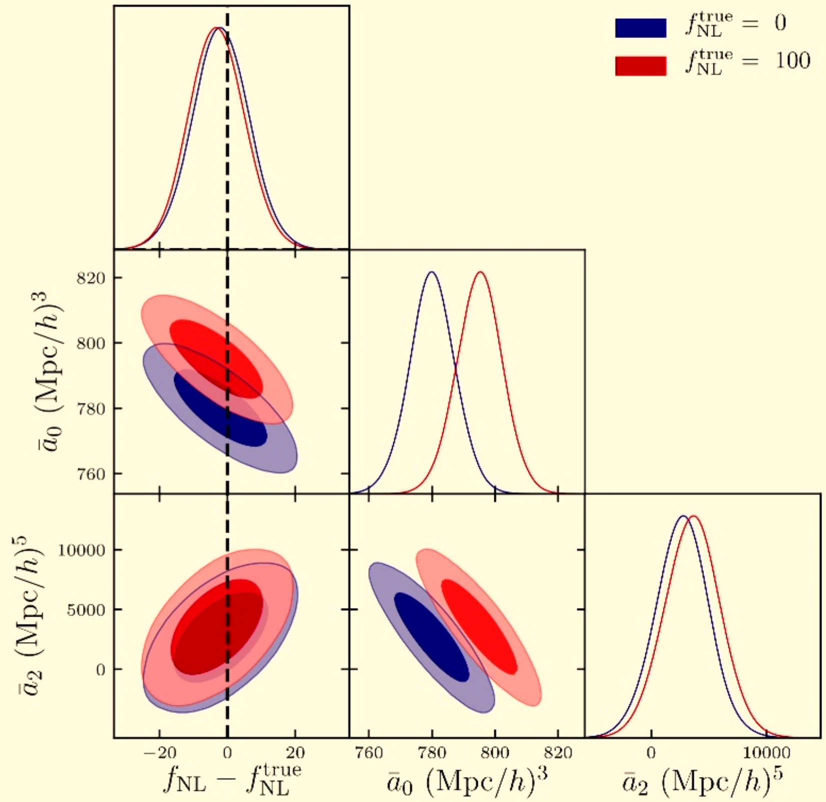
- Characterized by **three free parameters**: $\{f_{\rm NL}, \bar{a}_0, \bar{a}_2\}$
- **Goal:** validate model using measurements of B_m and P_m from N-body simulations
  - Likelihood analysis with covariance of B_m and P_m estimated from simulations
    - Joint likelihood in $\hat{B}_m$ and $\hat{P}_m$ for sample variance cancellation



$$\lim_{q\ll k_{\rm NL},k} B_m(q,k,k') = \left[\frac{6\Omega_{m0}H_0^2}{q^2T(q)D_{\rm md}(z)} \frac{\partial \log P_m(k)}{\partial \log \sigma_8^2}\bigg|_{\rm SU} f_{\rm NL} + \bar{a}_0 + \bar{a}_2\frac{q^2}{k^2}\right] P_m(q)P_m(k)$$

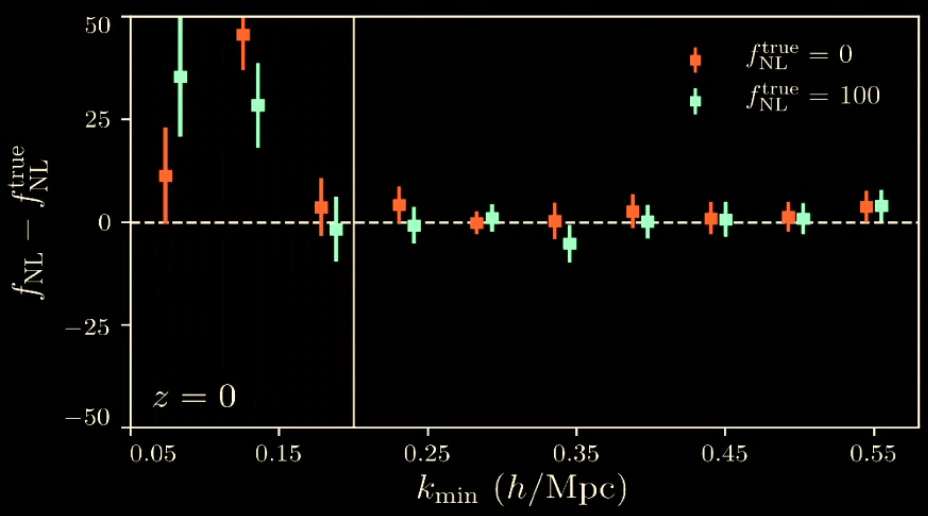


Marginalized Posterior at z=0



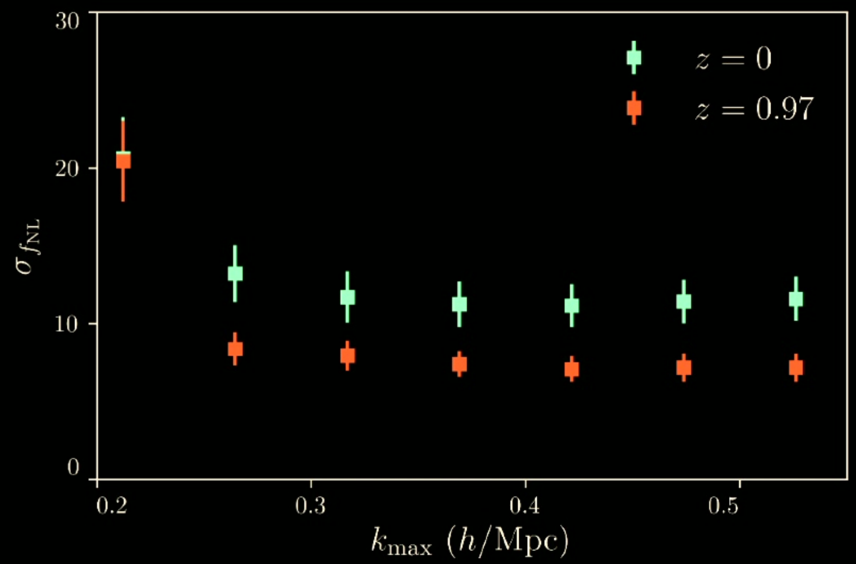
Marginalized Posterior at z=0.97

(i) How squeezed do the triangles need to be?



We recover the true value of fNL for kmin>0.2h/Mpc

(ii) How much information is in non-linear regime?



