Relativistic one-loop matter bispectrum

Jorge Noreña
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Based mostly on:

A. Kehagias, A. Moradinezhad, J. N., H. Perrier, A. Riotto, 2015
L. Castiblanco, R. Gannouji, J. N., C. Stahl, 2018

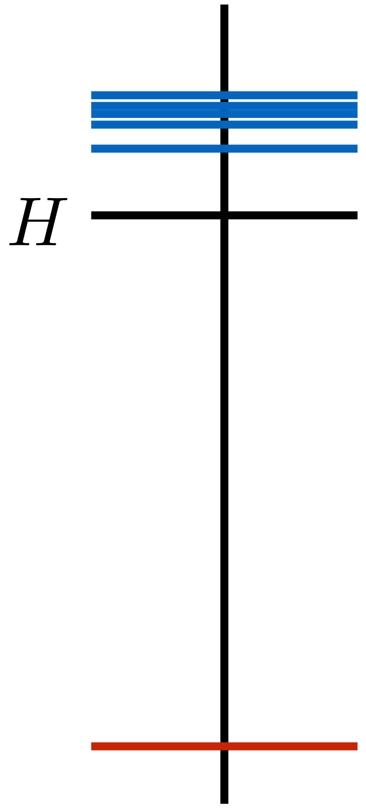
Outline

- Introduction, non-Gaussianity
- Relativistic galaxy power spectrum and bispectrum
- Relativistic one-loop bispectrum

Squeezed limit information

The squeezed limit contains model independent information about the physics during inflation

Single field



$$B(q, k_1, k_2) \overset{q \to 0}{\sim} \frac{1}{q}$$

J. Maldacena, 2003

P. Creminelli, M. Zaldarriaga, 2004

P. Creminelli, G. D'Amico, M. Musso, JN, 2011

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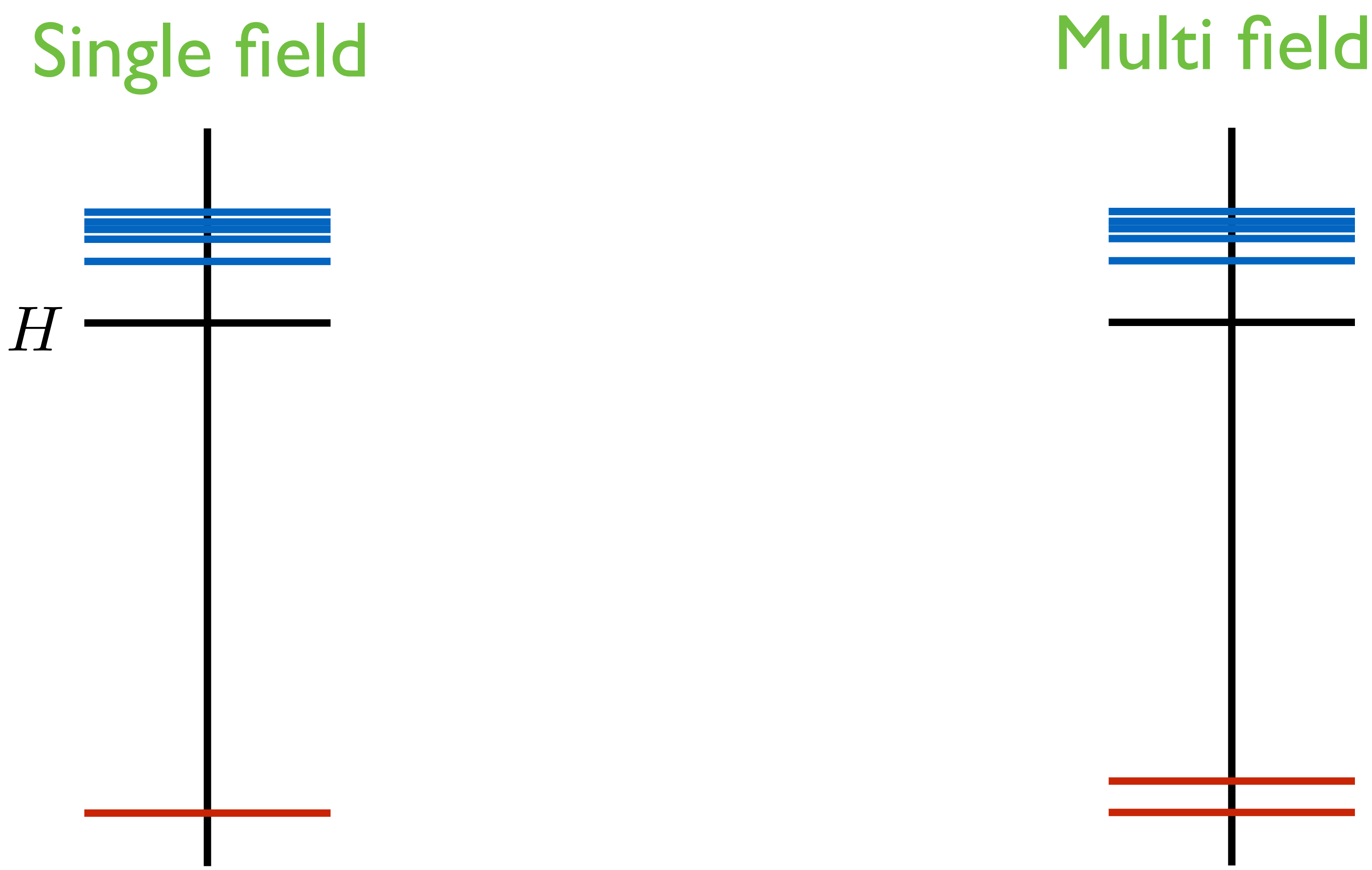

$$B(q, k_1, k_2) \stackrel{q\to 0}{\sim} \quad \frac{1}{q} \qquad \frac{1}{q^3}$$