Constraints saturate for k>0.3h/Mpc due to **non-Gaussian covariance**

Recap/what's next

- We can reliably constrain $f_{\rm NL}^{\rm loc}$ from small-scale squeezed matter bispectrum
  - Method is based on LSS consistency relations+separate universe approach
  - *In principle,* could improve future LSS searches for PNG
- What can we do with this result?
  - Extend result to lensing (**SG**+2023*)*
  - Extend to halos and include collapsed trispectrum (promising results from Giri+2023)
    - Can we get around the non-Gaussian covariance?
  - Generalize to redshift space (unsure)
  - Generalize to other models of PNG

Part ii) Generalization to the Cosmlogical Collider

“Massive-ish particles from small-ish scales”

2407.08731

SG, *Philcox, Hill, Hui*

Cosmological Collider Bispectrum Review

- Only difference for cosmological collider models is **potential derivative**

$$\lim_{q \ll k_{\rm NL}, k} B_m(q, k, k') = \frac{3\Omega_{m0} H_0^2}{2q^2 T(q) D_{\rm md}(z)} P_m(q) \left(\frac{\partial P_m(k)}{\partial \Phi_L(q)} \right) + \left(\bar{a}_0 + \bar{a}_2 \frac{q^2}{k^2} \right) P_m(q) P_m(k)$$

- Recall cosmo. collider squeezed bispectrum

$$\lim_{q \ll k} B_\Phi(q, k) = 4 f_{\rm NL}^{\Delta} \left(\frac{q}{k} \right)^{\Delta} P_\Phi(q) P_\Phi(k); \;\; 0 \leq \Delta < 3/2$$

- Local ($\Delta = 0$) is special case
  - Need to generalize separate universe calculation for $0 < \Delta < 3/2$?

Separate universe and the cosmological collider

- Consider small-scale modes $\delta_m(\boldsymbol{k}_1)$ and $\delta_m(\boldsymbol{k}_2)$ with **fixed amplitude,** but $\boldsymbol{k}_1 < \boldsymbol{k}_2$
- Add in **background** (~const.) potential fluctuation $\Phi_L(\boldsymbol{q})$
- Collider models have a **scale-dependent** response

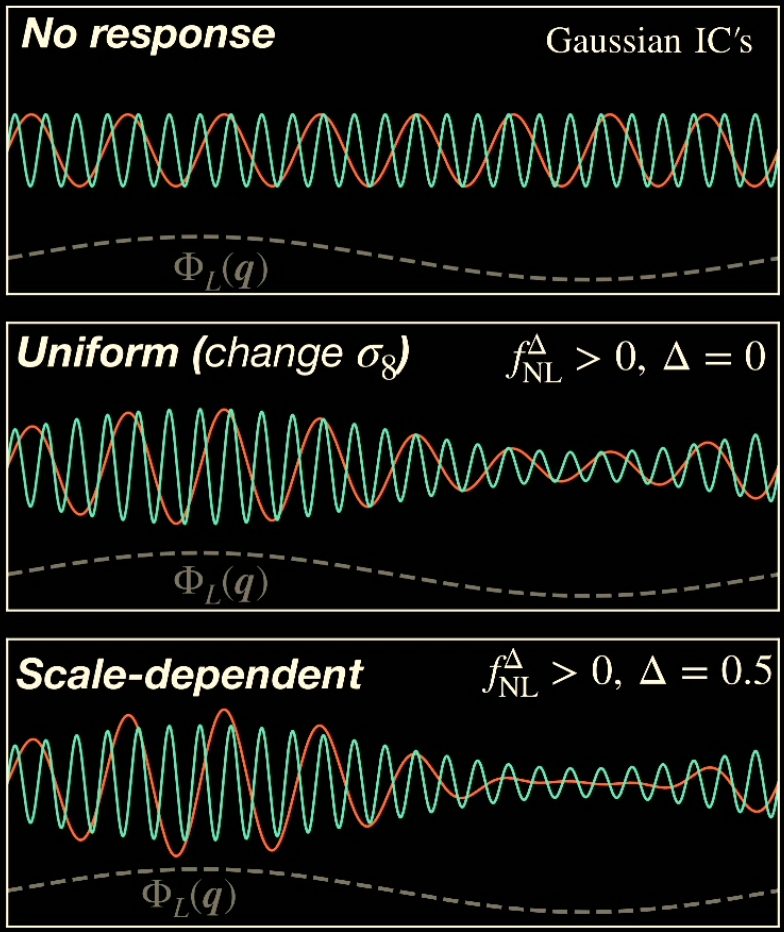
$$\delta_m(\boldsymbol{k}\,|\,\Phi_L(\boldsymbol{q})) = \left(1 + 2f_{\rm NL}^{\Delta}\left(\frac{q}{k}\right)^{\Delta}\Phi_L(\boldsymbol{q})\right)\delta_m(\boldsymbol{k})$$

Schmidt, Jeong, Desjacques, 2012

- Can compute $\partial P(k)/\partial\Phi_L(q)$ from sims with modified $P_m^{\rm lin.}$

$$P_m^{\rm lin.}(k\,|\,\epsilon,\Delta) \equiv \left(1 + 2\epsilon k^{-\Delta}\right)P_m^{\rm lin.}(k)\,.$$

$$\frac{\partial P_m(k)}{\partial\,\Phi_L(\mathbf{q})} = 2f_{\rm NL}^{\Delta}q^{\Delta}\frac{\partial P_m(k\,|\,\epsilon,\Delta)}{\partial\epsilon}\Bigg|_{\epsilon=0}\,.$$



Potential derivatives

- Compute logarithmic derivative from separate universe sims

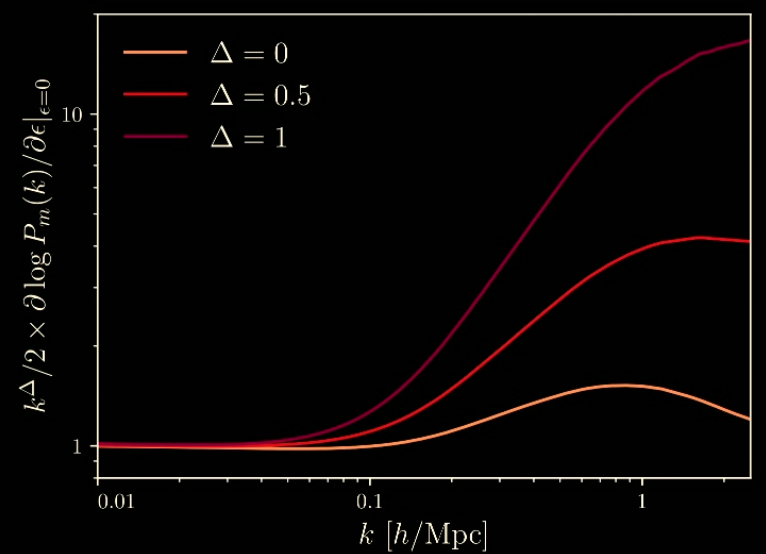
$$P_m^{\text{lin.}}(k\,|\,\epsilon,\Delta) \equiv \left(1+2\epsilon k^{-\Delta}\right) P_m^{\text{lin.}}(k)\,.$$

$$\frac{\partial P_m(k)}{\partial\,\Phi_L(\mathbf{q})} = 2 f_{\text{NL}}^{\Delta} q^{\Delta} \frac{\partial P_m(k\,|\,\epsilon,\Delta)}{\partial\epsilon}\bigg|_{\epsilon=0}\,.$$

Get from finite differencing SU sims with small $\pm\epsilon$

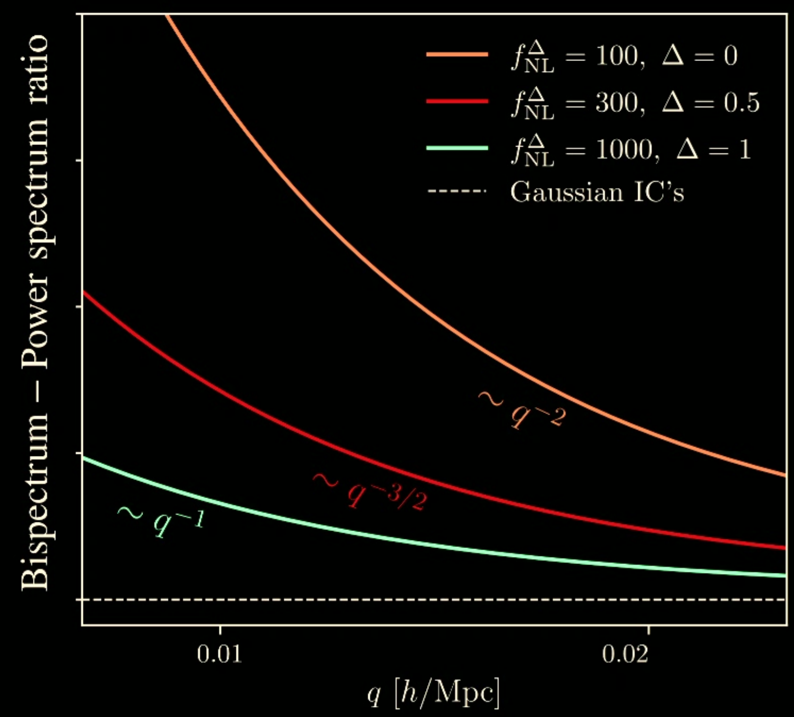
- Strong dependence on Δ
- Can also use sims to estimate non-Gaussian bias $b_{\Psi,\Delta}$

$$b_{\Psi,\Delta}(M,z) = \frac{\partial \log \bar{n}_h(M,z)}{\partial\epsilon}\bigg|_{\epsilon=0}$$