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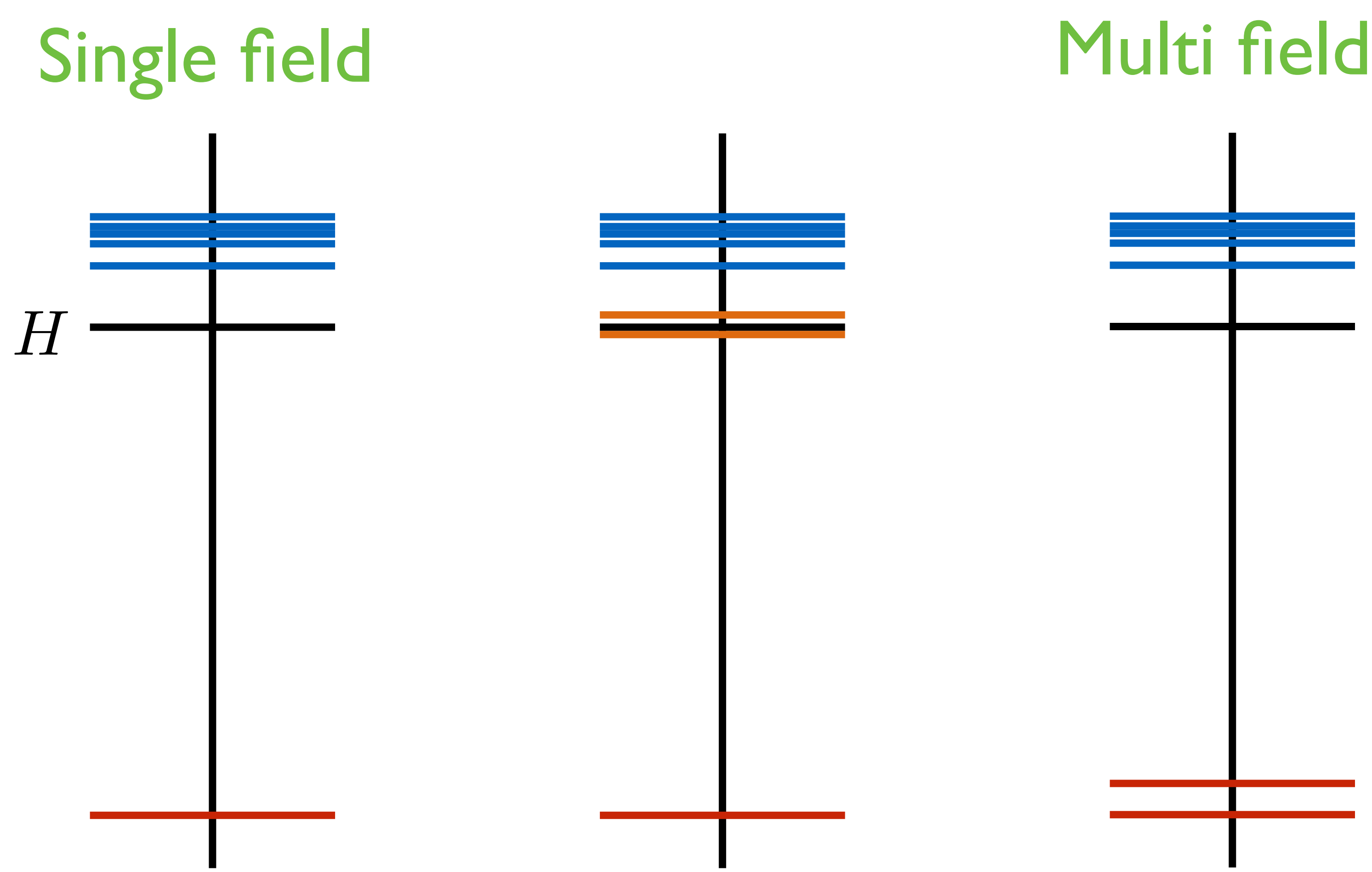

$B(q, k_1, k_2) \overset{q \to 0}{\sim}$ $\frac{1}{q}$ $\frac{1}{q^\alpha}$ $1 < \alpha < 3$ $\frac{1}{q^3}$

X. Chen, J. Wang, 2009

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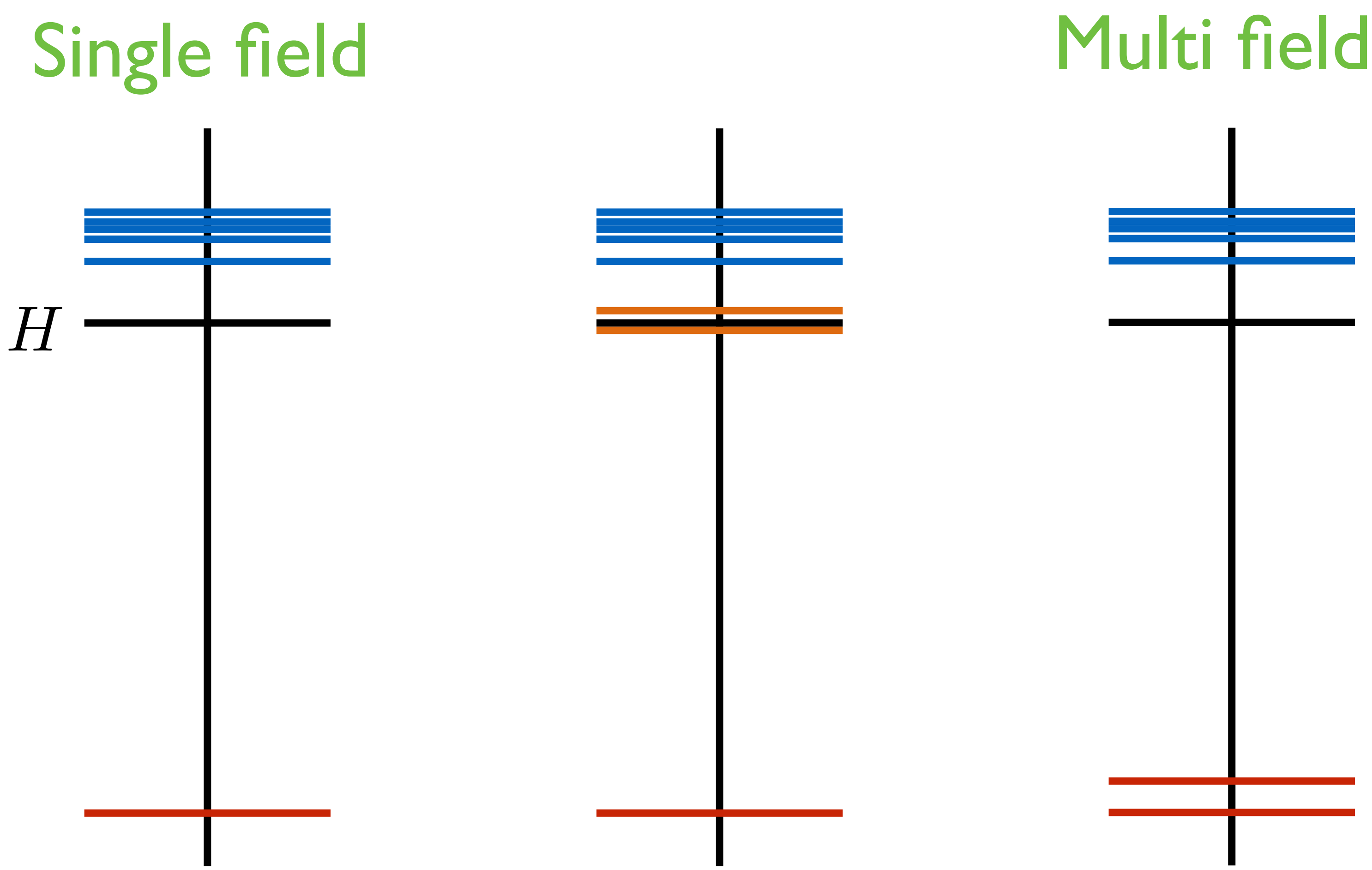