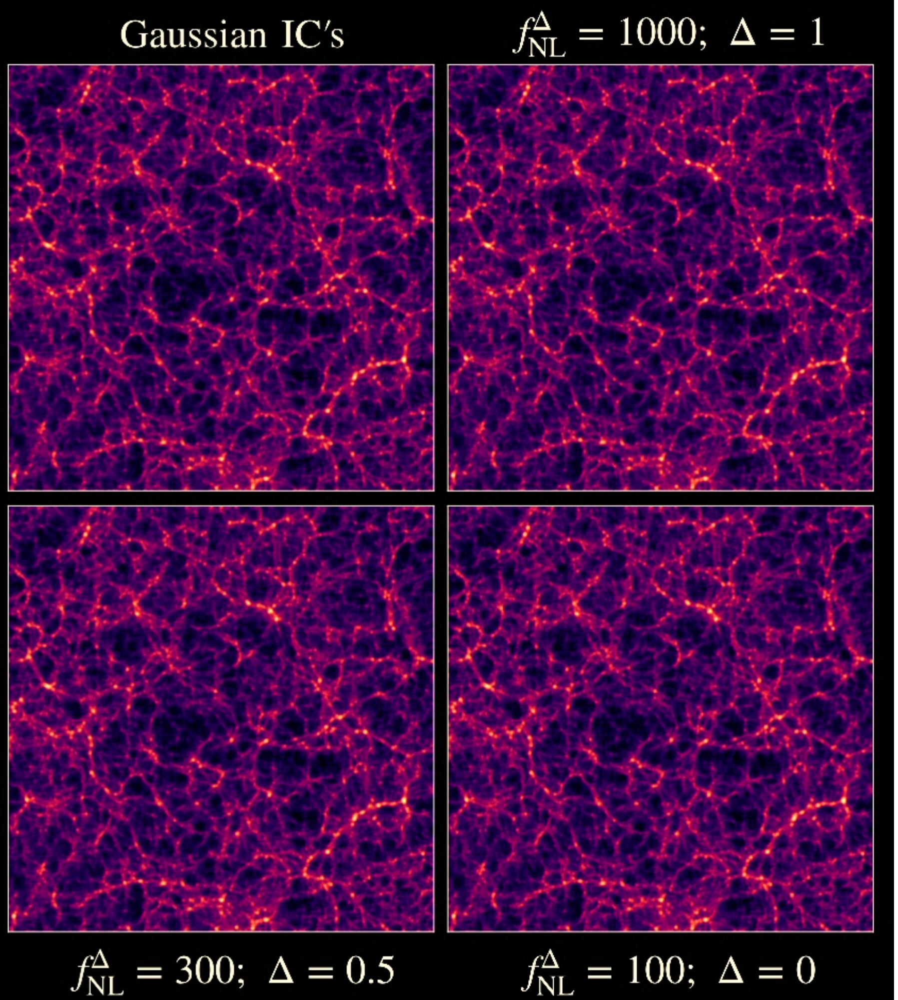


Separate universe potential derivatives for different values of Δ

N-body simulations with collider bispectrum



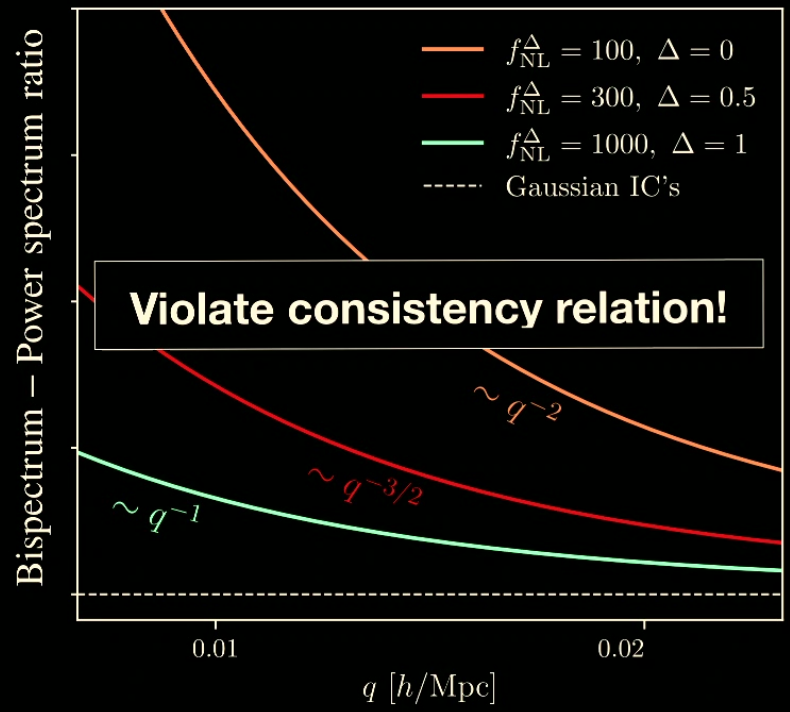
GADGET



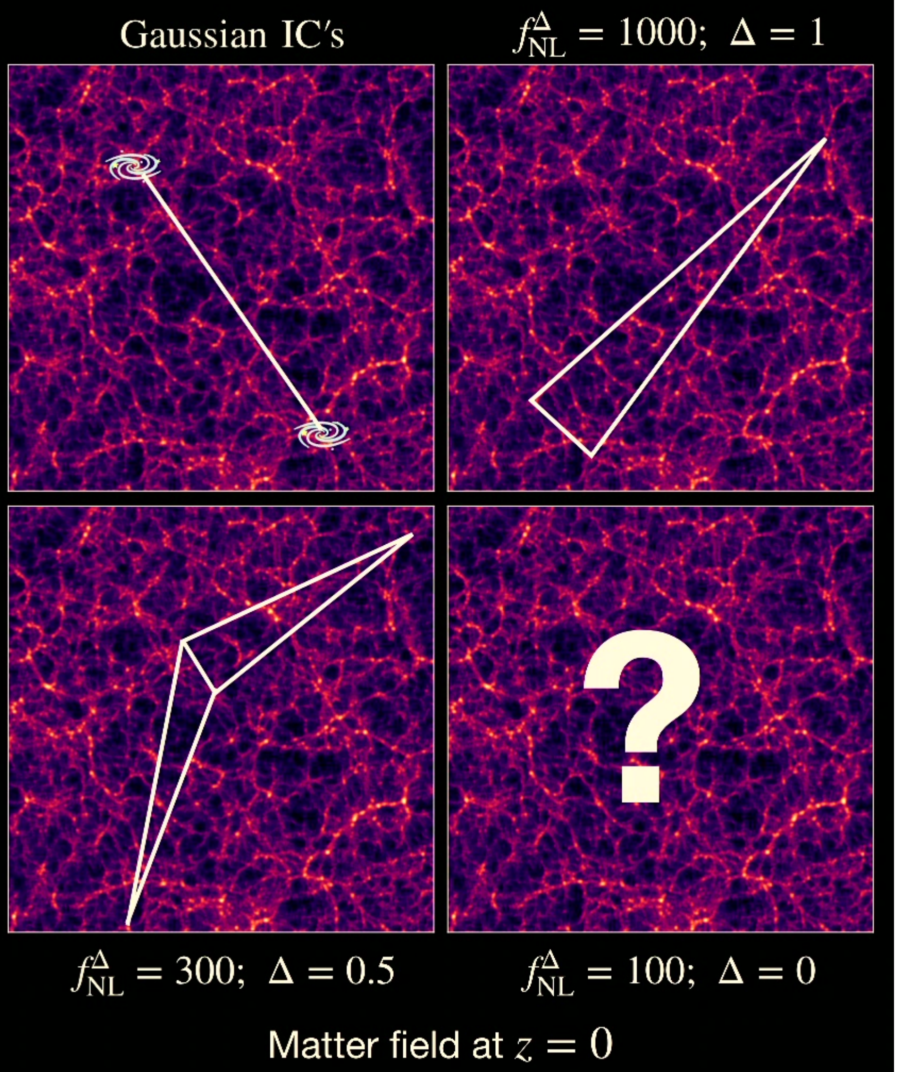
Matter field at $z = 0$

- Added squeezed collider templates to **2LPTPNG**
- Ran suite of simulations with same settings as **QuijotePNG**, but collider primordial bispectrum

N-body simulations with collider bispectrum

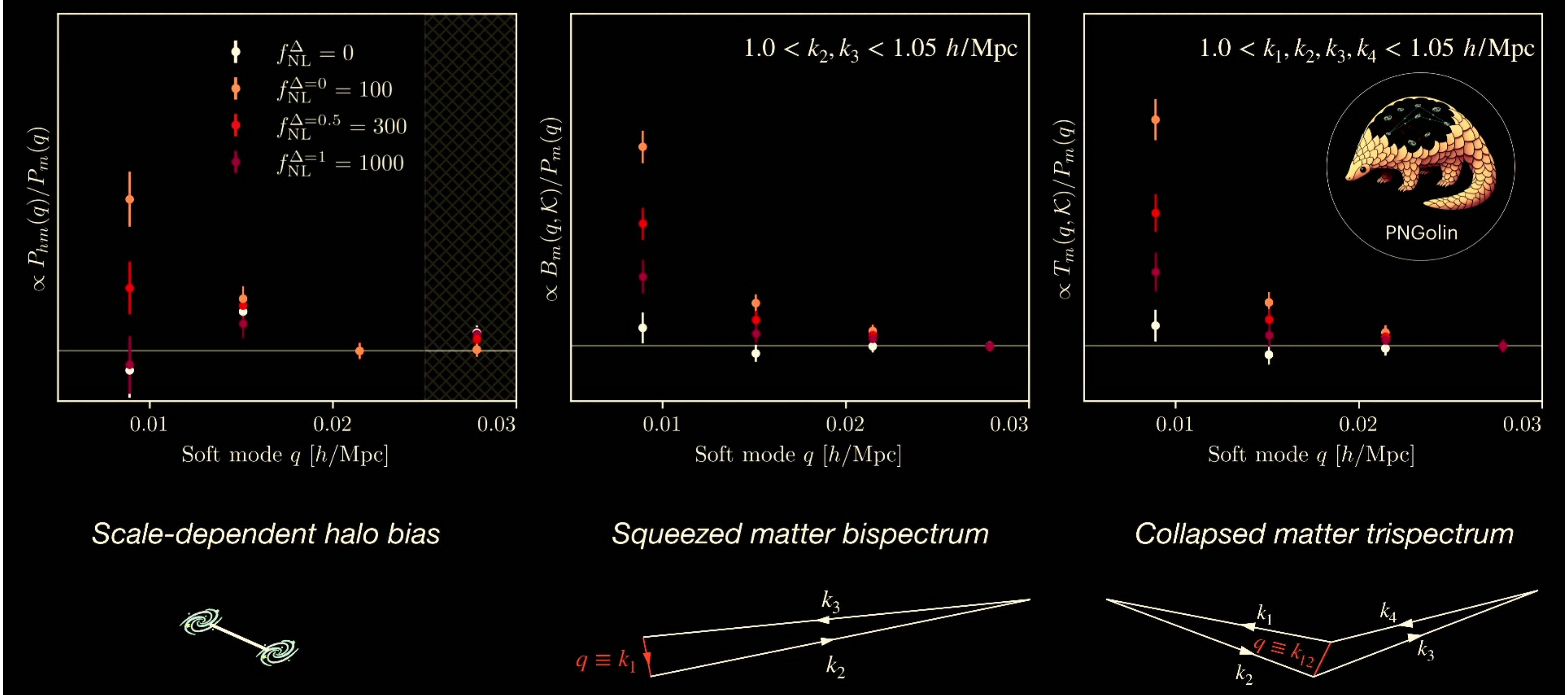


→ **GADGET**



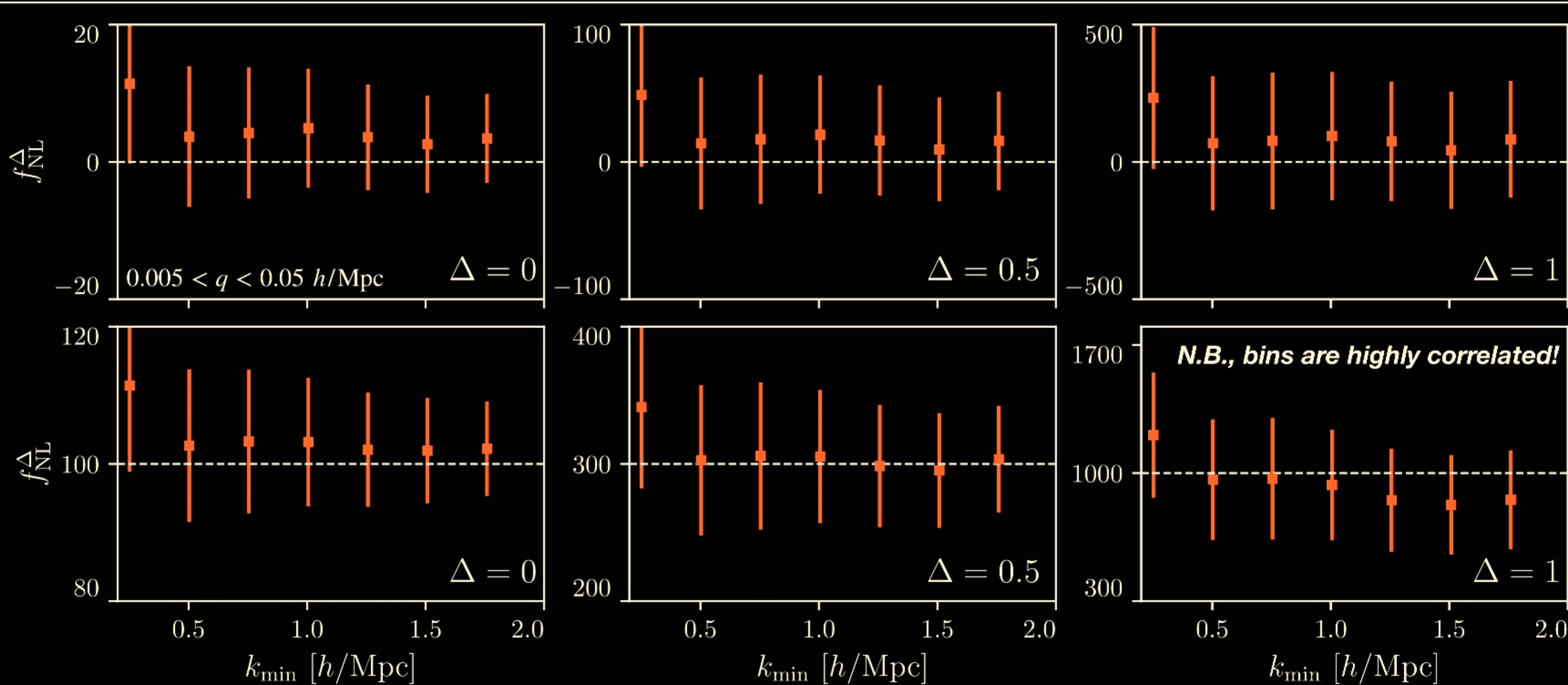
- Added squeezed collider templates to **2LPTPNG**
- Ran suite of simulations with same settings as **QuijotePNG**, but collider primordial bispectrum

Imprints of the cosmological collider on LSS correlators



*https://github.com/samgolds/PNGolin

Constraints from squeezed bispectrum at $z = 0$



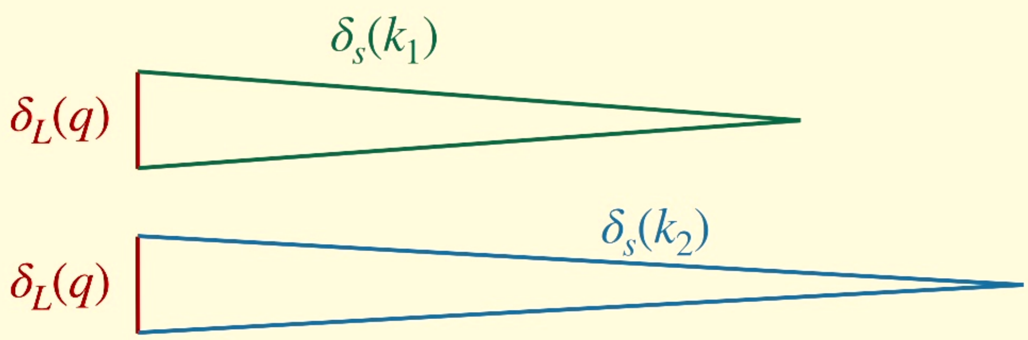
Unbiased constraints on f_{NL}^{Δ} using ***non-linear*** squeezed matter bispectrum for all models!