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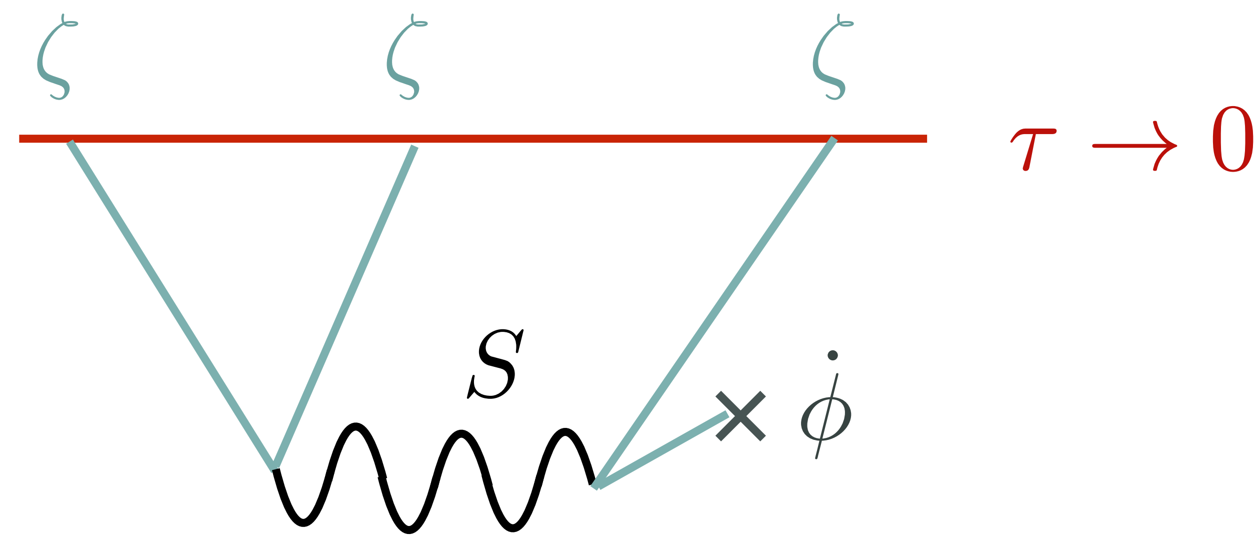
Figure: Assassi, Baumann, Green, 2012

Other fields



$$\langle \zeta(q)\zeta(k)\zeta(k)\rangle \sim e^{-\pi\mu}\left[e^{i\delta(\mu)}\left(\frac{q}{k}\right)^{\frac{3}{2}+i\mu} + e^{-i\delta(\mu)}\left(\frac{q}{k}\right)^{\frac{3}{2}-i\mu}\right] P_s(\cos\theta)$$

Characteristic angle dependence

$$\mu = \sqrt{\frac{m^2}{H^2} - \left(s - \frac{1}{2}\right)}$$

J. Maldacena, N. Arkani-Hamed, 2015
H. Lee, D. Baumann, G. Pimentel, 2016
A. Riotto, A. Kehagias, 2017
A. Moradinezhad, H. Lee, J. Muñoz, C. Dvorkin, 2018
L. Bordin, P. Creminelli, A. Khlemintsky, L. Senatore 2018

It's intrinsically non-linear

At large scales we can describe matter as a fluid

$$\frac{\partial \delta}{\partial \tau} + \nabla \cdot [(1+\delta)\vec{u}] = 0$$

↓

Continuity

$$\frac{\partial \vec{u}}{\partial \tau} + \mathcal{H}\vec{u} + \vec{u} \cdot \nabla \vec{u} = -\nabla \Phi$$

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Euler

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Solutions are often written as an expansion for small perturbations

$$\delta(\vec{k},t) = \sum_{n=1}^{\infty} a^n(t) \int_{\vec{k}_1 \ldots \vec{k}_n} F_n(\vec{k}_1, \ldots, \vec{k}_n)\delta_o(\vec{k}_1) \ldots \delta_o(\vec{k}_n)$$

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The bias can be non-linear, k-depdt., etc. $\delta_g = b_1 \delta + b_2 \delta^2 + c_s \partial_i \partial_j \Phi \partial^i \partial^j \Phi + \ldots$

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All of this generates a large and difficult to quantify non-Gaussian signal!!

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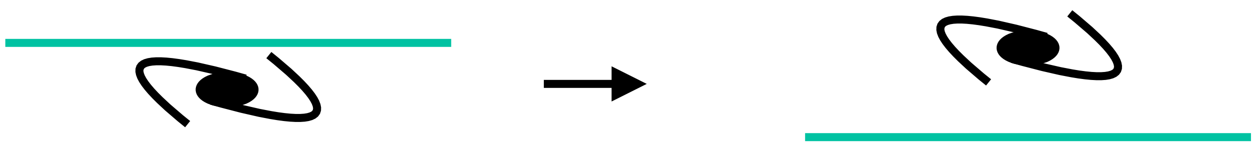
A homogeneus gravitational potential has no physical meaning

$$\Phi \to 0$$



Peloso, Pietroni, 2013 Kehagias, Riotto, 2013 Creminelli, JN, Simonović, Vernizzi, 2014