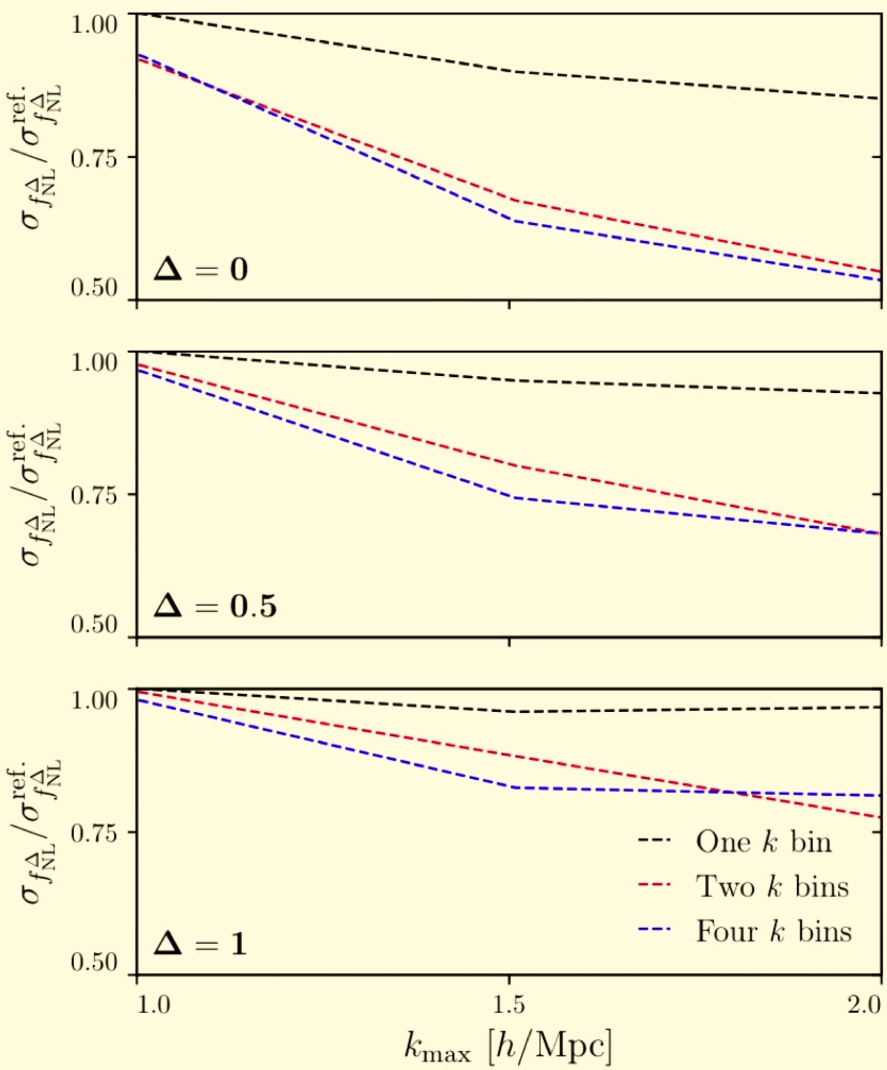
Information content

- Do we learn anything at small scales (high k)?
  - Yes! Assuming we use multiple k bins

Similar results in de Putter+18 and Giri+23

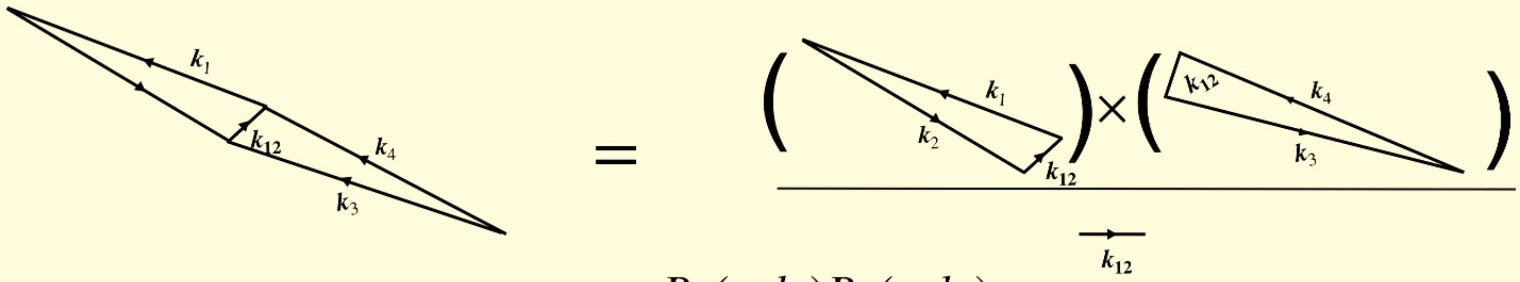
- Multiple bins cancels cosmic variance from long mode (just like multi-tracer)