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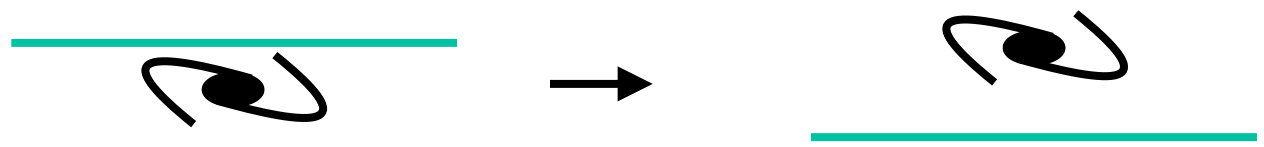
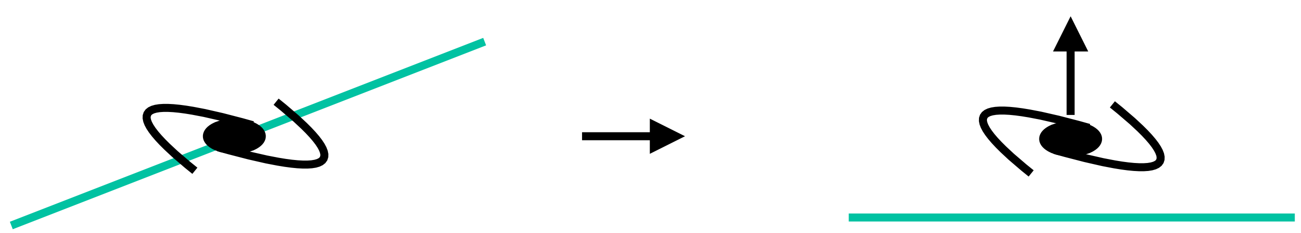


A homogeneus gravitational force can be set to zero by going to a freely falling frame

$$\nabla\Phi \to 0$$

$$\vec{V} \to \vec{V} - t\nabla\Phi$$



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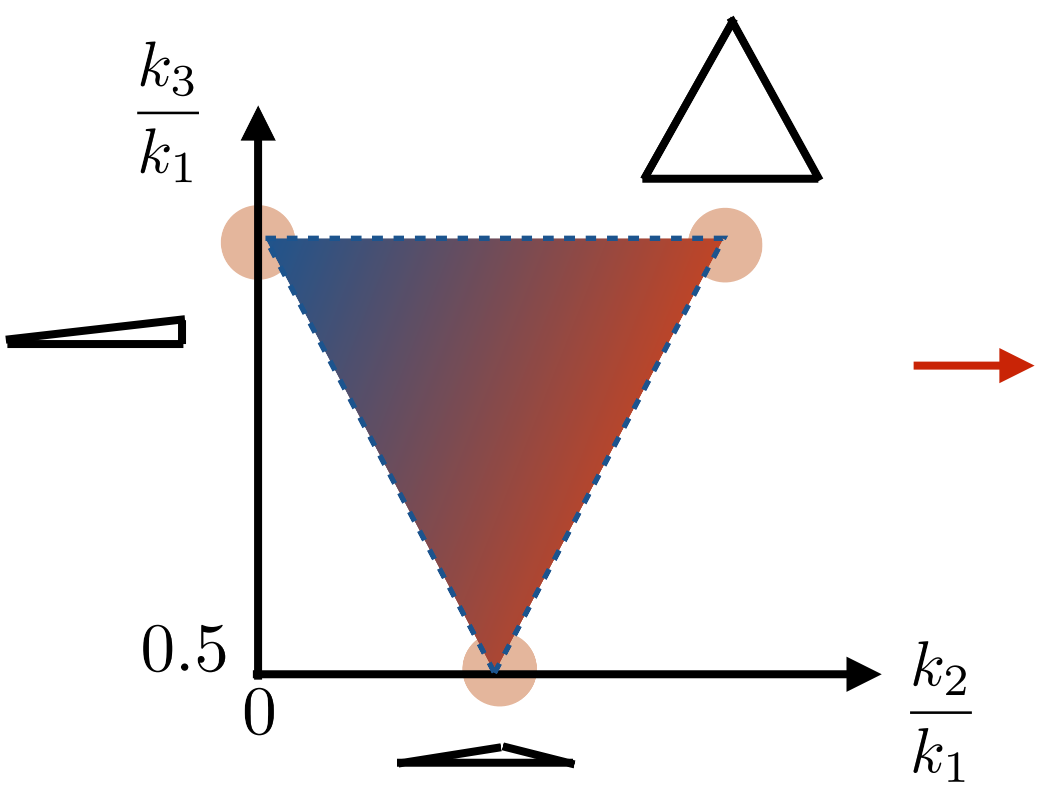
Non-Gaussianity: Can we improve?

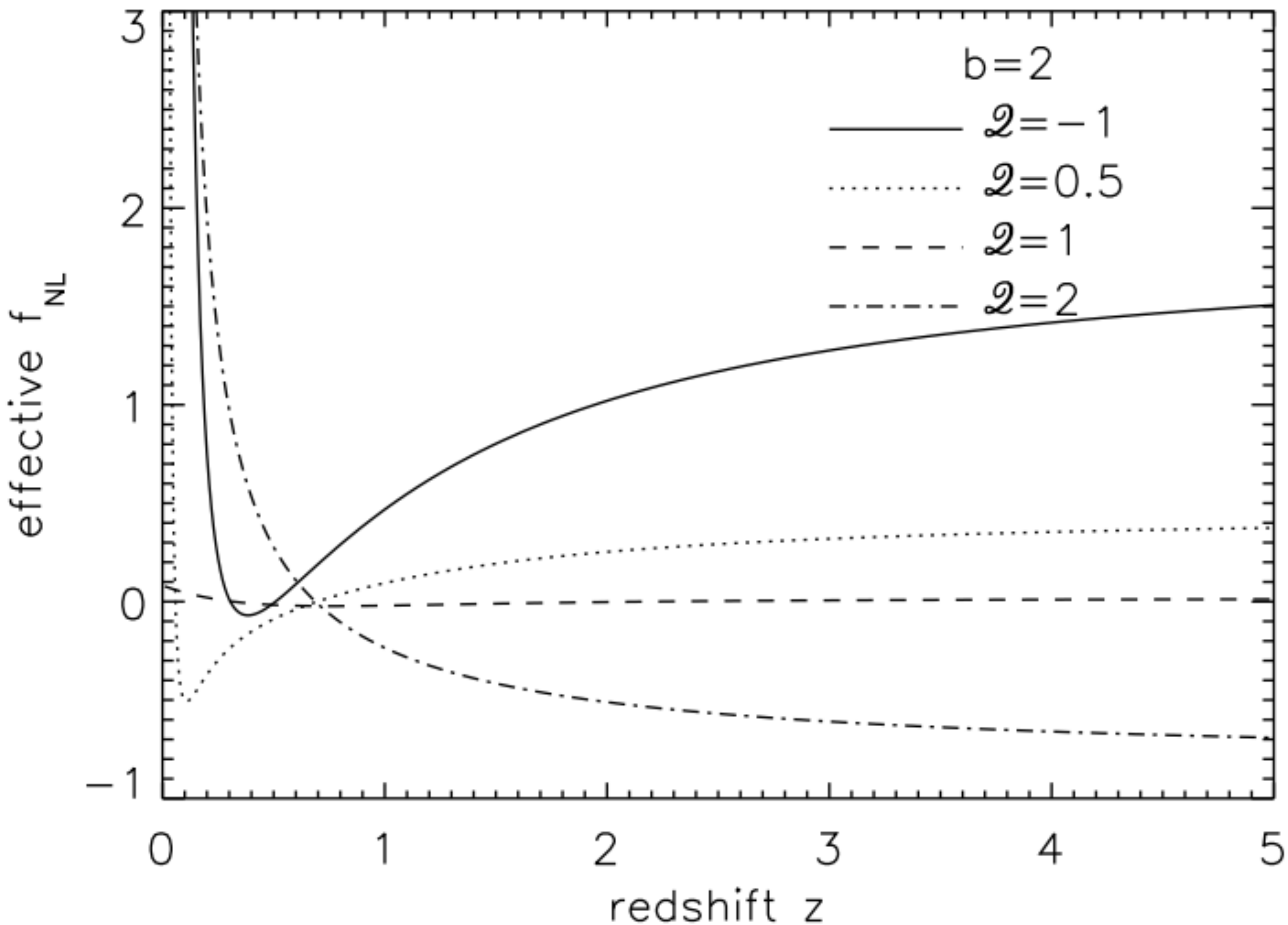
$$\langle\zeta(\vec{k}_1)\zeta(\vec{k}_2)\zeta(\vec{k}_3)\rangle = (2\pi)^3\delta(\vec{k}_1+\vec{k}_2+\vec{k}_3)B(k_1,k_2,k_3)$$