The collapsed trispectrum

- Collapsed trispectrum~(squeezed bispectrum)^2

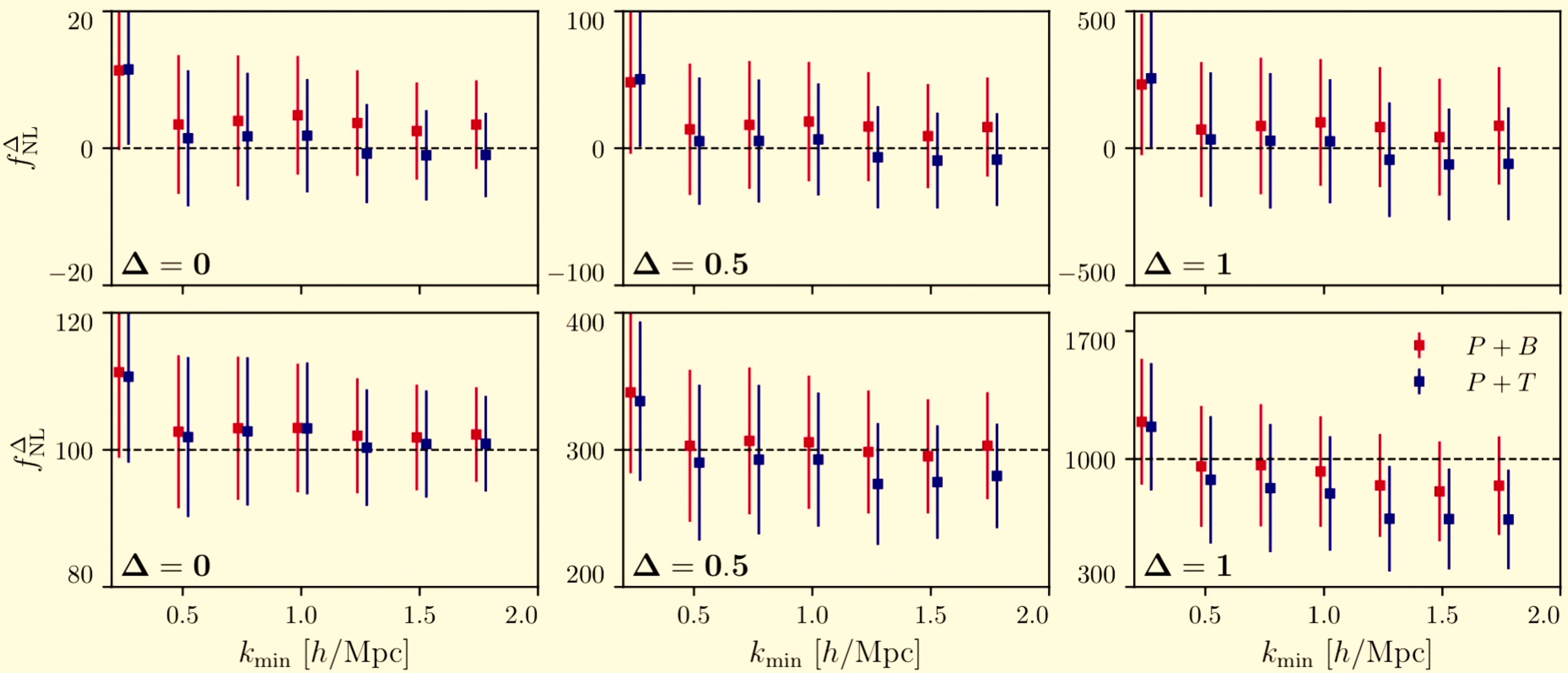


$$T_m(q, k_1, k_3) = \frac{B_m(q, k_1) B_m(q, k_3)}{P_m(q)} + T_0(k_1, k_3),$$

- Squeezed bispectrum model can be used to study the collapsed trispectrum
  - Measurement is main challenge: https://github.com/samgolds/PNGolin

(Based on Coulton+23)

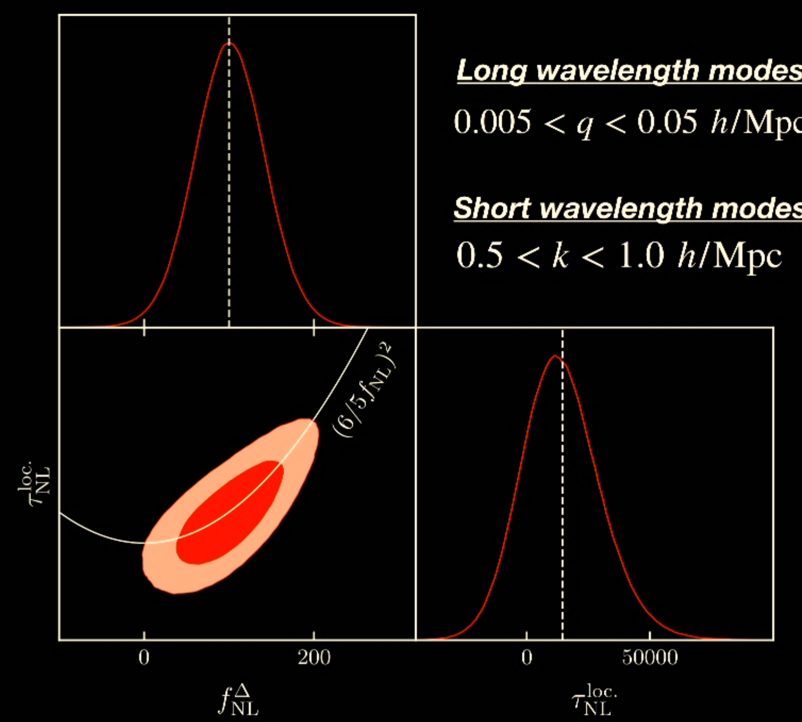
Validating trispectrum model



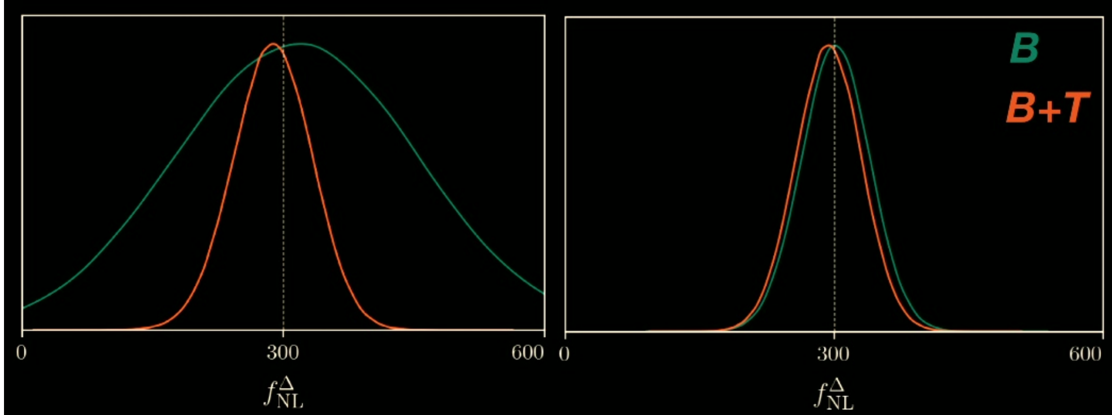
Collapsed trispectrum

- What can we learn from the trispectrum?
  - Higher-order PNG
  - Cosmic variance cancellation

P+B+T joint analysis



Unknown $P_{mm}(k)$ **Known** $P_{mm}(k)$



Scale-dependent halo bias

- Squeezed bispectrum leads to **scale-dependent bias** *(Dalal+07, Slosar+08, Desjacques+08)*

f_{NL}^{Δ} degenerate with non-Gaussian bias

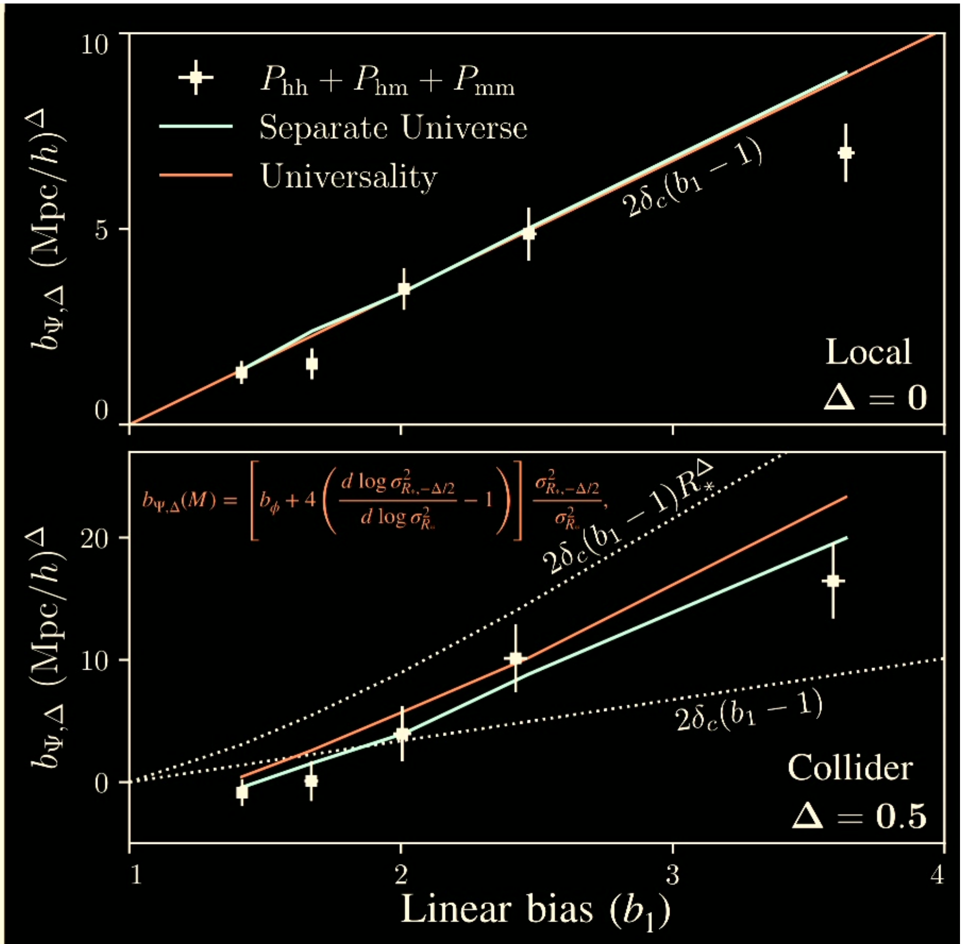
$$P_{hm}(q) = \left[b_1 + \frac{3\Omega_{m0}H_0^2}{2D_{\rm md}(z)} \frac{b_{\Psi,\Delta} f_{\rm NL}^{\Delta}}{q^{2-\Delta}} \right] P_m(q)$$