Degenerate with non-linear growth, biasing and astrophysics.

While we believe that the squeezed limit is much more solid.

Relativistic power spectrum



Jeong, Schmidt, Hirata, 2011

Relativistic bispectrum

Standard steps to compute the bispectrum

- Expand the metric and stress tensor in perturbations

$$ds^2 = -(1+2\Phi)dt^2 + 2\omega_i dx^i dt + a^2((1+2\Psi)\delta_{ij} + \gamma_{ij})dx^i dx^j \qquad \rho = \bar{\rho}(1+\delta)$$

Jolicoeur, Umeh, Maartens, Clarkson, 2014 … 2019,
Di Dio, Durrer, Marozzi, Montanari, 2014, 2015
Yoo, Zaldarriaga, 2014, Fanizza, Yoo, Biern, 2018 …

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- Fix a gauge:

Poisson:	Synchronous-comoving:
$\partial_i \omega_i = 0$	$u^0 = \frac{dx^0}{d\tau} = 1$
$\partial_i \gamma_{ij} = 0$	$\partial_i \gamma_{ij} = 0$

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- Solve for the photon geodesic at second order to get lensing and redshift space distortions.

Jolicoeur, Umeh, Maartens, Clarkson, 2014 … 2019,
Di Dio, Durrer, Marozzi, Montanari, 2014, 2015
Yoo, Zaldarriaga, 2014, Fanizza, Yoo, Biern, 2018 …

Estimating non-linearities + GR

Let us estimate how large these effects can be for the bispectrum

Lets expand the "observed" over-density as

$$\delta_{obs} \sim \delta_o + \alpha\phi + F_2\delta_o^2 + F_2^R\phi\delta_o$$

The bispectrum in the squeezed limit will then be

$$\langle \delta^L_{obs}(\mathbf{q})\delta^s_{obs}(\mathbf{k})\delta^s_{obs}(\mathbf{k})\rangle \sim 2F_2P_\delta(q)P_\delta(k) + 2\alpha\frac{H^2}{q^2}F_2P_\delta(q)P_\delta(k) + \frac{H^2}{q^2}F_2^RP_\delta(k)P_\delta(q)$$

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$$+ P_\delta(q)\int_{\mathbf{p}} F_3F_2P_\delta(|\mathbf{k}-\mathbf{p}|)P_\delta(p)$$

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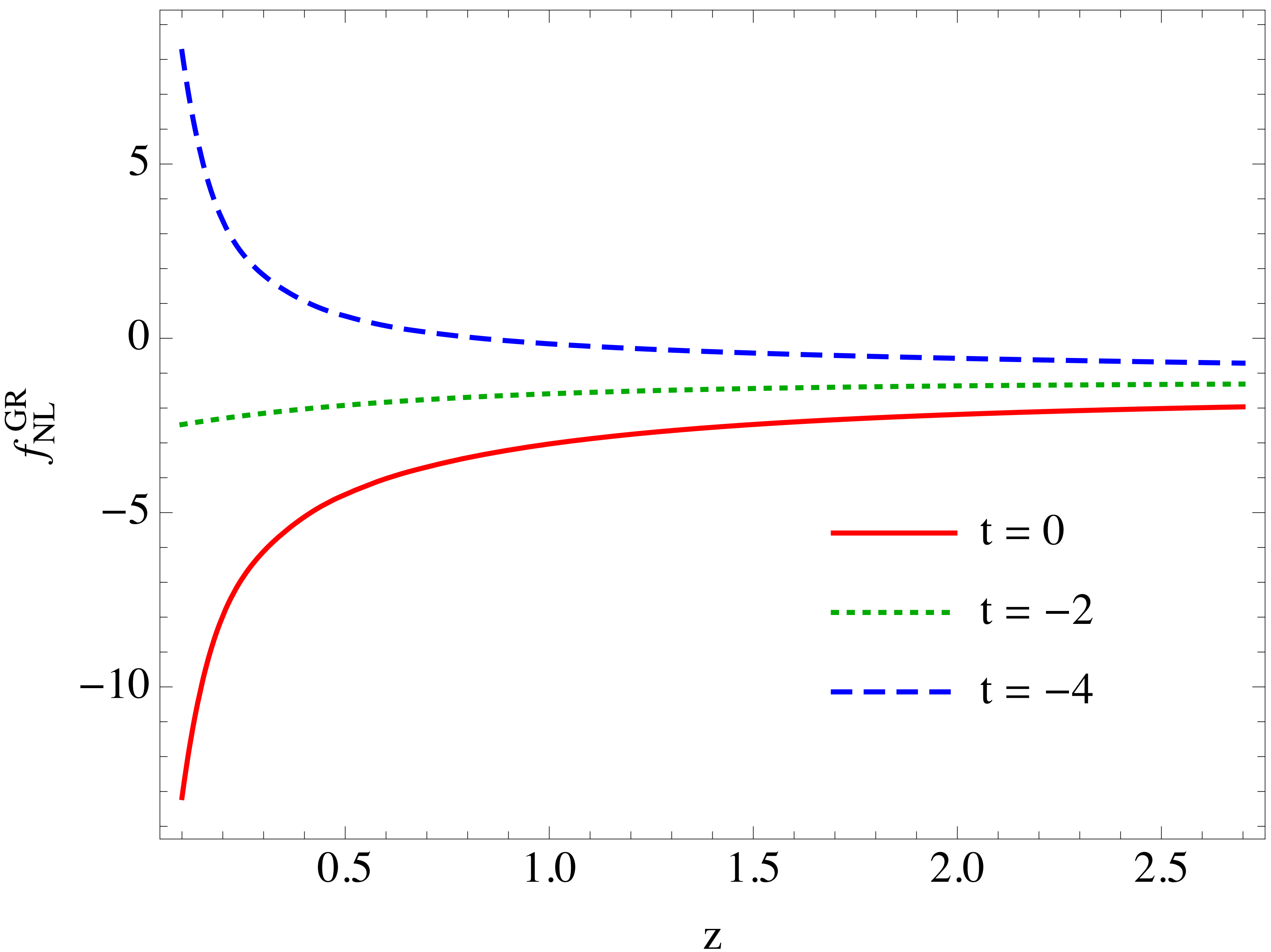
The very squeezed limit

Sum of all terms going like $\langle \Phi \delta \delta \rangle$



A. Kehagias, A. Moradinezhad, JN, H. Perrier, A. Riotto, 2015

Castiblanco, Gannouji, JN, Stahl, 2018

Weak field approximation

The 1-loop bispectrum requires 4th order perturbation theory…

Seems impossible in GR, but… even on small scales:

$$\Phi \sim \mathcal{O}(10^{-5}) \qquad \vec{v} \sim \mathcal{O}(10^{-3})$$

Density, however, becomes non-linear $\delta = \frac{2k^2}{3a^2H^2}\Phi$

Green, Wald, 2011, Adamek, Durrer, Kunz, 2014

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For simplicity take the universe to be Einstein de Sitter.

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Differences with Newtonian case

Newtonian case

Relativistic corrections

Castiblanco, Gannouji, JN, Stahl, 2018

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Reabsorb $\langle \delta \rangle$ in $\bar{\rho}$.

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$$\Longrightarrow \langle\delta\rangle = 0$$

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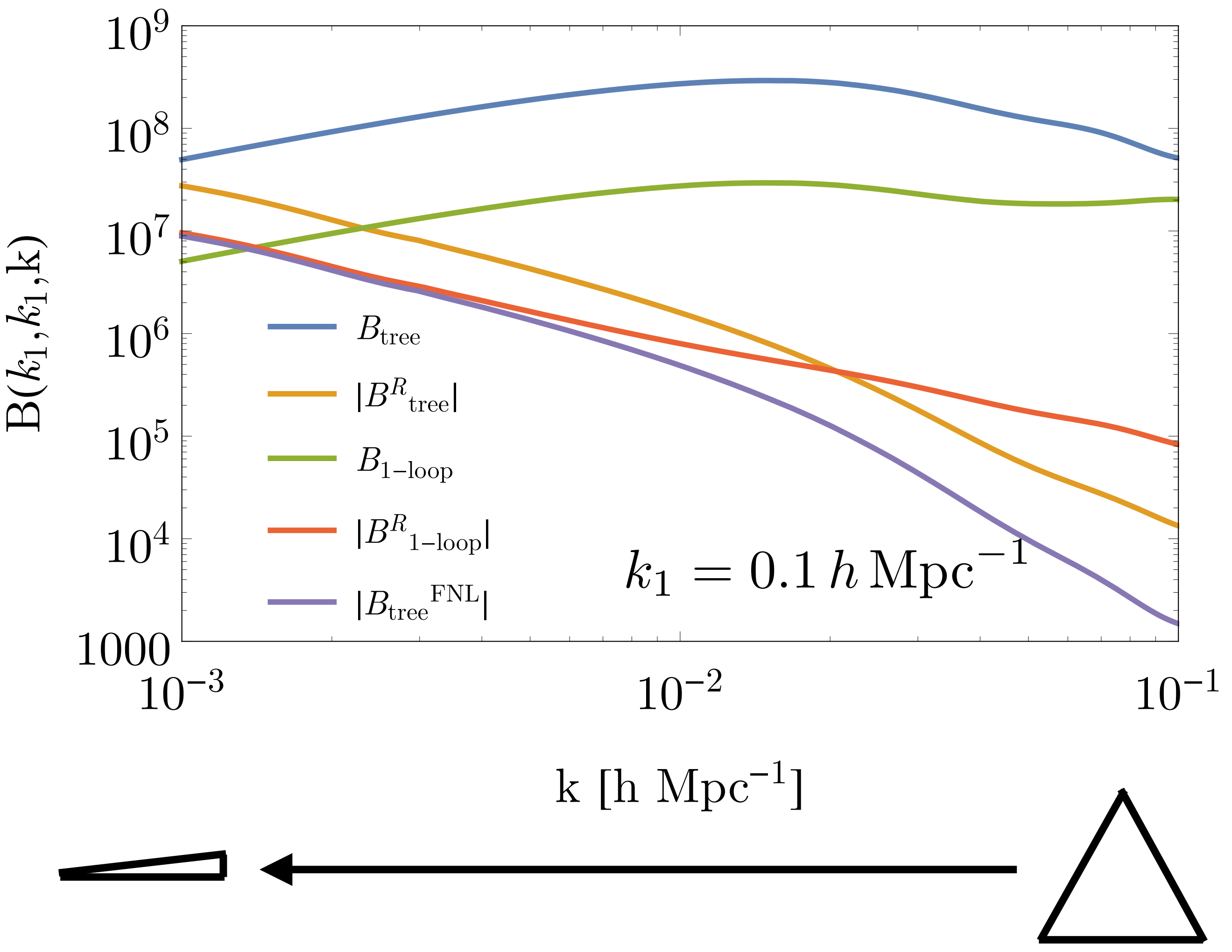
Reabsorb $\langle\Phi\rangle$ with $\bar{p}$.