Power depends on Δ

- Fit for $b_{\Psi,\Delta}$ at fixed $f_{\rm NL}^{\Delta}$ and Δ
  - Test predictions for galaxy biasing in non-local PNG *e.g., Shandera+2010, Schmidt & Kamionkowski, 2010 Schmidt+2012*

$$b_{\Psi,\Delta} = \frac{2\,\partial \log \bar{n}_h}{\partial \epsilon}\bigg|_{\epsilon=0},$$

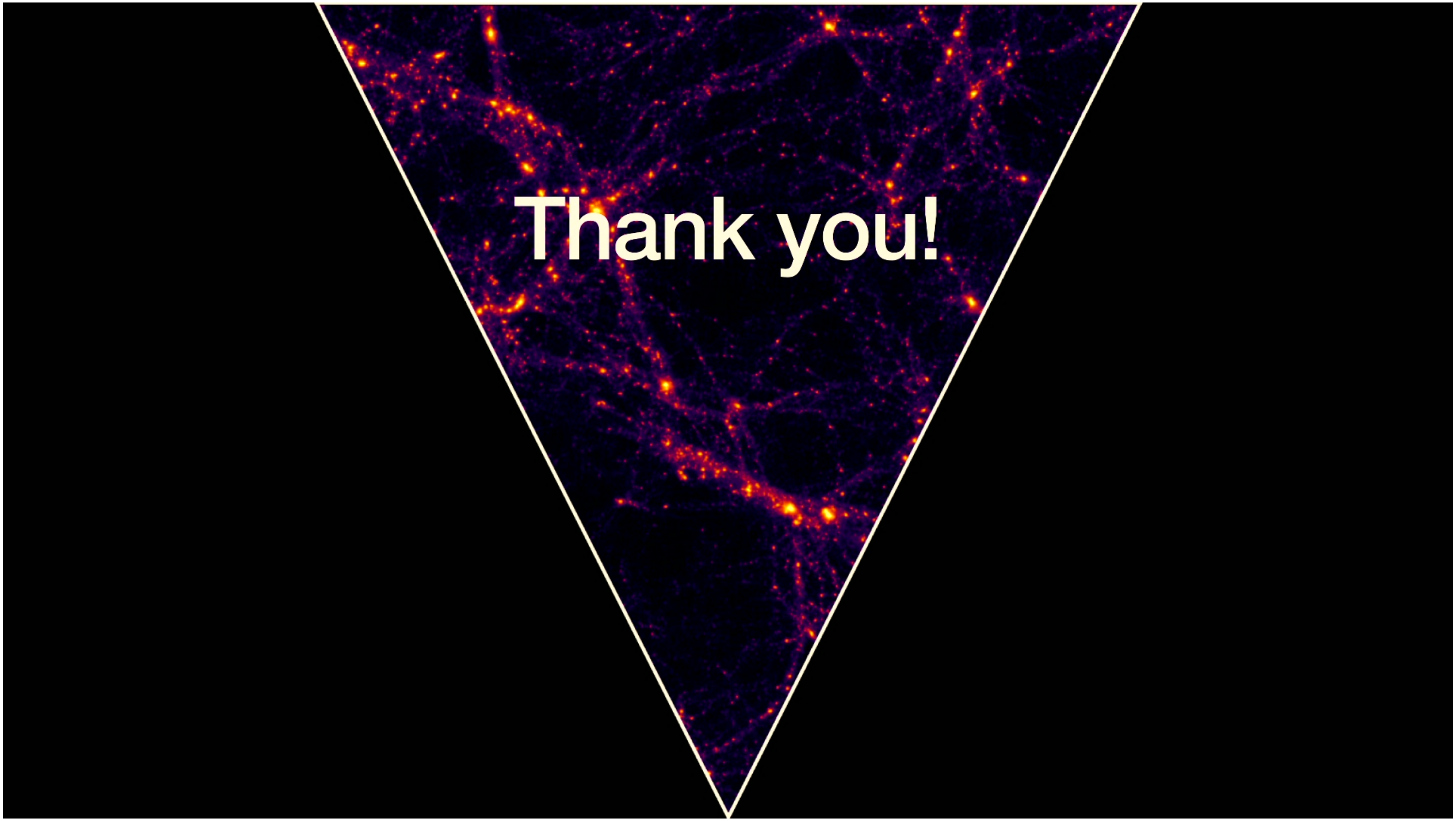
  - **Galaxies will be more challenging…**



Fits to **halo** catalogues from sims agree with separate universe and universality.

Conclusions

- Consistency relations provide opportunity to learn about PNG from non-linear LSS
  - Constructed and validated ***non-perturbative*** models for squeezed B_m and collapsed T_m
    - Validated up to $k_{\rm max} = 2\ h/{\rm Mpc}$ for local PNG and Cosmo. Collider
- Tools developed here could be useful for other works
  - Publicly available trispectrum estimators
  - Methods for generating sims with Cosmo. Collider PNG
  - Validation of separate universe approach for Cosmo. Collider **scale-dependent bias** *(e.g., Green, Guo, Han, Wallisch, 2023)*
- Future directions
  - E.g., **spin/oscillatory bispectra**, B_g and T_g, **multi-tracer/**$\mathbf{b_{\Psi,\Delta}}$, CMBxLSS, can we constrain Δ?
  - Is the bispectrum/trispectrum even a good statistic in the non-linear regime?


Thank you!