Result

Synchronous



Castiblanco, Gannouji, JN, Stahl, 2018

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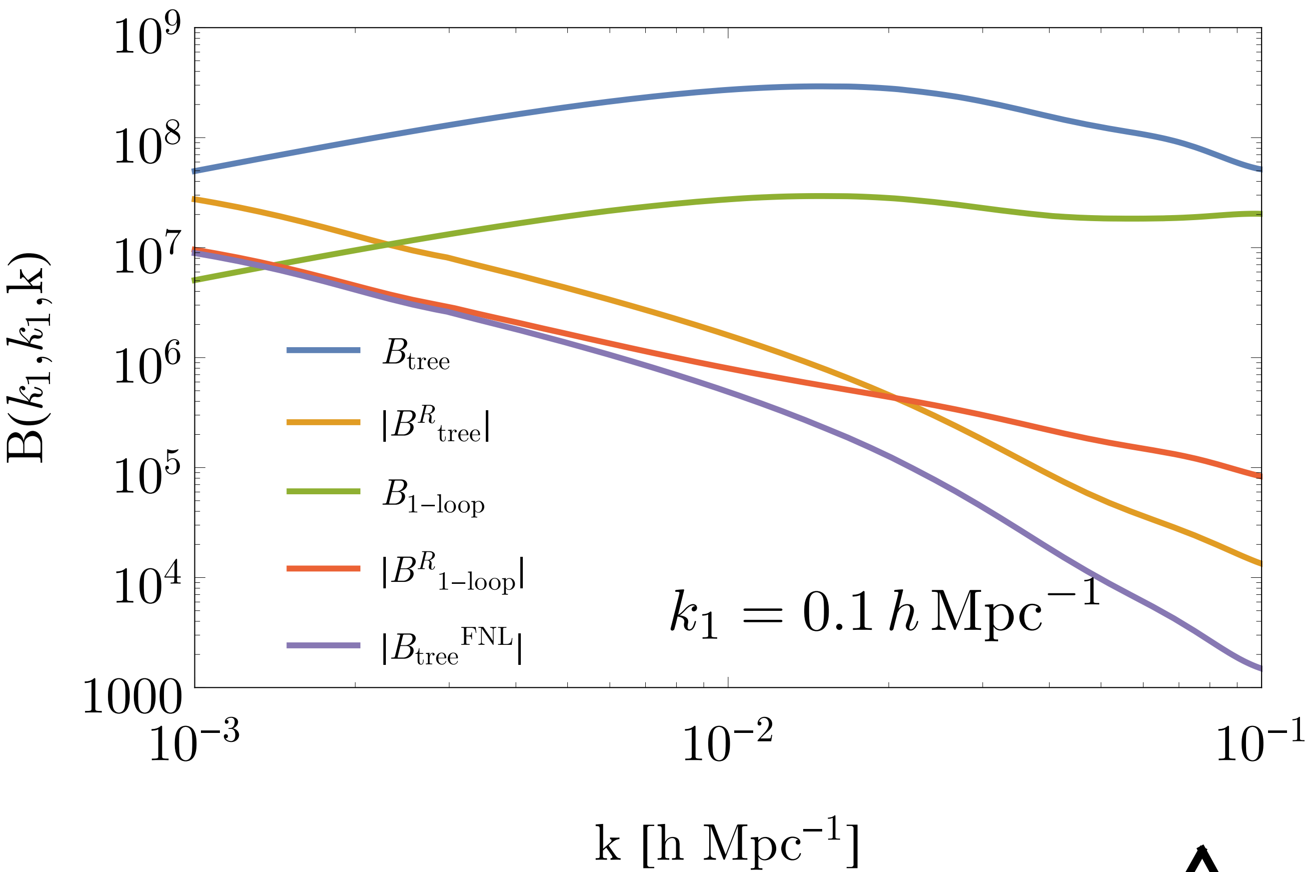
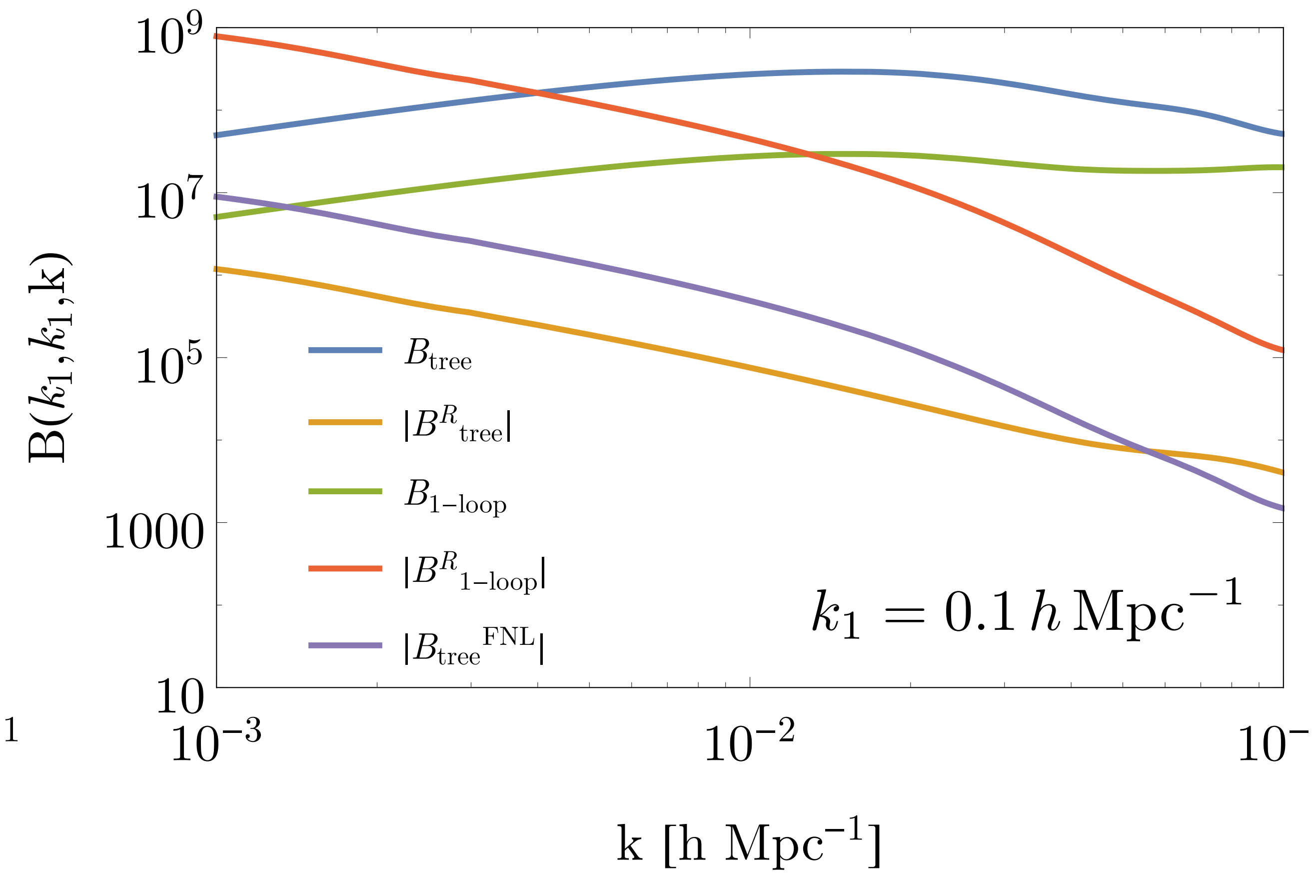
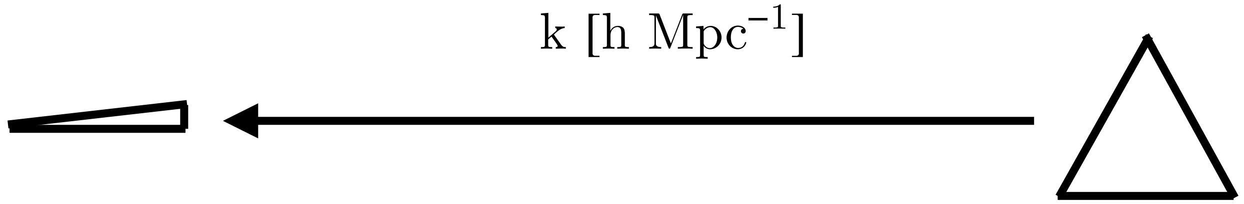


Poisson

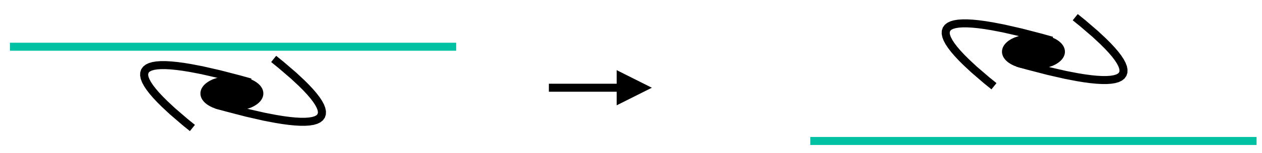




Calles, Castiblanco, Gannouji, JN, Stahl, in progress…

Bias

Galaxy formation is a local process, insensitive to a very long mode



In a local frame, the gravitational potential nor the gradient of the gravitational potential should appear in the bias expansion.

Easy, expand in $\nabla^2\phi$ and $\partial_i\partial_j\phi$. But…

Pajer, Schmidt, Zaldarriaga, 2013

Creminelli, JN, Simonović, Vernizzi, 2014

Kehagias, JN, Perrier, Riotto 2015

Umeh, Koyama, Maartens, Schmidt, Clarkson, 2019

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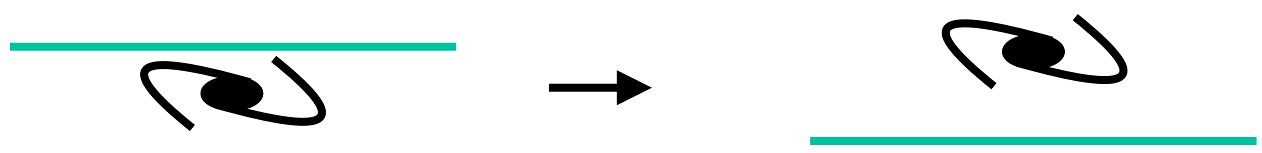

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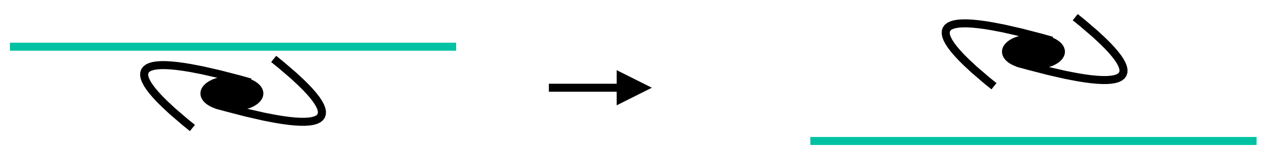

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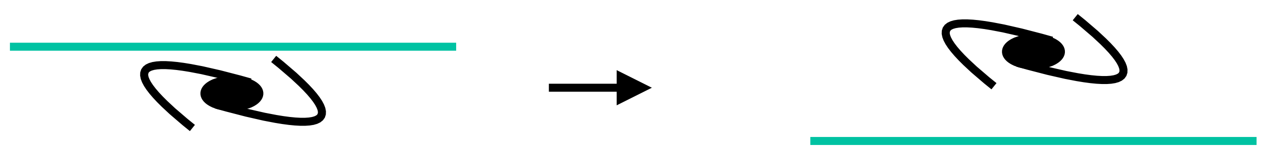

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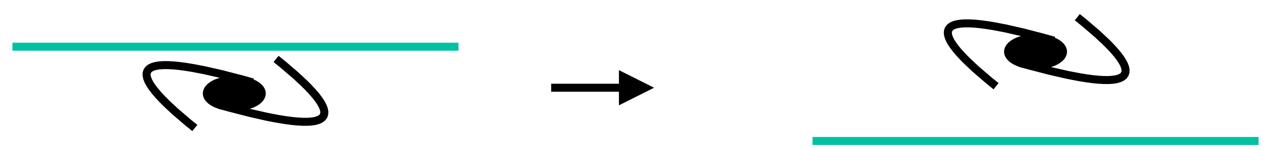

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Pajer, Schmidt, Zaldarriaga, 2013

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Conclusions

- The squeezed limit of the bispectrum can be degenerate with relativistic projection effects when measured either with the scale-dependent bias or the galaxy bispectrum.
- In order to use information from mildly non-linear scales for the squeezed limit bispectrum, it is crucial to compute it at one loop in GR.
- We have computed the metric to the appropriate order in two different gauges.
- GR effects are important (only) if you hope to achieve

$$\Delta f_{\rm NL} \sim \mathcal{O}(1)$$

THE
END